Neural Network Recovery of Gaps in Geomagnetic Field Records

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Abstract: *The paper demonstrates the capabilities of neural network recovery of ground-based geomagnetic field records at a selected magnetic station using similar magnetic field data at another station. By the example of the restoration of disturbance records made at the magnetic stations Kakioka, Kanoya, Alma-Ata, Hermanius, San Juan, Tucson, Honolulu with and without data from the OMNI satellite system on the parameters of the solar wind and interplanetary magnetic field, it is shown that the technique of artificial neural networks can to successfully fill in the gaps and failures in the records of individual observatories of the global network of magnetic observation stations. The created artificial neural network tool can be used for scientific and applied problems of geomagnetic information recovery.*

Keywords: magnetic recording, magnetic observatory, geomagnetic storm, magnetosphere, artificial neural network, solar activity, forecast.

I. INTRODUCTION

The solution of a number of problems of solar-terrestrial communications, the search for methods for remote diagnostics of near-Earth space, the establishment of leading intramagnetospheric processes require the creation of a global picture of geomagnetic disturbances and operational monitoring of its changes. Unfortunately, for various reasons, sometimes there is no possibility of creating too frequent a network of magnetic stations. There are various methods that allow using the correlation analysis of magnetic records at different magnetic stations with some accuracy to restore the magnetic records of one station from another [1, 2]. This accuracy is determined primarily by the mutual arrangement of the stations and depends on what characteristic scale of disturbances needs to be restored. Often, periodic variations of the type of solar diurnal have a masking effect on the recovery process of irregular magnetic disturbances.

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In the present work, an attempt is made to reconstruct the records of disturbances of the horizontal component of the geomagnetic field at a selected low latitude station from magnetic records at stations located also near the geomagnetic equator. For this, the technique of artificial neural networks (TIN) is used. For this purpose, a recurrent ANN with backward propagation of error was used, which has a feedback loop coming from a hidden layer (Elman ANN). Our experience with the application of the ANN technique for geophysical tasks [3-18] suggests the appropriateness of using this particular version of the ANN. The architecture of this ANN is presented in Fig. 1. When working with the selected ANN, the output value was understood as magnetic recording at the station where it is necessary to restore the recording. Magnetic records at one or a number of stations, magnetic records at which are always available, were understood as input quantities. When setting up the study, the prepared functions with a period of 24 hours were used as additional input values. The latter were used in the framework of the original method developed here to eliminate the masking effect of the solar-diurnal variation and, therefore, improve the restoration of magnetic recordings in general.
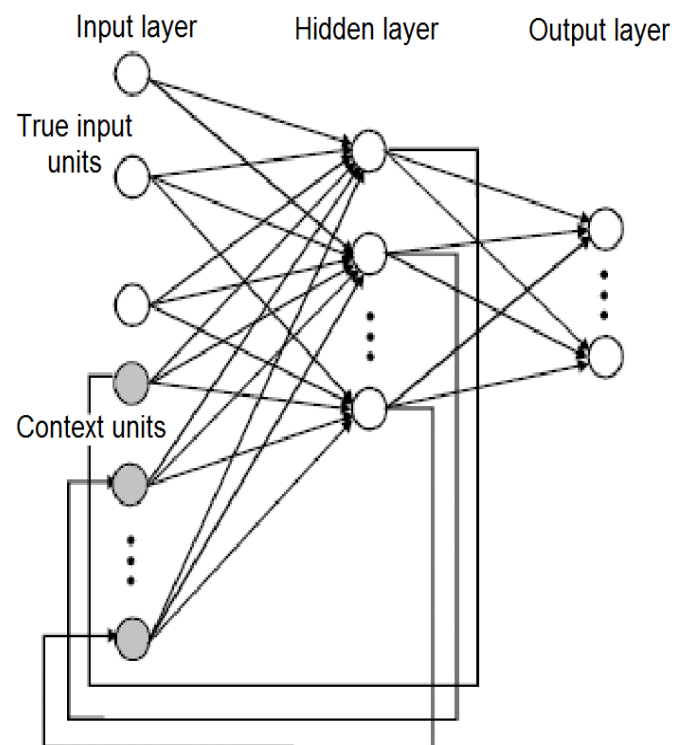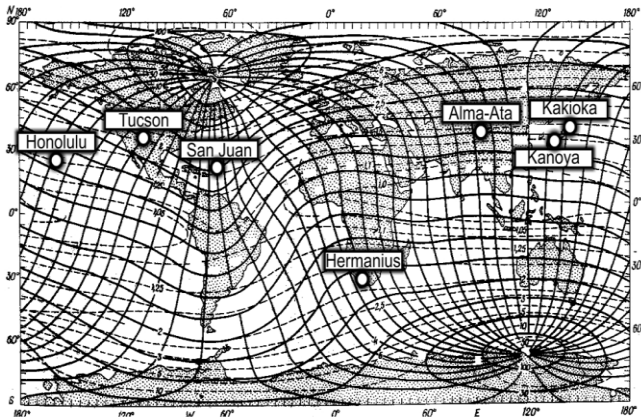

