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Multiple Linsley method for EAS energy determination in LAAS

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Abstract. The observation of the primary energy spectrum in its energy region of 10^{16} eV to 10^{19} eV by using compact Extensive Air Shower (EAS) arrays and the time structure of EAS particles which was studied by Linsley (Linsley method) have been carried out by the Large Area Air Shower group. We have estimated the EAS core distance by using only an EAS array and the Linsley method. To improve the determination accuracy of the primary energy, we consider the estimation method of the core distance by using two EAS arrays (multiple Linsley method). We report on the idea of the multiple Linsley method and the comparison of simulation results in various observation modes.

1. Introduction

Cosmic rays have been studied in order to understand the origin of the primary cosmic rays, its propagation mechanism and many other phenomena, and various experiments have been carried out. The Large Area Air Shower (LAAS) experiment is also one of them and has been carried out for the observation of Extensive Air showers (EASs) since 1996 [1, 2]. This experiment has researched EAS events observed simultaneously by EAS arrays located at distance of several 100 km to about 900 km. Each EAS array which have eight scintillation counters typically in the LAAS experiment, and they are installed on several observation sites in Okayama University of Science (OUS), Nara Sangyo University and Hirosaki University in 2018. The experimental results in large scale observations are reported on GZ-effect events [3, 4] by the photon disintegration in Ultra High Energy cosmic rays, and anisotropy of cosmic rays [5]. Additionally, Okayama group in LAAS has studied of the primary energy spectrum, a correlation between solar modulation and cosmic rays, and a comparison of hadronic interaction models.

The LAAS EAS array is compact one which have eight scintillation counters (up to eight scintillation counters) and covers an area of several 100 m^2, because the array is designed for the observation of simultaneous and large scale EAS events. Thus, the observation of the lateral distribution of electrons and muons is difficult, and the primary energy of EASs is not able to be obtained. However, ideas and experimental results obtained by Linsley [6] allowed the estimation of the primary energy of EASs in the primary energy region of 10^{16} eV to 10^{19} eV by using even a compact EAS array. The estimation of the EAS core distance has been carried

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out by using only an EAS array. In addition, we plan to estimate the core distance by using more than an EAS array.

We report on the simulation results of the acceptance and the accuracy of the primary energy determination in the estimation method in the EAS core distance by using two arrays.

2. EAS arrays

There are five EAS arrays which are described as OUS1, OUS2, OUS3, OUS4 and OUS5, respectively, in Okayama University of Science in Okayama, Japan. Figure 1 shows the arrangement of OUS arrays in the campus of Okayama University of Science. The OUS1∼OUS3

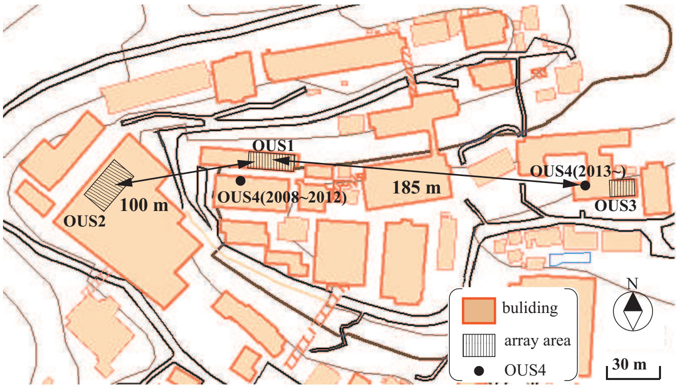

Figure 1. The arrangement of OUS arrays. This campus map is made by using a data in the Geospatial Information Authority of Japan [7].

are installed on the rooftop of buildings in OUS, and the OUS5 is installed on the ground in OUS's botanical garden located at ∼ 2km distance from OUS. The OUS4 array is installed in the same building set on the OUS3. The distance between the OUS1 and the OUS2 is about 100 m, and the distance between the OUS1 and the OUS4 is about 185 m.

OUS arrays equip eight plastic scintillation counters typically, of which size is 50 cm × 50 cm × 5 cm and a PMT. Each counter is covered a stainless-steel case of 0.5 cm thickness. Data acquisition system consists of a TDC, a ADC and a shift register module which is only equipped with the OUS1. Timing information of the event trigger of EAS is obtained by using a GPS module. Data of the TDC, the ADC and the GPS, and the shift register are stored in a Linux OS PC and a Windows OS PC, respectively. The EAS event trigger signal is generated by hitting more than three scintillation counters within 2.5 μs.

