Estimation of the state of the cosmic ray flux based on neural networks

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Abstract. An automated method is proposed for assessing the state of the cosmic ray flux on the base of neural networks. The method allows using the data of neutron monitors to determine the state of the cosmic ray flux in accordance with the a priori specified states of the neural network. The paper evaluates the method and presents the results of its application during periods of increased solar activity and magnetic storms. The possibility of realizing the method on-line is demonstrated.

1 Introduction

Solar cosmic rays are one of the main factors of space weather [1]. With a significant increase in the level of radiation damage, there is a negative and, in some cases, a destructive effect on space crews, satellites and ground-based positioning and communication equipment [2]. The study of the dynamics of cosmic rays is carried out according to the data of the world network of neutron monitors [3]. The detected time series of data have a complex non-linear structure [4-6]. The data from ground stations are secondary cosmic rays and, in addition to valuable information on processes and interactions in near-earth space, contain a high level of noise (natural interference, such as precipitation, wind, etc., and instrumental errors). Due to these factors, as well as taking into account the incomplete knowledge of the properties of cosmic rays and other aspects, the problem of operational and accurate forecasting of space weather remains open [1, 2]. In order to predict effectively the space weather, it is necessary to develop mathematical methods for the analysis and prediction of cosmic ray data. At present, special attention is paid to the development of methods for on-line assessment of

At present, special attention is paid to the development of methods for on-line assessment of cosmic ray dynamics and timely detection of sporadic effects such as events of ground level enhancements (GLE). GLE events are strong proton enhancements, which determine the limiting energy of solar cosmic ray protons. They are a consequence of large solar flares, but the acceleration mechanism that produces particles up to tens of GeV is not completely understood. These phenomena pose a serious radiation danger to human health and life [8]. Up to now, there are no models and methods capable to analyze the data of neutron monitors on-line and with sufficient accuracy. The classical methods used [9-12] are poorly adaptable to the changing of complex non-stationary structure of neutron monitor data, as a result of which they are ineffective for studying anomalous processes in the dynamics of cosmic rays.

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Modern methods, such as the station ring method and the global survey method [13, 14], make it possible to determine the main characteristics of the dynamics of the cosmic ray flux with acceptable accuracy. But due to complex mathematical calculations the problem of automating these methods has not been solved. Taking into account the lack of study of the nuclear-physical and astrophysical properties of the dynamics of cosmic rays, as well as, in general, the processes occurring in near-earth space, it is proposed to use the neural networks. Neural networks have a number of advantages compared to traditional computing systems [15, 16]. This mathematical technique allows solving problems with unknown connections and regularities in the data, it is relatively resistant to noise and it is able to adapt to signal changes. An important aspect is also the fault tolerance in its hardware implementation and the potential ultra-high performance. The approach considered in the paper was first proposed in works [5, 17]. It is based on the use of vector quantization neural networks LVQ [18]. The constructed neural networks classify the neutron monitor data and determine the state of the cosmic ray flux. Evaluation of the work of neural networks showed the possibility of their application in real time. The effectiveness of the method has been experimentally approved during periods of low and high solar activity.

2 Description of the method

The LVQ network is supervised learning algorithm [18]. Figure 1 shows the structure of the LVQ neural network. It includes two layers: (1) the Kohonen layer, which performs clustering of input vectors; (2) a linear layer associated with the corresponding clusters k of l predetermined classes [18]:

$$F_l = \sum_k w_{kl} y_k$$

where w_{kl} are weight coefficients of the neuron *l* of the linear layer associated with the neuron *k* of the Kohonen layer, y_k is the output value of the neuron *k* of the first layer.

During the training of the neural network in the Kohonen layer, a winner neuron p is determined on the base of the estimate of the distance S:

$$D = S_{\min}(X, W_k) = \min \|X - W_k\|.$$

The output value of the winning neuron p is equal to 1: $y_p = 1$, and of other neurons - equal to zero: $y_k = 0$, $k \neq p$. Thus, based on the results of the Kohonen layer, the network classifies the input vectors X. Namely, the winning neuron establishes the belonging of the input vector X to the class associated with the given cluster.



