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Simulation and Parameterization of Longitudinal Development Using Different Hadronic Interaction Models

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ABSTRACT

The importance of investigating ultra-high energy cosmic ray particles interactions was investigated in this work. Different hadronic interaction models such as (SIBYLL, EPOS, and QGSJET) were used air showers simulation AIRES program (version 19.04.00). In addition, the shower size of Extensive Air Showers (EAS) was calculated by estimating the longitudinal development. Moreover, the longitudinal development simulation of the two primary particles (iron nuclei and proton) was performed, taking into account their primary energies effect as well the zenith angle for charged particles that produced in the EAS, with energies (10^{17} and 10^{19}) eV. At such extremely high energies (10^{17} and 10^{19}) eV, new parameters as a function of the primary energy were obtained by fitting the longitudinal development curves of EAS using Lorentz function. Comparison of the results showed a good agreement between the values obtained from the parameterized longitudinal development using the Lorentz function with experimental results by Pierre Auger EAS observatory as well the simulated results by Sciutto for the primaries iron nuclei as well proton, with the electrons and the charged muons secondary particles of high energies.

KEYWORDS: Cosmic rays; extensive air showers; longitudinal development; AIRES program.

الخلاصة

في هذا العمل تم التحقيق من أهمية دراسة تفاعلات جسيمات الأشعة الكونية ذات الطاقة العالية. تمت محاكاة مختلفة لنماذج تفاعل هادرونيك مثل (SIBYLL,EPOS,QGSJET) باستخدام برنامج محاكاة الدشات الهوائية ايرس (الاصدار **19.04.00**). أيضًا ، تم حساب حجم الانهمار للانهمارات الهوائية الممتدة (EAS) من خلال تقدير التطور الطولي. علاوة على ذلك ، تم إجراء محاكاة التطور الطولي للجسيمين الأساسيين (نوى الحديد والبروتون) ، مع مراعاة تأثيرات الطاقات الأولية وكذلك زاوية الذروة للجسيمات المشحونة التي تم إنتاجها في EAS ، مع طاقات $\mathbf{10^{17}}$ و $\mathbf{10^{19}}$ الكترون فولت. في مثل هذه الطاقات العالية جدا، تم الحصول على معلمات جديدة كدالة للطاقة الأولية من خلال تركيب منحنيات التطور الطولي للانهمارات الهوائية الممتدة باستخدام دالة لورنتز أظهرت مقارنة النتائج توافقًا جيدًا بين القيم التي تم الحصول عليها من التطور الطولي المحدد باستخدام دالة لورنتز والنتائج التجريبية بواسطة مرصد بيير اوجر للانهمارات الهوائية الممتدة وكذلك النتائج المحاكاة بواسطة Sciutto لنواة الحديد الأولية وكذلك البروتون ، مع الإلكترونات والميونات المشحونه كجسيمات ثانوية ذات الطاقات العالية.

INTRODUCTION

Characteristics of EAS investigation triggered via ultra-high energy cosmic rays (CRs) is crucial [1]. In addition, high-energy CRs have been detected through the chain reaction EAS that are produced in the air surrounding the Earth. Since certain primary particles are directly undetectable. Therefore, they must be investigated based on the showers that measured in different ways [2]. It is observed, when any high-energy astronomical (cosmic rays) collides with an atom in the atmosphere surrounding the Earth, it generates a shower of secondary particles, which interact and generate more secondary particles before reaching the Earth's surface [3]. Primary CR properties must be deduced for the particle and ratios in the shower and the creation of the shower in the atmosphere [2]. We should point out that this research offers a unique perspective on studying the cascades that result from CR interactions with the nuclei of the Earth's Atmospheric atoms, as they produce much higher energy than those obtained in man-made collisions on the characteristics of the hadron interaction at high energies [3]. A simple analytical model cannot thoroughly explain the comprehensive shower creation because these events are too complicated too complicated [4].

