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Substitution for lost one-hour means of the geomagnetic elements for the first half of the 20-th century at the Hurbanovo Geomagnetic Observatory by means of neural networks

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Abstract: The existence of long-acting observatories by itself does not guarantee that their historical magnetograms are available or complete. In the archive of the Hurbanovo Geomagnetic Observatory (acronym HRB; geographical coordinates 47.86°N, 18.19°E), records of the geomagnetic field made on photo paper covering the period between the two World Wars were found for which the values of the baselines are unknown. We studied if a feed-forward neural network with one hidden layer can be used to supplement one-hour means of the geomagnetic elements D, H and Z of observatory HRB, using for this purpose the geomagnetic data of observatories Potsdam, Seddin and Niemegk (all of them being referenced to Niemegk). We focused our interest on the first half of the 20-th century. The neural-network model for element D proved to be applicable to substitute for the lost data of the magnetic declination at observatory HRB; however, the usability of the model for both elements H and Z turned out to be limited to a few years close to beginning or end of data gaps. Further we supplemented the time series of annual means of geomagnetic elements D, H and Z at observatory HRB with the model data.

Key words: geomagnetic observatory, historical data, hourly means, annual means, neural networks

1. Introduction

Long-lasting series of correct and continuous time series of the geomagnetic field records are crucial for studying secular changes of the geomagnetic field. Likewise, the magnetograms covering many years of observations are a useful material for analyses of relations between the geomagnetic activity

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and some other phenomena, such as the solar activity or changes of the planetary climate. Such series of the geomagnetic data are provided by old magnetic observatories. Unfortunately, the existence of a long-acting and unceasingly working observatory by itself does not guarantee that the historical magnetograms of it are available or complete. There were many reasons for the incompleteness; the most important of them sprang from history: warfare or other rude events. The circumstances sometimes interrupted geomagnetic observations; another time, a part of valuable observed information was completely lost.

The data which we dealt with in the paper were those of the Geomagnetic Observatory at Hurbanovo (until 1948 called Stará Ďala, Ógyalla or Ó Gyalla in Hungarian). The acronym of the observatory is HRB. It is a mid-latitude magnetic observatory with geographical latitude 47.86^{o}N and longitude 18.19°E.

The initial stages of the observatory are connected with Dr. Miklós Konkoly-Thege, the director of the state Institute for Meteorology and Earth's Magnetism in Budapest. As the expansion of Budapest disturbed the geomagnetic observations made at Buda, Dr. Konkoly-Thege moved the observatory instruments to his astronomical observatory at Ógyalla/Stará Ďala in 1890. The geomagnetic observatory was officially founded ten years later, on September 30, 1900. The history of the observatory had been narrated in detail by *Ochabová and Ochaba (1977)* as well as *Prigancová and Vörös (2001)*. From their papers we can learn about the periods which were covered with the registrations of the complete sets of the geomagnetic field; when, on the other hand, data gaps occurred; and which years had registered only one or two elements (Fig. 1).

Beginning in 1893, the results of the geomagnetic observations were published in monthly and annual reports. In 1894, the observatory obtained new magnetic variation instruments of the Mascart type, manufactured by Carpentier. In 1898 (*Prigancová and Vörös, 2001*) or 1899 (*Ochabová and Ochaba, 1977*), the new variation pavilion was built in which the Carpentier's magnetographs were installed. One of the instruments was made for photographic recording. In 1903 the equipment of the observatory was furnished with new absolute instruments – the Wild theodolite together with an earth inductor enabled determining three magnetic elements; D, H and I. Starting with this year, the photographic magnetograms are available

