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Performance of GPS-synchronized EAS arrays in LAAS experiments

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Using data sets observed during 2.5 years with the Large Area Air Shower (LAAS) experiments in Okayama area, the primary cosmic ray energy spectrum were obtained by applying cuts on the number of coincidences of 4 extensive air shower (EAS) arrays, which are synchronized by GPS time stamp system within 1 μs accuracy. The spectral indices in the energy ranges of $10^{15} - 10^{16}$eV and $10^{16} - 10^{18}$eV were obtained and were consistent with assumed ones within statistical errors. The methods to determine the energy spectrum without evaluating the parameters for each individual EAS in each LAAS array, were reported in this paper.

1. Introduction

The understanding of origin and acceleration mechanisms of extremely high energy cosmic rays represents one of the most important aspects of high energy astrophysics. EASs produced by high energy cosmic ray have been observed, indicating the primary cosmic ray spectrum extends in energy beyond Greisen-Zatsepin-Kuzumin cutoff expected if the particle is hadronic in nature and comes from sources at distance greater than 50Mpc [1].

The LAAS experiments have deployed 9 EAS arrays in large part of Japan, in order to find intensity correlations of ultra high energy cosmic rays, by using GPS synchronized EAS arrays [2, 3]. The accuracy of a registered time stamp is 1 μs in UT. Since 2002, four EAS arrays have been operated in Okayama area as part of LAAS experiments, of which baselines are ranging from 100m to 1km [4]. The purposes of these arrays are to study the cosmic ray energy spectrum, anisotropy in arrival direction of cosmic rays and multiple EAS events. In this paper, we report the results on energy spectrum analysis from these four arrays as well as the analysis method.

2. LAAS in Okayama area and Analysis

The LAAS experiments have deployed four compact EAS arrays in the campus of Okayama Univ. of Science (OUS) and Okayama Univ. (OU) , since 2002. Three EAS arrays of them are deployed in OUS and one array in OU. The array size are limited by the dimensions and layout of the buildings in which the array was constructed. Each particle detector contained a 50cm$\times$50cm$\times$5cm thick plastic scintillator viewed by a 60mm diameter Hamamatsu H7195 photo-multiplier tube at the top of a detector hat of each enclosed box. If the two particle detectors, of which separation is 80cm, fire within 100ns period, the array is triggered. When trigger request generated, the data acquisition system registered the pulse height (ADC) and timing (TDC) of each particle detectors. The arrival time of each EAS was provided by GPS-controlled event timing module(Kaizu 3051A), in universal time with an accuracy of 1μs. The shower angles were reconstructed by fitting a shower front plane to measured TDC values at each detector. To identify EAS data from raw data, it was applied that the number of coincidences Nc was greater than 3 (Nc$\geq$3).

The time difference of EAS events between two arrays are calculated to find correlated EAS events in arrival time distributions. It can be expected that time difference spectra are well expressed as an exponential distribution because most of EAS events arrive randomly in time. However, it is apparent from Fig. 1 that the significant excess of event rates is found at around 1μs time difference in OUS-OUS combinations and OU-OUS combinations. Taking account of the resolution of GPS system, EAS front structures, and the baseline of array combinations, the EAS event pairs within 3μs are defined as a single EAS event which hits multiple EAS arrays simultaneously. The event rates obtained under the 3μs cut for all combinations of arrays are summarized in Table 1.