The reaction often called a cascade continues until the average energy possessed by these single and multiple particles drops below their critical energy, which is often lost due to multiple collisions rather than other radiative processes [5]. Therefore, it is normally modeled using a Monte Carlo (MC) simulation of each individual shower particle's transport and interaction, based on our current understanding of interactions, decays, and particle transport in matter [6]. Because of the intricacies of the systems involved in the design of an air shower, numerical simulations are frequently utilized to conduct in-depth analyses of its properties. So, affects both of the simulation the interactions for particles and transport in the atmosphere, as well as the model assumptions, affect quantitative results [7]. All of the processes that have a major impact on the shower's actions must be taken into account by the simulating algorithms. So are all of other reactions such as electrodynamic interactions, hadronic collisions, photonuclear processes, particle decays, and so on [8, 9]. The shower size as a function of the primary energy particles is seen in the current calculations. While, the simulation of the longitudinal development performed via the AIRES program for (iron nuclei and proton) primary particles with the two energies (10^{17} and 10^{19}) eV for two different zenith angles (0° and 30°). The longitudinal development of secondary particles at the electrons and the muons charged secondary particles was simulated. By the Lorentz function are obtained using new parameters of longitudinal development, the dependence of the number of particles produced in EAS as a function of the primary energy particles inside with two energies (10^{17} and 10^{19}) eV. The comparison, which gave a good agreement, enter the estimated longitudinal development of the charged particles and Pierre Auger EAS observatory as well the simulated results by Sciutto of high energies.

THE LONGITUDINAL DEVELOPMENT

Several charged particles into an EAS can be considered a function related to atmospheric depth is referred to as the longitudinal shower profile [10]. The longitudinal profile of EAS counts on the type, mass, and energy of the fallen primary particle. The atmospheric depth at which the width of a shower it's maximum of charged particles, one of the important parameters that can be characterized by its EAS which is called $X_{\max}$, and related to the primary particle mass, extending from a proton to an iron. Protons generate showers for a given energy, which evolve on average deeper in the atmosphere than the showers of nuclei. Moreover, the parameter $X_{\max}$ describes the inclined depth in (g / cm^2) where the number of charged particles occurred during the development of an air shower. This parameter provides information about the composition of the primary CRs. Thus, the mean depth of shower maximum $X_{\max}$ distribution carries important evidence about the essential composition related to the primary shower particles [11].

Because of the kind of the hadronic and the interactions related to electromagnetic fields involved, as well as the various particle decay merits, a 10^{15} eV primary proton will create on average about 10^6 particles at sea-level, of which approximately 80 % photons, roughly 18 % electrons, around 1.7 % muons, and nearly 0.3 % hadrons. Additionally, the neutrinos will be originated by feeble decays of particles; meanwhile, they stay undetectable by normal EAS procedures.

During the development of an EAS, each new generation of secondary particles carries less energy per particle than the previous generation. Particles increase up to the shower maximum, $X_{\max}$, where the energy of the particles becomes too small to generate new particles [12]. Adequately, the profile of longitudinal EAS, i.e. the development of the number of charged particles (shower size) with the atmospheric depth X (the atmospheric distance, which has been actually passed) can be determined by the Gaisser–Hillas function [13], for the electron size as following:

$$N_e(X) = N_e^{max}\left(\frac{X - X_o}{X_{max} - X_o}\right)^{(X_{max}-X_o)/\lambda} exp \qquad (1)$$

with X is a depth during observation, X_0 is a depth during the first interaction, and $X_{\max}$ is a depth related to the shower maximum. λ, is the attenuation parameter (about 70 g cm^{-2}). ($X_{\max}$–X_0) is the difference value counts on the energy E_0 and the kind of the primary. Meanwhile, ($X - X_{\max}$) is the difference value is referred to the development level and growth roughly logarithmically versus the energy [14].