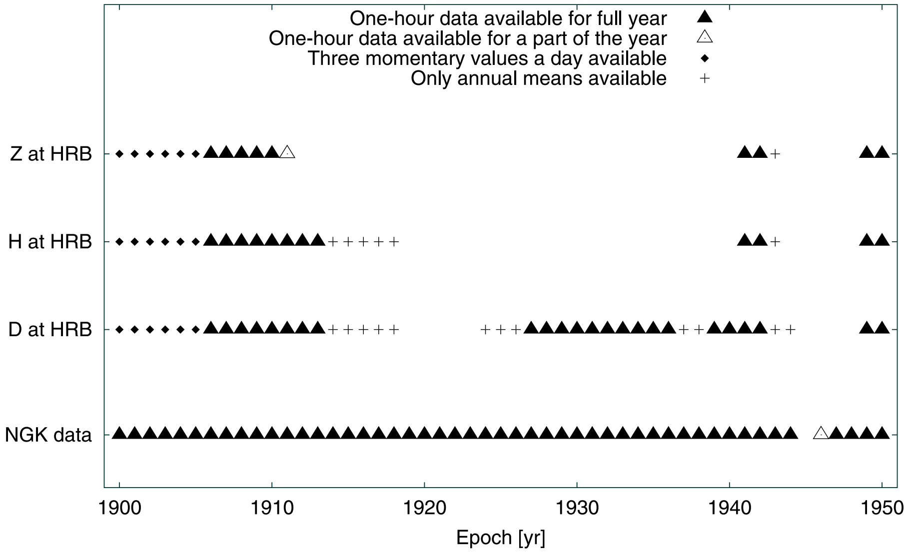

Fig. 1. Time periods when the values of geomagnetic elements D, H and Z are available for observatory HRB in the first half of the 20-th century. Intervals with one-hour means obtainable for observatory NGK (all geomagnetic elements) are also indicated. The years for which the annual means of the HRB geomagnetic elements are known, but at the same time the one-hour means have been lost, are shown as well. Momentary values of the geomagnetic elements D, H and Z observed three times in a day; at 7:00, 13:00 and 21:00; are available instead of one-hour means at observatory HRB prior to 1906.

in the archives of the Hurbanovo Geomagnetic Observatory. In 1911 the records of the vertical variometer became unreliable and observations of the inclination lost their significance, but the observations and recordings of the declination and horizontal intensity went on until the end of World War I in 1918.

Observations of the declination were renewed in 1924. Somewhere in 1938 registrations of the horizontal intensity restarted. Then stormy events leading up to World War II came. Despite the turbulent period, the observatory succeeded to develop and continue the observations. However, at the end of 1944 the absolute instruments were taken away from the observatory and a new gap in the observations commenced. In 1948 a set of instruments for recording the geomagnetic elements D, H and Z was reconstructed and absolute instruments were obtained. That year the name of

Stará Ďala changed to Hurbanovo. Since January 1, 1949, a complete series of the records of all geomagnetic elements are available for the Hurbanovo Geomagnetic Observatory (*Ochabová and Ochaba, 1977*).

In the archive of the Hurbanovo Geomagnetic Observatory magnetograms were found covering virtually the whole period between the two World Wars, including most of the wartime. They were the records of the geomagnetic field elements made on photo paper; however, a part of them was of poor quality. Some registered only incomplete set of geomagnetic elements, in certain cases only the magnetic declination. Moreover, the values of their baselines are unknown. So far we have not answered the question whether absolute measurements were not carried out that time, or their results were lost by misadventure. Probably the different answers are true for the different periods.

This paper studies if neural networks can be used to supplement the geomagnetic data for the data gaps of the Hurbanovo Observatory, using for this purpose the geomagnetic data of the observatories Potsdam, Seddin and Niemegk (all of them being referenced to Niemegk). These observatories belong to the oldest magnetic observatories in the world, and their one-hour means are available for the time period which we need for the supplement. Our interest was focused on the first half of the 20-th century, since the geomagnetic observatories were rare in Central Europe that time, and Stará Ďala Observatory was one of them. This uniqueness adds to the value of the geomagnetic data of the observatory.

Applicability of artificial neural networks, especially so-called recurrent networks, to similar tasks has been showed by *Barkhatov et al. (2002)*. He produced one-hour geomagnetic data for the Alma Ata Observatory, Kazakhstan, on the base of Japanese observatory Kakioka. Nevertheless, we could not use his method without adaptation – his recurrent network requires continuous time series of training patterns, which are not at our disposal.

Therefore, the purpose of this paper is to show that the supplementation of the HRB geomagnetic data based on data from the observatories Potsdam, Seddin and Niemegk can be achieved by means of simpler neural networks than those used by *Barkhatov et al. (2002)*. Then the supplemented one-hour data are produced to fill the gap in time series of the geomagnetic field observed at HRB.

