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A METHOD FOR DETERMINATION OF THE ANGULAR COORDINATES OF EAS CORES

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ԼՄՀ ԱՌԱՆՑՔԻ ԱՆԿՅՈՒՆԱՅԻՆ ԿՈՈՐԴԻՆԱՏՆԵՐԻ ՈՐՈՇՄԱՆ ԵՂԱՆԱԿ

Մշակվել է ԼՄՀ առանցքի անկյունային կոորդինատների որոշման մի եղանակ և ժամանակավոր կանալների արագ չափարկման մի համակարգ՝ սցինտիլյատորների զույգային կանգնեցման հիման վրա։ Ստացվել են զենիթային և ազիմուտային անկյունների ըստ մոդելային տվյալների որոշման սխալները՝ հեղեղի ճակատի տարբեր առաջադրված տատանումների համար։ Արդյունքները որոշակիացված են «ԱՆԻ-88» փորձի համար։ Բերված են ԼՄՀ առանցքների զենիթ-անկյունային բաշխման նախնական արդյունքները։

Երևանի ֆիզիկայի ինստիտուտ
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МЕТОД ОПРЕДЕЛЕНИЯ УГЛОВЫХ КООРДИНАТ ОСИ ШАЛ

Разработана методика определения угловых координат оси ШАЛ и система оперативной калибровки временных каналов на основе парных задержек сцинтилляторов. Получены ошибки определения зенитных и азимутальных углов по модельным данным для различных задаваемых флюктуаций фронта ливня. Результаты конкретизированы для эксперимента "АНИ-88" (МАКЕТ-АНИ). Приведены предварительные данные по зенитно-угловому распределению осей ШАЛ.

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A METHOD FOR DETERMINATION OF THE ANGULAR COORDINATES OF EAS CORES

A technique for determination of the angular coordinates of EAS cores is developed and a system of rapid calibration of time channels based on scintillator pair delays is designed. The accuracy of the zenith and azimuth angles determination by model data for different shower front fluctuations is obtained. The results are specified for the "ANI-88" experiment. Preliminary data on the zenith-angular distribution of EAS cores are presented.

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The technique of determination of the angular coordinates of EAS cores detected by an experimental setup is based on the assumption of a flat shower front (disk) with a given fluctuation of electron density. In case of an experimental setup containing m scintillators located on the observation level with coordinates x_i, y_i, z_i ($i=1,\dots,m$), under the assumption of a flat shower and at absence of fluctuations the problem of determination of the zenith (θ) and azimuth (φ) angles of EAS cores is solved analytically in Refs [1,2] at m=3,4, respectively.

The fluctuations in the EAS front electron arrival time distribution (EAS depth fluctuations) lead to the fact that the analytical solutions determine not exact, but approximate values with an accuracy correlating to the shower front fluctuations. Besides, the margin of errors depends on the interlocation of the scintillators in the setup.

A way to decrease the errors of estimation of θ and φ is increasing the number of scintillators measuring the time of EAS front arrival at the setup and averaging of θ_j and φ_j from a set of different combinations of three or four at a time, respectively [1,2].

In this paper a method of averaging of the estimations of θ_j and φ_j ($j=1,\dots,J$) obtained by means of m scintillators separated into J groups of three scintillators ($J=C_3^m$) in each, is discussed. Averaging was performed with the weights proportional to the area of the triangle on the vertices of which the scintillators of a group were located. When averaging the estimations of θ_j and φ_j in groups of four scintillators, the weight factors were not taken into account because of symmetric location and equality of the squares on the vertices of which the scintillators were located [2].

At the same time, it is obvious that the methods used in Refs [1,2] to determine the angular coordinates of EAS cores by means of averaging of estimations obtained from scintillator groups (three or four in each group), require additional investigations on that the estimations are unbiased and effective.

Besides, these methods have a drawback connected with the problem of choosing the number and combination of detector groups, having the purpose to decrease the intercorrelations in the (θ_j,φ_j)-pair-averaging procedure.

