AN ANALYSIS OF THE HYDROGEN MASER FREQUENCY DRIFT PREDICTION POSSIBILITY FOR STEERING UTC(PL)

Łukasz Sobolewski[1], Wiesław Miczulski[1], Albin Czubla[2], Maciej Gruszczyński[2], Roman Osmyk[2]

1) *University of Zielona Gora, Institute of Metrology, Electronics and Computer Science, Szafrana2 Str., 65-516 Zielona Gora, Poland*
(✉ *l.sobolewski@imei.uz.zgora.pl*)

2) *Central Office of Measures, Time and Length Department, Elektoralna 2 Str., 00-139 Warsaw, Poland*

Abstract

The article focuses on the possibility of using a new method based on predicting the hydrogen maser frequency drift to control the Polish Time Scale UTC(PL). Controlling the national UTC(k) scale is very important from the point of view of the fact that the UTC(k) time scale is also the basis for determining the official time in a given country, and is also used in scientific research and the economy. The article describes in detail the new UTC(PL) steering method based on predicting the hydrogen maser frequency drift, and a number of research works that have been carried out. The obtained preliminary results of the research on the use of the new UTC(PL) predicting method clearly showed the great potential of the presented method. The obtained residuals are within the range of ±0.73 ns indicate a very good quality of predicting as compared with type A uncertainties of UTC(PL) input points. It may allow UTC(PL) to be classified as one of the best time scales. Nevertheless, the method has its imperfections, which the authors plan to eliminate as part of further work on improving the method.

Keywords: prediction UTC – UTC(k) differences, frequency drift, UTC(PL) Time Scale, UTC scale, time scale correction.

1. Introduction

Atomic frequency standards are the basis for the construction of systems for the generation and control of national *coordinated time scales* (UTC(k)) in about 80 centres: time and frequency laboratories of the *National Metrological Institutes* (NMIs), *Designated Institutes* (DIs) and observatories [1]. In Poland, such activities are carried out by two centres: *Time and Frequency Laboratory of the Central Office of Measures* (TF GUM) in Warsaw and the Astrogeodynamic Observatory of the Space Research Centre of the Polish Academy of Sciences in Borówiec n/Poznań. Data from atomic clocks compared to local UTC(k) scales and comparison data between these time scales have been sent to the Time Department of the BIPM, which calculates the *coordinated universal time scale* (UTC) on their basis according to a specific complex algorithm every month. UTC is the main reference in realization of the SI second and dissemination of standard frequencies and time signals. UTC includes leap seconds to ensure consistency within the fixed limits with astronomical time UT1 resulting from the Earth's rotation. The national time scales UTC(k) are also the basis for determining the official time in a given country. The UTC(k) frequency signals are used as a reference for establishing national measurement standards of length (based on optical frequency comb) and DC voltage (based on Josephson effect). They are also used, among others, in scientific and metrological laboratories, satellite navigation and astrogeodynamic observations, synchronization of telecommunications services, information technology, banking.

The imperfection of atomic clocks is their instability and frequency drift, which results in the need for continuous correction of UTC(k). The BIPM Time Department, based on the received clock and comparison data, determines UTC with outputs in the form of the [UTC – UTC(k)] differences for the previous month for each UTC(k), for the MJD dates (Modified Julian Date) ending with the digits 4 and 9. These results are published in "Circular T" bulletin [2] around the 12th day of the following month. Until July 1, 2013 (the beginning of the regular publication of UTC Rapid), they have been the main basis for correcting the rate and drift of master clocks being fly-wheels for UTC(k), most often based on prediction of the correction using the linear regression method [3]. In a few cases, stochastic differential equations [4] and Allan deviations [5] had been also used.

In order to increase the accuracy of determining the predicted corrections for UTC(PL), performed with the usage of the linear regression method, the team from the Institute of Metrology, Electronics and Computer Science of the University of Zielona Góra (IMEI UZ), within the framework of cooperation started in 2006 with TF GUM, proposed conducting research on determining the [UTC – UTC(PL)] differences for each day by using the *polynomial interpolation method* (PCHIP) available in the Matlab package. In the same year, they also proposed using *neural networks* (NN) for prediction of corrections, the input of which has been also provided with data prepared for each day. The research has been carried out using first the MLP and RBF type NNs. The obtained research results showed achieving higher prediction accuracy in a shorter time for the RBF type NN [6] in relation to prediction with the usage of the linear regression method. However, the disadvantage of using this type of NN is the long time needed to select a specific network structure and its training. For one RBF type NN structure, this time is about 1 hour, and for an MLP type NN, almost 4 hours. In 2010, IMEI UZ proposed GMDH type NNs, which belong to the group of self-organizing networks. A significant advantage of using this type of network is the automatic adjustment of their structure and number of neurons to the nature of changes in the time series given as input in the training process. The conducted studies have shown that the final prediction result is achieved in no more than 2 minutes, with a higher accuracy of predictions than the previously used methods [7]. However, the problem of maintaining the best possible consistency of UTC(PL) with UTC resulted from the long delay in issuing the "Circular T" bulletin by BIPM was still present. Since January 1, 2012, BIPM has launched the Rapid UTC pilot project, the aim of which is to determine the auxiliary UTC Rapid (UTCr) scale for each day every week. UTCr is calculated based on the daily data from clocks and time transfer systems sent to the BIPM for the entire week by approximately 80 laboratories. Based on the determined UTCr published weekly since July 2013, every Wednesday, the [UTCr – UTC(k)] differences for the previous week for each participating UTC(k) labs are made available on the BIPM ftp server [8]. When determining the UTCr scale in the current month, the corrections and weights of individual clocks are assigned with the same values that have been used for the UTC in the previous month. The obtained research results [9] confirmed the benefits of using GMDH type NNs for prediction UTC(PL), the input of which is provided with data of a one-day interval. Methods of constructing time series have also been developed, including the gaps of data from the atomic clock [10]. All the research results cited above clearly indicated an improvement in the accuracy of UTC(PL) realization by the caesium clock. This has been the basis for the official application of GMDH type NN for UTC(PL) prediction in 2016. Since then, UTC(PL) prediction is performed by IMEI UZ on regular basis.