2. Data used

We used the data collected by the Hurbanovo Geomagnetic Observatory, which belongs to the Geophysical Institute of the Slovak Academy of Sciences. In order to avoid confusion, we used the present-day name of the observatory, that means Hurbanovo (HRB), also for the older epochs of the observatory's history. The data which we used were one-hour means of the magnetic declination D, and the horizontal and vertical components H and Z, respectively.

Along with the the data of HRB, we used one-hour means of elements D, H and Z observed at observatories Potsdam, Sedding and Niemegk, all of them referenced to Niemegk. Again, in order to simplify the orientation within the text, we named all the data from these three observatories as the data of Niemegk (NGK). We obtained them from the web page of the World Data Center for Geomagnetism, Kyoto, Japan (`http://wdc.kugi.kyoto-u.ac.jp/hyplt/index.html`).

For assessment of the proposed neural-network model, we used also geomagnetic data observed at observatories Munich (MNH), Maisach (MAS) and Fuerstenfeldbruck (FUR). They were annual means which we took from the Version 1.3. of the CD-ROM distributed by Geophysical Observatory Fuerstenfeldbruck, University of Munich, Germany, in 2002. Other data used for the assessment were the annual means observed at observatory Wien Auhof (WIA), which are available through the World Data Center for Geomagnetism, Edinburgh, UK (`http://www.geomag.bgs.ac.uk/data_service/data/annual_means.shtml`).

Further data which were compared with the modeled ones were those of the 11th Generation International Geomagnetic Reference Field (IGRF11), which has been released by Working Group V-MOD of the International Association of Geomagnetism and Aeronomy, and is available at web page `http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html`.

3. Method of neural networks

In this paper we used artificial neural networks to fill the data gaps which occurred in the time series of one-hour means of geomagnetic elements for observatory HRB. A similar problem was considered by *Barkhatov et al. (2002)*, who employed a neural network in order to produce substitutes for missing data at observatory Alma Ata. They produced one-hour means of the horizontal component. As inputs to their model, they used the corresponding values of H observed at observatory Kakioka. The neural network used by them was the recurrent network, which is able to grasp temporal relations inherent in time series through a layer of hidden neurons called a context layer (*Gurney, 1997*). Concerning the long distance between Kakioka and Alma Ata, such an advanced type of neural network was necessary.

The recurrent networks, however, have a fundamental disadvantage: the training patterns need to be arranged without gaps in chronological sequence. Such a requirement stems from the training algorithm according to which, in addition to learning from new patterns applied in a new training step, these networks learn from the preceding steps as well.

In our study, however, we had training patters from different periods which were considerably distant from one another. The data gaps between them lasted years or even decades. Thus, we were compelled to employ another type of neural networks which does not require long unbroken series of training patters. A feed-forward network with one hidden layer (*Demuth et al., 2007; Gurney, 1997*) appeared to be a good alternative. A more technical introduction to the neural network is given in Appendix A.

Replacing the recurrent network by the network of a simpler architecture was permitted by reason of the distance between Niemegk (52.07°N, 12.67°E) and Hurbanovo (47.86°N, 18.19°E), which is substantially shorter comparing with that in *Barkhatov et al. (2002).* The difference in geographical longitudes of NGK and HRB is 5.52°, which means that the phenomena due to the diurnal variation of the geomagnetic field occur at Hurbanovo 22 minute before they are recorded at Niemegk. We considered this time shift in the structure of patterns which the neural networks were fed with: When the value of a geomagnetic element at HRB for an one-hour interval t was produced, the values of the geomagnetic element at NGK for both intervals t and $t + 1$ hour entered the neural networks as input parameters.

In order to provide their neural network some time marker, *Barkhatov et al. (2002)* supplemented the input parameters with a sawtooth function, the period of which was set to 24 hours. We used their idea; however, we dealt with much longer time series as did *Barkhatov et al. (2002)* hence we needed to consider the annual and the secular variations of the geomagnetic field in addition to its diurnal variation. Consequently, two sawtooth functions were included to our input parameters, with periods of 24 hours and 1 year, respectively, together with a strictly increasing function.

