Long-term stability of the neutron monitors global network for overall monitoring period

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Abstract. Three independent methods for estimating the long-term stability of detectors of the world network of neutron monitors and muon telescopes are proposed. Conditions that determine the long-term stability of the detectors.

1. Introduction

To research physical processes in the interplanetary medium and to determine the structure of the heliosphere as a whole, such a powerful ground instrument as the world network of neutron monitors and muon telescopes has been used for six decades. To obtain the long-period characteristics of the interplanetary medium, the temporal stability of the functioning of the network as a whole and of its individual elements is extremely important, and estimating the quality of the data of each station in the network is the task of this article. Such a task was posed and earlier [1-4].

Several new aspects were taken into account in this paper: a) the data series under consideration was supplemented with data from the last decade, b) the analysis of the spectrum of variations was carried out for the 2009 database, and this allowed to increase the accuracy for the determined spectrum parameters, c) to solve the problem, new ltvd database was developed d) the changes of the rigidity of geomagnetic cutoff were taken into account [5-6] for a network of cosmic ray stations for the period under review.

In order to quantify the quality of the device data, it is necessary to have a standard. Often an unreasonable approach is used, when a "reliably" working station is adopted as this standard. A number of stations really have "reliably working" status, but they are difficult to be used as a standard, since each station registers cosmic rays in its own range of cosmic ray spectrum.

In this paper, the model of cosmic rays variations developed in [7] is used as a standard. Naturally, the discrepancy with the model for each station is associated with the data quality of this station. Of course, this approach has its drawbacks, since the construction of an adequate model itself is a difficult task. But this problem can be solved by the method of successive approximations if, with appropriate modifications of the model, it is possible to describe the variations of cosmic rays in the heliosphere quite well over a sixty-year observation period.

Along with the model method, another independent method for estimating station stability is developed, which can be called as “the group” method. In this method, all stations are divided into several groups. When forming groups, it is necessary to satisfy rather contradictory requirements: in each group, the variations should be minimally different and the number of detectors should be as large as possible (at least three). Several approaches are possible here.

In the case of the method of groups/averages the average (or median) values of the variations in
each group are considered as standard values. The method of groups/means (in contrast to the method of groups/medians) allows us to estimate the errors of the found efficiencies. Possible variations in this method are not excluded, and this is an its drawback. Another option, the group/relationship method is implemented by a much more complex algorithm, but the primary variations are automatically eliminated, which is its advantage. With the help of the developed mathematical algorithm, a given set of stations is divided into "reliable" and "unreliable" operating stations. The criterion of "reliability" is the confidence interval within which observed counting rates (which are freed from the primary variations) are changing. In this case, a group of stations that has the same variations and is defined as "reliably" operating is used as a standard, and they should be in the majority. This method for each station makes it possible to determine the efficiency of the detector, and, what is even more important, the accuracy of its evaluation.

Each method has its advantages and limitations, but on their joint basis it is possible to obtain reliable quantitative estimates of the long-term stability. Current analysis was based on the data from the world network of neutron monitors, muon telescopes and stratospheric sounding stations, which can be found in the database of the monthly-averaged resolution data [8].

2. The principle of continuous evaluation of the stability of detectors

Let us figure out the dependence of the relative efficiency of the detector with the observed variations of the counting rate and with the variations of the standard detector. The efficiency of the counter \( \varepsilon \) is the probability of registering the particle, which penetrates the working volume of detector. In order to move from the observed counting rate \( N \) to the true counting rate, it is necessary to calculate \( N/\varepsilon \).

Therefore, the efficiency of the detector can also be defined as the number by which the observed counting rate needs to be divided in order to get rid of the variations associated with the internal changes of the detector itself or with the electronic path.

Therefore, proceeding from the definition of variations as \( v = N/N_B - 1 \), the variation of the measured counting rate of the detector \( N \), taking into account its effectiveness \( \varepsilon \), can be written as:

\[
v = \frac{N}{N_B} \varepsilon - 1,
\]

where \( N_B \) is the detector’s counting rate in the base period. Comparing the variations \( v \) in the counting rate of the detector with somehow chosen "standard" variations \( v_s \), \( v \), and taking into account detector’s efficiency, we get

\[
\frac{N}{N_B} \varepsilon - 1 = v_s \quad \text{and} \quad \varepsilon = \frac{v + 1}{v_s + 1}, \tag{1}
\]

i.e. effectiveness is determined only by observable \( v \) and "standard" \( v_s \) variations and this underlies of continuous evaluation of effectiveness. Starting from (3) and from the law of addition of random errors, the error of the found efficiency is

\[
\sigma_{\varepsilon} (\text{stat}) = \frac{1}{v_s + 1} \sqrt{(v_s + 1)^2 \sigma_v^2 + (v + 1)^2 \sigma_{v_s}^2} \tag{2}
\]
where $\sigma_v$ and $\sigma_s$ are the statistical errors of the experimentally and of the "standard" detector determined variations. The statistical errors $\sigma_v$ are

$$\sigma_v = N_B^{-2} \sqrt{N_B^2 \sigma_N^2 + N^2 \sigma_{N_s}^2}.$$  \hspace{1cm} (3)

