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R&D on EAS radio detection with GRANDproto

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In order to study ultra-high-energy cosmic-ray (UHECR) sources, we need not only to know their direction, energy and chemical composition, but also acquire large statistics of experimental data, with large effective area and high duty cycle. Radio antennas present some attractive aspects in this perspective, with very low unit costs, easiness of deployment over large areas and 100% duty cycle. They therefore seem to be a promising technique for detecting UHECRs.

In the Tianshan Mountain range (Xinjiang Autonomous Region, China) a radio-interferometer named 21 CMA was deployed, which aims at studying the epoch of reionization by detecting the hydrogen 21 cm radiation. On this site, the Sino-French cooperation experiment TREND (Tianshan Radio Experiment for Neutrino Detection) has performed autonomous detection and identification of EAS with a stand-alone and self-triggered array of 50 radio antennas. This inspires us to investigate the polarization characteristics of the radio signal with a hybrid array of 24 scintillators and 35 antennas measuring the x, y and z components of the electric field emitted by air showers. This hybrid setup is expected to provide a quantitative evaluation of the EAS identification and background rejection of the radio technique. If successful, this experiment would open the door for stand-alone, giant radio arrays dedicated to the study of high energy cosmic particles, such as the GRAND project.

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1. Introduction

The 21cm array (12CMA) was built in the Tianshan mountain range, XinJiang, China by the National Astronomical Observatory of China. Taking advantage of the very good electromagnetic environment of this remote experimental site and the existing infrastructures, the Tianshan Radio Experiment for Neutrino Detection (TREND) was deployed in 2008 on the 21CMA site (Fig.1). It

Fig. 1: Picture of the 21CMA antenna array and one scintillator detector from the TREND experiment.

is an array of radio antennas used to investigate the possibility to perform autonomous radio detection and identification of extensive air showers (EAS). Results of the TREND project are briefly described in section 2. The long term perspective of TREND is to deploy a giant array dedicated to the detection of cosmic neutrinos, through the detection of the Earth-skimming EAS produced by the decay in the atmosphere of tau leptons derived from the charged-current interaction of tau neutrinos underground [1-3]. The associated project is called GRAND (Giant Radio Array for Neutrino Detection) [4] and would require an extremely efficient rejection of background events, given the very low rate of neutrino events expected. To investigate this specific issue, the TREND collaboration proposes to deploy on the same site as TREND a hybrid array named GRANDproto, composed of 35 radio antennas and 24 scintillators. This project, in particular the development of the scintillator array is described in sec. 3, conclusion is presented in sec. 4.

2. Results of the TREND experiment

The TREND experiment ran from 2009 to 2014. Its primary goal was to establish the possibility to perform autonomous detection and identification of EAS with a radio array. TREND relies on a very fast acquisition system, allowing to record 5 µs-long waveforms sampled at a 200MS/s rate, for a trigger rate up to 200Hz for each antenna. The identification of EAS candidates is performed offline through a selection algorithm based on specific features of EAS radio signals: flat wave front, focused trigger pattern at ground, random time and directions of arrival. A first phase with only 6 antennas allowed validating TREND's acquisition system and EAS search procedure. 15 antennas were then deployed early 2010 over an area of 350 m × 800 m. Three scintillators were installed at the same location, with independent trigger system and reconstruction procedure. It was found that some EAS radio-candidates were in spatial and temporal coincidence with scintillators events. This shows that these radio events have indeed been induced by EAS and therefore constitutes an unquestionable proof that autonomous radio-detection and identification of cosmic rays has been performed by TREND [5].

The TREND array was then extended to 50 antennas in 2011. During years 2011 and 2012, the TREND monopolar antennas were oriented along the East-West direction. In the data of 317 live days during this period, 465 EAS candidates were selected, following the identification procedure defined in [5]. The distribution of the direction of arrivals of these 465 events shows a clear North-South asymmetry, as expected from the geomagnetic effect, the dominant process for EAS electromagnetic emission [6]. A massive Monte-Carlo (MC) study of the TREND detector response to EAS with energies between 5×10^{16} and 5×10^{17} eV and isotropic direction of origins down to 80 ° in zenith angle was then completed. This simulated response, generated with the CONEX code [7] for air shower simulation, EVA [8] for their electromagnetic emission and NEC [9] for the antenna response, exhibits a very similar distribution of directions of arrivals for simulated energies between 8×10^{16} and 2×10^{17} eV and zenith angles smaller than 70 °.