Fig. 1. Elman ANN architecture

Fig. 2. Geography of magnetic observatories involved in the study

II. USED DATA AND METHODS OF THEIR PROCESSING

As the processed material, magnetic recordings made at Kakioka, Kanoya, Alma-Ata, Hermanius, San Juan, Tucson, Honolulu stations (Fig. 2) in 1979 and data from the OMNI satellite system on solar wind (SW) and IMP. Due to the presence of failures in the operation of geomagnetic stations and the satellite system, the data was subjected to preliminary processing, the purpose of which was to eliminate the sections of the failures of long duration. Moreover, sections lasting less than four hours were linearly approximated. Due to the fact that a periodic function with a period of 24 hours was used as one of the ANN input values, the duration of the eliminated data sections containing failures was a multiple of 24 hours. As a result, 5496 hours of data without fail were able to select ANN for training. The data obtained in this way were divided into three sequences: training 3500 hours, estimated - 1000 hours and test - 996 hours (in the interval 12.00 UT August 12 - 23.00 UT August 30) to check the quality of its work. The X data thus obtained were normalized according to the following scheme:

1) For each parameter, its average for the entire time interval of 5496 hours was calculated;
2) The sequence of differences of each value and the mean is obtained;
3) The maximum modulo value of these differences was found;
4) Each value obtained in paragraph 2 is divided by the maximum.

$$X_N = \frac{\left(X - \bar{X}\right)}{\max\left|X - \bar{X}\right|},$$

where X is a series of source data, $\bar{X}$ is the average value for the entire interval.

The architecture and algorithm of the selected ANN were implemented by a specially created computer program that allows visual monitoring of changes in weights and training errors. Training ANN was carried out as follows. At each training step, the increments of weights (coupling coefficients between neurons) were calculated on the basis of the integral quadratic learning error obtained during the operation of the ANN with the training sequence. Then, the integral quadratic

error on the estimation sequence was calculated. In the learning process, these two errors are reduced simultaneously. Learning stops when the learning error stops decreasing or the learning error continues to decrease, and the error in the evaluation sequence increases. Such a stop means that the ANN does not further learn the desired patterns, but begins to simply memorize the training sequence.

As the main objects for the study, we used the horizontal component records at Alma-Ata magnetic stations (geographic coordinates 43.25°N, 76.92°E and geomagnetic coordinates 37.98°N, 148.72°E) and Kakioka (geographical coordinates 36.23°N, 140.19°E and geomagnetic coordinates 28.76°N, 210.77°E). The initial experiment consisted in restoring records of the horizontal component of the earth's magnetic field at one station from records at another station. As an objective characteristic of the quality of recovery, the magnitude of the prediction efficiency is used, defined [4] as:

$$PE = \left(1 - \frac{\sum_{\mu=1}^{N}\left(T^{\mu} - O^{\mu}\right)^2}{\sum_{\mu=1}^{N}\left(T^{\mu} - \langle T \rangle\right)^2}\right) \cdot 100\%, \quad \mu = 1, 2, ...N$$

where is T^{μ} the target (actually registered) value for comparison with the output for the μ-th example in the input sequence, O^{μ} is the value of the μ-th output of the ANN for the μ-th example of the input sequence, $\langle T \rangle$ is the average of all the target values of the ANN output, N is the number of points of the target process. Thus, the recovery efficiency is understood as the unit reduced by the value of the average relative variation, which in turn is the ratio of the standard error to the variance of the target process [12, 14].