Event signals generated with counters are digitalized by a discriminator and are temporarily stored in the shift register. When the shift register receives the event trigger signal, timing information of event signals within ±2.5 μs time window from the trigger timing is stored to the Windows PC. The time accuracy of the shift register is 5 ns.

A GPS module is used for obtaining timing information of the event trigger and for synchronizing observation time among EAS arrays. The time accuracy of this module is maintained at 1 μs by receiving 1 pps GPS signal.

The OUS4 is used for obtaining the zenith angle of EAS. The OUS4 equips scintillation counters for the event trigger at the top layer and the bottom layer. The event trigger signal is generated by the coincidence of both counters. There are four scintillation counters as anticounters on each side of the OUS4. The trigger counters and the anticounters allow the restriction for the EAS zenith angle. When only the counters for the event trigger hit, a EAS zenith angle is obtained as within 30 degree. The OUS4 had been installed in the building located at distance of ~ 10 m from the OUS1, and was relocated to the near site of the OUS3 in 2013. The update of the OUS4 was reported on reference [8].

3. Estimation of EAS core distance

3.1. Linsley method

The relation between the EAS thickness and its core distance r had been studied by Linsley. His results allow the estimation of the EAS core distance with a compact EAS array. We described the estimation method of the EAS core distance by using EAS thickness as the Linsley method.

We defined a dispersion of the arrival time distribution of particles in each EAS as σ_t. The average of σ_t in observation data is described as $\langle\sigma_t\rangle$. In the Linsley method, $\langle\sigma_t\rangle$ is described as

$$\langle\sigma_t\rangle = \sigma_{t0}\left(1+\frac{r}{r_t}\right)^b, \tag{1}$$

where $\sigma_{t0} = 1.6$ ns, $r_t = 30$ m, $b = (2.08 \pm 0.08) - (0.4 \pm 0.06)\,\mathrm{sec}\theta + (0 \pm 0.06)\log\left(E/10^{17}\ \mathrm{eV}\right)$, θ and E are the zenith angle and the primary cosmic ray energy [6], respectively. The parameter b depends on θ and E, however, is used by the averaged value. The averaged b is 1.65 and is nearly equal to when $\theta \sim 30$ degree. We rewrite Eq. 1 as

$$r = r_t\left(\frac{\sqrt[b]{\langle\sigma_t\rangle}}{\sigma_{t0}} - 1\right), \tag{2}$$

and plot $\langle\sigma_t\rangle$ against r in figure 2.

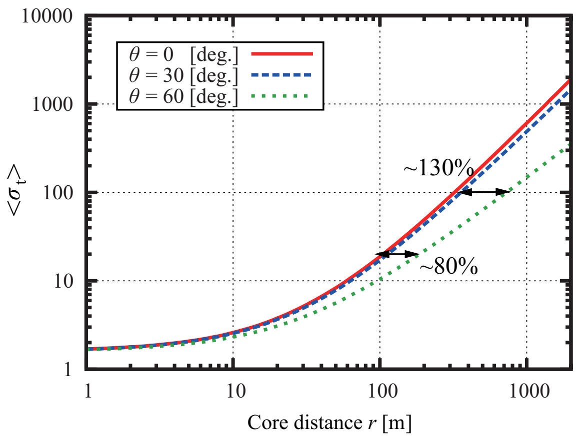

Figure 2. The relation of r and $\langle\sigma_t\rangle$, when $\theta = 0,\ 30,\ 60$ degree.

The systematic error of estimated r increase in increasing a difference between the true zenith angle and the averaged one. When $\theta = 60$ degree, the systematic error are 80 % ($\sigma_t = 20$) and 130 % ($\sigma_t = 100$), respectively.

The arrival time distribution of EAS is assumed to be a gamma distribution by Linsley. An estimator of the dispersion of the distribution is

$$\sigma_t = \frac{\langle t\rangle^2}{2}, \tag{3}$$

where t is the arrival time of EAS particles. We have adapted the median to the estimator, because of suppressing noise events. The discussion for estimators is reported on Okita [9]. Thus, σ_t is described as

$$\sigma_t = \frac{\sqrt{2}}{1.67} t_{\mathrm{m}}, \tag{4}$$

where t_{m} is the median of the arrival time distribution of EAS particles. Using Eq.2 and Eq.4, the core distance r is described as

$$r = 30 \left((1.35 t_{\mathrm{m}})^{\frac{1}{1.65}} \right). \tag{5}$$

3.2. Multi Linsley method

We have estimated the EAS core distance by using only an array. Additionally, we approach the estimation method by using two arrays and the Linsley method. This method is described as the Multiple Linsley method in this paper.