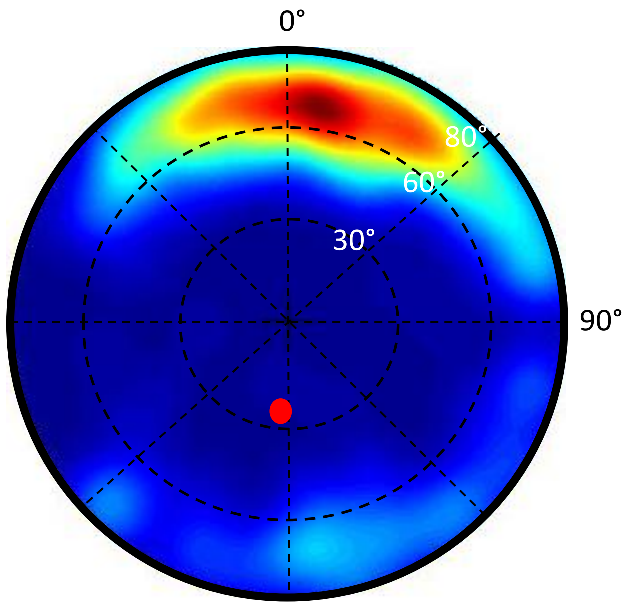

Fig. 2: skyplot of the 465 EAS candidates selected from the 2011-2012 TREND dataset. North corresponds to azimuth angle φ = 0° (top) and East to φ = 90° (right). The largest circle corresponds to zenith angle θ = 80°.

This result shows that EAS could be detected successfully by TREND, with limited contamination by background events. However, there is problem on the background rejection and estimation of the background contamination rate in the full data set, and is, in this respect, not sufficient for neutrino search. In the perspective of the GRAND project, an alternative method, based on the polarization pattern of the detected events, will therefore be investigated in order to reach the satisfying level of performance in terms of background rejection.

3. Proposed polarization experiment

A characteristic signature of EAS radio signals is their polarization. Electromagnetic radiation emitted by EAS is mainly due to the geomagnetic effect, a phenomenon corresponding to the deviation of the shower's electrons and positrons from their trajectory under the influence of the Lorentz force $\boldsymbol{F}=\pm e\boldsymbol{v}\wedge\boldsymbol{B}_{geo}$, where $\boldsymbol{B}_{geo}$ is the Earth magnetic field and $\boldsymbol{v}$ the particle velocity. This induces at first order a linear polarization of the EAS radio signal, perpendicular both to the geomagnetic field and to the direction of propagation of the shower. A more refined prediction of the polarization pattern can be performed through simulation, as shown successfully by the AUGER-AERA experiment [10]. We believe that the measurement of this polarization pattern over all triggered antennas for a given event could be an efficient criterion to discriminate EAS from background events.

We therefore propose to deploy a hybrid array composed of 35 antennas and 24 scintillators to check this hypothesis and assess its discrimination power. The antennas are composed of 3 arms, allowing a complete determination of the wave's polarization at the antenna location. Only events with a polarization pattern compatible with what is expected for EAS would be selected as EAS candidates, all others rejected. The scintillator detector array installed on the same site would be used for cross-check: independent detection and compatible reconstruction by the two arrays would clearly sign the EAS nature of the events. This setup would therefore allow determining quantitatively the background rejection potential of this technique. In the following we detail the development of the hybrid array.

3.1 Antenna array

The preferred idea is that the detection unit should be composed of three antenna arms orientated along three perpendicular directions (Fig. 3). Maximum amplitudes measured on the three corresponding channels for a given transient signal would allow determining the polarization information of the electromagnetic radiation, which may prove to be a key element for EAS identification.

Fig.3: Prototype of the 3-arms antenna

A very basic trigger logic would be preferred: the raw analog signals from the three channels would be independently compared to a fixed threshold set at a few times the electromagnetic background noise level, and the envelope of the signals from all three channels would be recorded when a transient pulse exceeds the threshold on any of these channels. This straightforward solution is valid as long as no strong background noise source dominates the electromagnetic background: as the trigger is built on the raw analog signal, there is indeed no way that a specific frequency or source could be filtered out before trigger stage.

Simulations of background EAS signals are included in our MC study in order to perform a reliable estimation of their contribution [4]. Ten 3-arms antennas have been tested on site since 2014 and behave as expected.