III. SEARCH FOR AN OPTIMAL NEURAL NETWORK ARCHITECTURE

The main attention is paid to the restoration of magnetic records at the Alma-Ata station from the records at the Kakioka station. In this example, a study was conducted to find the optimal ANN architecture to obtain the smallest recovery error. It has been established that with an increase in the number of neurons in the hidden layer, the quality of recovery increases [14]. This is especially true for restoring recordings at the Alma-Ata magnetic station at one Kakioka station. The quality of recovery (PE) increases from 48 to 58% with an increase in the number of hidden neurons from 6 to 20. An increase in hidden values over 20 becomes ineffective. An introduction to delay line network architecture improves recovery. The optimal delay line length with 5% improvement is 5-6 hours. Experimentally, an ANN variant was found that gives the best result in terms of the smallest error, stability, and minimum computer time. This number of neurons of the hidden layer is 10 and the length of the delay line is 5 hours, which provides PE in 61% (Fig. 3). All further studies were conducted with this variant of the ANN.
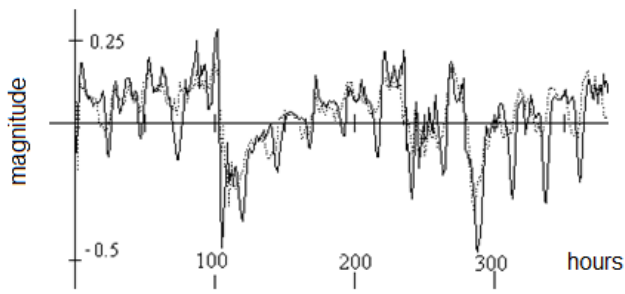
Fig. 3. An example of neural network recovery of records at an Alma-Ata magnetic station for one Kakioka station (PE=61%). Solid line - real data, dotted line - neural network recovery

For comparison, in Fig. Figure 4 shows the actual records on Alma-Ata and Kakioka superimposed on each other (solid and dashed lines, respectively). PE for simple replacement (without the participation of ANN) of records on Alma-Ata with records on Kakioka is 11%. When changing the direction of record recovery: Kakioka by Alma-Ata, the recovery efficiency drops to 30%. As can be seen from Fig. 4, magnetic events associated with diurnal variation at Kakioka occur earlier than at the Alma-Ata station for the difference in local time. It is this that leads to the fact that the restoration in the presence of daily variation turns the operation from recovery into prediction for the interval determined by the difference in local time. This is undoubtedly a more difficult task than recovery.
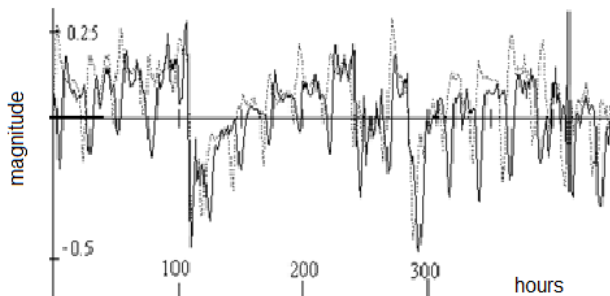
Fig. 4. Real records on Alma-Ata and Kakioka, superimposed on each other (solid and dashed lines, respectively)

The study of changes in the quality of training and the effectiveness of the ANN to restore records caused by the variation of its architecture was also carried out for the entire studied group of stations. Based on the data presented in them, one can judge the effect on the operation of the ANN of the number of hidden neurons and the length of the delay line. More visual is. It has been shown that an increase in the number of hidden neurons significantly improves learning. However, an increase in latent values over 20 becomes ineffective. To a lesser extent, the delay line affects.