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RESULTS AND DISCUSSION

AIRES Simulations

Shower evolution is far too intricate to be properly characterized by straightforward analytical models. In addition, to conduct correct shower modeling evolution, Monte Carlo (MC) simulation of interaction and transport of each individual particle is required. Lately, MC packages are employed for simulating EAS using AIRES system [15]. Various hadronic interaction models are utilized for these event generators, such as SIBYLL [16], QGSJET [17] and EPOS [18]. Therefore, the air shower simulation programs are made up of a variety of interconnected procedures that run on a data set with a variable number of records, changing the contests and increasing or decreasing the size of the data set according to predetermined laws. Internal control procedures in AIRES' simulation engine continuously check and report particles touching the ground and/or moving over predetermined observing surfaces between the ground and injection stages. The number of showers was determined and then the identified elementary particles were determined, as well as its energy that can interact together with atoms of the atmosphere. Then we define the name of the task, as well as the kinetic energy of electrons, muons, and gamma rays. Next, we define the thinning level and the zenith angle, and then choose the observing levels for the array to be used. Finally, define the name of the secondary particles resulting from the chain reaction. Diffractive interactions have a direct impact on the shower's progress. Also, that fact is clearly confirmed by graphing the densities of showers versus the shower core of atmosphere, at certain value of energies of 10^{17} and 10^{19} eV. The graphs were plotted depending on the data incoming from simulations executed via the AIRES system for assorted hadronic interaction models (SIBYLL, QGSJET and EPOS). The simulation was employed to investigate the production of primary particles (iron nuclei as well the proton) resulted from air showers with two primary energies (10^{17} and 10^{19}) eV and explore the longitudinal development growth of various hadronic interaction models created subsequent primary CRs of the extremely high value of energy react with the atmosphere and organize overall correlated production data [4]. The AIRES program was used to carry out the entire simulation procedure, which profited by the adoption of the thinning level 10^{-6} relative.

In figure 1 the effect of zenith angles (0˚and 30˚) was shown on the longitudinal development for electrons secondary particles at the fixed primary energy 10^{17} eV for primaries iron nuclei as well proton. Through the shapes, when changing the angle of incidence, the $X_{\max}$ will change and the number of particles, for $X_{\max}$ (the higher of the angle incidence, the lower the $X_{\max}$), as for the number of particles, it depends on the primary particles and the nature of the interactions. Here we notice a decrease in the proton and an increase in the iron nucleus. The reason is due to the particle's inclination at an angle, so it cuts a horizontal distance with a vertical distance. The x-axis is the depth of the atmosphere for the reaction processes of the shower particles, and the y-axis is the number of the shower particles produced in the atmosphere during the reaction process.

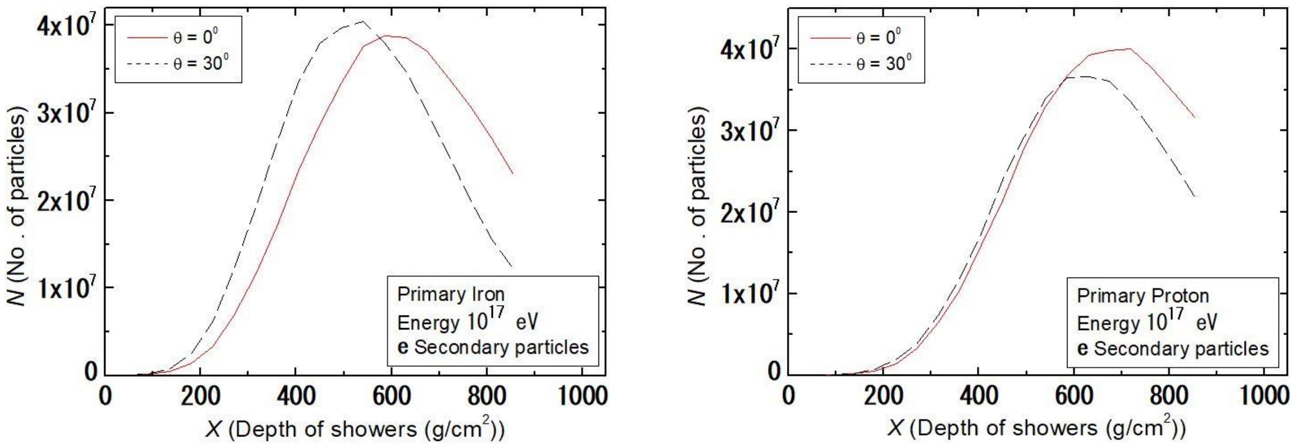

Figure 1. The zenith angle effects of longitudinal development for two primaries such as the iron nuclei (left) as well proton (right) on electrons secondary particles at the fixed primary energy (10^{17}) eV.

In Figure 2 the simulation of longitudinal development was shown for different hadronic interaction models (SIBYLL, QGSJET, and EPOS) for the primaries (iron nuclei and proton) at the fixed energy 10^{17} eV and inclined zenith angle (θ = 30°), for electrons secondary particles.