Taking into account that $N = 2$ and $\sigma_{N_s}^2 = N_B/n$, where $n$ is the number of intervals for the base value averaging (in our case $n = 12$), for the error of the experimentally found variations, we obtain

$$\sigma_v = \frac{(v+1)}{\sqrt{N}} \sqrt{1 + \frac{v+1}{n}}.$$ \hspace{1cm} (4)

The statistical errors of the calculated variations for the monthly-averaged intervals of averaging are negligibly small $\sigma_v \approx 10^{-5}$, statistical errors $\sigma_{s,v}$ of the variations of the "standard" detector are determined by the method used and are given below.

In addition to statistical performance errors $\sigma_v (\text{stat})$, it is necessary to take into account difficult-to-evaluate systematic errors $\sigma_v (\text{sys})$, which may be significant.

The greatest contribution to systematic errors for the model method is, of course, due to the "incorrect" shape of the model spectrum used. This error can be only found by carrying out calculations for various forms of spectra, but it can be roughly estimated, assuming in the three-parameter spectrum the parameter $b=0$, i.e. assuming the spectrum is purely power-law. The upper bound for the systematic error yields $\sigma_{sys} = 0.005$. Systematic errors are large enough for the group method. To ensure an acceptable number of stations in the group, it is necessary to form them from stations in a wide range of rigidities; which give a decisive contribution to systematic errors. For the groups under consideration, the maximum value is $\sigma_{sys} = 0.017$.

Taking into account all sources of errors, efficiency is defined as affectivity $= \varepsilon \pm \sigma_{\text{stat}} \pm \sigma_{\text{sys}}$. As will be shown below, the total error is $\approx \pm 0.02$.

3. The model method

In [7], a spectrum of long-term variations of cosmic rays was determined using a specially improved for the researching of long-term variations variant of the global survey method [9]. The analysis was carried out on the database of monthly-averaged data of neutron monitors (45 stations), stratospheric detectors (3 stations) and the multidirectional muon telescope Nagoya. The observed variation $\delta N^i/N_i$ is $V\text{model}^i = \int_{R_0}^{R_0} W(R, R', h_0) \cdot \frac{\delta J}{J}(R) dR = a_{10} C_0^i$, where $\delta J/J(R)$ is the spectrum of isotropic variations, $C_0^i$ is the reception coefficient of the zero harmonic for the station under consideration.

The coupling functions $W(R, R', h_0)$ for the neutron component are taken from [10], for the muon component from [11] and for the stratospheric data from [12], here $R'$ is the geomagnetic threshold, $h_0$ is the level of observation. In the model, the spectrum of variations is given in a three-parameter form and presented as: $\delta J/J(R) = a_i/(b + R)^\gamma$. Parameters changing area is $\gamma = 1.2 \div 2$.\n
\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure_2.png}
\caption{Effective rigidity for various detectors - neutron monitors (triangles), a muon telescope (Nagoya) and a telescope of charged particles of stratospheric sounding. Horizontal risks are the boundaries of groups.}
\end{figure}
and $b = 0 \div 4$ GV. In [7] is shown that the three-parameter approximation of the spectrum of variations of galactic cosmic rays is suitable for describing the spectrum of long-term variations in the range of 5-50 GV. All variations are determined relative to the base period of 2009. Figure 1 shows the parameters found for the spectrum of variations of galactic cosmic rays $a_0$, $b$ and $\gamma$. The lower panel shows the standard errors of the experimental data and model, which make it possible to estimate the adequacy of the used model of cosmic ray variations. In this case, the expected error of the variations of the "standard" detector $\sigma_{v_s}$ in expression (4) defined as:

$$
\sigma_{v_s} = \left( \frac{\partial \nu}{\partial a_0} \right)^2 \sigma_{a_0}^2 + \left( \frac{\partial \nu}{\partial b} \right)^2 \sigma_{b}^2 + \left( \frac{\partial \nu}{\partial \gamma} \right)^2 \sigma_{\gamma}^2
$$

Errors of the variations (5), determined by the model, are summed from three terms, with the terms contributing 0.005%, 0.05%, 5% respectively, i.e. the error is mainly determined by the error of parameter $b$.

The main drawback of the method is its model dependence, but if the model well describes the variations in the range of rigidity in question, this method makes it possible to estimate the efficiency of all detectors.

4. Method group/medium (median)

All detectors are divided into several groups, within which the variations of different detectors should differ only statistically. The average (or median) values of the variations in each group are considered as a “standard” values. Four groups of stations with effective rigidities are formed within the intervals: $[0 \div 13)$, $[13 \div 18)$, $[18 \div 25)$ and $[25 \div 50)$ GV (figure 2). The effective rigidities $R_{\text{eff}}$ of all the detectors under consideration are compared in figure 2 (neutron monitors are divided into two groups: near the sea level-rectangles and mountain-triangles).

