Reception coefficients and energy characteristics of the ground level cosmic ray detectors.

KOBELEV P., BELOV A., EROSHENKO E., YANKE V.

N.V. Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation RAS N.V. Pushkov (IZMIRAN), Moscow, Troitsk, RU-142190, Russia

kosmos061986@yandex.ru

Abstract: In this paper the energy characteristics and reception coefficients of the zero-harmonic cosmic ray variations of neutron monitors and muon telescopes of the world wide network of stations with the two-parameter representation of the variations spectrum are presented. These characteristics were obtained for 161 neutron monitors and 12 muon detectors with a total of 80 registration destinations. Methodical questions of application of the considered approach are discussed.

Keywords: reception coefficients, neutron monitors, muon telescopes.

1 Introduction

For analysis data from world wide network of detectors different methods have been developed (Global Survey Method [1], [2], Globally Spectrographyc Method-GSM [3], which substantially represents a more complicated version of the spherical analysis and based on the reception vectors for different harmonics. Reception vectors account the type of observed particles, receiving properties of the each detector, its geographical position, the interaction of the primary cosmic radiation with the atmosphere and magnetosphere. In the zero-harmonic approximation, the reception vector is reduced to a reception coefficient. Since the issue of [4],[5], in which reception vectors for the neutron and muon components have been received for a practical application, the world wide network of stations has significantly changed and expanded. This is especially true for the muon detectors - to three telescopes veterans, Yakutsk, Nagoya and Hobart, about a ten muon detectors of various sizes were added. About two tens new neutron monitors was created. Therefore, it is necessary to calculate the reception vectors for the new detectors to describe the variations up to second harmonic.

2 Reception Coefficients of Neutron and Muon components of cosmic rays

In the zero-harmonic approximation, which we have to restrict ourselves in this paper, for the observed variations can be written

$$\nu^i = \delta N/N_{R_c} = \int_{R_c}^{R_u} \frac{m^i(R,h_0)J(R)}{N_{R_c}} \frac{\delta J}{J}(R)dR =$$

$$= \int_{R_c}^{R_u} W^i(R_c^i, h_0, R)\frac{\delta J}{J}(R)dR \qquad (1)$$

Here $m^i(R,h_0)$ and $W^i(R_c,h_0,R)$ integral multiplicity of generation and coupling function of primary and secondary variations, recorded by the detector i, located in the point with the rigidity of geomagnetic cutoff R_c and at atmospheric depth h_0. The spectrum of primary cosmic radiation and the spectrum of variations are designated as J(R) and $\delta J/J(R)$. For variation spectrum $(R \leq R_u)$ terminating on the rigidity R_u, one of the next parametric presentations can be used:

$$\delta J/J(R) = a_1 R^\gamma, \text{ or } a_1(b+R)^\gamma, \text{ or } a_1(b+R^\gamma), \text{ or}$$

$$a_1(1+(R/R_0)^\gamma) = a_1(1+bR^\gamma) \qquad (2)$$

where a_1 is amplitude of variations of the particles with a rigidity about of 1 GV. For daily variations more often first specter from the list is used, and for long-period variations last one. We have used last parametric presentation. To calculate the reception coefficient, normalized to 10 GV, the spectrum more often is used:

$$\delta J/J(R) = a_{10}(1+b(\frac{R}{10})^\gamma \qquad (3)$$

where a_{10} is amplitude of variations of the particles with a rigidity about of 10 GV which is close enough to the effective rigidity, recorded by a network of neutron monitors and muon telescopes. Expression (1) for the observed variations at the i = 1 .. k detectors can now be written as

$$\nu^i = a_{10}\int_{R_c}^{R_u} W^i(R_c^i, h_0, R)\delta J/J(R)dR, \text{ or}$$

$$\nu^i = a_{10}C_{00}^i(\gamma, b) \qquad (4)$$

where $C_{00}^i(\gamma,b)$ is a reception coefficient of the zero harmonic, which is defined as:

$$C_{00}^i(\gamma,b) = \int_{R_c}^{R_u} W^i(R_c^i, h_0, R)\delta J/J(R)dR \qquad (5)$$

As a result for k detectors that observe variations ν^i, we have a non-linear system of equations for the parameters (a,γ,b). By Taylor series expansion around of the zero approximation(a^0,γ^0,b^0), retaining only the first-order terms, namely,

$$\nu \simeq \nu^i\mid_0 +$$

$$A_1^i\mid_0 (a-a^0) + A_2^i\mid_0 (\gamma-\gamma^0) + A_3^i\mid_0 (b-b^0) \qquad (6)$$

such a system is linearized and solved by the method of successive approximations.