Parameterization of longitudinal development

The AIRES simulation was used for the primary iron nuclei as well proton and explores the longitudinal development for different hadronic models. A Lorentz function was used to parameterize the longitudinal development of showers that started in EAS, yielding four parameters for the various of the primary particles, where the Lorentz function was used to vary the secondary particles produced in the atmosphere, where several functions were applied and it was found that they are suitable and good with electrons and muons at the same time, the function is denoted by:

$$N(E) = \frac{2}{4\pi +} \tag{2}$$

when N is the number of particles of EAS showers as a function of the primary Energy ; , $_c$, and are obtained coefficients for longitudinal development (see Table 1). These coefficients are obtained by fitting the AIRES results, which are given by the polynomial form:

$$K(E) = a_o + a_1(E/eV) + a_2(E/eV)^2 \tag{3}$$

where $K(E) =,$ $_c$,, are parameters of Eq. (2) as a function of primary energy and a_o, a_1 and a_2 (eV) are their coefficients (see Table 1).

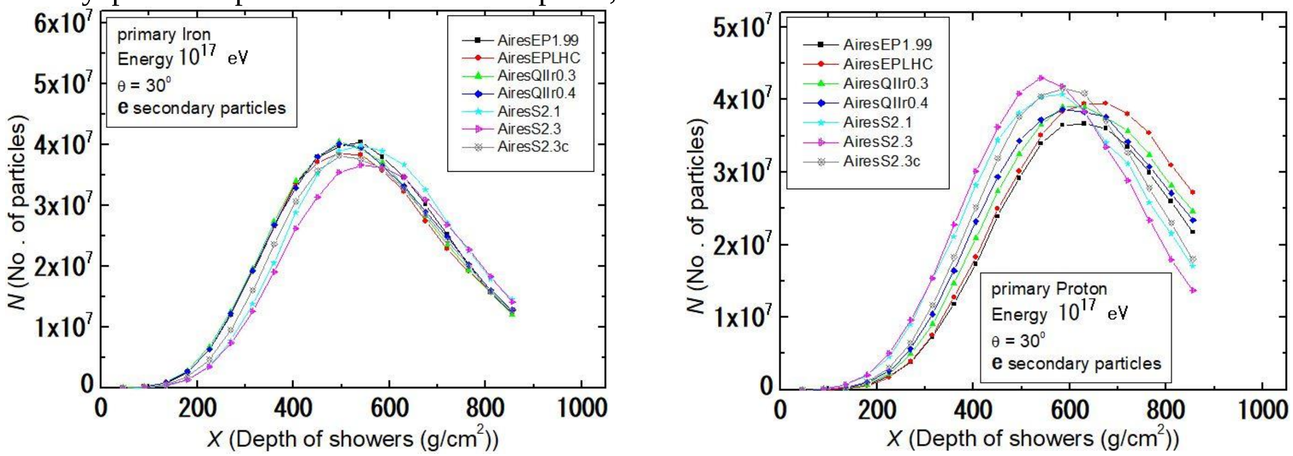

Figure 2. Comparison with different hadronic interaction models like (SIBYLL, QGSJET, and EPOS) of longitudinal development at the primary energy 10^{17} eV for secondary electrons.

Table 1. Coefficients of Lorentz function (Eq.2) by using the parameterize AIRES program simulation for the primaries iron nuclei and proton with the energies (1017 and 1019) eV and two zenith angles (θ = 0˚ and 30˚).

Primary particles	Secondary particles	$K(E)$ eV	Coefficients		
			a_0	a_1	a_2
p	e^-		280192.9	3.71×10^{-12}	-5.02×10^{-31}
		$_c$	-1.5×10^{6}	3.62×10^{-10}	1.97×10^{-30}
			365.006	6.4×10^{-17}	-4.64×10^{-36}
			46.87	1.19×10^{-17}	-8.58×10^{-37}
	mu^- &mu^+		5916.11	-4.93×10^{-13}	2.51×10^{-32}
		$_c$	62389.11	9.92×10^{-12}	-2.92×10^{-31}
			350.56	7.24×10^{-17}	-5.52×10^{-36}
			96.56	2.2×10^{-17}	-1.9×10^{-36}
Fe	e^-		253138.19	2.48×10^{-12}	-2.53×10^{-31}
		$_c$	-4.26×10^{6}	3.48×10^{-10}	1.52×10^{-30}
			341.67	8.77×10^{-17}	-7.37×10^{-36}
			48.63	8.15×10^{-18}	-6.09×10^{-37}
	mu^- &mu^+		-33747.79	-1.56×10^{-13}	-4.9×10^{-33}
		$_c$	184210.8	5.63×10^{-12}	-7.48×10^{-32}
			353.53	7.11×10^{-17}	-5.86×10^{-36}
			112.5	-6.93×10^{-18}	8.06×10^{-37}

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Figure 3 shows the parameterization of the shower density in EAS as a function of primary energy using Lorentz function (Eq. 2) for two primary energies (10^{17} and 10^{19}) eV and two zenith angles (0^{o} and 30^{o}) for the electrons and the muons charged secondary particles.

