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Predicting the Lithuanian Timescale UTC(LT) by means of GMDH neural network

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Abstract. The aim of the study is to examine the effectiveness of applying GMDH-type neural network and the developed procedure for predicting UTC(k) timescales, which are characterized with high dynamics of changes of the input data. The research is carried out on the example of the Lithuanian Timescale UTC(LT). The obtained research results have shown that GMDH-type neural network with a developed predicting procedure enables us to receive good prediction results for the UTC(LT). Better prediction quality was obtained using time series which are built only on the basis of deviations determined by the BIPM according to the UTC and UTC Rapid scales.
Keywords: electrical engineering, UTC(k) timescale, atomic clock, predicting [UTC – UTC(k)], GMDH neural network
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1. Introduction

The physical realization of the local time scales UTC(k) is carried out by the National Metrological Institutes NMIs. Each month, the International Bureau of Weights and Measures BIPM (*the French for Bureau International des Poids et Mesures*) determines the [UTC – UTC(k)] deviations for a given month for each UTC(k), which define the divergence of a local timescale in relation to the UTC [1, 2, 3]. They are determined with a five-day interval as average values per day on MJD (*Modified Julian Date*) days ending with digits 4 and 9.

The problem of maintaining the highest possible compatibility of UTC(k) with the UTC is due to the very complex and time-consuming process of calculating the UTC scale [1]. This results in a delay in issuing the BIPM “Circular T” bulletin containing the determined values of deviations for UTC(k), which is published between the 8th and 12th day of the following month. Only by predicting the deviations, it is possible to ensure the maintenance of the highest compliance of the UTC(k) in relation to the UTC. The designated value of prediction may constitute a basis for correcting the UTC(k) scale. Part of NMI laboratories are predicting the [UTC – UTC(k)] deviations. In the literature, for example in [4, 5, 6, 7] different methods, based on statistical models, are presented in this field. Predicting the deviations for the Polish Timescale UTC(PL), realized by the Central Office of Measures GUM (*the Polish for Główny Urząd Miar*), on the basis of commercial caesium atomic clock, was carried out on the basis of labour procedure based on the linear regression method [5]. However, papers [8, 9, 10, 11] present prediction methods based on artificial neural networks. Neural networks are very good mathematical tools, used for solving problems of a nonlinear character [12, 13, 14, 15].

The research on the application of neural networks for predicting the deviations for the UTC(PL) are carried out at the Institute of Metrology, Electronics and Computer Science of the University of Zielona Góra (*IMEI UZ*) in collaboration with the GUM. The most favourable results in the prediction of deviations has the GMDH (*Group Method of Data Handling*) — type neural network [9, 10]. GMDH-type neural network belongs to the group of self-organizing networks [16]. GMDH-type network structure is created automatically on the basis of prepared sets of training and testing data [17]. The results obtained for the GMDH-type neural network have been also significantly better than those obtained in the GUM by a linear regression method [9, 10]. In addition, GMDH-type neural network allows to obtain the final result of prediction in a much shorter time (a few minutes) than for linear regression (several hours) [18, 19]. Delay in publication of the "Circular T" bulletin results in that the first prediction of the deviation for the UTC(PL) is determined between 10th and a 20th day of the month. A positive impact on the result of prediction of the deviations for the UTC(PL) has the application of the deviations determined according to the UTC Rapid (UTCr) scale, introduced by the BIPM in 2012 [1]. The performed analysis of deviations values, set by the BIPM in relation to the UTC and UTCr scales for different UTC(k) timescales, has shown a very good correlation between the two groups of deviations [18, 19, 20, 21]. The differences between the values of deviations for the analysed timescales, relative to the UTC and UTCr scales for the same day, are on the level of only a few ns. This allows to shorten the prediction horizon, the day of the first prediction falls between 3rd and 7th day of the week. The results of research in this area, presented in [20], have been the basis for developing a new procedure of predicting the deviations for the UTC(PL) by means of GMDH neural network. Papers [18, 19] present the results of predicting the deviations based on this procedure. The obtained results are significantly better than those obtained using the linear regression method [5], used so far in the GUM or the method based on a Kalman filter [6].

The previous work on application of the GMDH-type neural networks and the developed predicting procedure for predicting UTC(k) are conducted on the example of the UTC(PL) [18, 19], UTC(BEV) [21], and UTC(AOS) [22] timescales. These timescales are characterised by relatively small values of deviations in relation to the UTC scale, small change in their dynamics, and a good stability of the clock realizing this scale. For example, for the UTC(PL) scale, the [UTC – UTC(PL)] values of deviations varied from –43 ns to 135 ns for the analysed period of time. However, the changes of a phase time, characterizing the stability of a caesium atomic clock, realizing the UTC(PL) scale, are shown in Fig. 1. This is significant because the sum of the determined values of deviations by the UTC and UTCr scale and the phase time for each day is the set of input data for the GMDH-type neural network in the process of predicting these deviations.