IV. RESULTS OF NUMERICAL EXPERIMENTS

The restoration of the normalized horizontal component of magnetic disturbances at 20 latent values and with a delay line of 10 hours at the Kakioka station from records at the nearby Kanoya station occurs with an objective estimate of 95%. This is better than directly replacing data at a Kakioka station at a nearby Kanoya station (91%). The quality of restoration

of the horizontal component at the output station decreases with increasing distance between the input and output stations.

In the conclusion of the work on the example of Alma-Ata and Kakioka stations, we pay attention to the consequences of the presence of solar-diurnal variation in magnetic recordings. Magnetic solar-diurnal variation has a strong noisy effect on the learning process of the ANN, i.e. does not allow ANN to isolate not so regular processes. To eliminate this action, a periodic function is introduced into the ANN structure in the form of an additional input quantity.

This function enables the ANN to bind the restored values to the time of day and thereby estimate the average daily variation. Two types of such periodic functions were used in the work - sawtooth and sinusoidal. The best result was obtained using a sawtooth function. This is apparently due to the fact that it better models the periodic change in the conductivity of the ionosphere. As a result, it was possible to improve the quality of record restoration at Alma-Ata station from records at Kakioka station from 61 to 70% (Fig. 5).
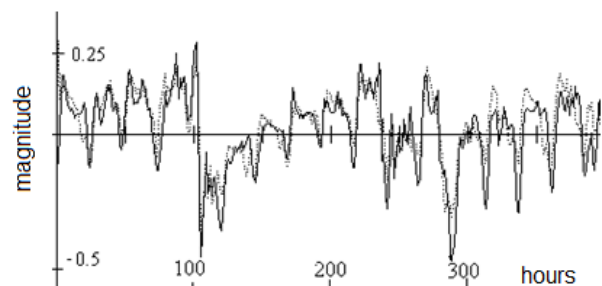
Fig. 5. Neural network restoration of records at the Alma-Ata magnetic station for one Kakioka station at the optimal ANN (PE=70%). Solid line - real data, dotted line - neural network recovery

In Fig. 6 compares real magnetic recordings on Kakioka and those recovered from records on Alma-Ata (changing the direction of recovery) and a sawtooth function. In this case, PE=64% is achieved, i.e. lower than in the forward direction. The deterioration is actually due to the presence of daily variation.
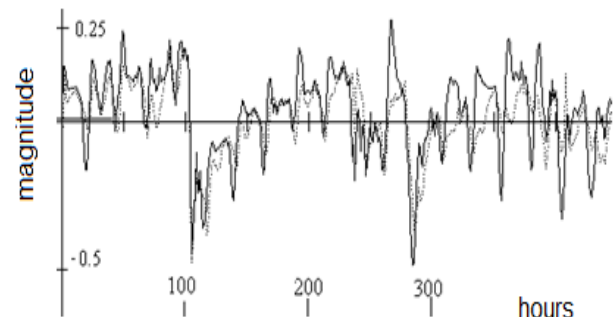
Fig. 6. Neural network restoration of records at the Kakioka magnetic station for one Alma-Ata station at the optimal ANN (PE=64%). Solid line - real data, dotted line - neural network recovery

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V. CONCLUSION

According to the results of this work, it can be argued that the artificial neural network (ANN) technique can be successfully used to reconstruct records of perturbations of the horizontal component of the geomagnetic field at a selected (output) low latitude station from magnetic stations (input) located near the geomagnetic equator. Moreover, the restoration of nearby stations occurs with high accuracy. For example, recordings at Kakioka stations are predicted with an accuracy of 95%. Introduction to the number of input values of the hourly average data on the parameters of the solar wind and interplanetary magnetic field does not give an improvement in the restoration of magnetic records.

This is apparently due to the fact that magnetic disturbances with scales of more than an hour at low latitude stations are caused by the development of a ring current, which is caused by large-scale changes in the near-Earth medium. Such magnetic disturbances are quite well restored with the help of ANNs at other stations without involving smaller-scale changes in the solar wind parameters. Progress in the restoration of magnetic records taking into account the parameters of the near-Earth medium can be achieved for magnetic disturbances that are recorded with a smaller averaging scale, for example, in 1 min. Then it becomes possible to talk about the restoration of sudden pulses of the geomagnetic field.

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