The restoration methods based on the principles of maximum likelihood and least squares are devoid of these drawbacks. On the basis of the information from all the scintillators with weights proportional to the measurement accuracy, these methods allow to obtain unbiased and asymptotically effective estimations of the angular coordinates of EAS cores. In the maximum likelihood method the quantities $\xi\equiv(\theta,\varphi)$ are obtained on the basis of the set of likelihood equations

$$\frac{\partial L}{\partial \xi} \equiv \frac{\partial}{\partial \xi} ln\left\{\prod_{i=1}^{m}\Phi(x_i,y_i,\ z_i,\ t_i|\xi)\Im(\theta)\right\} = 0\ ,$$

where $\Phi(\xi)$ is a function describing EAS front fluctuations; t_i are the measured values of the relative time of traversal of a scintillator with coordinates x_i,y_i,z_i by an EAS front; $\Im(\theta)$ is the known (*a priori*) spectrum of the zenith angles of EAS cores.

The inverse problem solution by the least squares method is adequate to minimization of the functional χ^2

$$\chi^2 = \sum\{(ax_i+by_i+cz_i - c_o\Delta t_i)^2/(\sigma^*_i)^2\}\quad , \qquad (1)$$

where x_i,y_i,z_i are the coordinates of the i-th scintillator; $\Delta t_i=(t_i-t_o)$ is the delay time of the signal from the i-th scintillator (ns) relative to a scintillator taken as a gauge; c_o is velocity of light in m/ns units; a,b,c are factors of the equation of a phase given as a normal; σ^*_i are errors in the EAS front arrival time measurements.

In case of Gaussian fluctuations of shower fronts and measurement errors, the least squares method, analogous to the maximum likelihood method, gives unbiased and effective estimations of parameters, but in the particular case of determining the angular coordinates of EAS cores it has the advantage of having an analytic solution:

$$\begin{aligned} sin(\theta) = \sqrt{a^2+b^2} \quad &or \quad cos(\theta)=c\ , \\ tg(\varphi) = b/a\ , \end{aligned} \qquad (2)$$

where the a,b,c cosines of the EAS core direction are defined as:

$$a=\Delta_{txz}/\Delta_{xyz},\ b=\Delta_{xtz}/\Delta_{xyz},\ c=\Delta_{xyt}/\Delta_{xyz}\ ,$$

and the determinants Δ_{uvw} have the following form:

$$\Delta_{uvw} = \begin{vmatrix} \omega_{xu} & \omega_{xv} & \omega_{xw} \\ \omega_{yu} & \omega_{yv} & \omega_{yw} \\ \omega_{zu} & \omega_{zv} & \omega_{zw} \end{vmatrix},\quad \omega_{pq} = \sum p_i q_i/(\sigma^*_i)^2\ .$$

Comparison of Methods

The accuracy of restoration of the angular coordinates of EAS cores was investigated by simulation of the real experimental situation for a setup composed of seven scintillation counters mounted at the vertices of two symmetrically located squares with diagonals of 32m. The central scintillator was common for the squares. The coordinates of EAS cores intersection with the plane of the setup (x_o,y_o) were simulated with uniform density within $x_o\in(-32,32m)$, $y_o\in(-16,16m)$. The EAS age parameter fluctuations were chosen to be Gaussian with the mean value of $\bar{s}=1$ and the mean square deviation $\sigma_s=0.15$. The spectrum of the total number of particles in EAS (N_e) had a power form with factor $\gamma_N=-2.5$ and threshold value $N_e^{(min)}=5\cdot 10^4$. The distribution of the zenith (θ) and azimuth (φ) angles of EAS cores was simulated according to the spectra $\mathfrak{J}(\theta)=\mathfrak{J}(\theta=0)\cos^{\rho}(\theta)$ and $J(\varphi)=const$, respectively. The EAS front thickness fluctuations were supposed to be Gaussian and the corresponding mean square deviations varied in the range $\sigma_F=0$-10ns. Using of the given values of EAS front fluctuations was based on the results of Ref.[3], where an approximated expression for $\sigma_F(ns)=2.6(1+r/30m)^{1.5}$ is given as a function of the distance (r) to the EAS core.

The results of calculation of the efficiency of different simulation methods for determination of the angular coordinates of EAS cores are shown in Table 1 and 2.

Table 1 presents the errors of restoration of EAS zenith $\sigma(\cos(\theta))$ and azimuth φ angles at different values of the EAS front fluctuations $\sigma_F=2,4,6$ns for three methods of solution of the inverse problem: the method of grouping of scintillators in three (III), the method of grouping of detectors in four (IV) and the least squares method (LSM). Table 2 presents the errors of restoration of EAS azimuth angles $\sigma(\varphi)$ in radians, at fixed values of the simulated showers zenith angles $\theta=0,10,20,30^{\circ}$. As is seen from Tables 1,2, minimization of the functional (1) (LSM) determines the angular coordinates of EAS cores much more accurately.