The comparison with Pierre Auger Observatory

The parameterized longitudinal development that was obtained using Eq. 2 (Lorentz function) was compared with the experimental results for the Pierre Auger Array [19]. This comparison gave a good compatibility for both primaries iron nuclei and proton with the fixed primary energy (10^{19}) eV for zenith angle (30^{o}) that initiated the electrons and muons charged secondary particles.

The comparison with simulated results by Sciutto

Figure 5 demonstrates the comparison between the parameterized longitudinal development shower size that was obtained using Eq. 2 Lorentz function (solid lines) and the data simulated via Sciutto (dash symbols) [20]. This figure displayed a good agreement for the production of the (electron positron) pair secondary particles initiated by the primaries the iron nuclei as well proton at energy (10^{17}) eV and the zenith angle ($\theta = 30^{\circ}$).

The error ratio was for both electrons (0.9881) and muons (0.9969), respectively, and this is a good percentage. We can consider that the Lorentz equation is well applied with both electrons and muons.

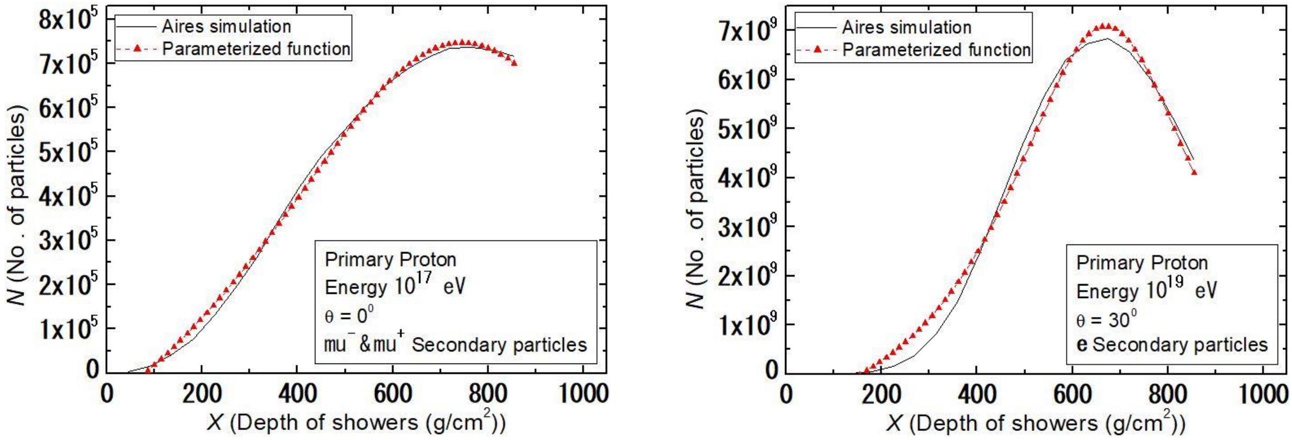

Figure 3. Longitudinal development that simulated with AIRES proton (solid lines) and one calculated with Eq. 2 (scattered) for primary proton at energies 10^{17} and 10^{19} eV for the electrons and the muons charged secondary particles.

