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Investigation of humidity using the muon component of cosmic rays

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Abstract. Determination of humidity is one of the most important types of hydrometeorological and glaciological observations performed in agriculture, hydropower and water supply. The work is devoted to the development of physical basis of moisture determination method, based on attenuation of the flux of cosmic-ray muons. The relationship between the intensity of muons registered in the underground room of the Tien Shan mountain research station (Almaty) and relative humidity was studied. The results of studies show that the values of the normalized mutual correlation function between the rows of muon intensity and relative humidity vary from 0.3 to 0.7, depending on the coincidence scheme. The data obtained from the muon telescope located at the the Tien Shan mountain research station was used in the work.

1. Introduction

The possibility of using muon fluxes to estimate the amount of water and humidity is considered. This problem is solved using muons generated by cosmic rays in the atmosphere. The properties of muons are considered with reference to the problem of determining the amount of water and moisture using cosmic rays.

2. Instruments and methods

During studying of meson fluxes with energies within 100 GeV, one can neglect the recording of π- and K mesons in pion-hadron and kaon-hadron collisions, and also in the production of pions in K decays. In this case, for the energy spectra of vertically incident muons at sea level, the difference does not exceed 3%. In these approximations, the transport of mesons in the atmosphere is described by the following equation:

$$\left\{\frac{\partial}{\partial h}+\lambda_\mu^{-1}+m_\mu\left[p\tau_\mu\rho(h,\theta)\right]^{-1}\right\}\mu(E,h,\theta)=G_\mu(E,h),$$

where λ_μ - mean meson mean free path to inelastic interaction; m_μ, τ_μ, p –meson mass, its lifetime and momentum, respectively; $\rho(h,\theta)$ – air density at depth h and in direction θ; $G_\mu(E,h) = G_\mu(E,h,R_i)$ - function of meson generation by μ-nucleons and nuclei; $\mu(E,h,\theta)\,dE = \mu(E,h,\theta,R_i)\,dE$ – intensity of mesons of μ type ($\pi^{\pm}$, $K^{\pm}$) with energies from E to $E+dE$ at atmosphere depth h, propagating in a single solid angle under the zenith angle θ, R_i - rigidity of geomagnetic cutoff.

The solution of above equation has the following form:

$$\mu(\mathrm{E},\mathrm{h},\theta)=\int_0^h dh'\exp\left[-\frac{h-h'}{\lambda_\mu(E)}-\frac{m_\mu}{\tau_\mu p}\int_{h'}^{h}\frac{dh''}{\rho(h'',\theta)}\right]G\,(E,h')$$

The relationship between the temperature and pressure of the atmosphere h_0 has the form:

$$T(h_0)=T_s\left[1+\alpha\theta(h_0-h_t)\left(\frac{h_0}{h_t}-1\right)\right]$$

where T_s - stratospheric temperature; h_t - pressure over the tropopause; α - parameter characterizing the temperature gradient in troposphere; $\theta(x) = 1$ at $x>0$ and $\theta(x) = 0$ at $x<0$. During calculations, it was used $T_s = 250\ K$, $h_t = 200\ g/cm^2$, $\alpha = 0{,}073$. Relation ρch and θ has the following form:

$$\rho(h,\theta)=\rho\,(h,\cos\theta^*)\approx gh\cos\theta^*/[R_0T(\cos\theta^* h)]$$

where θ^* - effective angle, coinciding with θ in the plane atmosphere limit. For a spherical atmosphere with $\cos\theta \gg \sqrt{2H/R_i}$:

$$\cos\theta^*=\frac{\left(\frac{2H_0}{\pi R_E}\right)^{\frac{1}{2}}\exp\left(-\frac{\cos^2\theta R_E}{2H_0}\right)}{erfc\cdot\cos\theta\left(\frac{R_E}{2H_0}\right)};\qquad H_0=\frac{R_0T_S}{g},$$

where R_E - Earth's radius, R_0 - specific gas constant; H – height above sea level.

