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Comparison of linear regression method and GMDH neural network in predicting the UTC(PL) national timescale

***Abstract**. The paper presents research results on predicting the Polish Timescale UTC(PL) by the means of GMDH-type neural network and linear regression method for data prepared in the form of time series built on the basis of [UTC - UTC(PL)] and [UTCr - UTC(PL)] deviations and values of a phase time from UTC(PL). The obtained results show comparable prediction quality by means of GMDH-type neural network with prepared procedure of predicting and linear regression method modified by the author for timescale characterized with high stability.*

Streszczenie.** W pracy przedstawiono wyniki badań nad prognozowaniem Polskiej Skali Czasu UTC(PL) przy zastosowaniu sieci neuronowej typu GMDH oraz metody regresji liniowej dla danych przygotowanych w formie szeregu czasowego, zbudowanego z wartości odchyleń [UTC - UTC(PL)] oraz [UTCr - UTC(PL)] oraz wartości czasu fazowego z UTC(PL). Wyniki badań pokazały porównywalną jakość prognozowania z zastosowaniem sieci neuronowej typu GMDH i opracowanej procedury prognozowania oraz zmodyfikowanej przez autora metody regresji liniowej w przypadku skali czasu charakteryzującej się dużą stabilnością.* (Porównanie metody regresji liniowej i sieci neuronowych GMDH w prognozowaniu krajowej skali Czasu UTC(PL)).***

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

Introduction

Predicting the UTC(k) local timescales is required in order to ensure the highest possible compliance of this scale with the UTC scale, called Coordinated Universal Time. The necessity of predicting a timescale results from the delay in the publication by the International Bureau of Weights and Measures BIPM (the French for Bureau International des Poids et Mesures) the values of [UTC - UTC(k)] deviations for individual UTC(k), which define the divergence of UTC(k) in relation to the UTC. These deviations are determined once a month as average values per day on Modified Julian Date MJD days ending with digits 4 and 9. The process of calculating UTC scale is very complex and time-consuming [1]. It requires a collection and proper preparation of measurement data from local and remote comparisons of over 400 atomic clocks sent to BIPM by a National Metrological Institutes NMIs [1], which carry out the physical implementation of the UTC(k) scale on the basis of commercial caesium clocks or hydrogen masers. This results in a delay in issuing the BIPM "Circular T" bulletin containing determined values of deviations for UTC(k), which is published between about 7th and 17th day of the following month. In this case, the time horizon of the first prediction is within 10 to 20 days.

Delay in publication of the [UTC - UTC(k)] deviations by the BIPM adversely affect the result of prediction process of UTC(k) local timescale, and consequently on maintaining the best convergence of the UTC(k) with the UTC. For this purpose the BIPM has launched in 2012 a project called "A Rapid UTC" [1, 2], which main task is to expedite the transfer of information about the differences of the UTC(k) in relation to the UTC. On the basis of UTC Rapid scale, every Wednesday on the BIPMs ftp server the [UTCr - UTC(k)] deviations determined for the previous week are published, for each clock realizing the UTC(k) scale. This allows to shorten the time horizon of a first prediction to several days (from 3 to 7), which is beneficial from the point of view of the methods used for predicting the local timescale UTC(k).

The literature on the prediction of UTC(k) local timescales presents statistical methods based on: Allan deviations [3], linear regression method [4], Kalman filter [5], stochastic differential equations [6] or methods based on artificial intelligence [7, 8]. The estimated value of the prediction may be the basis for the correction of the UTC(k) scale. In a few NMI laboratories, whose results have been presented, for example in papers [9, 10], the correction of the UTC(k) scale is carried out on the basis of data from atomic fountains.

Institute of Metrology, Electronics and Computer Science of the University of Zielona Góra, in collaboration with the Central Office of Measures GUM (the Polish for Główny Urząd Miar) has been working on the application of neural networks for predicting the UTC(k) national timescales. The proposal of application of the neural networks 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 [11, 12]. Behavioural models created by a neural network have an internal structure and a working principle which corresponds to the behaviour of the original objects or processes. A unique feature of neural networks 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 a very good mathematical tool, used for solving problems of a nonlinear character [11, 12, 13, 14].