3.2 Scintillator array

Usually the performance of EAS radio detection should be checked or confirmed by another detection technique. The relevance of the radio signal on the energy and chemical components of the cosmic rays should be validated by another detection technique; scintillator is a commonly used detector. In this hybrid experiment, as the scintillator array will detect air showers only, it will be used to cross-check if selected radio candidates are indeed air showers or only background. Study on the energy and chemical components of the cosmic rays will be arranged in the next experiment. In addition to this, both the performance and cost are to be considered in the development of the scintillator. Based on these, the development of the scintillator is carried out.

3.2.1 Development of the scintillator detector

The advantage of plastic is its ability to be shaped, through the use of molds or other means, into almost any desired form with a reasonable degree of durability. Moreover, plastic scintillator has the advantage of fairly high light output and a relatively quick signal, with a decay time of ~2 ns. The air light-guide scintillator detector is very low cost and its shape can be adapted to the container. For above reasons, an air light-guide with large section to maximize the light yield and an adequate surface not to penalize the detector time resolution comes into the scope of our study.

The photons, produced inside scintillators by cosmic rays, are reflected on the polished surface of the scintillator when satisfying the requirement of total internal reflection, or at the surface of the reflective wrapping material when passing through the scintillator. After coming out of the scintillator, these photons run through the air light-guide to the sensitive area of the PMTs. Wrapping material around the scintillator could raise the reflectivity and amplify the photon numbers, because the photons are reflected by the wrapping material back into the scintillator again [11]. Various options have been investigated for the light guide reflective materials. Finally, Tyvek 1082D is selected as the reflective material to cover the inner surface of the light-guide box and to wrap the scintillator.

Fig. 4: Prototype of the scintillator detector

Considering that when light is incident on a rough surface and is isotropically reflected with equal intensity in all directions, surface roughness of the scintillator is investigated. As a result, EJ-200 plastic scintillator with four machined edges, one polished face and one sanded face is selected as the detection material whose size is 70.7 cm × 70.7 cm × 2 cm. Fig.4 shows the developed prototype of scintillator.

3.2.2 Optimization of scintillation detector layout

Table 1. Scintillator detector layout. EW: East-West direction, NS: North-South direction.

Layout No.	Colum (EW,x)	Row(NS, y)	Spacing(x) m	Spacing(y) m	Total area km^2
1	4	6	100	200	0.3
2	4	6	200	400	1.2
3	4	6	300	600	2.7

In order to combining with the antenna array, considering that our radio detector has a high sensitivity only at ≥10^{17} eV, the scintillator array should be sensitive in particular in this energy region. Besides, the events detected by the radio array should also be detected by the scintillator array, so the scintillator array is ought to be installed inside the antenna array. Based on these, three layouts listed in Table 1 are investigated through MC simulations.

(1) Figure Of Merit

If the detector array could get big signals with a maximum background rejection, it is the array we need. In respect of this, we define Figure Of Merit (FOM) as follows:

$$FOM = \frac{Signal}{\sqrt{Background}} \qquad (1)$$

Where, "Signal" is the detected high energy (≥10^{17} eV) cosmic rays, "Background" is composed of the muon background and the detected low energy (<10^{17} eV) cosmic rays.

The observed results presented in ref. [12, 13] shows that the flux of muon decreases along the atmospheric depth. At 2.7 km altitude, the muon (low energy) flux is 293 $m^{-2}s^{-1}$over the whole sky. Assuming a 5.7 μs window for the muon signal, we can compute a random background rate of ~0.12 Hz due to muons in the GRANDproto scintillator array.

（2）Simulation result

In the case of layout 1, FOM is 0.16 when muon background can be cut off (benefited from the radio data), 0.40 and 0.87 of layouts 2 and 3 respectively. It shows that with a fixed number of detectors a better performance is expected when we have larger detector spacing.

When the numbers of the scintillators are fixed, we get a small array area with a small spacing, which could not cover the whole antenna array; moreover, in the case of small spacing the low energy cosmic ray event, as a background, also has a high efficiency. In the simulation, the efficiency of the high energy part, the spacing and the rejection of the low energy background are taken into consideration at the same time.

