Method for determining angles in X-ray emulsion chambers (XRECs) (ADRON experiment)

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Paper presents an analysis of the measurement procedure of the zenith and azimuth angles υ and φ in the X-ray emulsion chambers (XREC) of ADRON and PAMIR experiments. Earlier, asymmetry was observed in distributions of azimuth angles of gamma and hadron families. A detailed analysis of methodological errors in measuring θ, φ angles allowed us to establish the causes of the distortion of azimuth angles distributions. There are two reasons: systematic errors in the measurement of zenith angles by MBS-2 microscopes, used both in the PAMIR experiment, and in the ADRON experiment, and the inclination of XREC based on the subsidence. Calculations showed that the total systematic error $\Delta\upsilon\approx4$ ° completely explains the observed azimuthal asymmetry. Formulas for correcting θ and φ angles are given. The recalculation of the angles by the indicated formulas showed that this corrects the distribution of the azimuthal angles φ. The REC plane should be set relative to the horizontal with an accuracy of no worse than 1 degree in order to avoid distortion of the angular distributions.

1 Introduction

Characteristics of cosmic rays (CR) in the energy region above 19^{15} eV are studied in ground-based experiments deep in the atmosphere. The spectrum and composition of CR is restored by parameters of extensive atmospheric showers (EAS) generated by CR nuclei. Of greatest interest is the small area of EAS near its axis, the EAS cores, where the most energetic hadrons are concentrated. The most informative core detector is the x-ray emulsion chamber (XREC) [1-8] . To determine the primary energy is necessary to register the entire shower, for this purpose XREC is combined with EAS electronic detectors in the so-called hybrid installations [9-15].

The hybrid experiment ADRON [16-19] was started in 1985 to combine the techniques of the EAS and the XREC. The unification of events in the XREC with the EAS was made statistically, using information about the location and angles of the EAS and events in the XREC. Such a method particularly requires obtaining reliable information about angles in the XREC [20-24]. It is known from practice that processing of film information always contains operator errors. To reduce the number of measurement errors, the angles of events in the REC were measured twice and by different operators. With a significant discrepancy between the values of at least one of two angles, a control measurement was made. This procedure reduced the number of errors from 10% to 2% [20].

The installation of ADRON was operated at the Tien Shan station (690 g/cm^2) from 1985 to 1991. In the experiment, two types of XRECs with an area of 162 m^2 were exhibited. The designs of both types of XRECs are shown in Figure 1. In 1985-1986, two half-years and in 1986-89 three one-year exposures of the hadron chamber were made in 1989-1991, two single-year exposures of a thin lead chamber.
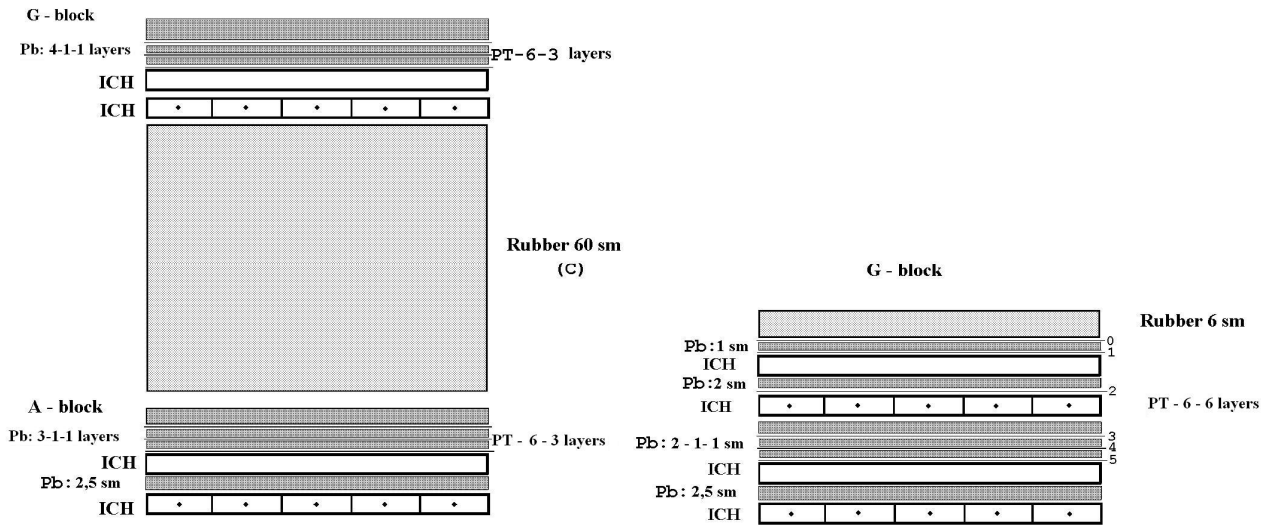
**Figure 1** – X-ray emulsion chambers (XRECs)
of the ADRON experiment