In June 2018, TF GUM changed the UTC(PL) master clock from a caesium clock to a *hydrogen maser* (HM) with autotuning of the resonance cavity. At a similar time, many leading centres made such changes to the implementation of their UTC(k). The paper [11] presents the results of research on the assessment of the quality of UTC(PL) prediction in the final period of the caesium clock operation, the transition period (lack of historical data for a new master

clock) and the proper period of hydrogen maser operation. The UTC(PL) prediction has been carried out using the GMDH type NN and appropriately selected time series data. The obtained research results once again confirmed very good UTC(PL) prediction in the above-mentioned periods of transition from the use of a caesium clock to a hydrogen maser. The results of research on steering UTC(PL) with the usage of hydrogen maser obtained so far indicate that it is characterized by a very high accuracy of its determination. It is comparable to the accuracies achieved by other NMIs (*e.g.* NPL) [2]), where the hydrogen maser is supervised by a caesium fountain. So far, there is no known application of GMDH-type NNs for time scales realized in other UTC(k) labs in the literature.

The active hydrogen maser is characterized by high short-term frequency stability and dominated frequency drift [12 - 17], the value of which depends on external conditions and can change over time. Hence, changing the master clock to a hydrogen maser for determining UTC(PL) also required changing the UTC(PL) control method, which is currently a 3-stage process. UTC(PL) is controlled by a microstepper, which has the ability to correct precisely the frequency value of the signal fed to its input and on whose outputs UTC(PL) is defined (10 MHz and 1 pps) - this is schematically shown in Fig. 1. The phase relations between the output signals from the microstepper are constant, *i.e.* the phase differences between the output second signals (1 pps) and the frequency signals (10 MHz) do not change over time.
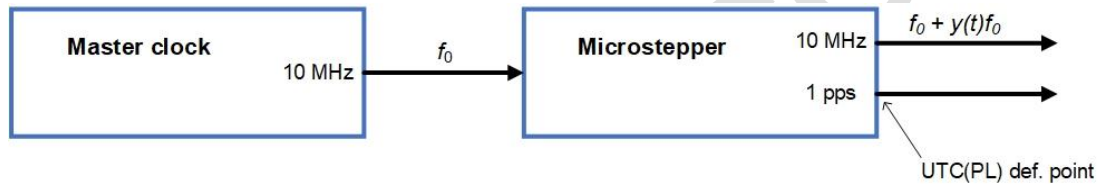

Fig. 1. UTC(PL) generation diagram in GUM (f_0– standard frequency of the master clock violated with offset and frequency drift, $y(t)$ - a total value of fractional frequency deviation corrected by microstepper currently).

The UTC(PL) control includes the following stages:

Stage 1 – determination and possible correction of the master clock frequency offset for the current day in order to maintain the best possible compliance of the frequency value with the SI second definition (operation carried out once a month or once every few months).

Stage 2 – determination and monitoring the current value of the master clock frequency drift so that the drift correction value entered into the microstepper allowed to keep up with the current frequency changes from the hydrogen maser (once a month or once every few months).

Stage 3 – determination the current UTC(PL) offset value relative to UTC and possibly introducing an additional correction to the frequency offset in the microstepper to gradually minimize the absolute value of the UTC – UTC(PL) difference (ongoing (weekly) monitoring based on "Circular T", UTCr and predictions performed by IMEI UZ). In order to maintain continuity and avoid sudden changes in UTC(PL) frequency and phase, the value of the single introduced change of this correction should not exceed an arbitrarily selected limit value (currently internally adopted: ±2.5E-15, *i.e.*: ±0.216 ns/day). In the frequency domain, control is carried out according to the formula:

$$y(t) = y_1 + \Delta y_2 \bullet t + y_3, \tag{1}$$

where: $y(t)$ is a current total value of fractional frequency deviation corrected by microstepper, y_1 and y_3 are corrections of frequency offset determined in the 1st and 3rd steps respectively, and Δy_2 – is a frequency drift correction determined in the 2nd step and entered to microstepper to change the frequency offset correction, t – time since the last change of microstepper steering parameters.