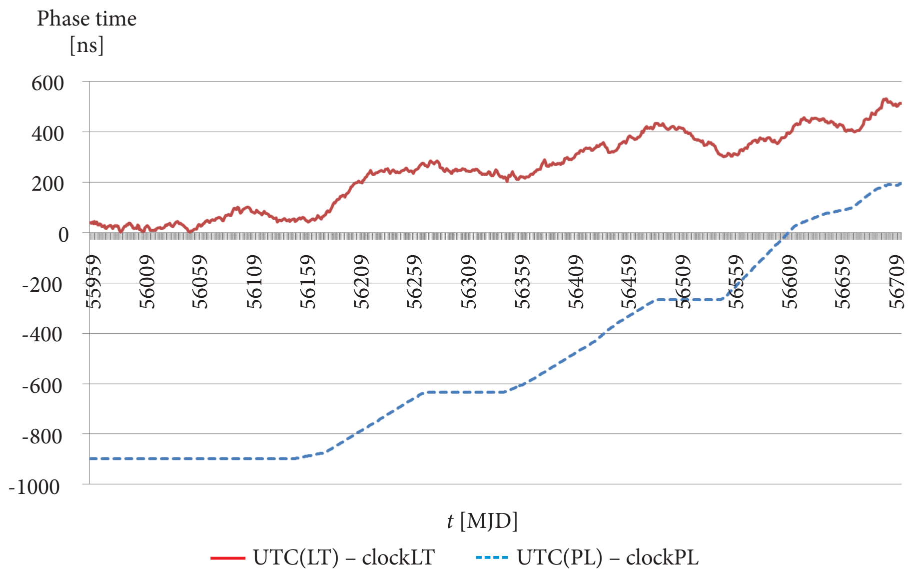

Fig. 1. Values of phase time for Polish Timescale UTC(PL) and for Lithuanian Timescale UTC(LT).

The aim of the study, which results have been presented in Section 3, is to examine the effectiveness of applying GMDH-type neural network and the developed procedure for predicting UTC(k) timescales, which are characterized with high dynamics of changes of the GMDH-type neural network input data. The studies have been conducted on the example of the Lithuanian Timescale UTC(LT), which is characterized by a greater clock instability of this scale compared to the clock realizing the UTC(PL) scale (Fig. 1) and the high values of the [UTC – UTC(LT)] deviations varied from 6 ns to 530 ns for the analysed period of time.

In addition, the UTC(LT) scale, analogous to the UTC(PL), is realized on the basis of a single commercial caesium clock. The paper presents the results of studies conducted for the UTC(LT) scale using the GMDH-type neural network according to the predicting procedure [18, 19] based on data prepared in form of the time series TS1, based on the values of phase time of a clock realizing the UTC(LT) scale and deviations determined by the UTC and UTCr scales. The results of these studies are compared with the results of predicting the deviations obtained for the UTC(LT) on the basis of the time series TS2 [21]. The proposal of this time series results from the possibility of replacing an atomic clock realizing the UTC(k) national time-scale with another clock. Then, there may be a lack of the required number of the time series elements for determining the correct value of a prediction. The proposed second-time series TS2 [21] is based only on the values of [UTC – UTC(k)] and [UTCr – UTC(k)] deviations determined by the BIPM. This time series consists of two subsets prepared according to the principle described for the time series TS1 in Section 3 wherein the elements of the first subset are only the values of deviations determined according to the UTC scale, and for the second subset are only the values of deviations determined according to the UTCr scale.

2. Input data preparation for the GMDH-type neural network

Predicting the deviations are carried out on the basis of the time series TS1, which constitute the training data set for the GMDH-type neural network, built on the basis of the values of [UTC – UTC(LT)] deviations determined according to the relation:

$$xb(t) = \mathrm{UTC}(t) - \mathrm{UTC}_{\mathrm{LT}}(t), \tag{1}$$

and the values of [UTCr – UTC(LT)] deviations determined according to the relation:

$$xbr(t) = \mathrm{UTCr}(t) - \mathrm{UTC}_{\mathrm{LT}}(t). \tag{2}$$

The time series TS1 consists of two subsets of elements prepared according to the rules defined in Fig. 2. The first subset contains a group of the data (from 1 to i) determined from the relation:

$$x_1(t) = xa(t) + xb(t) = \mathrm{UTC}(t) - \mathrm{clock}_{\mathrm{LT}}(t). \tag{3}$$