Further investigation of the functions of EAS zenith angles restoration errors was carried out by LSM, on the example of the "ANI-88" installation [4]. The number of scintillators measuring the EAS arrival time, was $m=20$. Their coordinates are given in Ref.[4]. The maximum distance between the scintillators is 64m. In the experiment the EAS front arrival time was measured with a step of discreteness of 5ns and the start pulse indefiniteness time was 2.5ns. Beside these parameters, which are taken into account in the simulation, the calculations involved the Gaussian

fluctuations of the EAS front thickness with mean square deviation in the range $\sigma_F=0$-10ns. The number of electrons in scintillators was simulated with account of Poisson fluctuations with mean values determined from the Nishimura-Kamata-Greisen approximation.

Fig.1 shows the errors of EAS zenith angles restoration at $\sigma_F=5$ns for showers with different total number of electrons $N_e=5\cdot 10^4$, $1\cdot 10^5$, $5\cdot 10^5$, $1\cdot 10^6$. It is seen that when $N_e>2\cdot 10^5$, the error of the zenith angle determination is the least and depends on N_e weakly. Figs 2,3 show the errors of restoration of EAS zenith and azimuth angles, respectively, at $N_e=\infty$, $\sigma_F=6$ns and the simulated EAS zenith angles $\theta=10,20,30^{\circ}$. The limits include the sum over all the other values. Fig.4 shows the distribution of the zenith angle restoration errors at $N_e=5\cdot 10^4$ and $\sigma_F=1,3,5,7$ns.

Calibration

The parameters requiring additional calibration for determination of the angular coordinates (θ,φ) by measuring the EAS front arrival time are the mean values of the shift (t_i^*) and fluctuations (σ_i^*) of the EAS front arrival time measurement by scintillators, which are due to the signal cables length, delays of the photomultipliers and signal transformation circuits. Since these parameters may change in time, calibration must be carried out operatively, during the whole experiment.

The possibility for such calibration is laid in the measurement of the central moments of distribution of the value ($\Delta t_{ik}=t_i-t_k$) for $i\neq k$ (distribution of pair delays between (i) and (k) scintillators). The expression for the central moments ($<\Delta t>$, $<\Delta t^2>$) of pair delays at $z_i - z_k$ is:

$$<\Delta t^n>_{ik} = \frac{1}{c_0}\frac{1}{H}\int_0^{\pi/2}\int_0^{2\pi} g(\theta,\varphi)\cos(\theta)\sin(\theta)\mathfrak{J}(\theta)d\theta d\varphi , \qquad (3)$$

where $g(\theta,\varphi)=R_{ik}\mathit{sin}(\theta)\mathit{cos}(\alpha_i-\varphi)$, a_i are determined via the scintillator coordinates $x_i=R_{ik}\mathit{cos}(\alpha_i)$, $y_i=R_{ik}\mathit{sin}(\alpha_i)$ and the distance R_{ik} between them. The parameter (H) determines the angular distribution normalization, $H=\iint cos(\theta)sin(\theta)\Im(\theta)d\theta d\varphi$. The first two moments in (3), $<\Delta t>=0$ and $<\Delta t^2>\approx(R_{ik}/1m)ns$, respectively, at the zenith angle distribution $\Im(\theta)\sim cos^{\rho}(\theta)$, where $\rho\cong6$.

Thus, by measuring the moments of pair delays of all the scintillators with respect to one of them (it is desired it be a scintillator, the response of which determines the condition of EAS detection) one can determine the parameters of the shift $t^*_i=<t_i-t_o>$ and fluctuations $\sigma^*_{io}=\sigma(t_i-t_o)-<\Delta t^2>_{io}$ of the i-th scintillator with respect to the (k=0)-th scintillator chosen as a gauge ($k\neq0$). In experiments the accuracy of determination of the shift t^*_i must be better than the step of discreteness of the scale of time measurements by the scintillators. The statistics (N) necessary for the given accuracy of measurement $\delta(t^*_i)$, the mean value of t^*_i, can be determined from the approximation $\delta(t^*_i)\approx\sigma^*_{io}/\sqrt{N-1}$. Note that the value of σ^*_{io} is not identical to the error of the EAS front arrival time (σ_i) measurement by the i-th scintillator, but relates to it as:

$$(\sigma^*_{io})^2=\sigma^2_i+\sigma^2_o+\sigma^2_{Fi}+\sigma^2_{FO}\approx2(\sigma^2_i+\sigma^2_F)\ , \tag{4}$$

where σ^2_{Fk} is the dispersion of EAS front thickness fluctuations on the point, where the k-th scintillator is located ($k\equiv i,o$).