The most important factor in maintaining high accuracy of UTC(PL) phase and frequency is the knowledge of the current value of the master clock frequency drift and the ability to monitor its changes in advance. Hence, the next stage of cooperation between IMEI UZ and TF GUM is related to a new proposal for UTC(PL) prediction presented by TF GUM. It concerns prediction of the hydrogen maser drift. The principle of UTC(PL) prediction is presented in Section 2, and preliminary research results in Section 3.

2. UTC-UTC(PL) prediction method taking into account the master clock frequency drift

One of the important parameters characterizing the properties of atomic clocks involved in determining UTC(k) is the frequency drift, which determines the accuracy of this scale. Determining the drift value for a given atomic clock realizing UTC(k) is possible based on the nonlinear function of the clock phase changes $x(t)$ in time

$$x\ t\ = a_2 t^2 + a_1 t + a_0, \tag{2}$$

where: a_0 - a_2 are the coefficients of the 2nd order polynomial.
Relation (2) describes the time difference between the atomic clock time compared to the time defined by the UTC scale on a given day, *i.e.* the difference (*clock − UTC*) as a function of time t in a given interval. The derivative of the phase changes $x(t)$ over time corresponds to the current frequency offset $y(t)$ expressed in relative values. Knowing the instantaneous values of the phase $x(t)$ at different times, the average frequency offset in this time interval can be calculated.

This is the result of the fact that accumulated phase time changes of frequency signal come from many instantaneous frequency variations (deviations from the nominal value) multiplied by their duration time (the integral of instantaneous frequency variations over time), so the derivative of phase changes over time is a relative value of instantaneous frequency offset. This is a consequence of the adopted phase time definition in time and frequency metrology [*e.g.* 18, 19]. Because of frequency and phase variations are very small or relatively slow, then the first two terms of Taylor series expansion are usually sufficient to approximate clock phase time evolution correctly [*e.g.* 18 - 20]. Therefore, the linear and 2nd order terms in (2) correspond to clock phase changes caused by an averaged frequency offset and an averaged frequency drift of the clock over the analysed period respectively. The omitted higher-order terms may affect the changes in the averaged values of the frequency offset and frequency drift in a longer time observation. For this reason, the determination of the clock phase changes should be repeated every month based on the available new UTC − UTC(k) data.

For the hydrogen maser realizing UTC(PL), Fig. 2 shows an example scatter plots illustrating the change of the *clock − UTC* value, *i.e.* the change of the clock phase time $x(t)$, every 5 days in the interval of 250 days, from MJD = 60094 to MJD = 60339, where t - is the number of days that have passed since MJD = 60094. Fig. 2a shows the raw data converted from "Circular T", while Fig. 2b shows example *clock − UTC* values with a reduced frequency offset, where it is clearly visible that the clock phase changes are approximately a quadratic function of time. For a clearer illustration of the changes in the frequency of the master clock realizing UTC(PL), Fig. 3 additionally shows the values of the master clock frequency offset for the same period of time. Corresponding to the expanded uncertainties of frequency offset of the master clock for UTC(PL), the visible different lengths of the bars in Fig. 3. were the result of the periodic switching of the base link used for UTC − UTC(PL) calculations between the GPS PPP method

($u_A = 0.3$ ns) and the GPS P3 method ($u_A = 0.7$ ns). This figure clearly shows the occurrence of frequency drift (approximately linear changes in frequency offset over time) and additional measurement noise (values do not lie exactly along one curve).

For the data presented in Fig. 2 (as well as based on the conclusions drawn from Fig. 3), the values of the coefficients from a_0 to a_2 for function (2) determined by the regression method (using a quadratic function) are as follows:

$$a_2 = -0.0034 \text{ ns/day}^2 = -3.94\text{E-}17/\text{day}; \qquad a_1 = -3.9461 \text{ ns/day}; \quad a_0 = -500 \text{ ns}.$$
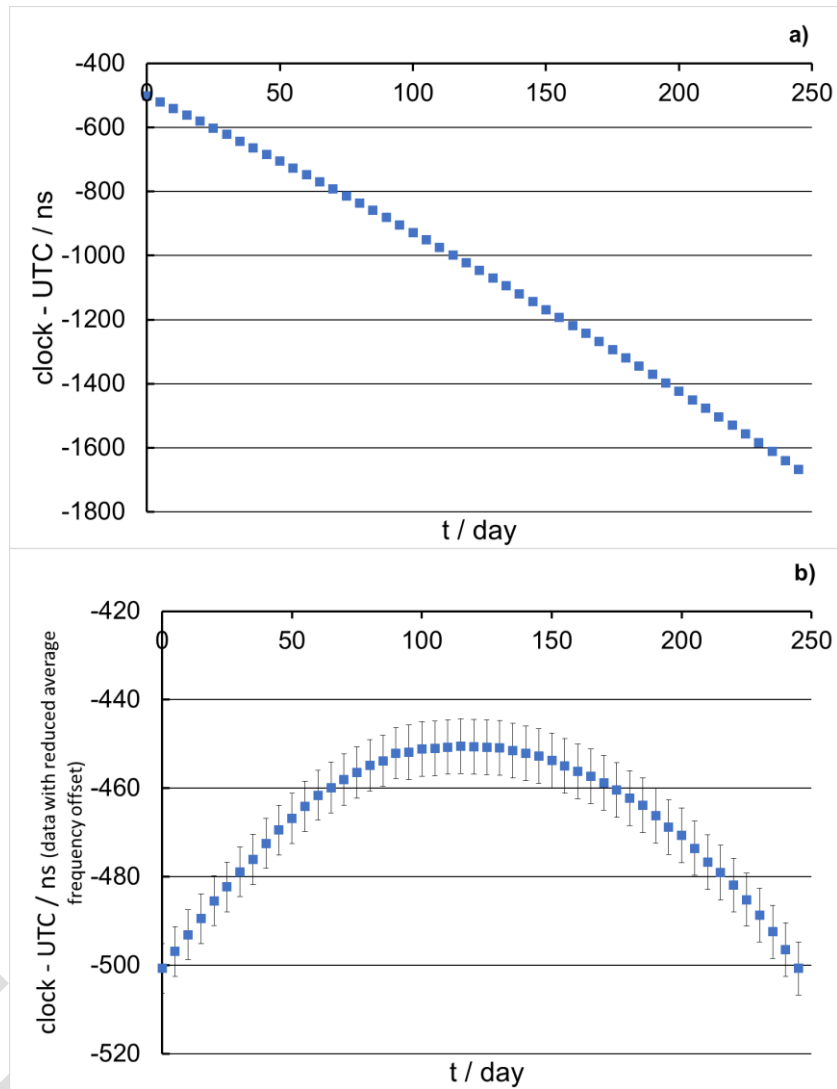

Fig. 2. Exemplary observed differences clock – UTC for the master clock for UTC(PL) a) and exemplary observed differences clock – UTC for the master clock for UTC(PL) with reduced average frequency offset b). (the bars correspond to the expanded uncertainties derived from the "Circular T" bulletin - based on the published uncertainty u for UTC – UTC(PL))

In the next step, the derivative $y(t)$ of function (2), corresponding to the time changes of the clock frequency offset, is determined by the relationship:

$$y(t) = \frac{dx}{dt} = 2a_2 t + a_1, \tag{3}$$

in which the coefficient $2a_2$ in (3) is the averaged value of the frequency drift per day. For the analysed example (Fig. 2), this drift is approximately $-7.9 \cdot 10^{-17}/\text{day}$. The drift value determined

in this way may be time-variable and also dependent on the length of the historical data vector taken into account for UTC – UTC(PL) prediction.
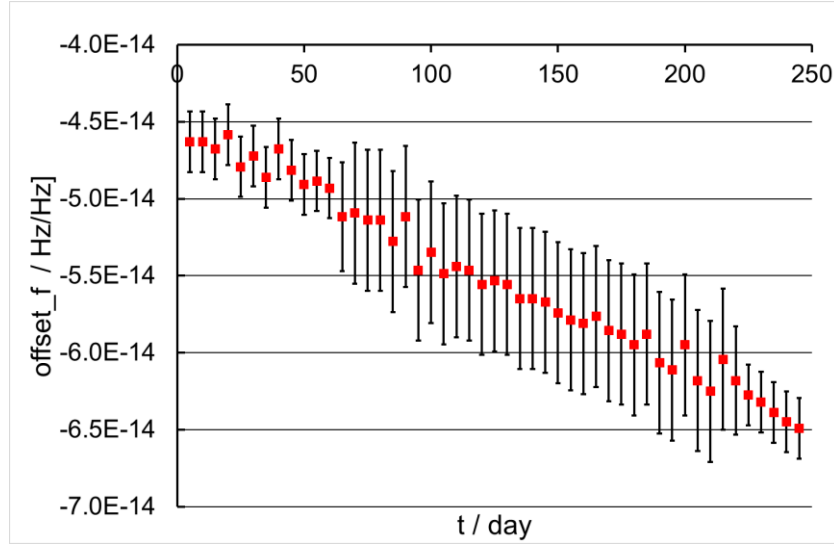

Fig. 3. Exemplary observed frequency offset for the master clock for UTC(PL).
(the bars correspond to the expanded uncertainties derived from the "Circular T" bulletin - based on the uncertainty u_A for UTC – UTC(PL) and for 5-day intervals, following the CCTF WGMRA guideline [21]).

The above feature has been a contribution to the development of a new method for UTC(PL) prediction, based on the function described by (2). In the developed prediction procedure, the optimal range of historical input data should also be determined.

3. Preliminary results of UTC(PL) predicting studies using the method based on hydrogen maser frequency drift

This section presents the results of UTC(PL) prediction studies using a new method based on frequency drift prediction, described in section 2. These results cover the period from February to July 2024.