Obtained results of research related to the application of neural networks such as MLP, RBF, GRNN and GMDH, which have been presented for example in papers [7, 15, 16, 17] clearly indicate that the best-quality predictions have been obtained by means of the Group Method of Data Handling GMDH neural network [18, 19]. The GMDH type neural network has also been subjected to studies on predicting the deviations for UTC(PL) using the values of deviations determined by BIPM based on UTC and UTC Rapid scales. The obtained research results, which have been presented in papers [20, 21], have confirmed the possibility of using the UTC Rapid scale for predicting [UTC - UTC(PL)] values based on GMDH type neural network by means of time series analysis method.

The conclusions from research carried out have been the basis for developing by the author the procedure of predicting the deviations for the UTC(k) local timescales by means of GMDH type neural network [22, 23]. This procedure has been verified for selected UTC(k) timescales realized on the basis of commercial caesium clock and hydrogen maser [24, 25]. The research results have shown that the developed procedure allows to achieve very good quality predicting of UTC(k) national timescales.

The aim of the study is to compare the method of predicting UTC(k) local timescale on the example of Polish Timescale UTC(PL) by means of GMDH type neural network based on the developed deviations predicting procedure [22, 23] and the LR linear regression method modified by the author with traditional linear regression method TLR, which has been used so far in the GUM. The modification consists in taking into account more data, designated for each day for a period of one month, compared to data for a period of one month, taking into account only data on MJD days ending with digits 4 and 9. The paper presents the results of predicting the [UTC - UTC(PL)] deviations based on data prepared in the form of a time series, built on the basis of deviations determined according to UTC and UTC Rapid scales. Additionally, the obtained research results have been compared with the research results obtained by means of TLR method.

Input data preparation for the GMDH type neural network and linear regression method

The basis for preparing the input data in the form of time series for GMDH type neural network and LR method are [UTC - UTC(PL)] deviations determined according to relation:

(1) $xb(t) = UTC(t) - UTC_{PL}(t)$

on MJD days ending with the digits 4 and 9, and the [UTCr - UTC(PL)] deviations determined by relation:

(2) $xbr(t) = UTCr(t) - UTC_{PL}(t)$

designated on each day.

In order to use the $xbr(t)$ deviations for the construction of the time series, a comparative analysis of the values of these deviations with the $xb(t)$ deviations determined by BIPM for the Polish Timescale UTC(PL) has been carried out. The analysis showed a very good convergence of the $xbr(t)$ deviations in relation to $xb(t)$ deviations. Differences between $xbr(t)$ and $xb(t)$ deviations on the same day are only on a level of few ns.

The created time series consists of two subsets of elements prepared according to the rules defined in Fig. 1. The first subset contains a group of data (from 1 to i) determined from relation:

(3) $x_1(t) = xa(t) + xb(t) = UTC(t) - clock_{PL}(t)$,

published by the BIPM from day t_0 to day t_n, for which the last value of this time series before the publication day (t_{pub}) has been known. The values of $xa(t)$ are the historic results of the measurement of the phase time between 1 pps signals from $UTC_{PL}(t)$ and the atomic clock realizing this scale ($clock_{PL}$), determined on each day according to relation

(4) $xa(t) = UTC_{PL}(t) - clock_{PL}(t)$.

In order to designate the values of $xb(t)$ on each day a Hermite's interpolation function available in MATLAB has been used. This allowed a five-fold increase in the set of $xb(t)$ deviations. The second subset is a complement of time series by a group of data determined on the basis of relation

(5) $x_2(t) = xa(t) + xbr(t) = UTCr(t) - clock_{PL}(t)$,

between days t_n and t_{nr}, published by the BIPM on day t_{pubr} (Fig. 1). 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 $xb_p(t_{pred})$ is performed.