To estimate the value of σ_i from (4), it is necessary to measure the distribution of pair delays of scintillators, the distance between which is zero (R_{io}=0). The condition R_{ik}=0 can be realized when information from one scintillator is extracted by two photomultipliers simultaneously. In this case the eq.(4) is reduced to $(\sigma^*_{io}(R_{io}=0))^2\approx\sigma^2_i+\sigma^2_o\approx2\sigma^2_i$, which defines the characteristic errors of time measurements by the scintillators.

Fig.5, e.g., shows the distribution of (t_i-t_o) at (R_{io}=0) obtained by the method described above, in the "ANI" experiment. The mean square of the distribution deviation $\sigma^*_{io}\approx6ns$ at the mean value of $t^*_i=2.55\pm0.5ns$. So, in the experiment the time measurement error does not exceed the step of the time scale discreteness (5ns) and the EAS angular parameters restoration accuracy is mainly defined by the shower front depth fluctuations measured by the setup.

Fig.6 represents the preliminary results of the experiment "ANI-88" [4] on investigation of the zenith-angular distribution of EAS cores with $N_e>2\cdot10^4$. The magnitudes of the quantity $ln[cos(\theta)]$ are put along the abscissa, where the zenith angle θ is defined according to (2). The ordinate axis corresponds to the integrated intensity in the number-of-particles units. The data statistics is 2000 events (~40 hours of operation of the setup). The accuracy of the inverse problem solution by the method described above, was controlled by the criterion χ^2, and for ~90% of showers $\chi^2/m\ll1$. For comparison, Fig.6 presents the results of simulation of the real experimental situation at the "ANI-88" installation with the zenith-angular distribution factor ρ=6 and fluctuations σ^*_{io}=15ns (eq.(4)).

In Fig.6, the agreement between the data within the experimental errors, in the whole range of angles $\theta\in(0-60^{\circ})$, indicates correctness of the technique developed and allows to plan the accuracy of determination of the angular distribution factor $(\Delta\rho/\rho)$=0.1% during one year of operation of the installation "ANI-88".

Table 1

METHOD	$\sigma[cos(\theta)]$			$\sigma[\varphi]$ rad.		
	2ns	4ns	6ns	2ns	4ns	6ns
III	0.0078	0.015	0.024	0.53	0.70	0.88
IV	0.0080	0.015	0.023	0.48	0.60	0.76
L S M	0.0075	0.014	0.021	0.10	0.21	0.23

Table 2

METHOD	$\theta=0^\circ$	$\theta=10^\circ$	$\theta=20^\circ$	$\theta=30^\circ$
III	2.4	1.2	0.8	0.70
IV	2.3	1.1	0.7	0.55
L S M	2.2	0.3	0.2	0.08