Two groups of data have been used to prepare the input data input for the UTC(PL) steering method based on the hydrogen maser frequency drift prediction: $xa(t)$ values and $xb(t)$ values, determined according to the following relationships:

$$xa\ t\ = UTC_{PL}\ t\ - clock_{PL}(t), \tag{4}$$

$$xb\ t\ = UTC\ t\ - UTC_{PL}(t), \tag{5}$$

where: $xa(t)$ - phase time values between 1 pps signals from UTC(PL) and the clock ($clock_{PL}$) from local measurements in GUM, $xb(t)$ - UTC – UTC(k) values published in the "Circular T" bulletin.

Finally, for the prediction method taking into account the frequency drift, the input data in the form of the TS1 time series, described in detail in [10], is determined from the relationship:

$$x\ t\ = xa\ t\ + xb\ t\ = UTC\ t\ - clock_{PL}\ t\ . \tag{6}$$

The method of creating input data is additionally presented in Fig. 4 [10]. Each month, after the publication of $xb(t)$ data by BIPM in the "Circular T" bulletin at day t_{pub}, the TS1 time series is updated with data determined according to the relationship (6) until day t_n. This ensures the continuity of historical data used to predict UTC(PL) at day t_{pred} using the method based on the

hydrogen maser frequency drift, as well as full compliance with the latest data published by
BIPM ($xb(t)$) presenting the divergence of a given UTC(k) in relation to UTC.
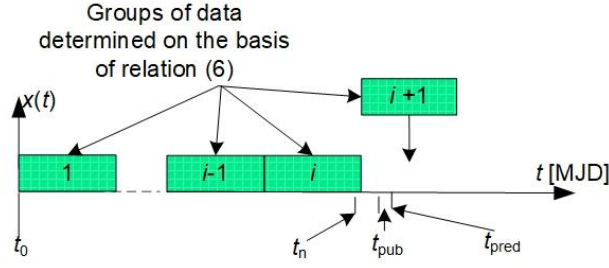

Fig. 4. Method of time series TS1 preparation.

In the case of the prediction method discussed, the appropriate prediction of the value $xb(t)$
is made. The output is the $x_p(t_{pred})$ prediction. Taking into account the phase time value of the
clock realizing the UTC(PL) scale $xa(t_{pred})$, measured on the day of prediction calculation (t_{pred}),
the prediction of the difference $xbp(t_{pred})$ is calculated from the relationship:

$$xbp(t_{pred}) = x_p(t_{pred}) - xa(t_{pred}). \tag{7}$$

By comparing the obtained $xbp(t)$ predicted values with $xb(t)$ values on MJD days ending
with digits 4 and 9, the quality of UTC(PL) prediction can be determined. The discrepancy
between the predicted $xbp(t)$ value and the $xb(t)$ value published by BIPM for the same
prediction day is determined by the residue (r), calculated from the relationship:

$$r(t_{pred}) = xb(t_{pred}) - xbp(t_{pred}). \tag{8}$$

In the case of the prediction method taking into account the hydrogen maser frequency drift,
the first step is to determine the optimal range of historical input data, determined based on (2).
The preliminary empirical studies on the selection of the historical data period showed the need
to search for the optimal range of these data for each prediction determination in the following
months. As a result of these studies, the authors found that the most favourable prediction
results are obtained for historical data in the range of 60 to 180 days. However, optimization
and selection of a specific value representing the amount of data for which the best prediction
results have been obtained are still required. For this purpose, a statistical measure in the form
of the *MAE* (Mean Absolute Error) error [22] is used, which allowed determining the most
optimal range of data in a given month.

Table 1 presents a summary of the *MAE* error values for all historical data ranges and all
prediction months. The optimal historical data value for a given month is marked in light green.

In turn, Fig. 5 shows the residual values when determining predictions for the first prediction
month (February 2024) for the assumed values of the historical data length ending for each set
of this data on January 30, 2024 (MJD 60339). These studies show that the most favourable
period of historical data is 60 days, which is also confirmed by the results in Table 1.

Table 1. Summary of *MAE* error values for different lengths of historical data ranges and all prediction months.

Input data\Month	180 days ns	150 days ns	120 days ns	90 days ns	60 days ns
February 2024	1.00	1.40	1.21	0.99	0.13
March 2024	0.72	0.23	0.54	1.74	0.83
April 2024	1.48	0.42	0.73	0.38	0.62
May 2024	0.33	2.49	0.75	0.56	0.44
June 2024	2.75	1.08	1.67	1.08	0.42
July 2024	2.16	1.35	0.40	1.59	0.23

Fig. 6 presents the results of the received predictions for UTC(PL), and Fig. 7 presents the results of the obtained residuals for the predictions made for all analysed months of 2024. In order to be able to compare the results of the received predictions directly with the $xb(t)$ data determined by BIPM in the "Circular T" bulletin for UTC(PL), the residual values are calculated according to the relationship (8) for MJD days ending with the digit 4 and 9.