For spectrum $\delta J/J(R) = a_1(1+bR^\gamma)$, zero-harmonic reception coefficient is determined as

$C_{00}(\gamma,b) = \int_{R_c}^{R_u} W^i(R_c^i,h_0,R)(1+bR^\gamma)dR =$

$1 + b\int_{R_c}^{R_u} W^i(R_c^i,h_0,R)R^\gamma dR,$

and expansion coefficients (6) are:

$A_1^i = C_{00}^i(\gamma,b), A_2^i = a_1 b\int_{R_c}^{R_u} ln(R) * W^i(R_c^i,h_0,R)R^\gamma dR$

$A_3^i = a_1\int_{R_c}^{R_u} W^i(R_c^i,h_0,R)R^\gamma dR = a_1(C_{00}^i - 1)/b$

As well a and b is linear parameters, the corresponding coefficients is determined by zero-harmonic reception coefficients. For non-linear parameter γ, it is necessary to calculate special integral. Similarly, for spectrum $\delta J/J(R) = a_1R^\gamma$, zero-harmonic reception coefficient is determined as

$C_{00}(\gamma,b) = \int_{R_c}^{R_u} W^i(R_c^i,h_0,R)R^\gamma dR,$

and expansion coefficients (6) are

$A_1^i = C_{00}^i(\gamma,b), A_2^i = a_1\int_{R_c}^{R_u} ln(R)W^i(R_c^i,h_0,R)R^\gamma dR$

And for spectrum $\delta J/J(R) = a_1(b+R)^\gamma$, zero-harmonic reception coefficient is determined as

$C_{00}(\gamma,b) = \int_{R_c}^{R_u} W^i(R_c^i,h_0,R)(b+R)^\gamma dR,$

and expansion coefficients (6) are

$A_1^i = C_{00}^i(\gamma,b),$

$A_2^i = a_1\int_{R_c}^{R_u} ln(b+R)W^i(R_c^i,h_0,R)(b+R)^\gamma dR$

$A_3^i = a_1\gamma\int_{R_c}^{R_u} \frac{1}{b+R}W^i(R_c^i,h_0,R)(b+R)^\gamma dR$

To solve the equation (6) is sufficient to perform several iterative steps, starting from the point of zero approximation (a^0,γ^0,b^0)

2.1 Coupling Function of Neutron component

For polar coupling functions of a neutron component we used an approximation

$$W(R) = \alpha(k-1)exp(-\alpha R^{-(k-1)})R^{-k} \qquad (7)$$

with the altitude dependence of parameters and obtained in [7]: for a minimum (1965) and maximum (1969) solar activity, correspondingly (h_0 in bars):

$ln\alpha_{min} = 1.84 + 0.094h_0 - 0.09exp(-11h_0);$

$k_{min} = 2.40 - 0.56h_0 + 0.24exp(-8.8h_0)$

$ln\alpha_{max} = 1.93 + 0.150h_0 - 0.18exp(-10h_0);$

$k_{max} = 2.32 - 0.49h_0 + 0.18exp(-9.5h_0)$

2.2 Coupling Function of Muon component

Directional non-normalized coupling function of the muon component, which recorded under a zenith angle θ, in [8] is proposed to approximate with an expression

$$W(R,\theta,h^0) = \beta * exp(-\alpha * z^{-\delta}) * z^{-k} \qquad (8)$$

$z = R/R_m$,where R_m is median rigidity in GV Approximation parameters are defined as follows:

$\alpha = 0.37R_m^{0.1}, k = 1.82R_m^{0.02},$

$\beta = 540R_m^{-(0.82+0.2ln(R_m))}muon/(m^2 * s * sr * GV),$

$\delta = 1.1$

In this approximation, the key parameter is the median rigidity. If muon detector located at a depth of h_0 m.w.e. in the atmosphere and under the screen with d m.w.e. thick, those cut-off muons with energy $< \varepsilon$(for example, for ε = 0.316 GeV d = 0.025 m.w.e.), then in the case of a plane-parallel screen, median rigidity can be approximated in the form $R_m = 2.25(\frac{\lambda*h_0+d}{cos\theta})^{1.04}$, or in the case of spherically-symmetric screen (for example, ionization chambers) $R_m = 2.25(\frac{\lambda*h_0}{cos\theta}+d)^{1.04}$ The coefficient λ controls the dependence of the coupling functions on the level of solar activity: λ= 2 and $\lambda = 2 + 1.013/h_0$ for minimum and maximum solar activity, respectively, which is especially important in the upper atmosphere detections, such as stratospheric measurements.