Adding to the time series new groups of data calculated from relation (5) it is possible to determine the next values of $xb_p(t_{pred})$ predictions in the following weeks. At the time of publication of the new "Circular T" bulletin, which contains the values of $xb(t)$ deviations, a new group of data i+1 (Fig. 1) is created based on relation (3), which for the respective days replace the data determined according to relation (5).

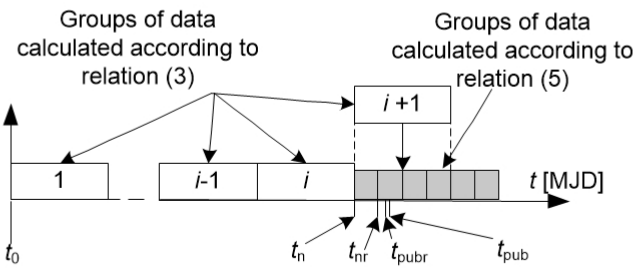

Fig.1. Creation of time series for GMDH and LR methods

In the case of TLR method the first $xb_p(t_{pred})$ prediction has been designated once a month on MJD days ending with the digits 4 or 9, which results from the date of publication of the "Circular T" bulletin. The input data are created according to the principle defined in Fig. 2 in accordance with the relation (3) for data for a period of one month, taking into account only data on MJD days ending with the digits 4 and 9.

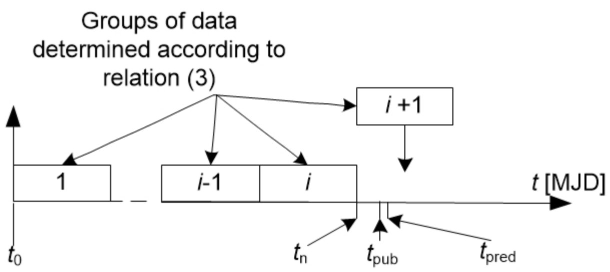

Fig.2. Creation of time series for TLR method

Research results for GMDH and LR methods

Predicting the Polish Timescale UTC(PL) by means of GMDH type neural network with the developed predicting procedure and based on the LR method has been carried out within 12 months from October 23, 2016 (MJD 57684) until October 28, 2017 (MJD 58054) on MJD days, ending with the digits 4 or 9.

The input data for the GMDH type neural network in the form of a time series have been constructed in accordance with Fig.1 based on the values determined from the relation (3) for the period from January 01, 2015 (MJD 57023) to

October 28, 2017 (MJD 58054) and the values determined from the relation (5) for the period from September 29, 2016 (MJD 57660) to October 28, 2017 (MJD 58054).

The input data for the LR method have been a time series containing data for a period of 30 days, preceding the day of the last known value determined by the relation (5) for the week in which the prediction has been calculated. In this case, the time series has been built according to the principle described in Fig. 1 based on the values determined from the relation (3) or (5) for the period from September 17, 2016 (MJD 57648) to October 28, 2017 (MJD 58054), depending on the date of publication of the "Circular T" bulletin.

In case of using such prepared time series at the output of the GMDH type neural network and LR method a value of ($x_{1p}(t_{pred})$) prediction is obtained. Taking into account the value of $xa(t_{pred})$ measured on the prediction determining day, the $xb_p(t_{pred})$ prediction is calculated from the relation

(6) $$xb_p(t_{pred}) = x_{1p}(t_{pred}) - xa(t_{pred}).$$

Figs. 3 and 4 present the obtained research results for GDMH type neural network based on the developed deviation predicting procedure [22, 23] and the LR method. Fig. 3 presents the values of $xb_p(t_{pred})$ predictions designated by the GMDH neural network and the LR method for UTC(PL) scale, which have been obtained for the prepared time series and values of $xb(t)$ deviations, determined by BIPM on the same day of prediction (t_{pred}).

In the case of predicting the values of deviations based on UTC Rapid scale in some cases, one or two predictions could be determined in a given week. In a large number of cases, the second predictions are characterized by worse results. It results from the extended time horizon of a prediction, which for the second predictions in a given week is 8 or 9 days. Hence, the results presented on Figs. 3 and 4 relate only to the first predictions.