The obtained values of $xbp(t)$ and $xb(t)$ (Fig. 6) are within ±5 ns, which indicates a very good quality of prediction and the possibility of classifying UTC(PL) for the group of the best time scales. Analysis of the $xb(t)$ values themselves indicates the quality of a given UTC(k) time scale. The closer the $xb(t)$ values published by BIPM are to zero, the UTC(k) time scale is characterized by better accuracy. UTC(k) time scales whose $xb(t)$ values are within ±10 ns belong to the group of the best time scales. The next two groups of scales are defined by the intervals of ±20 ns and ±50 ns. The UTC time scale is a virtual scale determined on the basis of data sent by local centres responsible for the implementation of their UTC(k). Data for UTC(k) scales in the first group are taken into account in the process of determining UTC with much greater weight, in relation to UTC(k) scales in the second and third groups. The obtained residual values (Fig. 7) are in the range from –0.73 ns to +0.68 ns, which also shows a very good prediction quality.
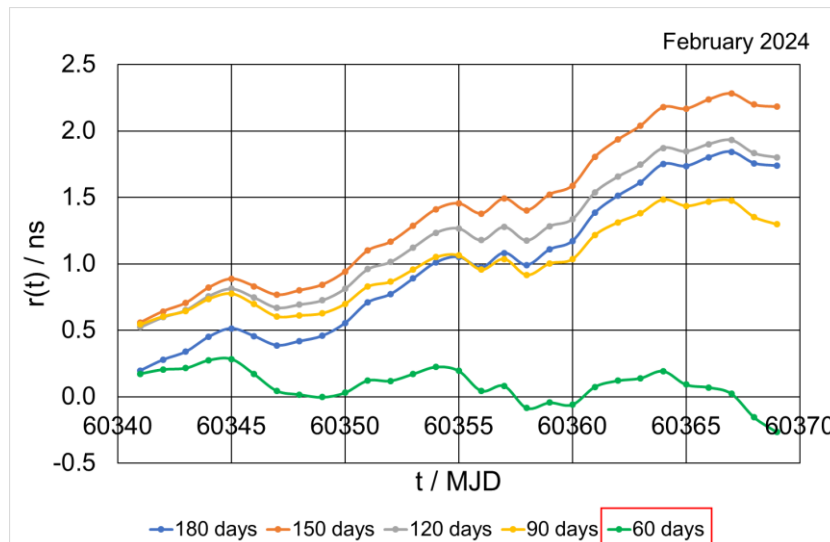

Fig. 5. Obtained residual values when determining the optimal length of data period for prediction method taking into account frequency drift.

Table 2 presents the values of prediction quality measures for the received predictions. The assessment of prediction quality is performed on the basis of discrepancies between the

predictions received $xbp(t_{pred})$ and the values of $xb(t_{pred})$, *i.e.* the values of residuals (r), which are also the basis for determining selected prediction quality measures (Table 2), presented in the literature [22, 23]. For this purpose, the mean error *ME*, the mean absolute error *MAE*, the mean squared error *MSE* with its components (MSE_1, MSE_2, MSE_3) and the root mean squared error (*RMSE*) have been used.
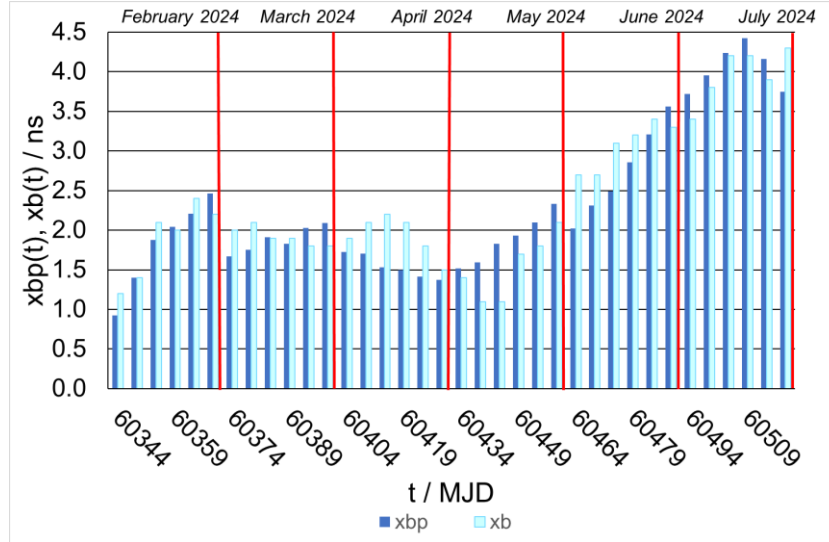