For comparison with EAS in the XREC, gamma-ray families with a total energy of $\sum E_\gamma \geq 10$ TeV were selected. Statistics of such events in the exposures of 1985-1989 (hadron chamber) was 2816 for the gamma-ray unit, and 2222 for the hadron block. In expositions of 1989-1991 (thin lead chamber) it was about 1004 of such events (gamma-family).

Figure 2 shows the spectra of the total energy of the families $\sum E_\gamma$ for the Γ-block and $\sum E_\gamma^h$ for the A-block of the hadron XREC [21]. In the Γ-block gamma-quanta families with energies above 2-4 TeV formed during the decay of π^0-mesons are detected. Charged $\pi^\pm$-mesons interact in the carbon block of the XREC. In this case, the π^0 mesons and gamma quanta from their decay are also registered in the hadron block of the XREC. The energy of these families of gamma quanta is denoted as $\sum E_\gamma^h$, where E_γ^h is the part of the charged hadron energy released into gamma quanta.

Figure 3 shows the distributions of selected events by multiplicity. The left figure shows the spectra in the Γ-block of the hadron XREC (upper spectrum) and the spectrum for a thin lead chamber (bottom). The break in the spectrum of the lead chamber is due to the presence of gaps occupied by ionization chambers. The right figure shows the multiplicity spectrum for the A-block of the hadron XREC.