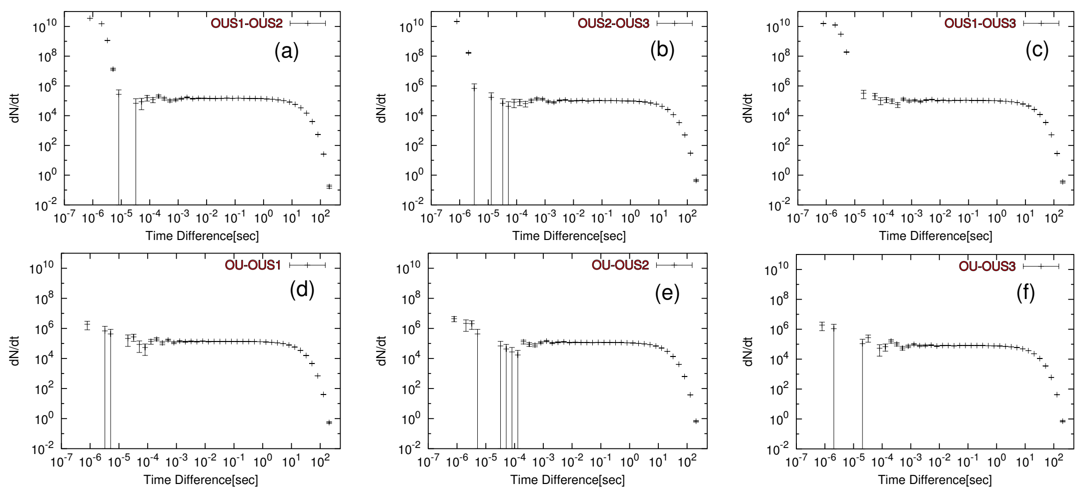

Figure 1. Time difference distributions for OUS-OUS and OU-OUS EAS array combinations: (a)OUS1-OUS2 ,(b)OUS2-OUS3 ,(c)OUS3-OUS1 for about 100m baseline combinations and (d)OU-OUS1, (e)OU-OUS2, (f)OU-OUS3 for about 1000m baseline combinations.

3. Array Performance Simulation

Monte Carlo simulations of each array performance were made on the basis of modified NKG lateral distributions of electron components with an energy threshold parameter equal to 5 MeV [5] and μ-on components[6]. The primary cosmic ray compositions are assumed as 90% protons and 10% Iron nuclei. The detectable angular range of EASs is less than 45 degree in LAAS arrays. The spectral indices of primary energy spectrum assumed in this calculation, are -2.7 for energies less than $10^{3.6}$TeV, and -3.2 for energies greater than that energy. The effective areas for each single array and each two-array coincident simultaneously were simulated under the condition required for EAS data acquiring and off-line analysis.

The results are summarized in Table 1. In case of single array detections, the observed primary energies range from 0.1 to 1.8 PeV. The primary energy of the EASs simultaneously detected in OUS-OUS combinations is about one order of magnitude greater than single array cases, which ranges from 3 to 30 PeV. And OU-OUS array combination allows to detect EAS of energies from 1 to 10 EeV. These energy selections with single or double array coincidences allow us to analyze the energy spectrum of EAS. The observed event rates are also compared with this simulation results, shown in Table 1. In figure 3, the integral spectrum obtained by synchronized EAS arrays is shown with simulation results and the energy spectrum assumed in this calculations. The data points determined by 4 sets of single array and OUS-OUS combinations are well described by $E^{-1.7}$. The spectral index of OU-OUS combinations is approximately -2.2. Although statistics are still poor in the highest data points, spectral indices obtained by LAAS experiments are in agreement with expected. Those results depend on an energy threshold parameter in NKG functions. In CORSIKA simulations, that values were selected as 7.5 MeV. The threshold energy dependences of average energies, effective areas and estimated intensity were shown in figure 2.

Table 1. Performance of LAAS EAS Array in Okayama area

Array	Median energy[eV]	Energy Range[eV]	Event Rate per day	
			Simulation	Observed
OU	6.3×10^{14}	$8.3 \times 10^{13} - 1.8 \times 10^{15}$	4630	2634
OUS1	5.3×10^{14}	$9.0 \times 10^{13} - 1.2 \times 10^{15}$	5510	3188
OUS2	6.3×10^{14}	$8.3 \times 10^{13} - 1.8 \times 10^{15}$	4650	3119
OUS3	5.3×10^{14}	$8.5 \times 10^{13} - 1.4 \times 10^{15}$	2630	2796
OUS1-OUS2	9.2×10^{15}	$2.4 \times 10^{15} - 1.9 \times 10^{16}$	70	98
OUS2-OUS3	1.4×10^{16}	$3.6 \times 10^{15} - 3.2 \times 10^{16}$	17	61
OUS3-OUS1	1.1×10^{16}	$3.0 \times 10^{15} - 2.6 \times 10^{16}$	25	66
OU-OUS1	6.9×10^{18}	$1.2 \times 10^{18} - 1.8 \times 10^{19}$	3.7×10^{-3}	8.0×10^{-3}
OU-OUS2	5.5×10^{18}	$9.9 \times 10^{17} - 1.3 \times 10^{19}$	5.1×10^{-3}	2.7×10^{-2}
OU-OUS3	6.5×10^{18}	$1.2 \times 10^{18} - 1.7 \times 10^{19}$	2.0×10^{-3}	1.0×10^{-2}