The structure of the patterns for our neural networks consisted of five input and one output parameters, which entered the networks through one of five input neurons, or emerged from a single output neuron. The input parameters were as follows:

1. one-hour mean of the geomagnetic element E at NGK for the t-th one-hour period;
2. one-hour mean of the geomagnetic element E at NGK for the $(t+1)$-th one-hour period;
3. consecutive number t of the one-hour period since the beginning of the time series;
4. consecutive number of the one-hour period within a day;
5. day of year.

There was only one output parameter:

– one-hour mean of the geomagnetic element E at HRB for the t-th one-hour period.

Geomagnetic element E means magnetic declination D, horizontal component H, or vertical component Z.

The work with the neural networks consisted of three standard steps described, for instance, in (e.g. *Demuth et al., 2007*):

1. The aim of the first step was to determine an optimal number of the neurons contained in the hidden layer. For this purpose 4000 patterns were assigned by random choice, which were used for training the neural networks holding various numbers of neurons in their hidden layers. Only the patterns based on data of years 1906–1953 could be used for which both NGK and HRB data were available – such a restriction was applied to all patterns used in steps 1 and 2. The performances of the networks were compared on the base of some other 800 randomly assigned patterns. We found that for all geomagnetic elements, D, H and Z, the best results were achieved if the hidden layers consisted of three neurons.

2. The following step was a training of neural networks. At this point, only the networks containing three hidden neurons were adapted to their task. The training was based on 4000 new randomly chosen training patterns while the proper number of training iterations were estimated by means of some other 800 patterns, called validation patterns, selected by random choice. The whole procedure of creating training and validation patterns as well as neural network training was repeated ten times for each of the geomagnetic elements D, H, and Z.
3. In the final step, one-hour means of geomagnetic elements D, H and Z for observatory HRB were produced. This time the patterns provided to neural networks were incomplete – they consisted of the input parts only. The patterns were created for those of the intervals within 1911–1948 for which only one-hour means of NGK were available, and gaps in HRB data occurred. For each geomagnetic element, the medians computed from the outputs of ten independently trained networks were considered as final model data.

In steps 1 and 2, we used the back propagation algorithm, which is based on the generalized delta rule, improved with a momentum term (*Gurney, 1997*). The results of step 3 are discussed in the following section.

4. Results and discussion

Feeding the trained neural networks with one-hour means of geomagnetic elements D, H and Z from observatory NGK, we obtained model values of the corresponding geomagnetic elements, one-hour means, for observatory HRB. We produced the model data for those periods of the first half of the 20-th century when some data gaps occurred in the time series of HRB. Listing the data in the paper would be highly unwieldy. Instead we stored the data on the web page of the Hurbanovo Geomagnetic Observatory (`http://www.geomag.sk/nn-model-old-data`).

In order to assess the performance of the neural network model, we carried out a test for 4000 randomly chosen complete test patterns selected in the periods for which both NGK and HRB data were available. According to the test, the model for the magnetic declination seems to be the best (Table 1). Nice agreement between the model data and the ones observed

Table 1. Statistics made for 4000 test patterns chosen within the periods when one-hour means of both HRB and NGK were available. Correlation coefficient (CC), root mean squared error (RMSE), and mean absolute error (MAE) are listed in the table. In order to enable mutual comparison of the statistics between different geomagnetic elements, besides the values for the magnetic declination given in arc minutes we indicated corresponding values in nanoteslas, too.

Measure of agreement	Geomagnetic element		
	D	*H*	*Z*
CC	0.9998	0.9973	0.9992
RMSE	2.53' (15.3 nT)	16.5 nT	24.2 nT
MAE	1.61' (9.8 nT)	10.7 nT	16.7 nT

at HRB is present in two examples for the magnetic declination (Figs. 2 and 3); the former shows the time series during some disturbed days, the latter displays quiet days with distinct diurnal variations. The model series are