Figure 4 shows the distributions of azimuth angles measured in the G and A-blocks of the hadron chamber (2 and 5 series, respectively) [21]. The azimuthal distributions are noticeable, at the level of 6σ, different from the uniform ones, which contradicts the data on CR at energies of the 10^{15} eV order and higher. This means that distortions of distributions must be linked with methodological reasons. Most likely this can be due to an error in definition of the vertical. It is known that due to a sharp decrease in the intensity of cosmic rays with an angle θ, the deviation from the vertical should lead to a significant non-distribution of events between different azimuthal directions.
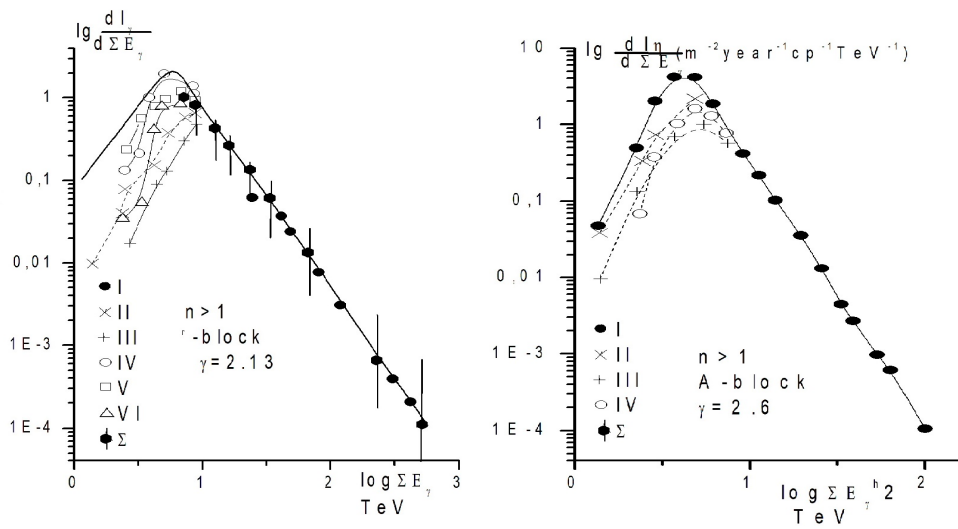
Figure 2 –The spectra of $\sum E_\gamma$ and $\sum E_\gamma^h$ for families selected in gamma and hadron blocks at $n_{\gamma,h} \geq 1$
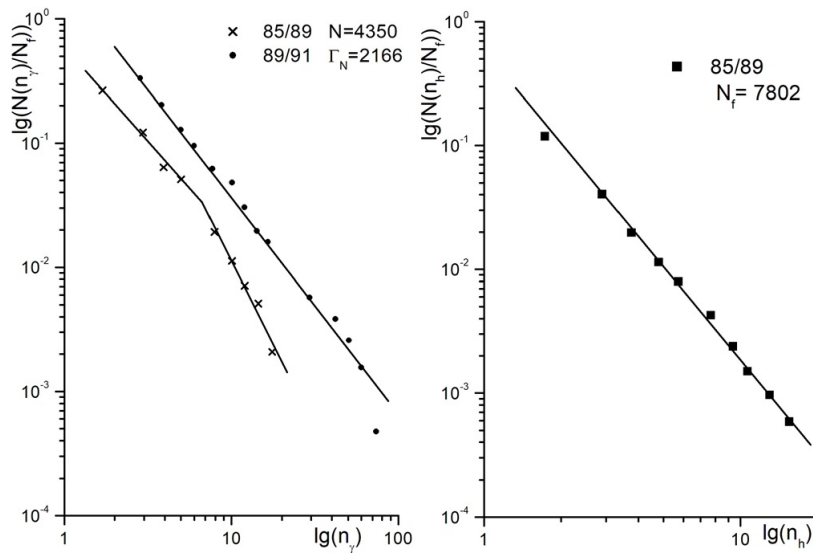
Figure 3 – Integral spectra of multiplicities in the G- and A-blocks of the XREC
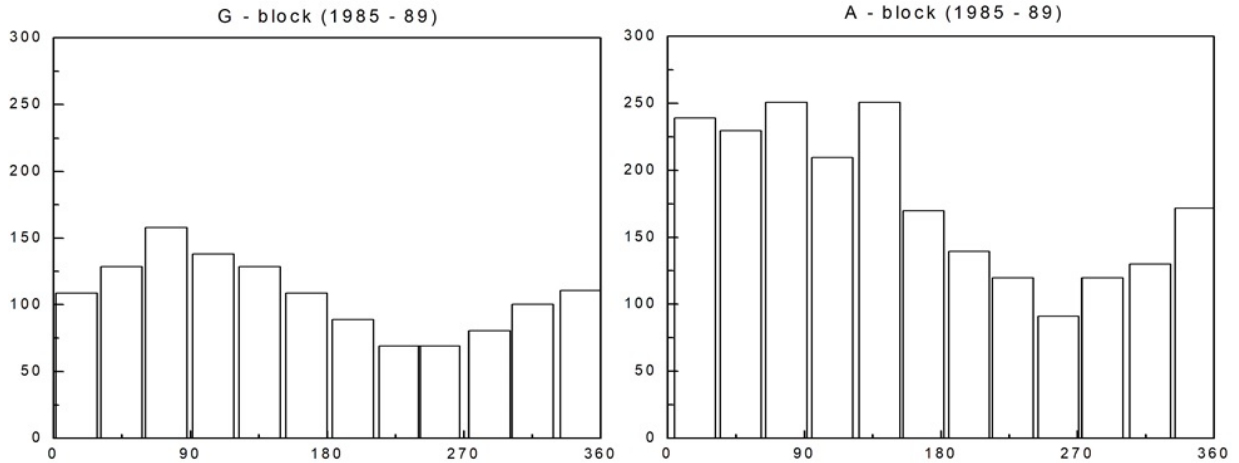(without selection on the threshold)

G - block (1985 - 89)

A - block (1985 - 89)

Figure 4 – Differential distributions of the azimuthal angles φ in the G- and A-blocks of the XREC.