The values of $xb(t)$ deviations are historical data published by the BIPM from the 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 $UTC_{LT}(t)$ and the atomic clock realizing this scale ($clock_{LT}$), determined on each day according to the relation:

$$xa(t) = \mathrm{UTC}_{\mathrm{LT}}(t) - \mathrm{clock}_{\mathrm{LT}}(t). \quad (4)$$

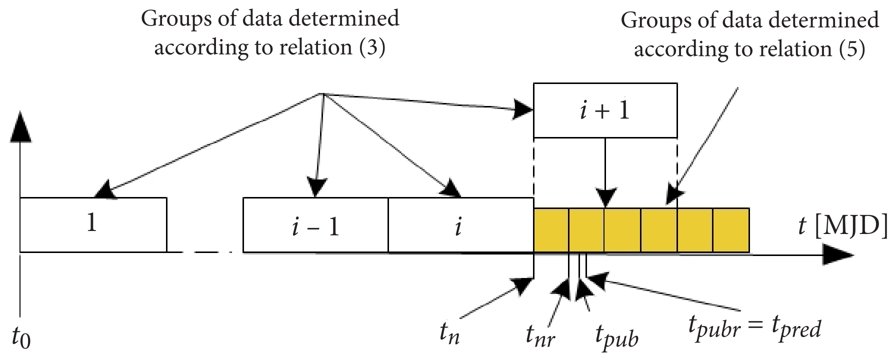

Fig. 2. Creation of time series TS1.

The $xb(t)$ deviations are published with a five-day interval. In order to determine the values of deviations on each day, a PCHIP interpolation function (Hermite interpolation available in MATLAB) is applied on the $xb(t)$ data set. This method, according to simulation research presented in [23], is several times better than linear interpolation and spline functions. The second subset is a complement of the time series TS1 by a group of data between the days t_n and t_{nr}, containing the values determined on the basis of the relation

$$x_2(t) = xa(t) + xbr(t) = \mathrm{UTCr}(t) - \mathrm{clock}_{\mathrm{LT}}(t). \quad (5)$$

The values of $xbr(t)$ deviations are published by the BIPM on the day t_{pubr} (Fig. 2). 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.

An important advantage of the time series TS1 is the possibility of adding every week the successive groups of data calculated on the basis of Eq. (5) and determining the successive values of $xb_p(t_{pred})$ in consecutive weeks. At the time of publication of a new "Circular T" bulletin containing the values of $xb(t)$ deviations, the new group of the data $i+1$ (Fig. 2) according to Eq. (3) is determined, which for the respective days replaces the existing data set based on Eq. (5).

3. Research results

Predicting the deviations for the UTC(LT) scale have been carried out for a period of 17 months, from MJD 56204 (October 4, 2012) to MJD 56714 (February 26, 2014), on MJD days ending with digits 4 and 9. The time series TS1 applied at the input of the GMDH-type neural network is created on the basis of the historical $xb(t)$ data for the period from MJD 55629 (March 9, 2011) to MJD 56714 (February 26, 2014), and the $xbr(t)$ for the period from 56170 to MJD 56714. In case of using this time series at the output of the GMDH-type neural network, the 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

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

Figures 3 and 4 show the research results obtained for UTC(LT) scale for input data prepared in form of the time series TS1. Figure 3 shows respectively determined by the GMDH-type neural network values of $xb_p(t_{pred})$ predictions for UTC(LT) scale, which have been obtained for the prepared time series TS1 and the values of $xb(t)$ deviations designated by the BIPM on the same day of prediction (t_{pred}), which are characterized with high values.

Figure 4 presents the values of residuals (r), calculated for these predictions according to the relation:

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

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

The calculated values of the 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 [24]: mean error (ME) and its relative value (MPE), absolute mean error (MAE) and its relative value ($MAPE$), mean square error (MSE) with its components (MSE_1, MSE_2, MSE_3) and their relative values (U_1, U_2, and U_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. The MSE_2 component indicates an error caused by the insufficient flexibility of prediction, which determines a lack of estimation accuracy of the predicted variable fluctuations. While the 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.