Estimates show that taking nonisothermicity into account is necessary for low-energy mesons at sea level:

One-dimensional kinetic equation describing the transport of muons in the atmosphere without taking into account Coulomb scattering and the motion of muons in the geomagnetic field:

$$\left\{\frac{\partial}{\partial h}+m_\mu[p\tau_\mu\rho(h,\ \theta)]^{-1}\right\}\mu\,(E,h,\theta)=\frac{\partial[\beta_\mu(E)\mu\,(E,\ h,\ \theta)]}{\partial E}+G_\mu(E,h,\theta),$$

Where is the function of generating muons in π_{μ_2} and K_{μ_2} – decays:

$$G_\mu(E,h,\theta)=\sum_\mu\frac{m_\mu B_\mu}{\tau_\mu\rho\,(h,\theta)}\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^{-1}\int_{E_\mu^-}^{E_\mu^+}\frac{dE_\mu}{p_\mu^2}\ \mu\,(E_\mu,h,\theta),$$

B_μ - relative decay probability; $B_\mu(\mathrm{E}) = -dE/dh$ - continuous losses of muon energy. Limits of integration are the following:

$$E_\mu^\pm=\frac{1}{2}\left[\left(\frac{m_\mu^2}{m_\pi^2}+1\right)E\pm\left(\frac{m_\mu^2}{m_\pi^2}-1\right)p\right].$$

at β_μ=β= const up to $E\approx 10^2$ the solution will be the following:

$$\mu(E,h,\theta)=\int_0^h dh'\,\omega_\mu(E,h',h,\theta)G_\mu(E_{h-h'},h',\theta)$$

where $\omega_\mu(E, h', h, \theta)$ - probability that the muon does not decay as the layer passes from $h'$to h, is equal:

$$\omega_\mu(E, h', h, \theta) =$$
$$\tilde{\psi}(E, h'_m, h)^{-\alpha\theta(hcos\theta^* - h_t)\frac{p_{\mu c}}{\beta h_t}} \times \left\{\psi(E, h'_m, h)^{-\alpha\theta(h\,cos\theta^* - h_t)}\psi(E, h', h)\right\}^{\frac{p_{\mu c}\sec\theta^*}{p_h}}($$

Also, there are the following denotions:

$$\psi(E, h', h) = \left[1 - \frac{m_\mu^2}{\omega^2}\frac{\beta(h-h')}{E}\right]\left[1 + \frac{\beta(h-h')}{E}\right]^{-1}\left(\frac{h'}{h}\right);$$
$$\tilde{\psi}(E, h', h) = \left[1 - \frac{m_\mu^2}{\omega^2}\frac{\beta(h-h')}{E}\right]\left[1 + \frac{\beta(h-h')}{E}\right];$$
$$\omega^2(E, h', h) = \frac{(Ep_{h-h'} + pE_{h-h'})(E_h E_{h-h'} + p_h p'_h - m_\mu^2)}{E(p_h + p_{h-h'}) + E_{h-h'}(p_h + p)};$$
$$\tilde{\omega}(E, h', h) = \frac{(Ep_{h-h'} + pE_{h-h'})(Ep_{h-h'} + pE_{h-h'})}{E + E_{h-h'}}$$
$$E_p = E + \beta h;\ p_h = (E_h^2 - m_\mu^2)^{1/2};\ p_{\mu c} = \frac{H_{0}m_\mu}{\tau_\mu},$$
$$h'_m = \max(h', h_t sec\theta^*)$$

at energies much larger βh, ω_μ has the following form:

$$\omega_\mu(E, h', h, \theta) \simeq \exp\left[-\frac{\alpha\theta(hcos\theta^* - h_t)(h - h'_m)}{h_t\left(\frac{p_{\mu c}}{p}\right)}\right] \times \left\{\frac{h}{h'}\left(\frac{h'_m}{h}\right)^{-\alpha\theta(hcos\theta^* - h_t)}\right\}^{\frac{p_{\mu c}}{p}cos\theta^*}.[1\text{-}4]$$

3. Results and discussion

A relation was obtained between the intensity of muons (Figure 1) recorded in the underground room of the Tien Shan mountain research station for the coincidence circuit 1 (Figure 2) and the relative humidity of atmosphere. 2-minute data of the intensity of muons was used of Tien Shan mountain research station of Ionosphere Institute of NCITC.