Fig. 4 present the values of (r) residuals, calculated for these predictions form relation:

(7) $$r(t_{pred}) = xb(t_{pred}) - xb_p(t_{pred}).$$

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.

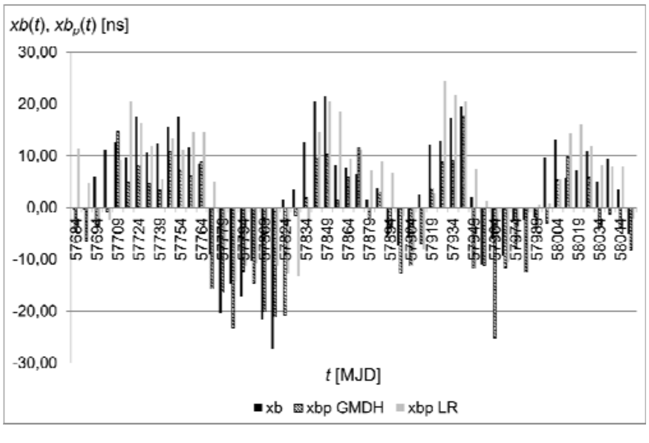

Fig.3. Determined values of $xb_p(t)$ predictions based on the time series for GMDH neural network and LR method and values of $xb(t)$ deviations determined by the BIPM for UTC(PL)

The calculated values of residuals (r) are the basis for evaluation of the quality of predicting with selected prediction quality measures. Table 1 shows the selected prediction quality measures [26]: mean error (ME), absolute mean error (MAE), mean square error (MSE) with 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 a MSE_3 component represents 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.

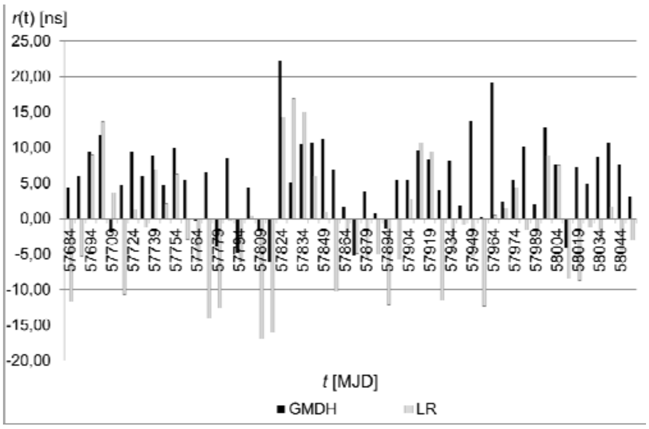

Fig.4. Determined values of r residuals for predicting $xb_p(t)$ for GMDH neural network and LR method

Table 1. Values of selected measures of quality of predictions for GMDH neural network and LR method LR

Measure of quality of prediction	GMDH	LR
max [ns]	22	17
min [ns]	-6.2	-17
ME [ns]	5.6	-1.4
MAE [ns]	6.7	6.7
MSE [ns^2]	64	68
MSE_1 [ns^2]	31	1.8
MSE_2 [ns^2]	0.6	0.7
MSE_3 [ns^2]	32	65
RMSE [ns]	8.0	8.2

Based on presented research results (Figs. 3 and 4) and the calculated values of measures of quality of designated predictions for GMDH type neural network and LR method (Table 1) the following conclusions can be drawn:

1. Comparison of ME, MAE and MSE_1 errors shows that in the case of LR method the predictions are less loaded than in the case of results obtained for GMDH type neural network.
2. The deviations predictions designated by the GMDH type neural network and LR method are characterized with small values of MSE_2 error. This means a good prediction of the volatility of the predicted values relative to the volatility of observed values for both methods.
3. In case of method based on GMDH type neural network in 45 cases out of 55 the received values of residuals are in the range of ±10 ns. The highest absolute value of residuum is 22 ns. In case of LR method in 40 cases out of 55 the received values of residuals are in the range of ±10 ns. The highest absolute value of residuum is 17 ns.
4. In the results obtained for both methods there are cases of high values of residuals. This is due to two factors. The first one is related to variable time horizon of the prediction, which varies from 3 to 7 days, depending on the date of prediction (t_{pred}), ending with a digits 4 or 9. The second factor is related to high dynamic of changes of the input data. Hence, for both methods high value of the MSE_3 error occur.