2 Estimation of the distortion of azimuthal distributions.

The differential CR spectrum with respect to the number of particles N at a depth x in the atmosphere is written in the form [22]:

$$\frac{dI}{dN \cdot d\theta \cdot d\varphi} = A(\theta, x)N^{-(k+1)} \sin\theta, \quad (1)$$

where k is the index of the spectrum of showers with respect to the number of particles.

If we do not take into account the change in the atmosphere density along shower path,

$$A(\theta, x) = \exp\left(-\frac{k}{\Lambda}\left(\frac{x}{\cos\theta} - x\right)\right) \approx \cos^{\frac{k}{\Lambda}x} \theta, \quad (2)$$

where Λ is the range of absorption of showers with the number of particles. Then the differential angular spectrum can be written in the form:

$$d^2I = \frac{m+1}{2\pi} I_0 \sin\theta \cos^m\theta \cdot d\theta \cdot d\varphi, \quad (3)$$

where I_0 is the total intensity of the events, and $m = \frac{k}{\Lambda}x$

If this expression is integrated with respect to υ, then we obtain:

$$dI(\rangle\theta) = \frac{I_0}{2m}\cos^{m+1}\theta \cdot d\varphi, \quad (4)$$

uniform distribution by φ.

Methodical deviation from the vertical is equivalent to rotating the coordinate system around any horizontal axis. Moreover, the redistribution of events between different intervals φ depends to a large extent on the value of the exponent m, which in our case is $m = 8.2$ and 9.1 for the hadron and gamma blocks, respectively.

We consider the transformation of the differential function d^2I, when the coordinate system rotates about the X axis by an angle α. Since the volume element $dV=r^2drd\Omega$ is an invariant of orthogonal transformations, and r does not change under rotations, then dΩ also remains unchanged. The transformation of $\cos^m\theta$ is more convenient to consider in Cartesian coordinates, and then return to spherical, but already in the rotated coordinate system. The rotation matrix at an angle α around the x axis has the form:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix}$$

Proceeding the corresponding transformation of the Cartesian coordinates and taking into account that $\cos\theta = z/r$, we finally obtain:

$$d^2I = \frac{m+1}{2\pi} I_0 \cos\theta \cos^m \alpha (1 - \sin\varphi \cdot tg\alpha \cdot tg\theta)^m \sin\theta d\theta d\varphi, \qquad (5)$$

Taking into account the smallness of α and that $\theta < 45°$, we can confine to the first two terms of the polynomial in parentheses. Integrating this expression with respect to θ within $\theta, \pi/2$, we obtain the differential distribution of azimuthal angles in the following form:

$$\frac{dI}{d\varphi}(\rangle\theta, \alpha) = \frac{\cos^{m+1}\theta}{2\pi} I_0 (1 - A\sin\varphi), \quad (6)$$

where

$$A = \frac{m(m+1)}{\cos^{m+1}\theta} tg\alpha \int_{\vartheta}^{\pi/2} \ln^2\theta \cos^{m-1}\theta d\theta, \qquad (7)$$

Taking into account that m is not an integer, the integral in the expression for the coefficient A must be found by numerical methods. The values of the integrals (6) over φ in the range from 0 to π, and from π to 2π give the expression for the asymmetry coefficient K:

$$K = \frac{\pi + 2A}{\pi - 2A}, \qquad (8)$$

Table 1 shows the results of calculating the values of A and K at the experimental values of m = 8.2 and m = 9.1 for the hadron and gamma XREC blocks, respectively. The last column shows the experimental values of K.

Table 1 — The asymmetry coefficients K

m	α	θ	A	k	K_{ex}
8.2	3°	0°	0.19	1.28	1.36±0.04
		20°	0.27	1.41	1.64±0.07
		30°	0.35	1.57	1.78±0.11
	4°	0°	0.26	1.39	1.36±0.04
		20°	0.36	1.59	1.64±0.07
		30°	0.46	1.84	1.78±0.11
9.1	3°	0°	0.20	1.30	1.26±0.04
		20°	0.29	1.45	1.44±0.04
		30°	0.38	1.63	1.52±0.12
	4°	0°	0.27	1.42	1.26±0.04
		20°	0.38	1.65	1.44±0.04
		30°	0.50	1.94	1.52±0.12

Comparison of the experimental and calculated data shows that the deviation from the vertical by an angle $\alpha = 3$-$4°$ explains the observed asymmetry.

