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Application of neural networks for predicting selected time scales on the basis of UTC and UTCr scales

***Abstract**. The paper presents research results on predicting the [UTC - UTC(k)] deviations by the means of GMDH-type neural network and data prepared in the form of time series built on the basis of [UTC - UTC(k)] and [UTCr - UTC(k)] deviations for the Austrian Timescale UTC(BEV) and the Lithuanian Timescale UTC(LT). The obtained results confirmed the possibility of applying the UTC Rapid scale for predicting the [UTC - UTC(k)] deviations by the means of GMDH-type neural network.*

***Streszczenie.** W pracy przedstawiono wyniki badań nad prognozowaniem odchyleń [UTC - UTC(k)] przy użyciu sieci neuronowej typy GMDH i danych przygotowanych w formie szeregu czasowego, zbudowanego na podstawie wartości odchyleń [UTC - UTC(k)] oraz [UTCr - UTC(k)], dla Austriackiej Skali Czasu UTC(BEV) oraz Litewskiej Skali Czasu UTC(LT). Otrzymane wyniki badań potwierdziły możliwość zastosowania skali UTC Rapid do prognozowania odchyleń [UTC - UTC(k)] w oparciu o sieci neuronowe typu GMDH.* **(*Zastosowanie sieci neuronowych do prognozowania wybranych skal czasu na podstawie skal UTC i UTCr*).**

Keywords: UTC(k) timescale, atomic clock, predicting [UTC – UTC(k)], GMDH neural network.
Słowa kluczowe: skala czasu UTC(k), zegar atomowy, prognozowanie [UTC – UTC(k)], sieci neuronowe GMDH.

Introduction

National Metrology Institutes NMI conduct physical realizations of local time scales UTC(k), which in most cases are realized by commercial cesium clocks or active hydrogen masers. International UTC scale, called Coordinated Universal Time, is determined by the International Bureau of Weights and Measures BIPM (fr. *Bureau International des Poids et Mesures*). The process of calculating the UTC scale is very complex and time-consuming. It requires a collection and proper preparation of measurement data from local and remote comparisons of more than 400 atomic clocks sent by an NMI [1] and the calculation of the UTC scale by BIPM. This results in a delay in issuing the BIPM "Circular T" bulletin, which is published between the 8th and 12th day of the following month. This bulletin contains calculated for a given month *xb*(*t*) deviation determined by the relationship:

$$xb(t) = UTC(t) - UTC_k(t), \tag{1}$$

which define the divergence of each UTC(k) in relation to the UTC. These deviations are determined by the BIPM with five day interval as average values per day on MJD (Modified Julian Date) days ending with digit 4 and 9. Due to a delay in publication of the "Circular T" bulletin, ensuring the highest compliance of the UTC(k) in relation to the UTC is only possible through predicting the *xb*(*t*) deviations. The designated value of prediction may constitute a basis for correcting the UTC(k) scale. Part of NMI laboratories are predicting the *xb*(*t*) deviations. The literature on the prediction of *xb*(*t*) deviations presents method based on statistical models, for example [2, 3, 4, 5], or methods based on artificial intelligence, for example [6, 7, 8, 9, 10].

Delay in publication of the *xb*(*t*) deviations by the BIPM adversely affect on the result of the prediction, and consequently on maintaining the best convergence of the UTC(k) with the UTC. Therefore, in order to expedite the transfer of information about the differences of the UTC(k) in relation to the UTC, BIPM on 1 January 2012 developed the "A Rapid UTC" project. On the basis of UTC Rapid (UTCr) scale, every Wednesday on the BIPMs ftp server the *xbr*(*t*) deviations are published, determined on each day according to the relationship:

$$xbr(t) = UTCr(t) - UTC_k(t), \tag{2}$$

for the previous week, for each clock realizing the UTC(k) scale. On 1 July 2013 this deviations are determined officially.

Institute of Metrology, Electronics and Computer Science of the University of Zielona Góra, in collaboration with the Central Office of Measures GUM (pl. *Główny Urząd Miar*) is working on the application of neural networks (NN) for predicting the values of the deviations for the Polish Timescale UTC(PL), realized by the GUM based on a single, commercial cesium atomic clock. The proposal of application of the NN stemmed from their properties. Neural networks can be used where there is a partial or total lack of knowledge of the rules that describe the objects or processes, i.e. a great complexity of problems occurs. Behavioral models created by a neural network have an internal structure and a working principle which corresponds to the behavior of the original objects or processes. A unique feature of NNs is their ability to build models via a method based solely on an analysis of specific examples, i.e. an inductive method. Neural networks are very good mathematical tool, used for solving problems of a nonlinear character [11, 12, 13, 14].