The core distance of EAS estimated independently by using the OUS1 and the OUS2 are described as r_1 and r_2, respectively. An EAS core position is estimated by the position with an overlap between r_1 and r_2. When there is not the overlap, we estimate the core position from the relation between r_1 and $r_2 + \Delta r_2$ ($r_1 > r_2$), or $r_1 + \Delta r_1$ and r_2 ($r_1 < r_2$), where Δr_1 and Δr_2 are systematic errors of r_1 and r_2, respectively. The selection criterion for the systematic error is within 100 % in consideration of the distance of two arrays.

4. Simulation result

The database of the lateral distribution and the shower size of electrons and muons required for carrying out the detector simulation is made by using Air shower simulation program AIRES [10]. In order to making the database, we assumed primary nuclei to be protons and irons, and hadronic interaction models to be QGSJET II-3 [11] /Hillas Splitting Algorithm [12]. The sampling of the primary energy E_0 is every $10^{0.1}$ eV in the primary energy region of 10^{15} eV to 10^{20} eV. The sampling of the EAS zenith angle θ is every 10 degree from 0 degree to 60 degree. The detector simulations of the OUS1, OUS2 and OUS4 are carried out by using this database. The procedures of the database simulation and the detector simulation are described in the reference [13].

4.1. Acceptance

Figure 3 shows the acceptance of each observation mode in case of proton primaries assumed. The OUS1 and the OUS1+2 represent the single observation of the OUS1 array only and the synchronized observation mode between the OUS1 array and the OUS2 array, respectively. And for the synchronized observation among above arrays and the OUS4, the OUS1+4 and the OUS1+2+4 are described, respectively. In a comparison of the OUS1 and the OUS1+2, the ratio of the acceptance of OUS1+2/OUS1 is about $1/2 \sim 1/3$ above $E_0 \geq 10^{17}$ eV, is $\sim 1/50$ in the low energy region. Similarly, in a comparison of the OUS1+4 and the OUS1+2+4, a ratio of the acceptance of OUS1+2+4/OUS1+4 is $\sim 1/5$ above $E_0 \geq 10^{17}$ eV, is $\sim 1/50$ in the low energy region. Event rates are expected to ~ 120 /day and ~ 1 /day in the OUS1+2 and the OUS1+2+4, respectively, because the average event rate of the OUS1 is ~ 6000 /day.

Figure 4 shows the acceptance of each observation mode in case of iron primaries assumed. The acceptance of each observation mode in iron primaries shows similar trend in case of proton primaries.

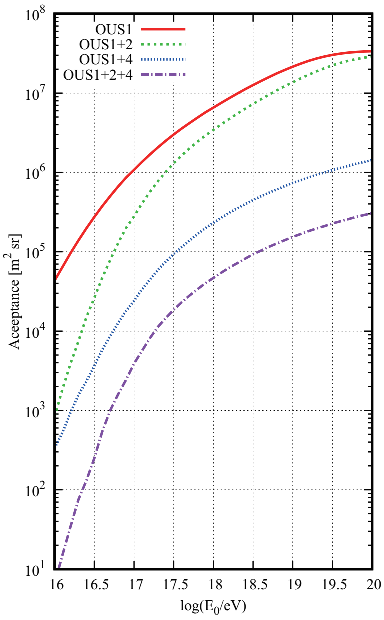

Figure 3. The comparison of four observations in the acceptance in the primary nucleus assumed to be proton.

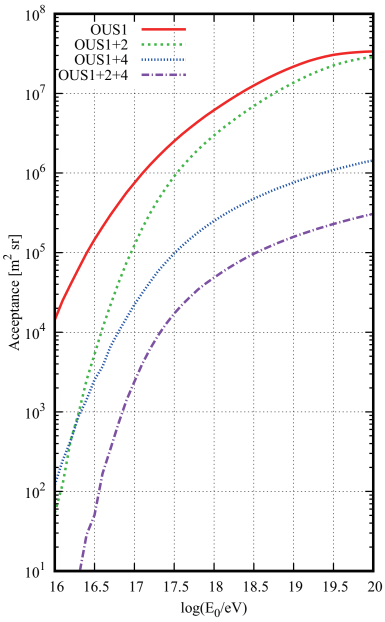

Figure 4. The comparison of four observations in the acceptance in the primary nucleus assumed to be iron.