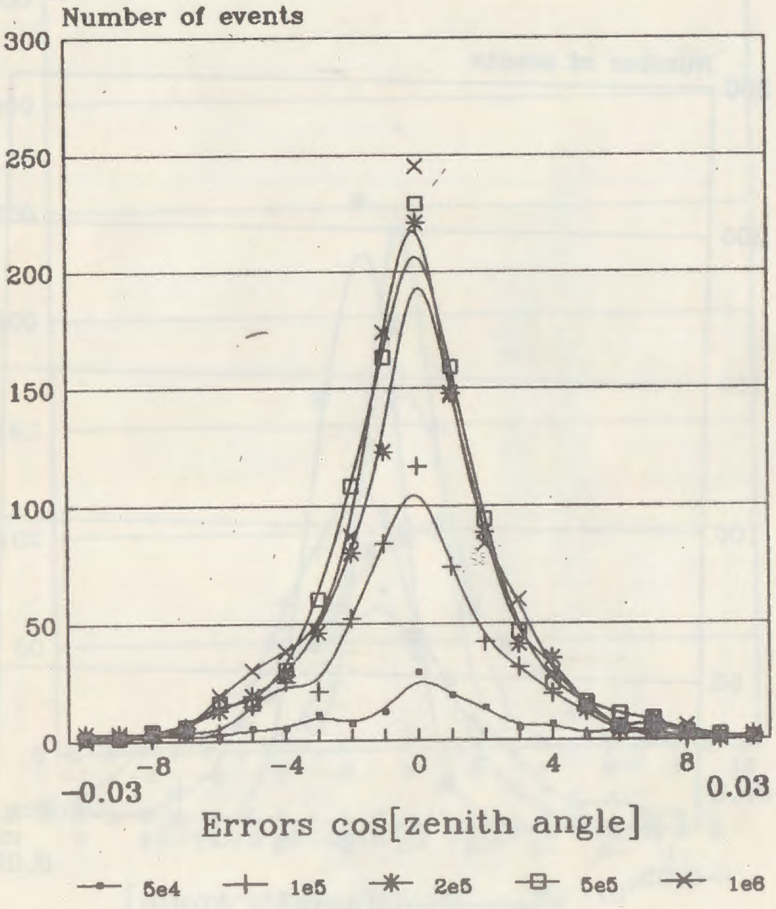
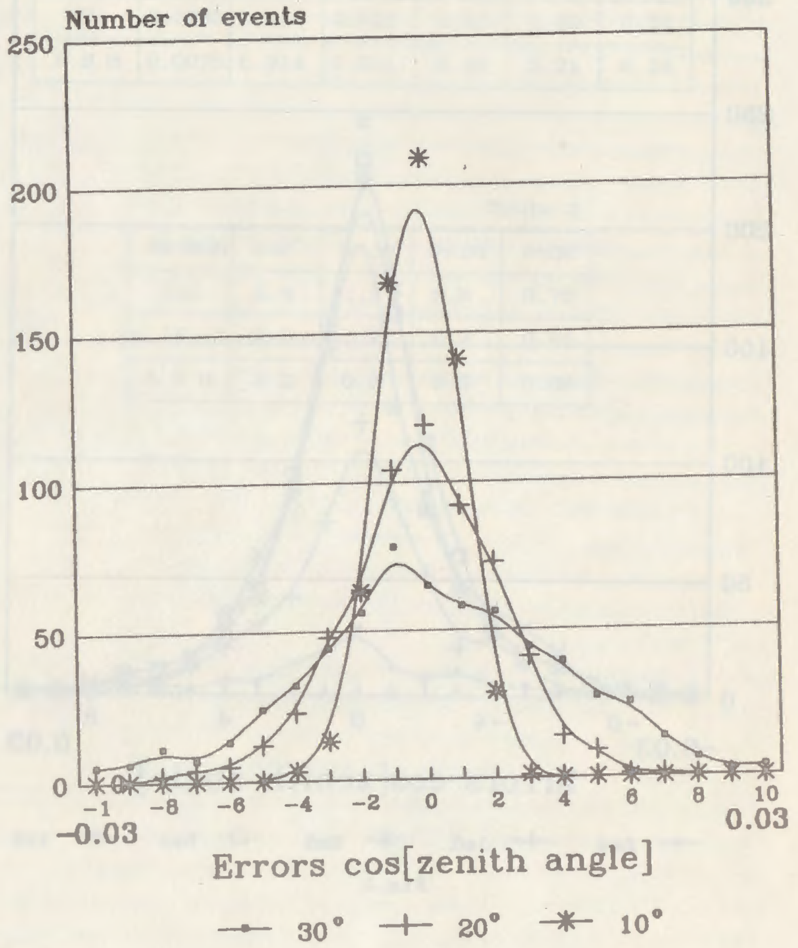
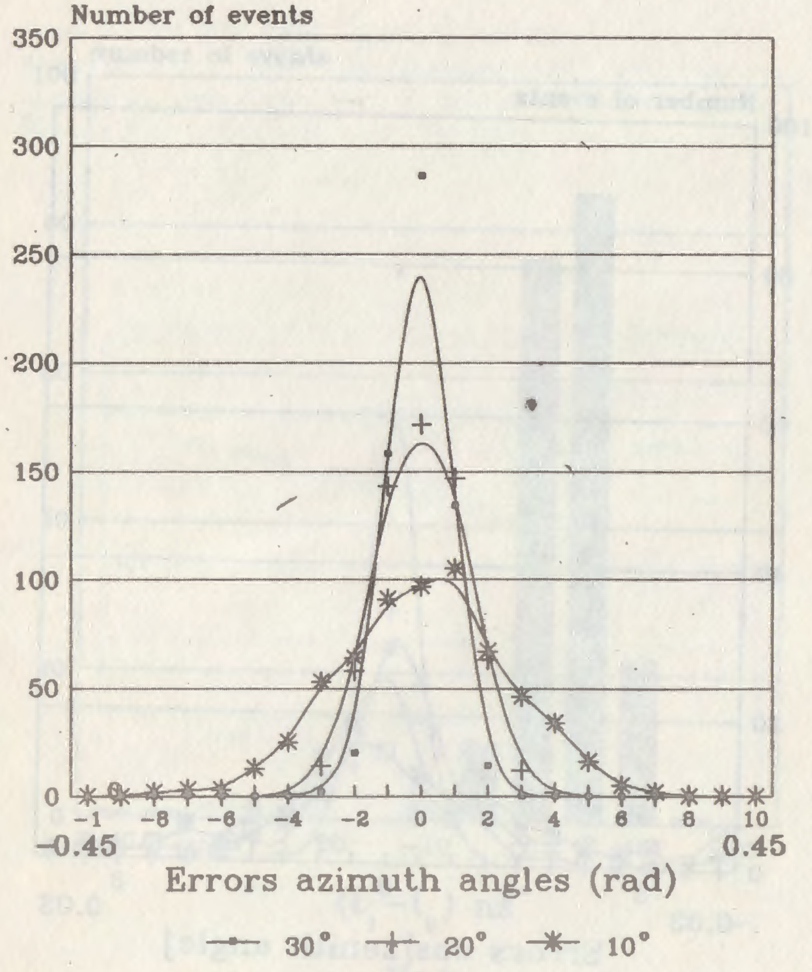