Fig. 1. LVQ neural network structure.

The work defines the following three classes of neural network state:

- 1. **Class I** determines the regular course of cosmic rays and corresponds to the absence of sporadic effects. Training and testing data sets were selected for quiet periods, when there was no flare activity, no fast solar wind fluxes from the visible side of the Sun along the line with the Earth, and, as an indirect factor, there were no magnetic storms and disturbances in the magnetosphere (in according to geomagnetic indices: A, K, Dst [19, 20]).
- 2. Class II determines the presence of small sporadic effects. The data sets were selected for the periods during which the occurrence of small flares on the Sun directed at the Earth and the presence of weak disturbances in the magnetosphere were observed.
- 3. **Class III** determines the presence of large sporadic effects. The data sets were selected for the periods during which solar and geomagnetic disturbance were detected such as the arrival of disturbed high-speed solar wind fluxes and/or an associated fast interplanetary shock in vicinity of the Earth, as well as the occurrence of a magnetic storm and strong disturbances in the magnetosphere.

3 Experiments and analysis of the results obtained

The experiments used minute data from neutron monitors at Inuvik, Irkutsk, Novosibirsk, Kingston, Thul, South Pole, Apatity, Moscow and Mawson stations [3] (see Figure 2). The periods of strong and moderate magnetic storms for 2013 - 2019 were analyzed. When constructing a training sample, the selection of data for each class was based on the above criteria (see p. 1-3). Taking into account the peculiarities of the dynamics of cosmic rays, neural networks were trained separately for periods with high (2013 - 2016) and low (2017 - 2019) solar activity (the activity of the Sun was determined by the F10.7 index [20]).



Fig. 2. Geographic map of neutron monitors.

In order to suppress a noise, the data from neutron monitors were processed based on the operation of wavelet-filtering. The operation of multi-scale analysis was used [21, 22]. The signal was presented in the form:

$$f(t) = f_{(-l)}(t) + \sum_{j=-1}^{-l} f_j(t)$$

where $f_{(-l)}(t)$ – approximating component of scale l, $f_{d,j}$ – detailing components of scales j = -1, ..., -l, $f_{(-l)}(t) = \sum_n c_{-l,n} \phi_{-l,n}(t)$, $f_j(t) = \sum_n d_{j,n} \Psi_{j,n}$, $\Psi_j = \{\Psi_{j,n}\}_{n \in \mathbb{Z}}$ – wavelet, $\phi_j = \{\phi_{j,n}\}_{n \in \mathbb{Z}}$ – basis generated by the scaling function, j – scale. The components $f_{(-l)}(t)$ of scales l = 1, 2, 3 are taken as a useful signal, and the $\sum_{j=-1}^{-l} f_j(t)$ components are taken as a noise.