The fact that the group/medium method does not rely on any model is its merit. The disadvantage of this method is the need to consider groups of stations with close effective rigidities of the detected particles, which is not always possible to accomplish in practice.

5. Group/relationship method

This method was originally developed for the internal quality control of data from cosmic ray detectors. The basis of modern methods of internal control is the division of the detector into the largest possible number of identical and independent elementary detectors. This approach allows us to determine the relative efficiency of each elementary detector, i.e. it allows a continuous
quality control of data [13]. The method of relations was adapted to analyze the long-term stability of network station detectors [1].

The conditions for the applicability of the group/relationship method for the problem of analyzing the long-term stability of detectors are the same as for the group/average method, i.e., integration of stations into groups of stations with very close energy characteristics.

6. Discussion of the results

In figure 3-4, the efficiency changes for some stations obtained by using all three given methods: model, group/average and group/relations methods. The efficiencies obtained by the group/relations method were determined by us earlier [1]. In addition, estimates of the corridor of their errors were made. For all stations, the results are shown on the website [8].

The coincidence in the details of the efficiencies found by three independent methods is evidence in favor of all methods and their correct application. An efficiency analysis shows that a constant drift of about 0.1%/year is observed at many stations for a sufficiently long or even entire period of observation (figure 3). The largest and constant drift, around -0.4%/year, is observed for the data of the station Goose Bay. Here is also shown the data corrected for the drift (curve c).

For some stations (figure 3, Beijing (and also Tibet, which is not listed here), an anomalously large annual temperature effect (2-4%) is observed. An insignificant part of this effect, <0.1%, is due to the actual temperature effect of the neutron component, while most of the temperature changes are due to local temperature changes affecting the elements of the electron path, although the Beijing station has quite good long-term stability. In the initial period of observations, the Beijing data were corrected for a local temperature effect.

ESOI station also has a large annual wave, but it is already connected with wet snow during the winter. In the initial observation period, the ESOI data were also corrected for the snow effect.

In figure 3 and figure 4 the moment of changing the IGY to NM64 (Deep River, Apatity) is clearly visible in the initial period of their work.

In general, changes in efficiency are sporadic in nature, apparently related to the human factor. Instrumental variations (or drifts) can be classified into: 1) daily and seasonal, associated with temperature changes; 2) long-term, associated with changing of the properties of sensors; 3) and sporadic instrumental variations.

If periodic variations are easily identified and corrected, it is extremely difficult to do this for long-term instrumental drift. The biggest error in the data appears from the pressure drift (up to 0.1%/year). The use of a constant value of barometric coefficient leads to a false 11-year wave with an amplitude more than 0.1%.
Large sporadic changes in efficacy may be caused by at least two reasons. First reason is a leakage of charge (micro breakdowns) through the high voltage circuit. Another reason is the inadequate stability of high-voltage power supplies. In addition, for some mountain stations, the effect of snow is very important. This effect can lead to a complete distortion of the variations.

For high-latitude stations (figure 5), an annual wave with an amplitude of about 1%, opposite in phase in the northern and southern hemispheres (Fort Smith and Kingston, Ottawa and McMurdo) is clearly observed [14]. The annual wave is due to the temperature effect of the neutron component and is negligible for equatorial stations. This indicates a good sensitivity of the technique used. All the results obtained in this paper in digital and graphical form could be found in the resource [8].

7. Conclusion
1. Coincidence of the found efficiencies in details indicates the applicability of all methods (model, group/average method and group/relations method). In addition, our model of variations describes well the modulation of cosmic rays over the entire sixty-year observation period.
2. For "good" stations (about 10), the drift can reach 0.04 %/year, which is an order of magnitude less than the possible long-period variations ~ 1%/year.
3. The number of stations that operating for several decades and having stability more than 2% for the entire observation period is about 30. However, many of them are still characterized by sporadic changes in efficiency. The characteristic drift is about 0.1%/year.
4. For many stations (about 40), the drift of data is generally in the background; the quality of the data is determined by numerous sporadic changes.
5. An annual temperature wave with an amplitude of about 1% is viewed which is in antiphase in N/S.
6. For individual stations (ESOI), the snow effect is clearly visible; for other detectors (Beijing and Tibet.) a large local temperature effect is observed.

Acknowledgments
This work was partially supported by the program of the Presidium of RAS №3, RFBR 17-02-00508 and РНФ 19-72-20085, support the project USU "Russian network of ground stations of cosmic rays". We are grateful to all the staff of the World Network of CR stations http://cr0.izmiran.ru/ThankYou.

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Figure 5. Illustration of the temperature effect of the neutron component by the example of two pairs of detectors.