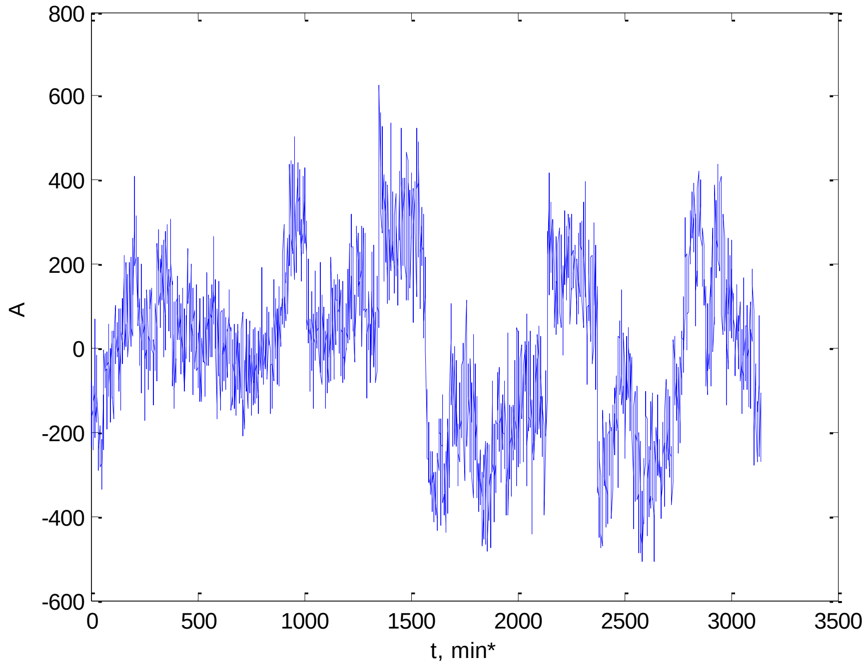

Figure 1. Uncorrected for 2-minutes data muon intensity in underground station for October 2016.