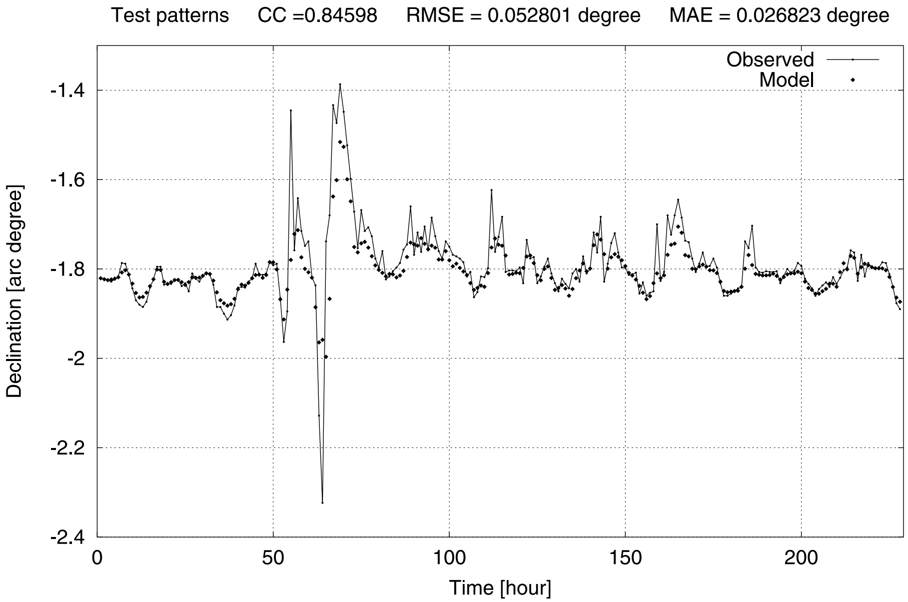

Fig. 2. Time series of both model and observed values of the magnetic declination for period 27/02/1941 – 10/03/1941, during which a geomagnetic storm occurred.

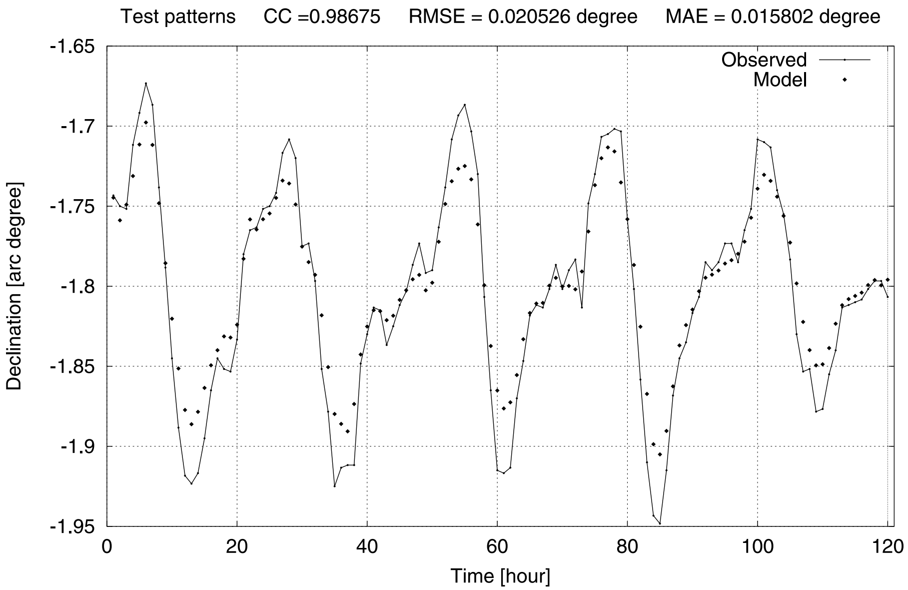

Fig. 3. Time series of both model and observed values of the magnetic declination for quiet period 26/06/1941 – 30/06/1941. A distinct diurnal variation is visible in this summer-time interval.

mildly smoothed as we compare them with the observations – that is a common shortage when modeling by neural networks. Such a good coincidence is not typical for modeled geomagnetic elements H and Z. Nevertheless, the years for which the test data were created coincide with those for which the training and the validation patterns were prepared; therefore, the results of this test should not be overestimated.

An alternative opportunity to estimate the quality of the neural-network model was given by the following: For some years in the first half of the last century the annual means of geomagnetic elements are known, but at the same time the one-hour means have been lost (Fig. 1). We believe that the valuable data from which the annual means were determined were irretrievably lost during the stormy historical events affecting the territory of Slovakia in the 20-th century. For all of those years one-minute values of the geomagnetic elements observed at NGK were preserved, which allowed our neural-networks to produce the corresponding HRB data. The annual means computed from the model one-minute means could be compared with the HRB annual means which were upheld (Table 2). The upheld data of HRB were also compared with the annual means produced by model IGRF11. For the magnetic declination our neural-network model provided markedly better results. For both horizontal and vertical components, however, the accuracies of the model values are comparable with the IGRF11 model data, but they does not superior them. This is probably due to those long data gaps that occurred in the time series of elements H and Z – the patterns based on such an imperfect data base contained likely insufficient information for more successful training of the neural networks.