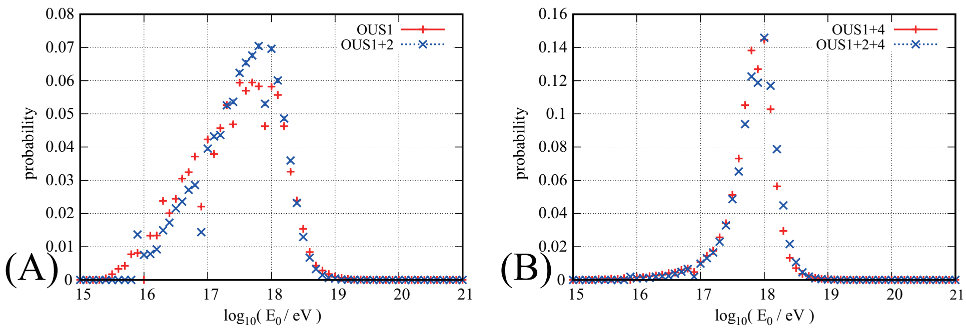

Figure 5. The primary energy energy distribution obtained by detector simulations assumed to be proton primaries at $E_0 = 10^{18}$ eV. (A) The comparison of the OUS1 and OUS1+2. (B) The comparison of the OUS1+4 and OUS1+2+4.

4.2. Accuracy of the primary energy determination

In the primary energy distribution obtained by detector simulations, figure 5 shows comparisons of distributions assumed to be proton primaries at $E_0 = 10^{18}$ eV. In the distribution of the OUS1, the peak energy of the distribution is $10^{17.7}$ eV and the FWHM is from $10^{16.5}$ eV to $10^{18.4}$ eV. The peak energy and the FWHM of the OUS1+2 are $10^{17.8}$ eV and from $10^{16.9}$ eV to $10^{18.4}$ eV, respectively. The primary energy distribution of the OUS1+2 is sharper than that of the OUS1 in the lower energy region than the peak energy in figure 5-(A). On the other hand, the primary energy distributions of the OUS1+2+4 is similar to that of the OUS1+4 in figure 5-(B), because the effect of the restriction of the EAS zenith angle is dominant.

In comparisons of each observation mode in iron primaries, the primary energy distributions assumed to be iron primaries show similar trends in case of proton primaries in figure 6.

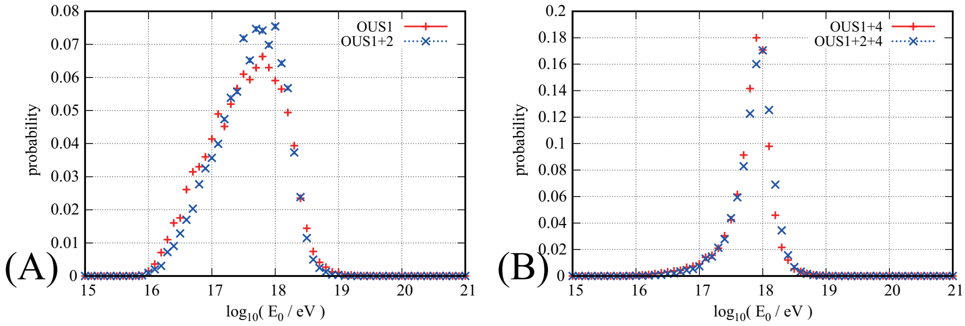

Figure 6. The primary energy energy distribution obtained by the detector simulation assumed to be iron primaries at $E_0 = 10^{18}$ eV. (A) The comparison of the OUS1 and OUS1+2. (B) The comparison of the OUS1+4 and OUS1+2+4.

5. Conclusion

Linsley method allows the estimation of the EAS core distance and the primary energy by using a compact EAS array in the LAAS experiment. As the results, we have been observed the primary energy spectrum in its energy region of 10^{16} eV to 10^{17} eV since 2008. In order to improve the accuracy of the primary energy estimation, we carried out the simulation for the Multi Linsley method. In addition we will develop an observation apparatus for the Multiple Linsley method.

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