The first results of research obtained [6] confirmed the possibility of using MLP (Multilayer Perceptron) and RBF (Radial Basis Function) neural networks for predicting the deviations for the UTC(PL). Another studies, the results of which are presented in [7, 8, 9], devoted on the use of GRNN (Generalized Regression Neural Networks) and GMDH (Group Method of Data Handling) neural networks for predicting *xb*(*t*) deviations. The studies showed that the best results in predicting the *xb*(*t*) deviations were obtained for GMDH NN [7, 8].

GMDH NN were subjected also to the research of predicting the deviations for the UTC(PL) using the deviations values determined by BIPM based on the UTC and UTC Rapid scales. The results of research presented in [15], confirmed the possibility of application of the UTCr scale for predicting the values of [UTC - UTC(PL)] based on a GMDH type neural network with the applied method of time series analysis.

The performed analysis of deviations values set by the BIPM in relation to the UTC and UTCr scales for other time scale realized on the basis of a single commercial cesium atomic clock showed a very good correlation between the two groups of deviations. Fig. 1 shows an example of a graph of *xb*(*t*) and the *xbr*(*t*) deviations published by BIPM for Lithuanian Timescale UTC(LT). The differences between the $xbr(t)$ and the $xb(t)$ deviations for the same day are on the level of only a few ns.

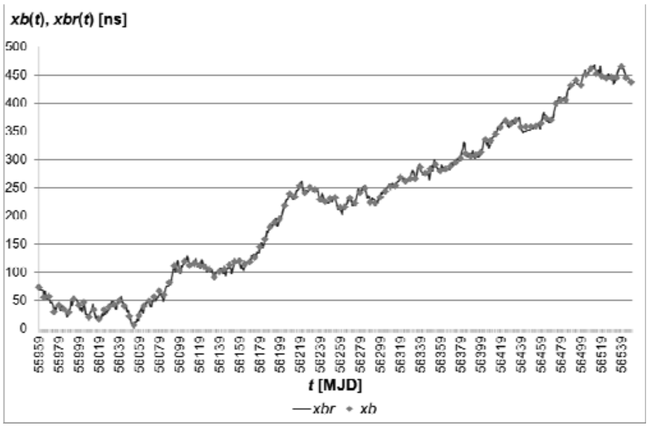

Fig.1. Values of $xb(t)$ and $xbr(t)$ deviations for the UTC(LT) scale

Thus, the objective of the study was to verify the applicability of the UTCr scale for predicting $xb(t)$ deviations for other time scales, realized on the basis of a single commercial cesium atomic clock. The paper presents research results on the prediction of $xb(t)$ deviations using GMDH NN and data prepared in the form of time series, built with values of $xb(t)$ and $xbr(t)$ deviations, for the Austrian Timescale UTC(BEV) and Lithuanian Timescale UTC (LT).

GMDH type neural network

GMDH neural network, using the group method of data handling, belong to the group of self-organizing networks. Group method of data handling is used in many areas, mainly related to the data acquisition, prediction, system modeling or optimization [16].

Fig. 2 presents a sample structure of a GMDH NN which, in the training process, is optimized for the number of hidden layers and for the number of neurons in these layers [16]. Neuron activation functions have a form of polynomials.

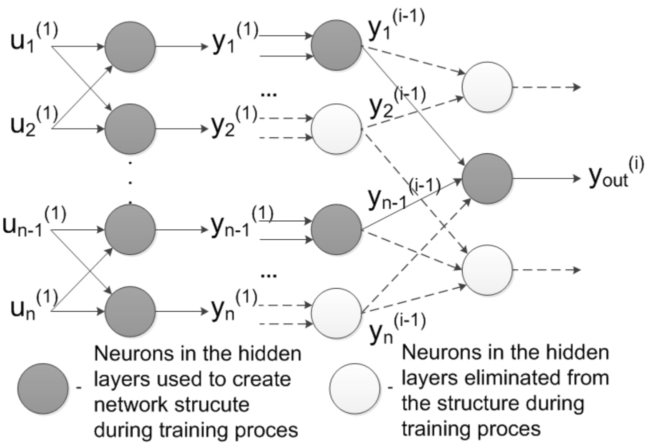

Fig.2. A sample structure of a GMDH type neural network

GMDH network structure is created automatically on the basis of prepared sets of training and testing data. In the course of the training process, the network expands and evolves until enhanced efficiency of its operation has been achieved [17]. Before the next layer of neurons will be attached to the current network structure, the components of the new layer are subjected to selection for precision of processing. Neurons that do not meet the criterion for assessing the condition imposed, i.e. processing error associated with these neurons is too large, are eliminated from the structure of the network.