Figure 3 shows the results of processing cosmic ray data during a strong magnetic storm occurred on September 8, 2017. In order to simulate the operational mode, data processing was performed in a sliding time window - a daily variation (a signal with the length of 1440 samples) was fed to the input of the neural network with an offset of one day. On the eve of the August 27-28 event, the solar wind speed (SWS) varied within $v = 350 \pm 50$ km/s, the interplanetary magnetic field (IMF) component fluctuated around undisturbed values from $Bz = \pm 3 \text{ nT}$ to $Bz = \pm 7 \text{ nT}$ [19]. The neural network (Figure 3 f, g), according to data from the high-latitude Mawson station (latitude: -67.60S, longitude: 62.88E), determines this period as quiet (Class I). Then, on August 30, the state of the cosmic ray flux changed, and small sporadic effects of Class II appeared. At the beginning of the day on August 31, an accelerated flux from an extensive coronal hole arrived, the SWS increased to 719 km/s during the day, IMF fluctuations increased to Bz=±19 nT, and a weak magnetic storm arose (Dst index reached -50 nT as shown in Figure 3 e). During September 1 and 2, SWS remained high within $v=600\pm100$ km/s, the maximum fluctuations of the IMF component were Bz= ± 8 nT, the geomagnetic field was slightly disturbed (K-index had values equal to 4 as shown in Figure 3 f). By the middle of the day on September 5, the SWS increased again to 600 km/s and the geomagnetic activity increased as shown in Figure 3 f. Neural network determines the period from August 31 to September 5 as weakly disturbed (Class II, see Figure 3 g). Then, due to the arrival of the accelerated flow from the coronal hole (crossed the central meridian on September 5), the SWS on September 7 increased to 670 km/s and the fluctuations of IMF increased (Bz= \pm 10 nT). At the beginning of the day on September 8, an accelerated flux from a coronal mass ejection hit the Earth (September 6 - an X9.3 outburst in group 2673), the SWS sharply increased to 847 km/s, fluctuations of IMF increased to Bz=±32 nT, and a strong magnetic storm arose (Dst-index reached -150 nT, K-index had values equal to 7, Figure 3 e, f). The results of the neural network operation on the eve of the magnetic storm (for 48 hours) on September 6 showed the occurrence of large sporadic effects (Class III, Figure 3 g). Comparison of the network results with SWS (Figure 3 d) and the Dst index (Figure 3 e) shows that the period of the cosmic ray state change coincides with the period of a sharp increase in the SWS and the Dst variation. Analysis of the data of neutron monitors (Figure 3 a, b) and their spectral structure (Figure 3 c) shows the emergence of a large-amplitude Forbush effect on 8 September. We also note that on 10 September, during the SWS increase (Figure 3 d), there was a sharp increase in the intensity of cosmic rays (Figure 3 a-c) and weak geomagnetic disturbances arose (Figure 3 f). The neural network determines the period from September 6 to September 12 as strongly disturbed (Class III, Figure 3 g). Comparison of the network operation results with the space weather data demonstrates the correctness of its solutions and confirms the effectiveness of the proposed method.



Fig. 3. a) NM data (Mawson), b) NM data using the Daubechies function 2, decomposition to the level m = 3, c) wavelet spectrum of NM data, positive anomalies are highlighted in yellow, negative - blue, d) solar wind speed, f) Dst-index, f) k-index, g) results of the LVQ neural network

Figure 4 demonstrates the results of cosmic ray data processing during a strong magnetic storm occurred on September 13, 2014. According to space weather data [28], on September 1-2, SWS varied within 400 km/s, the IMF components fluctuated around zero (Figure 4 d). Analysis of geomagnetic data (Figure 4 f) shows a small increase in geomagnetic activity on

September 2 (K = 4). Neural networks (Figure 4 g), according to the data of the high-latitude station Inuvik (latitude: 68.36, longitude: -133.72) classify this period as weakly disturbed (Class II). From September 3, SWS jumps of up to 450 km/s were caused by accelerated fluxes from coronal mass ejections [19]; on September 6, the IMF Bz component dropped to -9 nT, and weak disturbances in the geomagnetic field appeared (Figure 4 f). According to the results of the neural network operation (Figure 4 g), the state of the cosmic ray flux during this period changed: small sporadic effects (Class II) appeared on September 5, and the state is characterized as strongly disturbed (Class III) on September 6. Note that according to the Izmiran Space Weather Forecast Center a Forbush effect was registered on September 6, 2014 at 1524 UT [23]. A sharp decrease in the intensity of cosmic rays on September 6 is also observed in the filtered signal (fig. 4 b).



Fig. 4. a) NM data (Inuvik), b) NM data using the Daubechies function 2, decomposition to the level m = 3, c) wavelet spectrum of NM data, positive anomalies are highlighted in yellow, negative - blue, d) Bz (Gsm), f) Dst-index, f) k-index, g) results of the LVQ neural network.