Table 2. The accuracy of neural-network model annual means of geomagnetic elements D, H and Z compared with the accuracy of the IGRF11 model for the same geomagnetic elements. The measures of agreement of the IGRF11 model were calculated for the same years as were those of the neural-network model. (Note*: We had only a single value of the difference between the neural-network model value and the observed value of vertical component Z. Thus the values of RMSE and MAE related to Z in the table are mere single absolute differences)

Measure of agreement	Geomagnetic element					
	D [']		H [nT]		Z [nT]	
	NN model	IGRF11	NN model	IGRF11	NN model	IGRF11
RMSE	1.03	9.45	12.6	17.6	12.8*	20.0*
CC	0.75	9.11	11.5	13.7	12.8*	20.0*

We displayed obtainable annual means of the geomagnetic elements of observatories Hurbanovo; Wien Auhof; Munich; Maisach; Fuerstenfeldbruck; and Niemegk, including Potsdam and Seddin referenced to Niemegk, together with the annual means produced by both the IGRF11 and the neural-network models (Figs. 4, 5 and 6 display the observed annual means of geomagnetic elements D, H and Z, respectively.) The neural-network models for elements H and Z (Figs. 5 and 6) turned out to be unreliable in the midst of long data gaps – discontinuities occurred in the time series of H and Z near epochs 1930–1932, which seem to be unnatural and improbable. On the other hand, the neural-network model of the magnetic declination shows a more convincing course (Fig. 4) than that provided by the IGRF11.

The above-mentioned assessment indicates that the neural-network model

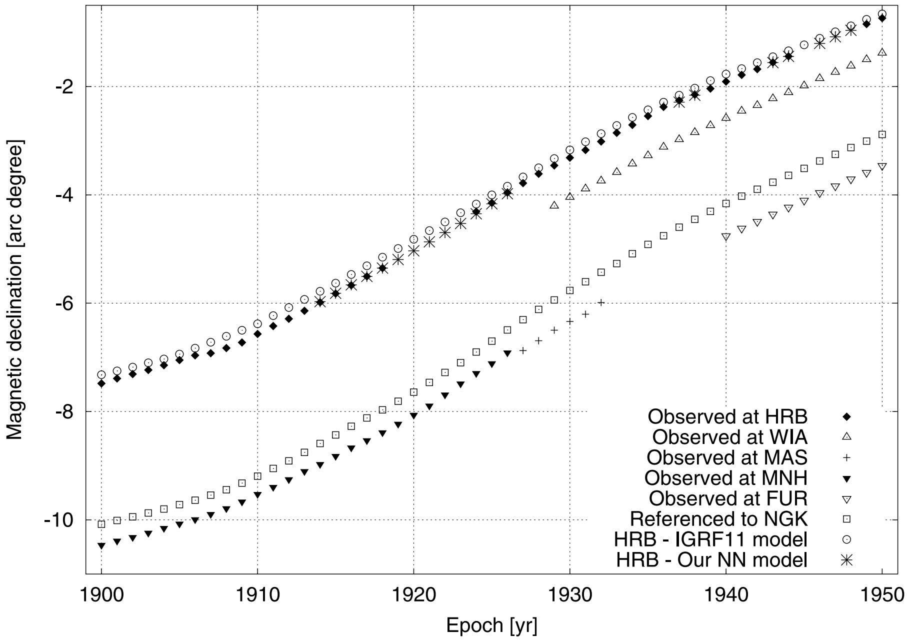

Fig. 4. Time series of annual means of the magnetic declination D computed for observatory HRB from the neural-network model displayed together with the observed annual means of D at observatories HRB, NGK (including observatories at Potsdam and Seddin referenced to NGK), Wien Auhof (WIA), Munich (MNH), Maisach (MAS), and Fuerstenfeldbruck (FUR). The time series of model IGRF11 for HRB is also shown in the picture.

for element D is applicable to substitute for the lost data of the magnetic declination at observatory HRB. The usability of the model for both elements H and Z is limited to a few years close to beginning or end of data gaps.