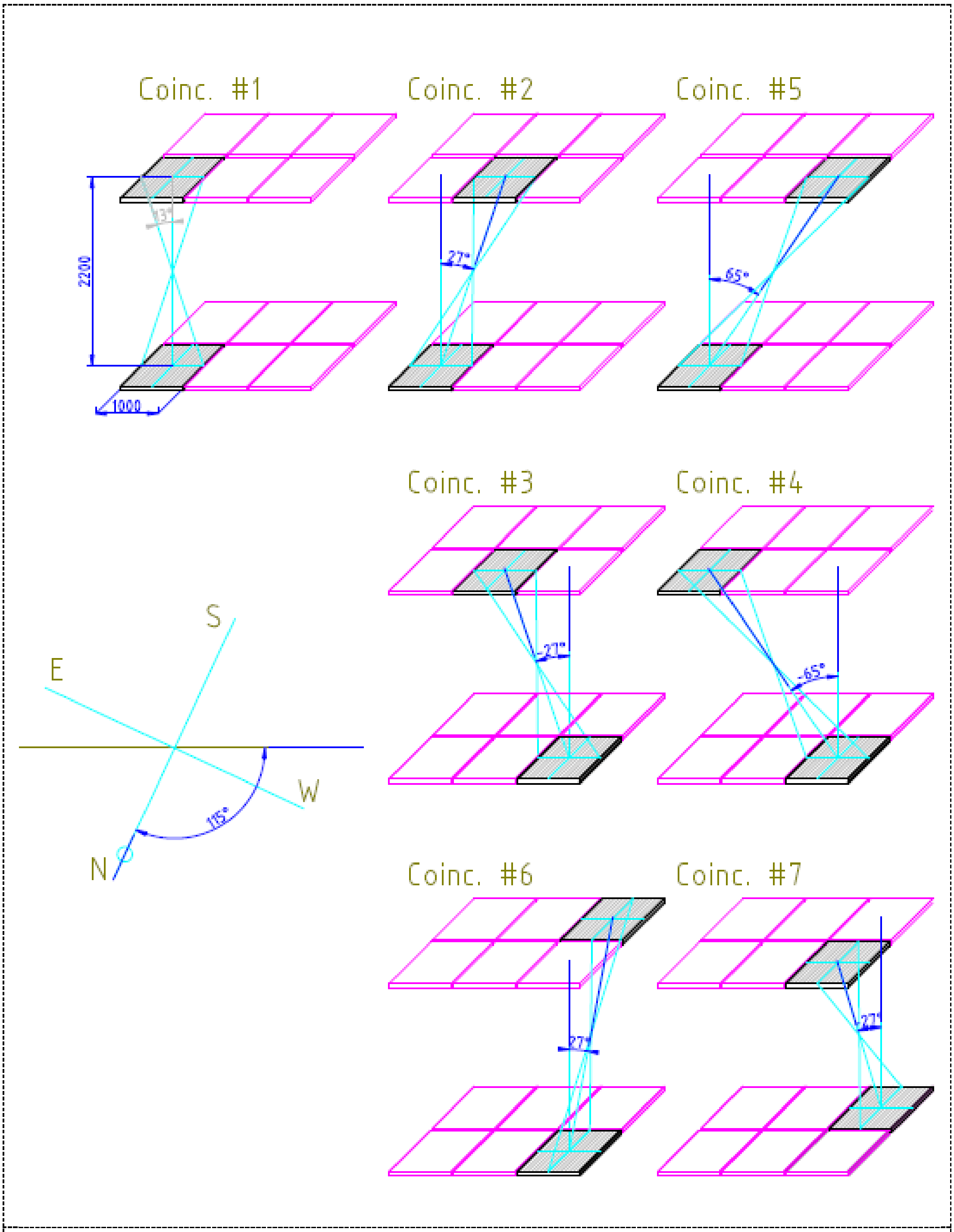

Figure 2. The scheme of muon coincidences.

4. Conclusions

Correlation analysis was carried out for those periods of time when an average correlation was observed between time series of minute values of counting rate and relative humidity. The results of the studies show that the values of normalized mutual correlation function between the rows of muon intensity and relative humidity vary from 0.3 to 0.7, depending on the coincidence scheme under consideration. So, for example, for the time period from October 1 to October 4, 2016, we see the

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strongest link in the scheme of matches according to scheme 5, as well as autocorrelation in scheme 3. (See Figures 3,4)