3 Reception coefficients of stratospheric sensing detectors.

Bringing these stratospheric sounding allows us to extend the investigated energy range to the region of lower rigidities up to a few tenths of a GV. For this , the data of ionizing radiation counter telescopes near the Pfotzer maximum (whose depth is between 80-120 mb, depending on the level of solar activity, geomagnetic cutoff rigidity) is used. In this case, we can also use the approximation of the coupling functions in the form (8), which is shown in the summary figure 1 for the 100 mb level and for minimum and maximum solar activity. We were limited to three points Murmansk, Moscow and Mirny; for which there is a long series of observational data, where such measurements are carried out at the moment.

4 Reception coefficients of the spacecraft detectors.

Bringing the data of spacecraft detectors expands more an investigated energy range in the area of small rigidity . Since the detector is situated outside the atmosphere, it is necessary to convert the equation (1) for receiving reception vectors. In equation (1) $m^i(R,H_0)$ is the integral multiplicity generation that defines the number of secondary particles of type i, incident on the detector at depth H_0 and formed as a result of the nuclear cascade process in the atmosphere caused by the primary particle with rigidity R_c, incident on the edge of atmosphere. Ideally, for spacecraft detector $m^i(R) \equiv 1$, but the effectiveness of any detector is depend on the rigidity of detected particles, and it is necessary to take into account the cascade multiplication of particles in the surrounding substance. Reception coefficients in this case can be written as

$$C_{00}^i(\gamma,b) = \int_{R_c}^{R_u} m^i(R)\frac{J(R)}{N_{R_c}}\frac{\delta J}{J}(R)dR \qquad (9)$$

As can be seen from (9), to calculate reception coefficients, it is necessary to clearly set the primary cosmic ray spectrum, taking into account the level of solar activity.

5 Discussion of results.

The most important parameter in calculating the reception coefficients, as it follows from (5), is a coupling function.

We have applied the coupling function of a neutron and muon components that have been tested by us in many applications, for example, in [6]. According to the previously performed calculations of cascade processes in the atmosphere using the corresponding kinetic equations, integral multiplicity and coupling functions were obtained; approximation for the neutron and muon component of which is given in [7] and [8], correspondingly.In figure 1 polar (differential and integral) coupling functions of the neutron monitor, muon telescope Nagoya (vertical and inclined) and stratospheric sounding telescopes of charged particles are compared. These coupling functions have been tested in solving many problems of space physics.

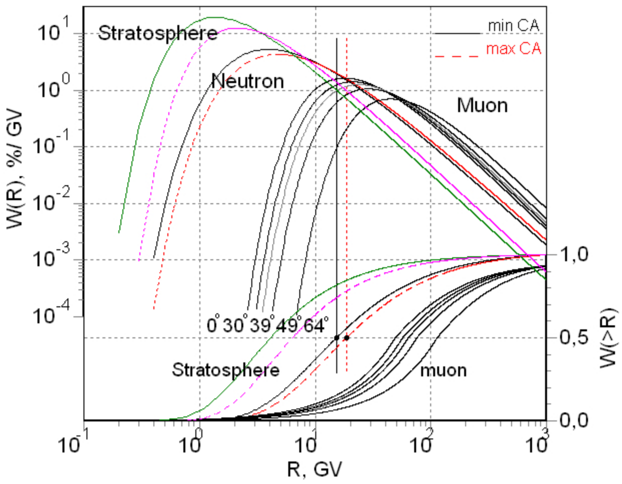

Fig. 1: Polar differential and integral function of the neutron monitor muon telescope Nagoya (vertical and inclined) and telescopes charged component of the stratospheric sounding.