Fig. 6. Obtained values of forecast $xbp(t)$ for all prediction months for most favourable input data ranges compared with $xb(t)$ values for UTC(PL).
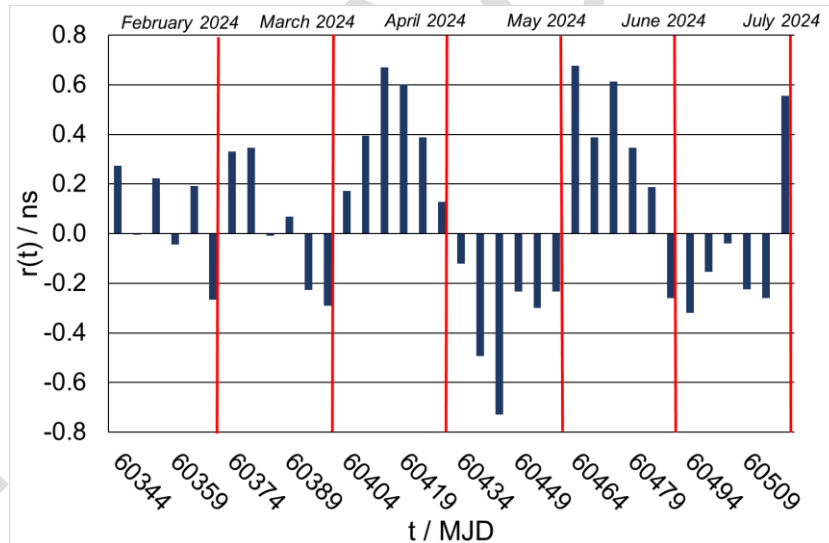

Fig. 7. Obtained residual values for all prediction months for most favourable input data ranges.

From the research results presented in Figs. 6 and 7 and Table 2 it can be concluded that:

1. The comparison of the values of all prediction quality measures and residuals indicates a very good quality of UTC(PL) prediction using the method based on the hydrogen maser frequency drift.
2. The obtained values of the UTC(PL) prediction residuals are within ±0.73 ns, which indicates a very good prediction quality as compared with uncertainties of the input points (u_A for UTC(PL)).
3. Comparison of the values of *ME*, *MAE* and MSE_1 errors shows that predictions are unbiased. The observed values of the residuals are multidirectional. The bias can be represented by *ME* with respect to *r_max* – *r_min*, *RMSE* or *MAE*. If the *RMSE* and

MAE are significantly larger than the absolute value of *ME*, we can say that the bias is small, but larger *RMSE* and *MAE* mean worse prediction accuracy.

4. For the UTC(PL) prediction using the method based on the hydrogen maser frequency drift, very small values of the MSE_2 and MSE_3 components occur. This means a very good prediction of the variability of the predicted values in relation to the variability of the observed values, and a high consistency of the direction of changes in the prediction in comparison with the direction of changes in the predicted value. This is caused by the very high stability of the UTC(PL).

Table 2. Values of forecast quality measures for all prediction months.

Quality measure of prediction	UTC(PL)
r_max / ns	0.68
r_min / ns	-0.73
ME / ns	0.07
MAE / ns	0.3
MSE / ns^2	0.13
MSE_1 / ns^2	0.004
MSE_2 / ns^2	0.0003
MSE_3 / ns^2	0.12
RMSE / ns	0.35

The above results are significantly influenced by the stability of the hydrogen maser, which is the master clock of UTC(PL) (continuously since 2018), which naturally has a positive effect on the quality of predictions with a longer time horizon. The use of longer sequences of historical data in predictions reduces the uncertainty of the mean value of the frequency drift, but at the same time increases the risk of incorrect determination of the current frequency offset due to the possibility of not keeping up with the current total changes in the drift and HM frequency offset, known only *a posteriori*. These errors can lead to larger discrepancies in UTC(PL) phase predictions. Therefore, the full UTC(PL) prediction method based on maser frequency drift predictions should be supplemented with a precise prediction of the changes in the UTC(PL) signal phase in the period since the publication of the last "Circular T" bulletin.

4. Conclusions

The preliminary results of the research on the possibility of using the hydrogen maser frequency drift to predict UTC(PL) have clearly shown the great potential of the presented method. The obtained residual results at the level of ±0.73 ns indicate a very good quality of prediction. Nevertheless, the method has its imperfections. In each month of prediction, the optimal range of input data for prediction should be selected. Due to the use of only monthly published UTC – UTC(PL) differences for the construction of input data, it is possible to make only one prediction in a given month. As part of further work on improving the method, the authors plan to eliminate the imperfections described above and conduct further tests on the use of the hydrogen maser frequency drift prediction to steer UTC(PL). They plan to perform studies on the prediction of the hydrogen maser frequency drift for time series prepared according to the methods presented in [9] and [10] using the UTC(PL) – clock phase time data, the UTC – UTC(PL) difference values determined according to the UTC scale, as well as the UTCr – UTC(PL) difference values determined according to the UTC Rapid scale, already determined with a one-day interval. It is also considered to include in the prediction data from a group of several active hydrogen masers, continuously compared with UTC(PL).

References

[1] Bureau International des Poids et Mesures (2020). *BIPM Annual Report on Time Activities*, 15.