Input data preparation for the GMDH type neural network

The basis for preparation of a time series (TS), which is a set of training and testing data for GMDH NN were the $xb(t)$ and $xbr(t)$ deviations designated based on the UTC and UTCr scales. Created time series consisted of two subsets of elements prepared according to the rules defined on Fig. 3. The first subset contains a group of data (from 1 to i) which are the $xb(t)$ deviations, designated based on relation (1), from day t_0 to day t_n, for which the last value of this time series before the publication day (t_{pub}) was known. Set of $xb(t)$ values has been subjected to the PCHIP interpolation function (Hermite interpolation available in MATLAB). As a result, it was possible to determine the values of $xb(t)$ deviation for each day. The second subset was a complement of time series TS by a group of data having values of $xbr(t)$ deviations (2) between days t_n and t_{nr}, published by the BIPM on day t_{pubr} (fig. 3). The publication day of $xbr(t)$ deviations could also be the day (t_{pred}), on which the prediction of $xb(t)$ deviation, hereinafter referred to as $xb_p(t_{pred})$ was performed.

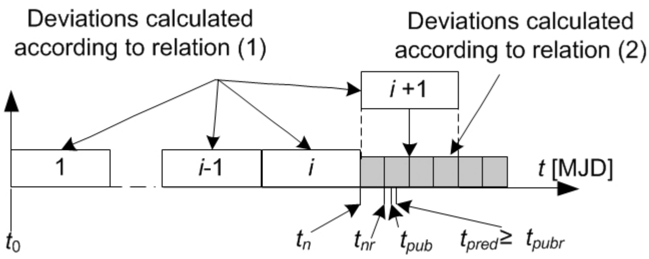

Fig.3. Creation of time series TS

By adding to the time series (TS) the successive groups of data calculated on the basis of relation (2), it is possible to determine the next values of $xb_p(t_{pred})$ in consecutive weeks. At the time of publication of a new “Circular T” bulletin containing values of $xb(t)$ deviations, the new group of data i+1 (fig. 3) according to relation (1) is determined, which for the respective days replaces the existing data set based on relation (2).

Research results

Predicting the values of $xb_p(t_{pred})$ for the Austrian Timescale UTC(BEV) and Lithuanian Timescale UTC(LT) was performed using GMDH Shell tool. In the training process of the GMDH NN the degree of the polynomial transfer function of the neuron, ratio of training to testing data and the automatic selection of its structure (the number of hidden layers and the number of neurons in these layers) were selected. In most cases of training of the GMDH neural network selectable function of neuron activation was a linear function. Then the obtained structure of the GMDH NN consisted of two or one hidden layer having two neurons.

Predicting the deviations was carried out for a period of 17 months, from MJD 56204 (4 October 2012) to MJD 56714 (26 February 2014), on MJD days ending with a digit 4 and 9. The time series applied at the input of the GMDH NN was created on the basis of historical $xb(t)$ data for the period from MJD 55629 (03 September 2011) to MJD 56714 (26 February 2014), and the $xbr(t)$ for the period from 56170 to MJD 56714. At the output of the GMDH NN a value of $xb_p(t_{pred})$ prediction was obtained, enabling the correction of the national time scale UTC(k).

Figures 4 to 7 show the research results obtained for UTC(BEV) and UTC(LT) scales. Figures 4 and 6 show respectively values of $xb(t)$ deviations, designated by the BIPM and determined by the GMDH NN values of $xb_p(t_{pred})$ predictions for UTC(BEV) and UTC(LT) scales, which were obtained for the prepared time series (TS) on the same day of prediction (t_{pred}).

In case of predicting the values of deviations using UTCr scale there are cases of one or two predictions in a given week. In the vast number of cases the second predictions were characterized by worse results. This was due to the extended prediction horizon, which for the second predictions in a given week was 8 or 9 days. Therefore, the results presented form fig. 4 to 7 relate only to the first predictions.

Figures 5 and 7 present the values of residuals (r), calculated for these predictions according to relation:

$$r(t_{pred}) = xb(t_{pred}) - xb_p(t_{pred}). \tag{3}$$

Residuals define the differences between the predicted value of $xb_p(t_{pred})$ and a $xb(t_{pred})$ deviation published by BIPM for the same day of prediction.