Fig.1



Number of events
250
200
150
100
50
0
-1
-8
-6
-4
-2
0
2
4
6
8
10
-0.03
0.03
Errors cos[zenith angle]
30°
20°
10°

Fig.2



Number of events
350
300
250
200
150
100
50
0
-1
-8
-6
-4
-2
0
2
4
6
8
10
-0.45
0.45
Errors azimuth angles (rad)
30°
20°
10°

Fig.3

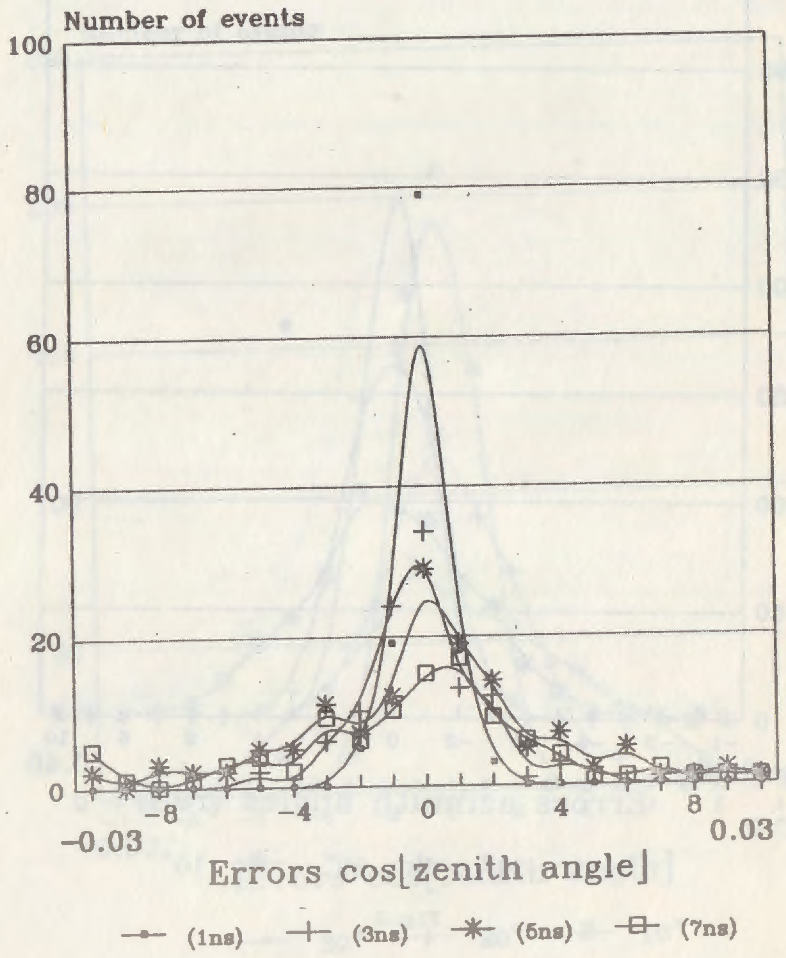

Number of events
100
80
60
40
20
0
-8
-4
0
4
8
-0.03
0.03
Errors cos[zenith angle]
(1ns)
(3ns)
(5ns)
(7ns)