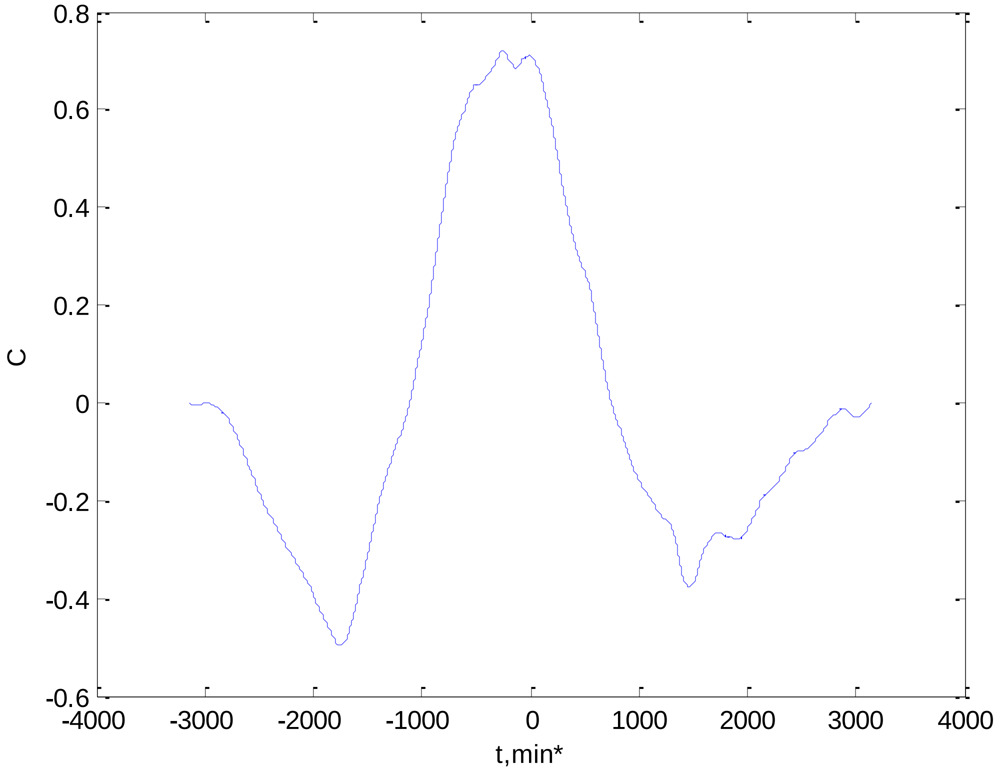

Figure 3. The normalized cross-correlation function calculated for time series of muon intensity (Scheme 5) and relative humidity for the period from October 1 to October 4, 2016

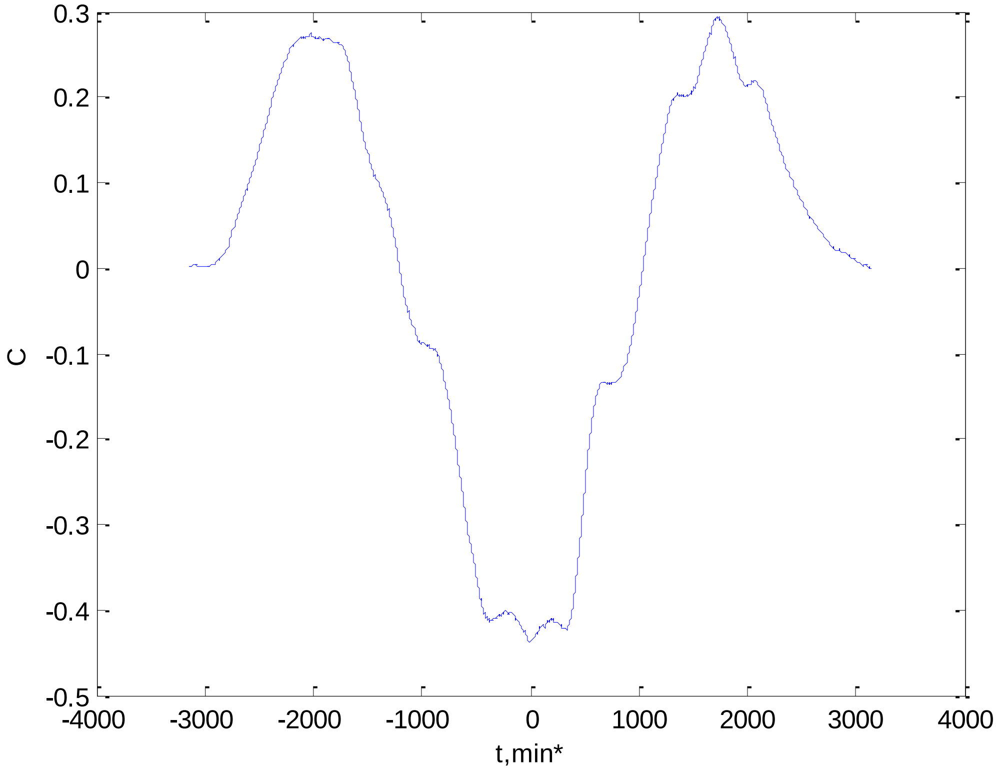

Figure 4. The normalized cross-correlation function calculated for time series of muon intensity (Scheme 3) and relative humidity for the period from October 1 to October 4, 2016

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