3 The procedure for measuring angles in XREC.

The RT-6M X-ray film used in the XREC has two emulsion layers applied on both sides to a substrate with a thickness of 200 μm. The zenith angle θ of the cascade passage through the film is measured by the relative shift of the darkening spots in the upper and lower layers. As the center of the spot, a region with a maximum of darkening is taken. The measurement is carried out using the BSM-2 microscope, which has a linear scale for determining the distance between the spots of darkening of Δ, and finding $tg\theta = \Delta/d$, where d is the thickness of the substrate. In addition, the microscope has an angular scale along which the azimuth angle of the cascade φ is determined. The azimuth angle is formed by the coordinate axis x and the straight line in the plane of the film passing through both darkening spots in the direction "towards the source". The angle φ is measured from the x-axis in a counter-clockwise direction. The scheme for measuring the angles is shown in the Figure 5. In each microscope, a linear scale for determining $\Delta(\theta)$ is calibrated using an object-micrometer. In our case, we used two microscopes

with a fission rate of 11.4 and 13.7 μm in the object plane with 7x zoom. The measurement errors for θ and φ are obtained from the geometric relationships in the following form:

$$\Delta\theta = K\cos^2\theta, \Delta\varphi = Kctg\theta, \qquad (9)$$

where K=0.058.

In the region of small angles θ the azimuth angle is not determined due to the overlap of the spots.

The magnitude of this region depends on the diameter of the spots D, i.e. from the energy of the cascades. The spot diameter is related to the energy by the empirical relationship D=35√(E_γ) μm, where E_γ in TeV.

The accuracy of determining the center of the spot *Δl~0.2D*.. Then, assuming that the overlap area of the spots is *Δl~0.5D*, we obtain the estimate θ_{nep} 10° for E_γ =4 TeV.
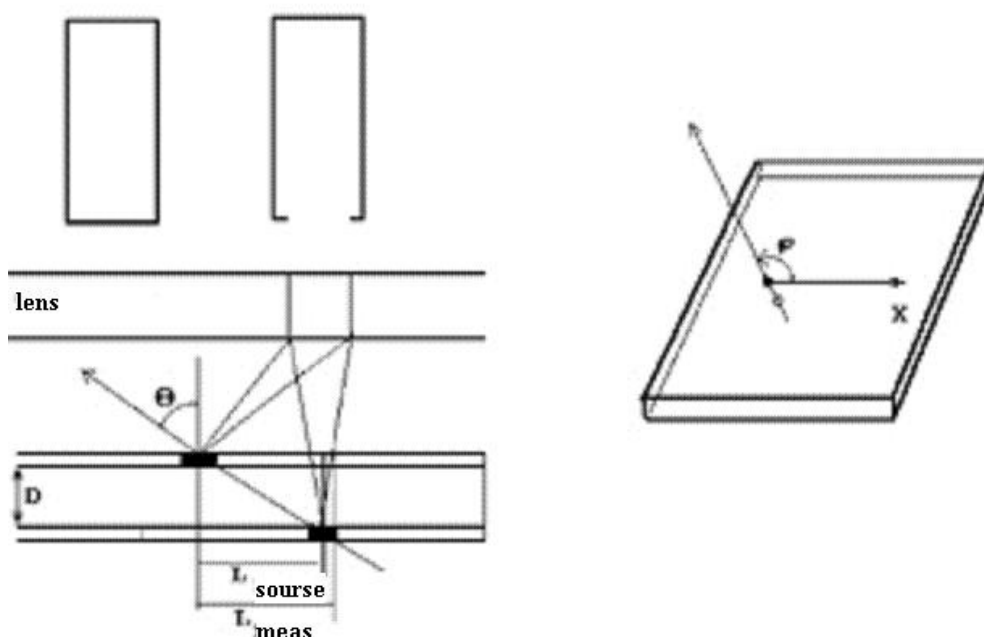

Figure 5 – Scheme of measurement of angles

4 Correction of azimuthal asymmetry

To test the azimuthal sensitivity of the X-ray film, it was irradiated with a radioactive source of gamma quanta BIS-1M. To eliminate the azimuthal inhomogeneity of the irradiation, the film was placed on the disc of the turntable and rotated at a speed of 45 rpm. Dimensions of the darkening were made inside the rings for different angles φ. As follows from the analysis of the data, the sensitivity of the X-ray film from the azimuth angle does not depend.