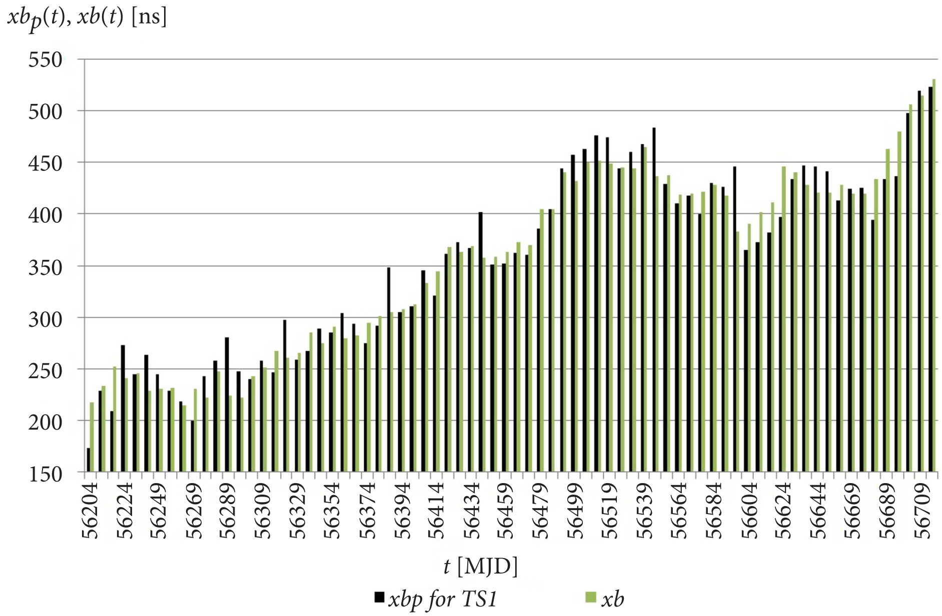

Fig. 3. Determined values of $xb_p(t)$ predictions based on the time series TS1 and values of $xb(t)$ deviations determined by the BIPM for UTC(LT).

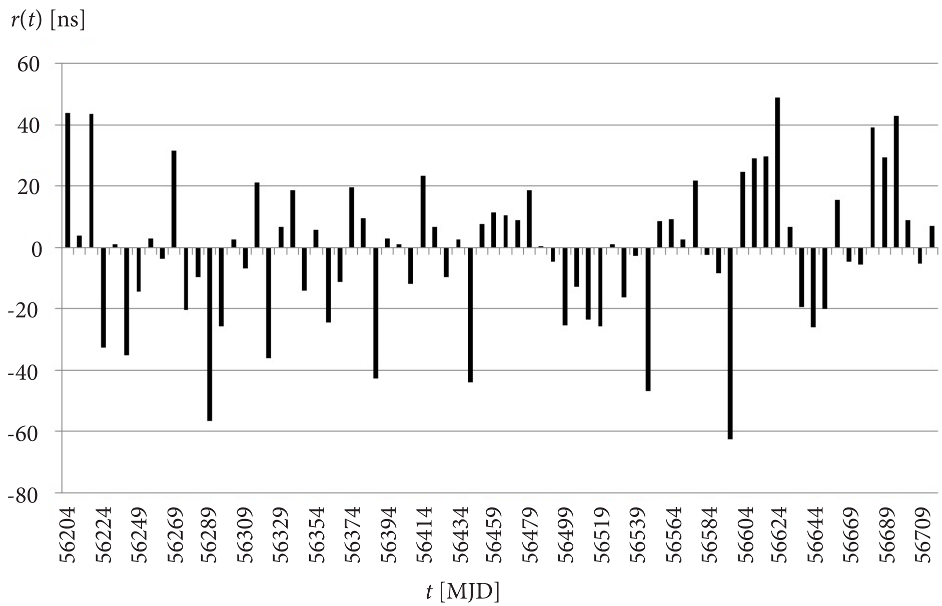

Fig. 4. Determined values of r residuals for predicting $xb_p(t)$ based on the time series TS1 for UTC(LT).

Table 1

Values of selected measures of quality of predictions for UTC(LT) for the time series TS1 and TS2 [21]

Measure of quality of prediction	UTC(LT) for TS1	UTC(LT) for TS2
max [ns]	48.96	26.47
min [ns]	–62.67	–36.45
ME [ns]	–1.1	–0.3
MPE [%]	–0.6	–0.2
MAE [ns]	18	9.1
MAPE [%]	5.6	2.8
MSE [ns^2]	552	136
MSE_1 [ns^2]	1.2	0.1
MSE_2 [ns^2]	0.01	0.5
MSE_3 [ns^2]	551	136
RMSE [ns]	24	12
U_1 [%]	0.2	0.08
U_2 [%]	0.002	0.3
U_3 [%]	99.7	99.6