Fig.4

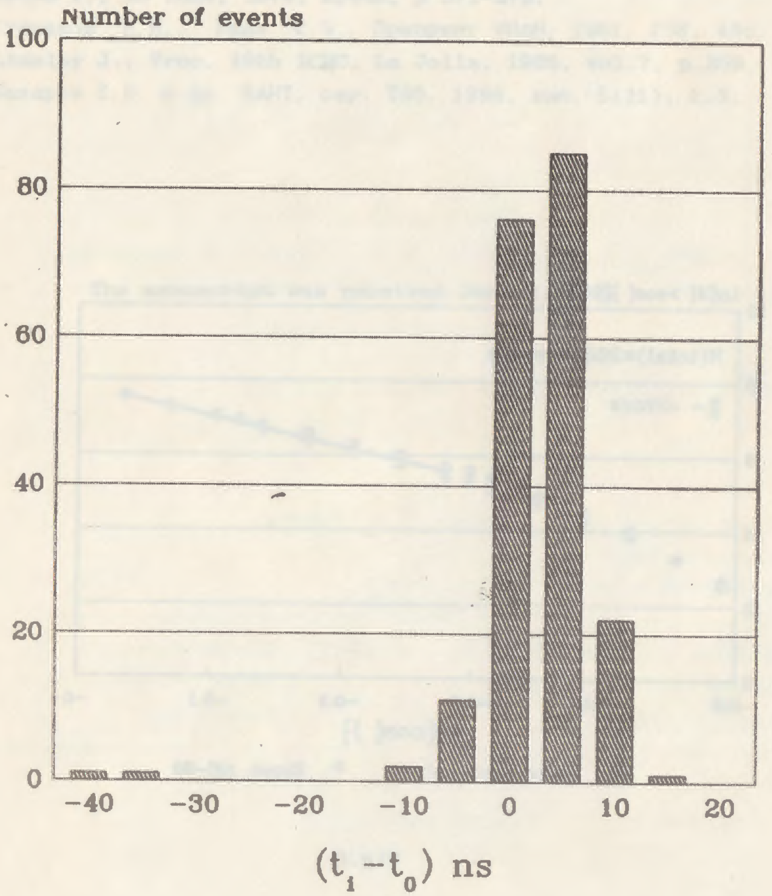

Number of events
100
80
60
40
20
0
-40
-30
-20
-10
0
10
20
$(t_1 - t_0)$ ns

Fig.5

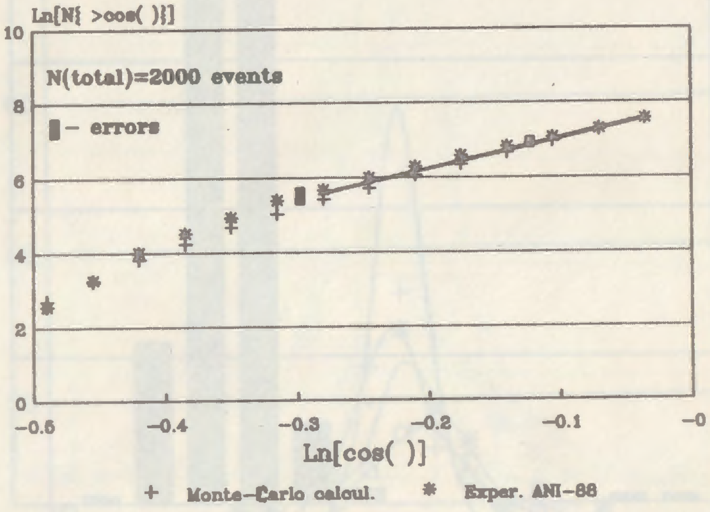


Fig.6

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МЕТОД ОПРЕДЕЛЕНИЯ УГЛОВЫХ КООРДИНАТ ОСИ ШАЛ

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