5. In case of results obtained for GMDH type neural network much smaller value of MSE_3 error have been obtained in relation to LR method. It follows that in the case of the GMDH type neural network we are dealing with better compliance of the change in the direction of the prediction with the change in the direction of the predicted value.
6. A comparison of the values of all prediction quality measures for both methods indicates a comparable quality of predicting the deviations.

Research results for TLR method

For the same period of time, i.e. from October 23, 2016 (MJD 57,684) to October 28, 2017 (MJD 58054) a studies on predicting the Polish Timescale UTC(PL) by means of conventional linear regression method (TLR), which has been used in the GUM has been performed. Analysed predictions have been carried out once a month for MJD days ending with a digit 4 or 9. The input data have been prepared according to the principle described in Fig. 2. The research results are summarized with the results obtained for the GMDH type neural network and LR method on the same day of determining the prediction. In the case of methods based on GMDH type neural network and LR the predictions have been made based on the data prepared in accordance with the principles described in Fig. 1. In addition, there have been situations where the date of determining the prediction by means of the TLR method has fallen on the day of the second prediction in a given week for a method based on a GMDH type neural network or LR. Thus, the results obtained as the second prediction for a given week have been included in the results of the research presented below.

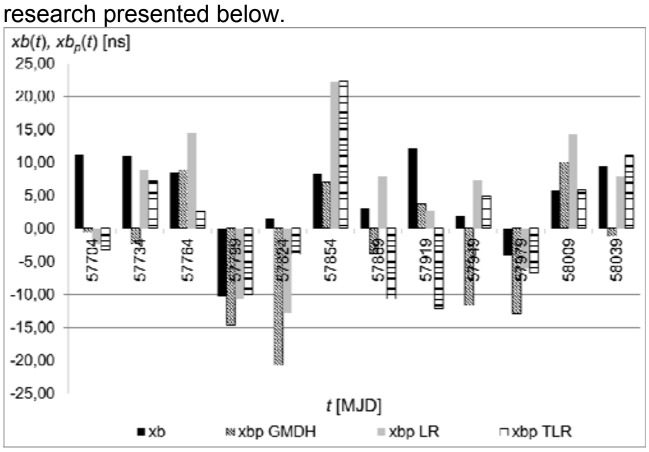

Fig.5. Determined values of $xb_p(t)$ predictions based on the time series for GMDH neural network, LR method and TLR method and values of $xb(t)$ deviations determined by the BIPM for UTC(PL)

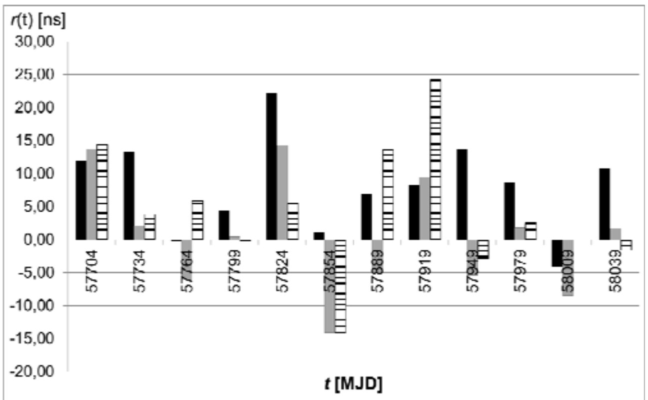

Fig.6. Determined values of r residuals for predicting $xb_p(t)$ for GMDH neural network, LR method and TLR method

Fig. 5 presents the research results of predicted deviations obtained for GMDH type neural network, LR method, and TLR method set with the values of $xb(t)$ deviations, determined by BIPM on the same day of prediction (t_{pred}).