Based on comparison of the research results for the time series TS1 (Figs. 3 and 4), with the results obtained for the time series TS2, presented in paper [21] and the calculated values of measures of quality of designated predictions for the UTC(LT) scale (Table 1), the following conclusions can be drawn:

1. In case of UTC(LT) scale, high changes of the values of $xb(t)$ deviations (Fig. 3), which change in the range from 6 ns to 530 ns and high instability of the clock realizing the UTC(LT) scale (Fig. 1) for the analysed period of time occur. This is due to a sporadic correction process of the Lithuanian Timescale.
2. In case of UTC(LT) scale and input data described by the time series TS1, in 45 cases out of 74 the received values of residuals are in the range of ±20 ns. The highest absolute value of residuum is 62.67 ns. In case of results for the time series TS2 [21], 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.
3. From a comparison of the values of all prediction quality measures, the best results of predicting the deviations have been obtained for the input data prepared on the basis of the time series TS2.

4. Comparison of *ME*, *MAE*, and MSE_1 errors and their relative values (*MPE*, *MAPE*, and U_1) for UTC(LT) shows that for the time series TS2, the predictions are less loaded than in the case of results obtained for the time series TS1.
5. The deviations' predictions, designated by the GMDH-type neural network for the time series TS1, are characterized with the smaller values of MSE_2 error and its relative value U_2 in relation to the time series TS2. This means better prediction of the volatility of the predicted values for the time series TS1 relative to volatility of the observed values. This is due to the method of construction of the time series TS1.
6. In the results obtained for the time series TS1 and the results obtained for TS2 [21] there are the cases of high values of residuals. This is due to two factors. The first one is related to a variable prediction horizon, which varies from 3 to 7 days, depending on the date of prediction (t_{pred}), ending with a digit 4 or 9. The second factor is related to high dynamics of changes of the input data. Hence, for both time series, the high value of the MSE_3 error component and its relative value U_3 occur.

4. Conclusions

The conducted studies and statistical analysis have shown that GMDH-type neural network with a developed predicting procedure enables us to receive good prediction results in case of high dynamics of changes of the input data. Better quality of prediction of the [UTC – UTC(LT)] deviations is obtained using time series, which is built only on the basis of deviations determined by the BIPM according to UTC and UTC Rapid scales. The results obtained for the Lithuanian Timescale UTC(LT) are characterized by lower residuals' values than the results obtained in case of the Kalman filter applied for predicting the UTC[NPL] timescale [6]. This scale is characterized by considerably lower values of [UTC – UTC(NPL)] deviations, their lower dynamics of changes and better stability compared to the UTC(LT) scale. In case of UTC(LT) scale and data prepared in form of the time series TS1, the obtained residuals in most of cases are in the range of ±20 ns, and for the data described by the time series TS2 they are in the range of ±10 ns. However, the results obtained by means of the Kalman filter for predicting the deviations for a single caesium clock show that most of residuals are in the range of ±50 ns and some of them reach the values of ±100 ns.

GMDH-type neural networks are characterized with very good predicting properties. They enable to receive better prediction quality for timescales characte-ring with low values of deviations determined by the BIPM, their small dynamics of changes and high stability [18, 19, 22], as well as for time scales characterizing with high values of deviations, their large dynamics of changes and high instability, compared to the methods based on statistical models, for example a linear regression method used so far in the GUM [5] or a method based on the Kalman filter [6].

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Prognozowanie Litewskiej Skali Czasu UTC(LT) z zastosowaniem sieci neuronowej typu GMDH

Streszczenie. Celem przeprowadzonych badań było sprawdzenie skuteczności zastosowania sieci neuronowej typu GMDH i opracowanej procedury do prognozowania skal czasu UTC(k), charakteryzujących się dużą dynamiką zmian danych wejściowych. Badania przeprowadzono na przykładzie Litewskiej Skali Czasu UTC(LT). Otrzymane wyniki badań pokazały, że sieci neuronowe typu GMDH z opracowaną procedurą prognozowania umożliwiają osiągnięcie dobrych wyników prognoz dla UTC(LT). Lepszą jakość prognozowania odchyleń [UTC – UTC(LT)] uzyskano przy zastosowaniu szeregu czasowego, który zbudowany jest wyłącznie na podstawie odchyleń wyznaczonych przez BIPM w oparciu o skalę UTC i UTC Rapid.

Słowa kluczowe: elektrotechnika, skala czasu UTC(k), zegar atomowy, prognozowanie [UTC – UTC(k)], sieci neuronowe GMDH

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