Table 2：Four layouts' efficiency comparison

Layout \ Energy(eV)	10^{16}	$10^{16.2}$	$10^{16.4}$	$10^{16.6}$	$10^{16.8}$	10^{17}	$10^{17.2}$	$10^{17.4}$	$10^{17.6}$	$10^{17.8}$
1	0.67	0.71	0.84	0.90	0.93	0.98	1.00	1.00	1.00	1.00
2	0.28	0.42	0.50	0.68	0.73	0.86	0.95	0.97	1.00	1.00
3	0.06	0.15	0.27	0.49	0.57	0.73	0.88	0.91	0.98	0.98

Table 3：Four layouts' event rate (events/day) comparison

Layout \ Energy(eV)	10^{16}	$10^{16.2}$	$10^{16.4}$	$10^{16.6}$	$10^{16.8}$	10^{17}	$10^{17.2}$	$10^{17.4}$	$10^{17.6}$	$10^{17.8}$
1	60.99	25.06	12.29	5.47	2.35	1.07	0.36	0.12	0.04	0.01
2	101.34	58.74	29.11	16.47	7.37	3.72	1.38	0.47	0.16	0.05
3	50.70	47.41	35.51	26.73	13.02	7.13	2.88	1.00	0.36	0.12

Table 2 and 3 present the simulation results (considering the cosmic rays in Zenith from 45°to 70°and azimuth from -20°to 20°(south direction), the cut condition is at least 3 detectors fired).

And thus, the scintillator array is optimized to layout 2， as a compromise between large detection efficiency and acceptable event rate above 10^{17}eV.

4. Conclusion

Since 2009, the R&D of EAS radio detection in China has been started via the cooperation between researchers from the Chinese Academy of Science and French CNRS at the site of the 21CMA. The TREND experiment shows it is possible to detect and identify EAS with limited contamination by background events. The TREND collaboration now proposes, as a necessary step towards a giant array dedicated to the search for neutrinos, a setup called GRANDproto, which aims at evaluating the possibility to perform an event-by-event identification of EAS from the waves' polarization information measured by the radio antennas. A scintillator array will be deployed in the GRANDproto setup as a cross check for the EAS nature of the events selected.

The air light-guide detector with large section to maximize the light yield and an adequate surface not to penalize the detector time resolution is developed according to the requirements of the TREND experiment. Various options have been investigated for the light guide reflective material and detector roughness. Finally, Tyvek 1082D is selected as the reflective material; and EJ-200 scintillator with four machined edges, one polished face and one sanded face is selected as the detection material.

According to the characteristics of the scintillator detectors and the requirements of TREND experiment, for 3 different detector geometries, the signal and background are estimated. Via using Figure Of Merit formula, the optimized detector layout is obtained.

Looking forward to the future, the hybrid setup with 24 scintillators and 35 antennas is expected to provide a quantitative evaluation of the EAS identification & background rejection of the radio technique. And if successful, this experiment would open the door for stand-alone, giant radio arrays dedicated to the study of high energy cosmic particles, such as the GRAND project.

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References

[1] E. Zas, F. Halzen, T. Stanev, *Electromagnetic pulses from high-energy showers: Implications for neutrino detection,* Phys. Rev. D, 1992, 45,362.

[2] X. Bertou and et al, *Tau neutrinos in the Auger Observatory: a new window to UHECR sources,* Astropart. Phys., 2002, 17, 183.

[3] E. Zas, *Neutrino detection with inclined air showers,* New J. Phys, 2005, 7, 130

[4] O. Martineau-Huynh et al., the Giant Radio Array for Neutrino Detcetion, these proceedings.

[5] D. Ardouin and et al., *First detection of extensive air showers by the TREND self-triggering radio experiment,* Astroparticle Physics, 2011, 34,717.

[6] D. Ardouin et al., Astropart. Phys. 31 (2009) 192. <arXiv:0901.4502 [astroph]>.

[7] T. Pierog et al. , <arXiv :0806.1262 [astroph]>

[8] K. D. de Vries, 5th International Workshop on Acoustic and Radio EEV Neutrino Detection Activities: ARENA 2012. AIP Conference Proceedings, Volume 1535. AIP Conference Proceedings, Volume 1535, Issue 1, p.133-137

[9] *http://www.nec2.org/*

[10] A. Aab et al., Probing the radio emission from air showers with polarization measurements, Phys Rev. D 89 (Mar., 2014) 052002, [arXiv:1402.3677].

[11] Janina Struth, Muon detection with scintillation detectors using indirect SiPM readout, Bachelor Thesis, September 2010

[12] Particle Data Group, Chinese Physics C Vol. 38, No. 9 (2014) 090001

[13] Otto Claus Allkofer, INTRODUCTION TO COSMIC RADIATION, Verlag Karl Thiemig, 1975 090001