Fig. 6 shows (r) residuals values, calculated according to the relation (7) for GMDH type neural network, LR method and TLR method.

Based on the calculated (r) residuals, the quality of predicting has been performed using the same selected prediction quality measures. The results obtained are presented in Table 2.

Based on presented research results (Figs. 5 and 6) and the calculated values of measures of quality of designated predictions for GMDH type neural network, LR method and TLR method (Table 2) the following conclusions can be drawn:
1. Comparison of *ME*, *MAE* and MSE_1 errors for UTC(PL) scale shows that in the case of LR method the predictions are the least loaded than in the case of predictions obtained for TLR method or GMDH type neural network.
2. The predictions of deviations designated by the GMDH type neural network are characterized with the smaller values of MSE_2 error in relation to LR and TLR methods. This means better prediction of the volatility of the predicted values relative to the volatility of observed values in case of GMDH type neural network.
3. In case of TLR method in 8 cases out of 12 the received values of residuals are in the range of ±10 ns. The highest absolute value of residuum is 24 ns. In case of method based on GMDH type neural network in 7 cases out of 12 the received values of residuals are in the range of ±10 ns. The highest absolute value of residuum is 22 ns. On the other hand, in the case of the LR method in 9 cases out of 12 the obtained values of residuals are in the range of ±10 ns. The highest absolute value of residuum is 14 ns.
4. In case of the results obtained for all three methods there are cases of high values of residuals. This is due to variable time horizon of the prediction. In case of methods based on GMDH type neural network and LR time horizon of the prediction depending on the date of prediction varies from 3 to 7 days. In case of TLR method the time horizon of the prediction is much larger and varies, depending on the date of publication of the "Circular T" bulletin from 10 to 20 days. Hence, for all three methods high value of the MSE_3 error occur.
5. In case of results obtained for GMDH type neural network much smaller value of MSE_3 error have been obtained in relation to other two methods. It follows that in the case of a GMDH type neural network we are dealing with better compliance of the change in the direction of the prediction with the change in the direction of the predicted value.
6. From a comparison of the values of all prediction quality measures the comparable results of predicting the deviations are obtained for GMDH type neural network and LR method.

Table 2. Values of selected measures of quality of predictions for GMDH neural network, LR method and TLR method

Measure of quality of prediction	TLR	GMDH	LR
max [ns]	24	22	14
min [ns]	-14	-4.2	-14
ME [ns]	4.3	8.1	0.4
MAE [ns]	7.4	8.8	6.9
MSE [ns^2]	106	112	71
MSE_1 [ns^2]	18	65	0.1
MSE_2 [ns^2]	11	8.9	14
MSE_3 [ns^2]	77	38	57
RMSE [ns]	10	11	8.4

Conclusions

The obtained research results and conducted statistical analysis confirmed the possibility of predicting the Polish Timescale UTC(PL) based on data prepared on the basis of deviations designated according to UTC and UTC Rapid scales by means of GMDH neural network based on the developed predicting procedure, as well as a linear regression method modified by the author with a new time series. The research results showed comparable predicting quality for both methods.

Publication of *xbr*(*t*) deviations is delayed 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 shorter time horizon of the prediction, than in the case of predicting the deviations based only on the deviations determined by the UTC scale. The author's method of preparation of the input data based on deviations determined by BIPM according to UTC and UTC Rapid scales have shown the superiority of the GMDH type neural network and the LR linear regression methods over the traditional linear regression method TLR. Such good results for the LR and TLR methods have also been obtained due to the fact that during this period the Polish Timescale UTC(PL) has been characterized by high stability.

In the case of time scales characterized by significantly lower stability and high dynamics of variations in the BIPM deviations, the results of which are presented in paper [25], worse prediction quality has been obtained by means of GMDH type neural network and the developed predicting procedure. Initial research made by the author show that in the case of such time scales, the linear regression method gives worse results than a GMDH neural network by several orders.

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