Then, on September 11 at 2302 UT, due to the accelerated flux from the coronal ejection (CME on September 9 from the M4.5/1N flare), the SWS sharply increased to 480 km/s, the IMF Bz component dropped to -14 nT (Figure 4 d) and disturbances arose in the geomagnetic field (Figure 4 e, f). At 1527 UT on September 12, due to the accelerated flux from the coronal ejection (CME on September 10 from the X1.6/2B flare), the SWS sharply increased to 670 km/s, then by the end of the day it became v=800 km/s, the IMF component dropped to values Bz = -15 nT (Figure 4 d). By the end of the day on September 12, the Dst index reached a value of -75 nT (Figure 3 e). The neural network classifies the period of magnetic storm as strongly disturbed (Class III). Analysis of the filtered cosmic ray signal (Figure 4 b) shows at the beginning of the day on September 12, the occurrence of a Forbush effect of small amplitude and a deep Forbush decrease in the second half of the day. The disturbed state of cosmic rays on September 12 can be also seen in the wavelet spectrum of the signal (Figure 4c). According to the IZMIRAN Space Weather Forecast Center a very strong Forbush effect was registered on September 12, 2014 at 1553 UT [23]. Comparison of the neural network results with the space weather data confirms the reliability of the solutions obtained.

Table 1 presents the results of application of neural networks during periods of strong and moderate magnetic storms according to the data of neutron monitors. The results confirm the fact of occurrence of sporadic effects on the eve of magnetic storms and testify to the effectiveness of the proposed method. During the main phases of magnetic storms, the state of the cosmic ray flux in most of the cases is characterized as strongly disturbed. The recovery of their level according to the data in Table 1 can last for several days.

Magnetic storms (station)	Anomalies before the storm (class/time before the storm)	Main phase of the storm (class)	Recovery phase (class)
10.07.13-16.07.13 Kingston	2/24h. 3/12h.	3	2
15.03.15-20.03.15 Kingston	2/48h. 3/12h.	3	2
16.01.16-22.01.16 Kingston	2/24 h.	3	2
21.08.18-28.08.18 Moscow	2/18 h.	3	2
12.03.18-19.03.18 Moscow	2/48 h. 3/24 h.	3	2
17.04.18-26.04.18 Moscow	3/ 24 h.	3	1
17.04.18-26.04.18 Novosibirsk	3/ 24 h.	3	1
4.10.18-11.10.18 Moscow	2/68 h. 3/9h.	3	2
5.07.19-12.07.19 Moscow	2/68 h. 3/12h.	3	1
5.07.19-12.07.19 Novosibirsk	3/ 68 h.	3	1
4.06.19-11.06.19 Moscow	2/9 h.	2	1
11.04.14-16.04.14 Inuvik	3/12 h.	3	2
11.04.14-16.04.14 Thul	3/32 h.	3	1
12.09.14-16.09.14 Thul	3/24 h.	3	2
12.09.14-16.09.14 Inuvik	2/60 h.	3	2
11.04.14-16.04.14 Moscow	2/48 h.	3	1
12.09.14-16.09.14 South Pole	2/24 h.	3	1
5.09.14-7.09.14 Inuvik	2/24 h	3	2
10.09.14-13.09.14 Inuvik	2/24 h	3	2
29.08.17-01.09.17 Mawson	2/27 h	2	2
5.09.17-09.09.17 Mawson	3/48 h	3	3

Table 1. Results of applying the method during periods of magnetic storms

4 Conclusions

The proposed method for analysis of data from neutron monitors has shown its effectiveness in detecting anomalous changes in the dynamics of the cosmic ray flux.

A number of events have experimentally confirmed the occurrence of sporadic effects in cosmic rays, which precede magnetic storms and serve as their predictors. During the periods of the main phases of magnetic storms, the state of the flux of cosmic rays in most cases was characterized as strongly disturbed, the recovery of their level lasted for several days.

The results of applying the method during periods of increased solar activity and strong magnetic storms are described in detail on the example of the events on September 13, 2014 and September 8, 2017. Comparison of the results of the constructed neural networks with space weather data confirmed the reliability of the solutions obtained.

Automation of the method allows it to be applied for the operational data analysis mode in space weather forecasting problems.

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