It turned out that the asymmetry arises from the presence of a systematic error in determining the angle υ and its azimuthal dependence. The scale for determining the distance *Δ* between the darkening spots on the upper and lower layers of the emulsion

was always located in the right eyepiece of the BSM-2 stereo microscope. The optical scheme of it is arranged in such a way that each of the eyepieces "looks" at the object table at an angle ~2°. This is clearly seen in Figure 6, on which the laser beam passes through the optical system, reflecting from the mirror on the stage. As a result, the angle υ decreases for cascades coming to the right of the microscope and increases for those coming from the left. Since the orientation of X-ray films during exposure and measurement always remains this simulated azimuthal asymmetry relative to the sides of the Light.

The magnitude of the distortion of the zenith angle was determined by the difference method. For each cascade, the angle υ was measured at two positions of the film corresponding to the angle

φ=0°and 180°. The difference between these values is 2α .As a result of the measurements, α =2.2°±0.5° was obtained for α. This is somewhat less than the required value, which follows from the calculations. Further testing showed that the missing 2° are added because of uneven subsidence under the XREC and the slope of the concrete foundation. In the Figure 7 corrected distributions of azimuth angles are given taking into account the systematic errors of the microscope and the inclination of the XREC base.
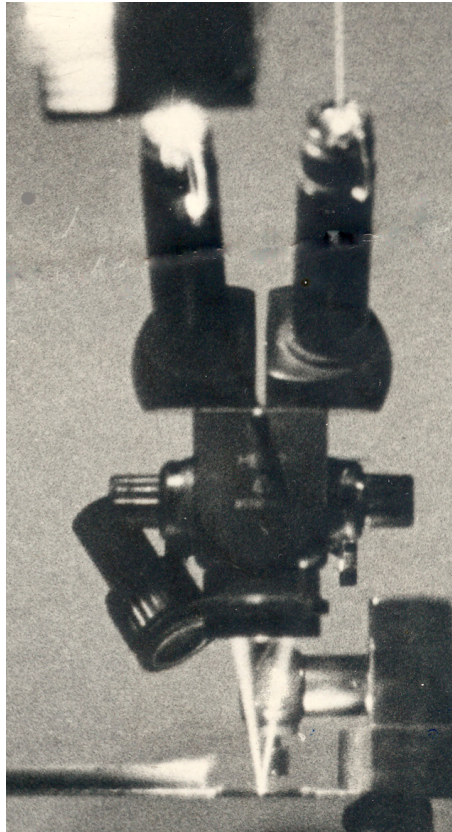
Figure 6 – Optical scheme for obtaining a stereo image
in the BSM-2 microscope.
The image is obtained by passing a beam of light from
the laser through the microscope optics
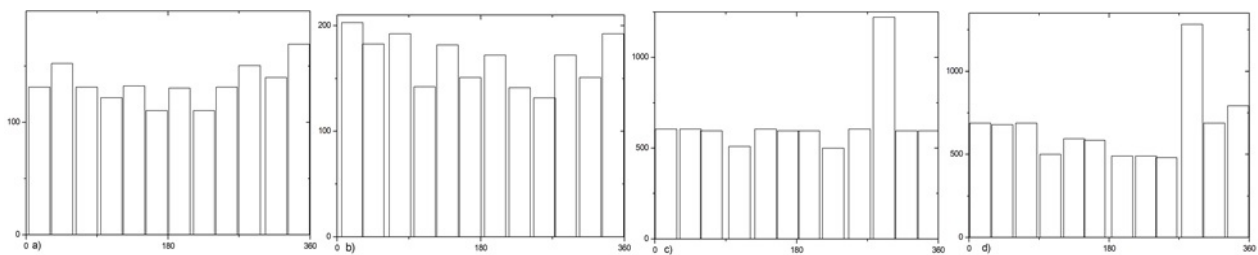
Figure 7 – Differential distributions of the azimuthal angles φ in the G-
and A-blocks of the XREC. Figures c) and d) are the same - θ >30°, but for θ >3°