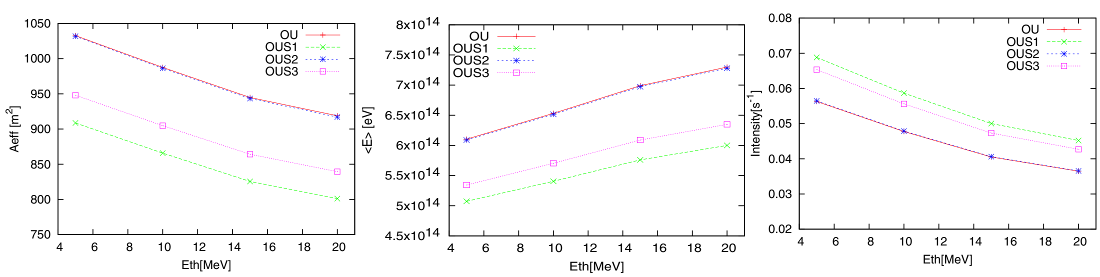

Figure 2. Threshold energy dependence of effective areas(left panel), average observed energy(center one) and primary cosmic ray intensity(right one).

4. Conclusions

LAAS experiments in Okayama area have operated for 2.5 years, four compact EAS arrays equipped with μs precise GPS timestamp. The data analysis method to detect simultaneous EAS events is to find event rate

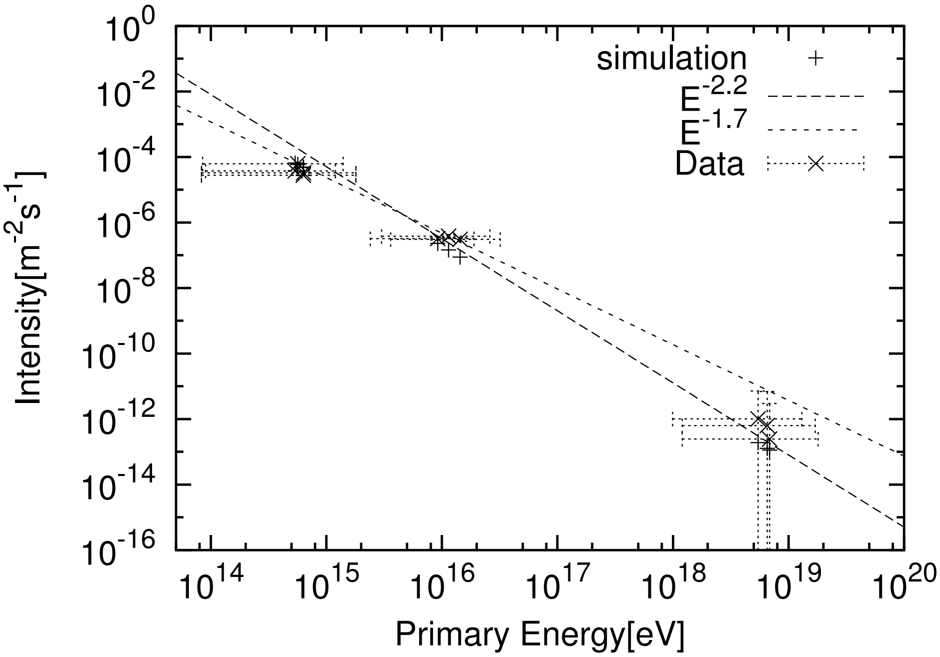

Figure 3. Integral cosmic ray energy spectrum with simulation results.

enhancements at several μs in time difference of EAS pair using two array dataset. In the simulation studies of array performances and simultaneous EAS event rate, observed energy ranges were estimated as about $10^{14} - 10^{15}$eV for each single array, $10^{15} - 10^{16}$eV for about 100m baseline arrays and $10^{18} - 10^{19}$eV for 1000m baseline arrays. The intensities observed at single arrays, 100m baseline arrays and 1000m baseline arrays are in agreement of the primary cosmic ray spectrum assumed in simulation studies.

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References

[1] N.Hayashida et al., Phys. Rev. Lett. 26(1994)3491-3494.
[2] N.Ochi et al., J. Phys. G:Nucl. Part. Phys. 29(2003)1169-1180.
[3] N.Ochi et al., Nucl. Phys.(Proc. Suppl.) B122(2003)337-340.
[4] A.Iyono et. al., Proc. 28th Int. Cosmic Ray Conf. (2003)199-202.
[5] E.J. Fenyves et al., Phys. Rev. D37 (1988)649-656.
[6] N. Hayashida et al., J. Phys. G:Nucl. Part. Phys. 21(1995)1101-1119.