5. Conclusions

Substitution for the missing one-hour means of geomagnetic elements at observatory HRB was studied in this paper. The proposed method relied on the one-hour means of the geomagnetic field observed at NGK, including data of Potsdam and Seddin referenced to NGK, and it employed artificial

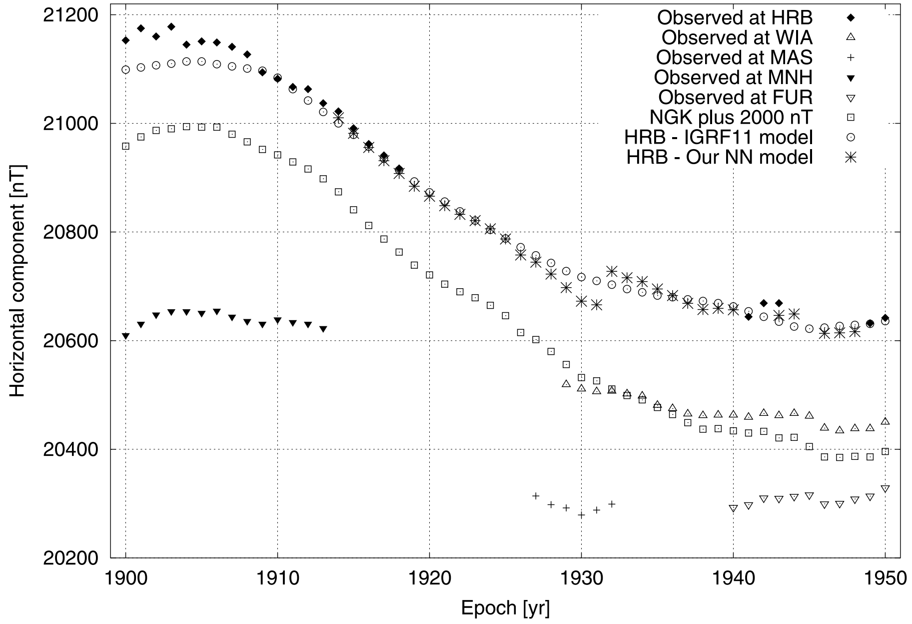

Fig. 5. Time series of annual means of the horizontal component H computed for observatory HRB from the neural-network model displayed together with the observed annual means of H at observatories HRB, NGK (including observatories at Potsdam and Seddin referenced to NGK), WIA, MNH, MAS, and FUR. The time series of model IGRF11 for HRB is also shown.

neural networks. The performance of the method was examined in three different ways: using test patterns, comparing the model annual means with the IGRF11 model quantitatively, and comparing the courses of time series of annual means with data observed at several old observatories besides the the IGRF11 data visually. We found that the neural-network model provided credible results for the geomagnetic declination, for which the data gaps were not so long as were the gaps of the other geomagnetic elements. The results made for both horizontal and vertical components were less satisfactory, particularly in the midst of the long data gap, which occurred between the two World Wars.

The method was used to substitute for lost one-hour means of geomagnetic elements at observatory HRB. The data gaps in question occurred in the first half of the 20-th century, and they took about one or two