For each event in the XREC, the corrected angles were determined by the formulas (10):

$$tg\theta_{ucnp} = (tg^2\theta^{u3m} + tg^2\alpha + 2tg\theta^{u3m} \cdot tg\alpha \cdot \cos\varphi^{u3m})^{\frac{1}{2}},$$

$$\cos\varphi_{ucnp} = tg^{-1}\theta_{ucnp}(\cos\varphi^{u3m} \cdot tg\theta^{u3m} + tg\alpha), \tag{10}$$

where α – is the total systematic error in the zenith angle θ.

5 Determination of random errors in measuring the angles θ and φ.

To obtain measurement errors 600 cascades were selected in the XREC HADRON and the values of their angles υ and φ were measured on four different microscope BSM-2. The Figure 8 shows the distributions of measurement errors $\varDelta\theta$, $\varDelta\varphi$, obtained by subtracting individual measurements from the average of four dimensions.

The distributions are practically Gaussian. The gross measurement errors making up θ 4% and φ 9%, were detected and eliminated during the two-dimensional measurement of angles. For measurement errors, the values $\varDelta\theta$,= -0.1.6±2.6 are obtained for zenith and $\varDelta\varphi$ =-0.1±8.6 for the azimuth angles.
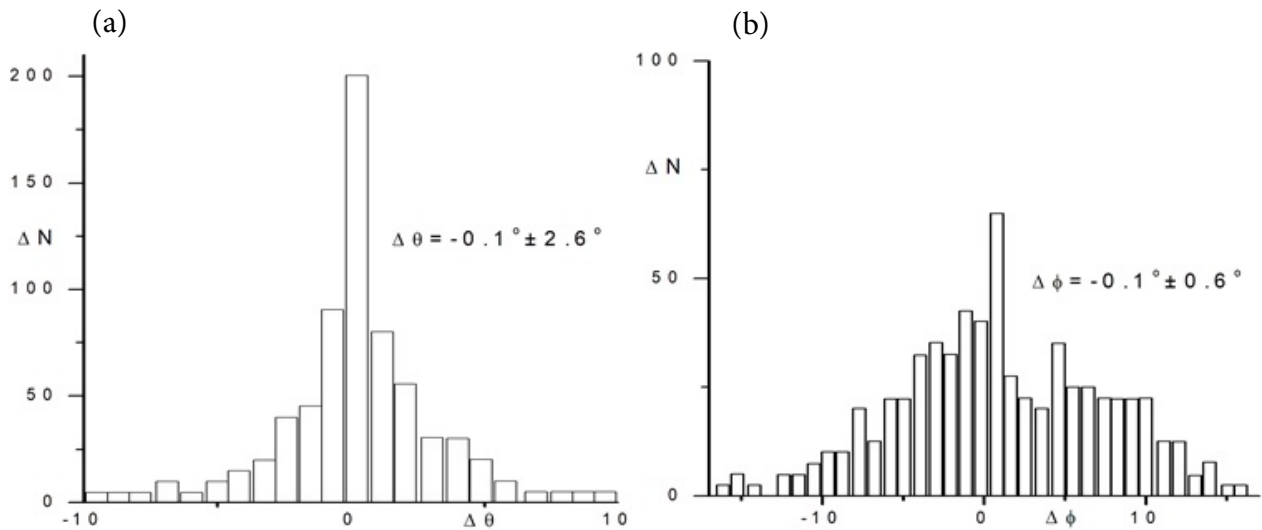
(a) (b)

Figure 8 – Distributions of measurement errors for zenith (a) and azimuth (b) angles

6 Conclusion

Summarizing the results we can conclude:

1. The method of measuring the angles θ and φ in the XREC with the help of stereomicroscopes BSM-2 introduces a number of distortions:

2. In the range of angles θ = 0-10°, the method does not work due to overlapping of the darkening heels.

3. The stereo effect in BSM-2 microscopes leads toa systematic distortion of the angles $\Delta\theta \approx 2°$.

4. In order to obtain undistorted angular distributions, the XREC plane should be exposed with respect to the horizontal with an accuracy not worse than 1°.

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