Effective rigidities R_{eff} for all considered detectors are compared in figure 2. The effective rigidities R_{eff} is defined as the rigidity of the particles of modulated primary cosmic radiation, when the variations of the particles flux with such rigidity are equal to variations of particles in all energetic range, which is given by variation spectrum. In addition to the effective values are often used other energy parameters, such as mean, median, mid-logarithmic values. If we consider only the characteristics of the detector, it is sufficient to use the mean or median values. When considering the characteristics of the detectors in the radiation field with a given spectrum, it is important type of problem being solved. If we study the behavior of particles of low-energy spectrum of the particles, it is preferable to use an effective value, and if it is important to increase the weight of the particles of the high-energy particle spectrum, that are useful mid-logarithmic rigidity or energy. And in general, in order of increasing values are: effective value, mean, median, mid-logarithmic, and the difference between them is greater, the steeper the energy spectrum.

Reception coefficients $C_{00}^{i}(\gamma, b)$ for minimum and maximum solar activity, for the convenience of practical use, were received in tabular form with a very small step: 0.05 for in the range from 0 to -2.2 and 0.3 for b in the range from 0 to 12.2. The range of variations limited by an upper threshold rigidity R_u= 1000 GV, but in general, R_u is considered as the parameter. Also were calculated table values for the effective rigidities. These characteristics were obtained

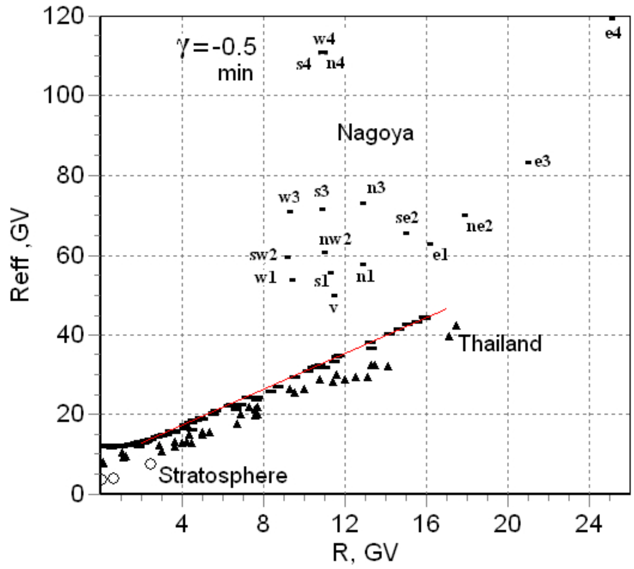

Fig. 2: Effective particle rigidity for different detectors - neutron monitors, muon telescope (Nagoya) and the telescope of charged particles of stratospheric sounding. Neutron monitors are divided into groups: near sea level (squares) and mountain (triangles).

for 161 of the neutron monitor and 12 muon detectors with a total number of 80 destinations of registration. Due to the large volume of data and for the convenience of practical use, the resource for calculated reception coefficients of muon telescopes was created [9], which stores the tables of coupling coefficients and lists of all detectors, for which such data is received. An example of one of the tables in three-dimensional graphical representation shown in figure 3. In figure 4 are shown the rigidity dependence for the re-

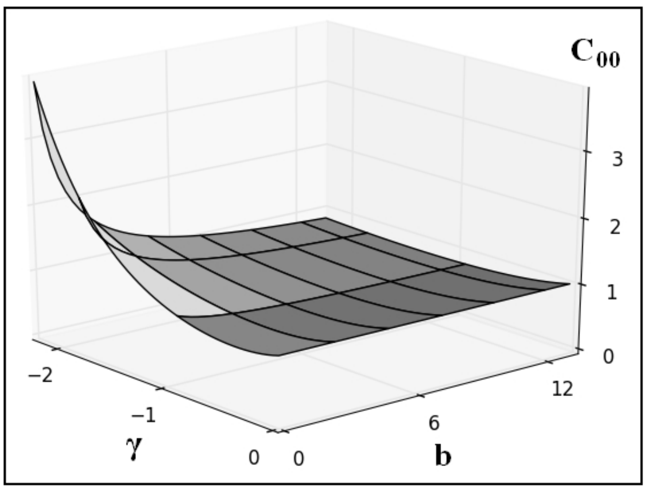

Fig. 3: Example of three-dimensional representation of the results of calculations for the receiving rate of the neutron monitor Apatity, a minimum of solar activity, Ru = 1000 GV.

ception coefficients of zero-harmonic for the network of neutron monitors, Nagoya muon telescope and stratospheric sounding detectors of charged particles for two values of the spectrum. As we would expect, all ground neutron monitors located above the latitude knee (R < 1.5 GV), have permanent reception coefficients. Outstand neutron monitors (shown by filled triangles)and the polar stations have highest coefficient. Stand out, of course, reception coefficients of stratospheric detectors, that are superior to the polar neutron monitor reception coefficients of 3-4 times. Coupling coefficients of different directions of telescopes are grouped around the values of the vertical geomagnetic cutoff rigidity, and the spread is determined by the east-west asymmetry.