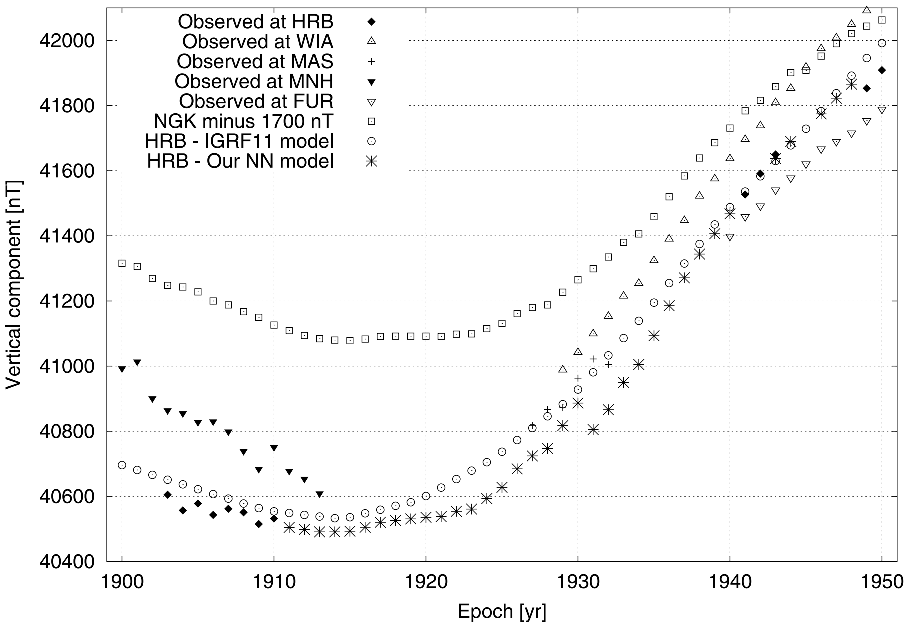

Fig. 6. Time series of annual means of the vertical component Z computed for observatory HRB from the neural-network model displayed together with the observed annual means of Z at observatories HRB, NGK (including observatories at Potsdam and Seddin referenced to NGK), WIA, MNH, MAS, and FUR. The time series of model IGRF11 for HRB is also shown.

decades, depending on the geomagnetic element considered. The substitute geomagnetic elements constitute large amount of data; we made them available on the web page of the Hurbanovo Geomagnetic Observatory (`http://www.geomag.sk/nn-model-old-data`).

In the future, the substitute one-hour means will be utilized to complete information about baselines of the HRB magnetograms for which heretofore the baselines could not be calculated because the absolute measurements disappeared.

Further, we made the time series of annual means of geomagnetic elements D, H and Z at observatory HRB more complete. The network of magnetic observatories was sparse in the middle of the last century; therefore, we believe that these additional data are valuable for the research of geomagnetic secular variations.

Acknowledgments. The results presented in this paper rely on the data collected at Niemegk Magnetic Observatory. We thank GFZ German Research Centre for Geosciences, for supporting its operation. We wish to thank Barbara Leichter for suggesting to use the data of Wien Auhof in this study. We also wish to acknowledge collecting the geomagnetic data by the World Data Centers for Geomagnetism, Kyoto, Japan, and Edinburgh, UK. Further we give thanks to Geophysical Observatory Fuerstenfeldbruck, University of Munich, Germany, for gathering the geomagnetic data of observatories Munich, Maisach and Fuerstenfeldbruck. We appreciate the 11th Generation International Geomagnetic Reference Field Model released by Working Group V-MOD of the International Association of Geomagnetism and Aeronomy. This work was supported by VEGA grant 2/0015/11 of the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences.

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APPENDIX A

A neural network represents an independent alternative to nonlinear modeling. The functioning of the neural network is based on the ability to learn input-output relations from a database organized in the form of patterns

(*Hertz et al., 1991; Gurney, 1997*). We have used a neural network which is known as feed forward neural network or multilayer perceptron network, which is represented by:

$$g : R^N \rightarrow R^n. \tag{1}$$

It consists of one input layer with N inputs, one hidden layer with q units and one output layer with n outputs. The output of the model with a single output neuron (output layer represented by only one neuron, i.e. $n = 1$) can be expressed according to *Nørgaard (1997)* by:

$$y = f\left[\sum_{j=1}^{q} W_j f\left(\sum_{l=1}^{N} w_{j,l}\, x_l + w_{j,0}\right) + W_0\right], \tag{2}$$

where W_j is the weight between the j-th neuron in the hidden layer and the output neuron, $w_{j,l}$ is the weight between the l-th input and j-th hidden neuron. We have used the same nonlinear activation function for all the neurons of the hidden layer, as well as for the output neuron in the form of the sigmoid

$$f(z) = \frac{1}{(1 + e^{-z})}. \tag{3}$$

For a given set of M patterns we define the normalized mean square error ($NMSE$) by

$$NMSE = \frac{\sum_{s=1}^{M} \left(y_s^{actual} - y_s\right)^2}{M^2}, \tag{4}$$

where y_s^{actual} denotes the actual given output and y_s the neural network output for the s-th pattern. The network is trained to minimize the $NMSE$ by a gradient method.