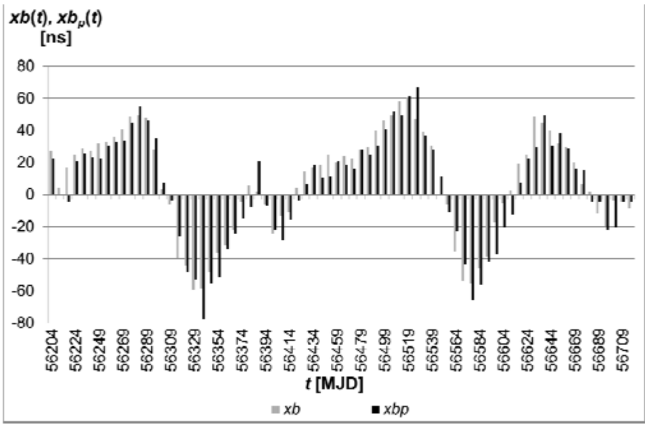

Fig.4. Determined values of $xb(t)$ deviations determined by the BIPM and values of $xb_p(t)$ predictions based on the time series TS for UTC(BEV)

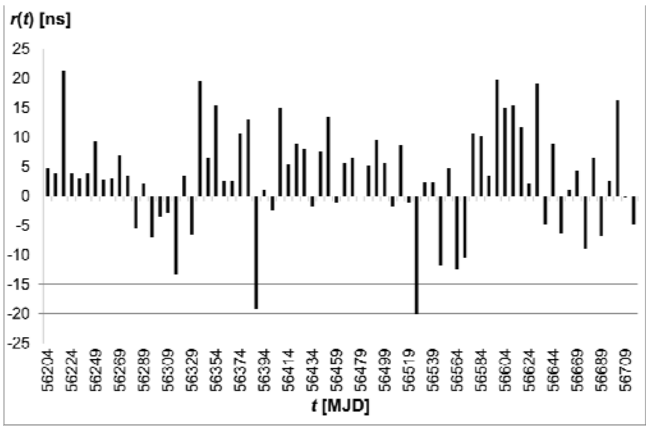

Fig.5. Determined values of r residuals for predicting $xb_p(t)$ based on the time series TS for UTC(BEV)

On the basis of calculated value of residuals (r) the evaluation of the quality of predicting with selected measures of the quality of prediction was performed. Table 1 shows the selected measures of the quality of prediction [18]: mean error (*ME*), absolute mean error (*MAE*), mean square error (*MSE*) and its components (MSE_1, MSE_2, MSE_3) and the root of the mean square error (*RMSE*).

The MSE_1 component determines the estimation inaccuracy of the prediction of the average value of the predicted variable, which represents the prediction load. MSE_2 component indicates an error caused by the insufficient flexibility of prediction, which determines lack of estimation accuracy of the predicted variable fluctuations. While an MSE_3 signifies the error related to the insufficient compliance of the change in the direction of the prediction with the change in the direction of the predicted value.

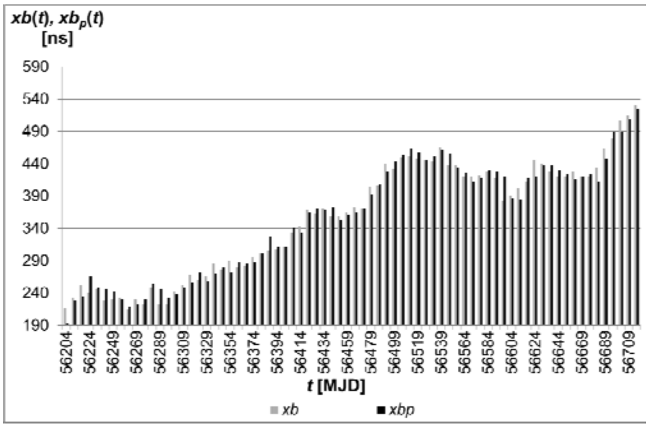

Fig.6. Determined values of $xb(t)$ deviations determined by the BIPM and values of $xb_p(t)$ predictions based on the time series TS for UTC(LT)