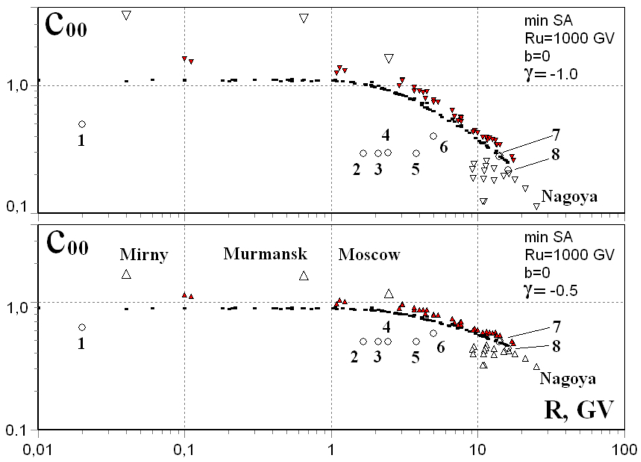

Fig. 4: Rigidity dependence of reception coefficients of CR zero-harmonic for the neutron monitor network (filled squares), stratospheric sounding charged-particle detectors (large triangles) and muon telescopes: Nagoya (small triangles) and vertical muon telescopes with numbers for: 1-South Pole, Vostok; 2-Yakutsk; 3 - Greifswald; 4-Moscow; 5 - Adelaide; 6 - Bure; 7 - YangBaJing; 8 - Guangzhou.

6 Summary and Conclusions

For all stations of worldwide network of neutron monitors, muon telescopes and existing stations of stratospheric sounding, reception coefficients for CR zero-harmonic was calculated. The same approach can be applied to calculate the reception coefficient for spacecraft detectors of charged particles taking into account their specific characteristics. Reception coefficients was calculated with high resolution in γ (0.05) and b (0.3), which is sufficient to solve the system of spectrographic equations (4), for example, by their linearisation (6). All calculation results are available on the resource [9], where the reception coefficients and lists of all detectors are stored. As an example of the described technique [6], we present the analysis of long-term variations in the zero- harmonic approximation for the three time points: during periods of high solar activity in June 1991 and November 2003 and in a unique period of minimum solar activity in October 2009. To do this, for each time point spectrographic system of equations was solved (4) by using data of the neutron, muon and charged component of stratospheric observations. As a result, for each time found solutions (a_{10}, γ, b) of the equations $v^i = a_{10}C^i_{00}(\gamma, b)$, which are shown in figure 5 (straight lines). In this figure also shown the experimentally measured speed of light variations for all types of detectors - muon telescope Nagoya, the network of neutron monitors and stratospheric detectors of ionizing radiation. The data in figure 5 speak well for reception coefficients calculated for all components of the entire range of rigidities.

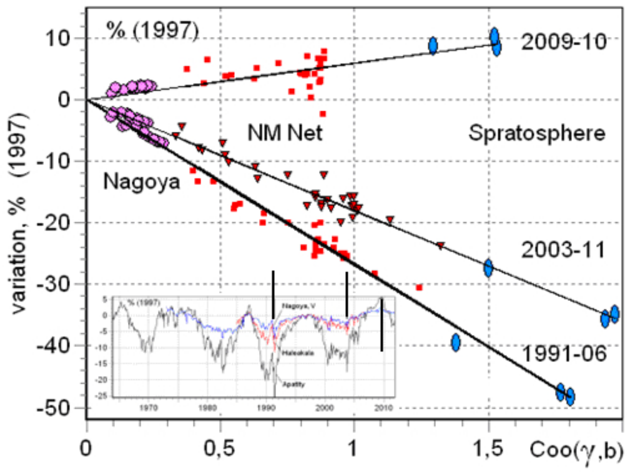

Fig. 5: The dependence of the variations of the muon, neutron and common components of the coupling coefficients for the three periods, marked by vertical curves on the inserted picture.

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