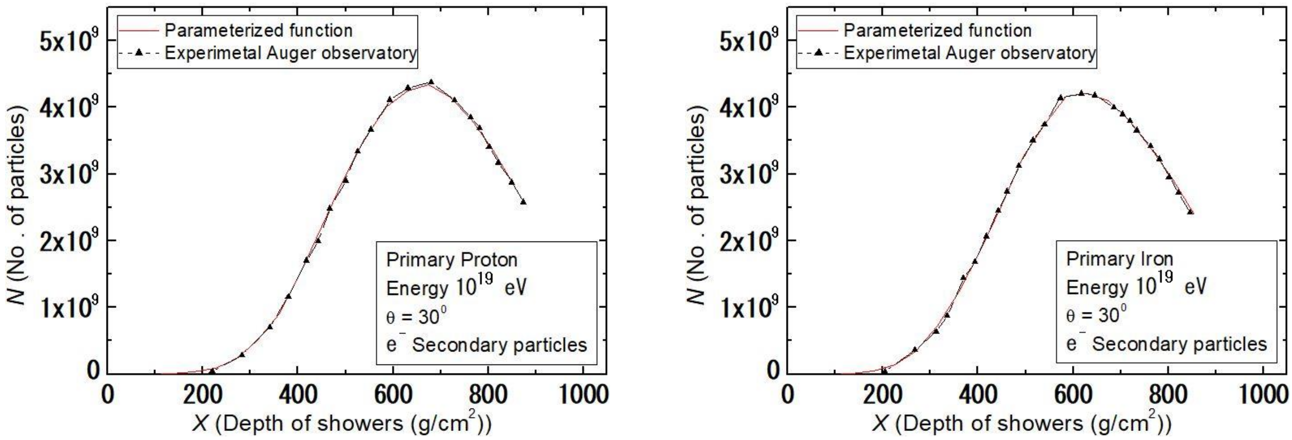

Figure 4. Comparison of the parameterized longitudinal development obtained using (Lorentz function) with the experimental results by Pierre Auger Array [19] the primary iron nuclei and proton at the energy 10^{19} eV.

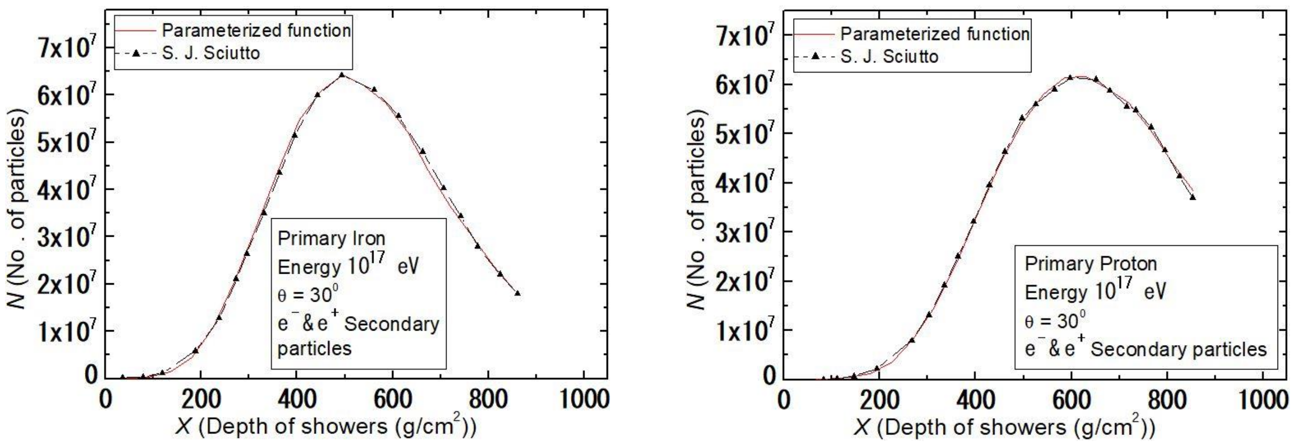

Figure 5. The comparison between the results obtained from the Eq. (2) and the data that simulated via Sciutto [20] for the primaries proton as well iron nuclei at energy (10^{17}) eV.

CONCLUSIONS

The simulation was obtained using AIRES program to the longitudinal development produced in EAS by various hadronic interaction models (SIBYLL, QGSJET, and EPOS) for primaries iron nuclei and proton. In addition, the simulation was obtained for two zenith angles (0˚ and 30˚) and two high energies (10^{17} and 10^{19}) eV for several secondary particles. The parameters of longitudinal development were calculated as a function of primary energy using the results of this simulation, through the Lorentz function for the primary iron nuclei as well proton. A good comparison was obtained of the parameterized longitudinal development with that measured with the Pierre Auger observatory as well the simulated results by Sciutto demonstrated the ability to give a possibility of analyzing for real events that detected in EAS arrays and determining around the ankle region of CR energy spectrum. The current method's main advantage is the capacity to create a library of longitudinal development samples that could be used for analyzing specific events recorded with the EAS array and reconstruction of the primary CRs energy spectrum as well as mass composition.

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