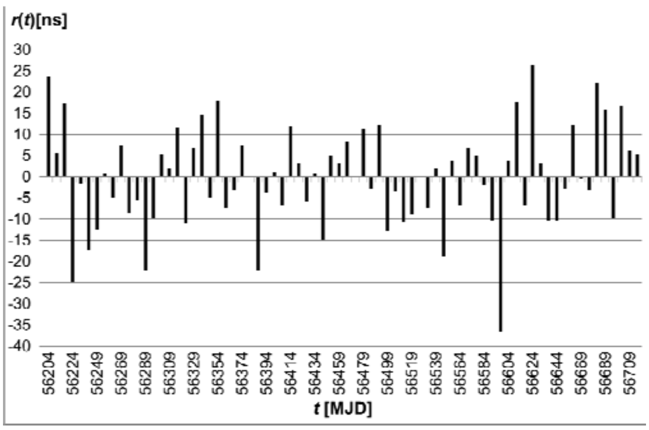

Fig.7. Determined values of r residuals for predicting $xb_p(t)$ based on the time series TS for UTC(LT)

Table 1. Values of selected measures of quality of predictions for UTC(BEV) and UTC(LT) timescales

Measure of quality of prediction	UTC(BEV)	UTC(LT)
max [ns]	21.35	26.47
min [ns]	-20.04	-36.45
ME [ns]	3.3	-0.3
MAE [ns]	7.5	9.1
MSE [ns^2]	86	136
MSE_1 [ns^2]	11	0.1
MSE_2 [ns^2]	1.7	0.5
MSE_3 [ns^2]	73	135
RMSE [ns]	9.3	12

On the basis of research results (fig. from 4 to 7) and the calculated value of measures of quality of designated predictions for UTC(BEV) and UTC(LT) (Table 1) sets out the following conclusions:

1. From a comparison of the values of all measures of the quality of predictions the best quality results of predicting the deviations (the lowest value of received measures) were obtained for the UTC(BEV) timescale.
2. In case of UTC(BEV) scale smaller changes of the values of $xb(t)$ deviations occurs (fig. 4), not

exceeding ±120 ns, in relation to changes in the values of *xb*(*t*) deviation at the level of ±310 ns (fig. 6) in case of UTC(LT) scale. This is due to frequent correcting process of the Austrian Timescale UTC(BEV), which is visible with the more dynamic changes in the direction of the *xb*(*t*) deviations trend (fig. 4).

3. In case of UTC(BEV) scale in 53 cases out of 74 the received values of residuals are in the range of ±10 ns. The highest absolute value of residuum is 21.35 ns. In case of UTC(LT) scale in 46 cases out of 74 the received values of residuals are in the range of ±10 ns. The highest absolute value of residuum is 36.45 ns.
4. Comparison of *ME*, *MAE* and MSE_1 errors for UTC(LT) scale indicates the unloaded predictions. The observed values of residuals are multidirectional.
5. For two presented time scales (UTC(BEV) and UTC (LT)) a relatively small component of MSE_2 was obtained. This means that the variation of the predicted values is sufficient in relation to the variability of the observed values.
6. In case of results obtained for two time scales there are cases of high values of residuals. This is due to higher or lower changes in the direction of the trend of the deviations designated by the UTC and UTCr scales, resulting from the steering of a time scale, and the prediction horizon, which depending on the date of prediction (t_{pred}), ending with the digit 4 or 9 in relation to the publication date of deviations according to UTCr scale (t_{pubr}), falling on Wednesday, changes from 3 to 7 days. Hence, for the UTC(BEV) and UTC(LT) scales a high value of error of MSE_3 component was obtained.

Conclusions

Publication of *xbr*(*t*) deviations is delayed up to three days in relation to several days delay in publication of *xb*(*t*) deviations. This means better quality of prediction for UTC(k) timescales based on the deviation determined by the UTC Rapid scale due to the shorter prediction horizon than in the case of the predicting the deviations for the UTC(k) based on the deviation determined by the UTC scale.

The obtained research results and statistical analysis confirmed the possibility of predicting [UTC - UTC(k)] deviations with the use of GMDH neural network based on data prepared on the basis of deviations determined by the UTC and UTCr scales. Lack of steering of the timescale (high values of *xb*(*t*) deviations) and a high dynamic of changes in direction of the *xbr*(*t*) deviations trend adversely affect on the quality of predicting the deviations for UTC(k).

Better prediction quality can be achieved by applying to the construction of the time series values of a phase time of the clock realizing local timescale UTC(k) and values of deviations determined on the basis of UTC and UTCr scales. However, in case of failure of the clock realizing the UTC(k) timescale, a lack of a sufficient number of training data in the form of the time series may occur. Time series based solely on the deviations designated by UTC and UTCr scales are independent of the clock data, and can be used for predicting [UTC - UTC(k)] deviations as a very good alternative in case of maintenance or failure of the atomic clock, realizing a local time scale UTC(k).

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