[2] Bureau International des Poids et Mesures. *BIPM Circular T*. https://webtai.bipm.org/ftp/pub/tai/Circular-T/cirt/ (access 21.08.2024)

[3] Czubla, A., Konopka, J. & Nawrocki, J. (2006). Realization of atomic SI secondo definition in context UTC(PL) and TA(PL). *Metrology and Measurement Systems 13*(2), pp. 149-159

[4] Panfilo, G., & Tavella, P. (2008). Atomic clock prediction based on stochastic differential equations. *Metrologia*, *45*(6). https://doi.org/10.1088/0026-1394/45/6/S16

[5] Bernier, L. G. (2003). Use of the Allan Deviation and Linear Prediction for the Determination of the Uncertainty on Time Calibrations Against Predicted Timescales. *IEEE Transactions on Instrumentation and Measurement*, *52*(2), 483-486. https://doi.org/10.1109/TIM.2003.810015

[6] Kaczmarek J., Miczulski W., Kozioł M., and Czubla A. (2013). Integrated system for monitoring and control of the national time and frequency standard. *IEEE Transactions on Instrumentation and Measurement*, *62*(10), 2828-2838. https://doi.org/10.1109/TIM.2013.2259751

[7] Miczulski, W., & Sobolewski, Ł. (2012). Influence of the GMDH neural network data preparation method on UTC(PL) correction prediction results. *Metrology and Measurement Systems*, *19*(1), 123-132.

[8] Bureau International des Poids et Mesures. *BIPM UTC Rapid*. https://webtai.bipm.org/ftp/pub/tai/Rapid-UTC/utcr/ (access 21.08.2024)

[9] Miczulski, W., & Sobolewski, Ł. (2017). Algorithm for predicting [UTC–UTC(k)] by means of neural networks. *IEEE Transactions on Instrumentation and Measurement*, *66*(8), 2136-2142. https://doi.org/10.1109/TIM.2017.2674778

[10] Sobolewski, Ł., & Miczulski, W. (2021). Methods of Constructing Time Series for Predicting Local Time Scales by Means of a GMDH-Type Neural Network. *Applied Sciences*, *11*(12). https://doi.org/10.3390/app11125615

[11] Sobolewski, Ł., Miczulski, W., & Czubla, A. (2021). Experimental Verification of the Neural Network Predicting Procedure Applied for UTC(PL). *IEEE Transactions on Instrumentation and Measurement*, *70*(8), 1-9. https://doi.org/10.1109/TIM.2021.3116297

[12] Johnson, E. H., & McGzlnigul, T. E. (1966). *Hydrogen maser frequency comparison with a cesium beam standard*, National Aeronautics and Space Administration, Washington D.C.

[13] Peters, H. E., Holloway, J., Bagley, A. S., & Cutler, L. S. (1965). Hydrogen maser and cesium beam tube frequency standards comparison. *Applied Physics Letters*, *6*(2), 34-35.

[14] Major, F. G. (2013). *The Quantum Beat - The Physical Principles of Atomic Clocks*. Springer, New York.

[15] Haibo, Y., Lili, Q., Shaowu, D., Wei L., & Hong, Z. (2009). The hydrogen maser and cesium clocks in time keeping at NTSC. *Proc. 2009 IEEE International Frequency Control Symposium Joint with the 22nd European Frequency and Time forum*, Apr. 2009, pp. 42-46.

[16] Kamas, G., & Lombardi, M. (1990). *Time and Frequency User's Manual*, NIST Special Publication.

[17] Sobolewski, Ł. (2017). Application of GMDH type neural network for predicting UTC(k) timescales realized on the basis of hydrogen masers. *Proc. Joint IEEE (FCS EFTF)*, Jul. 2017, pp. 42-46.

[18] Barnes, J. A. (1983, December). The measurement of linear frequency drift in oscillators. In *Proceedings of the 15th Annual Precise Time and Time Interval Systems and Applications Meeting*.

[19] Kartaschoff, P. (1985). *Częstotliwość i czas*, Wydawnictwo Komunikacji i Łączności (*in Polish*).

[20] Panfilo G., Harmegnies A. and Tisserand L. (2012). A new prediction algorithm for the generation of International Atomic Time. *Metrologia* 49, https://doi.org/10.1088/0026-1394/49/1/008

[21] Bureau International des Poids et Mesures. *CCTF WGMRA Guideline 4 (201209) Uncertainty in frequency* https://www.bipm.org/documents/20126/30132341/cc-publication-ID-310/f15432f2-cfa7-ac71-bd9d-a6f3168affb4 (access 10.01.2025)

[22] Pindyck, R. S., Rubinfeld, D. C. (1998). *Econometric Models and Economic Forecasts*. Boston, MA, USA: McGraw-Hill, 1998.

[23] Caldwell, R. B. (1995). Performance metrics for neural network-based trading system development. *NeuroVestJournal*, *3*(2), 22-26.

Lukasz Sobolewski received the MS degree in computer science from the University of Zielona Góra, Zielona Góra, Poland, in 2010, and the Ph.D. degree in electrical engineering from the University of Zielona Góra, Poland, in 2015.

Actually, he is employed as an Assistant Professor at the Institute of Metrology, Electronics and Computer Science, University of Zielona Góra. His research interests are mainly associated with the methods of artificial intelligence and its application in instruments and measuring systems.

Wieslaw Miczulski received the MS degree in electrical engineering from the Higher College of Engineering in Zielona Góra, Poland, in 1980, and the Ph.D. degree in electrical metrology from the Technical University of Wrocław, Poland, in 1989, and the D.Sc. degree in electrical metrology from the University of Zielona Góra, Poland, in 2002.

Actually, he is a Professor in the Institute of Metrology, Electronics and Computer Science, University of Zielona Góra. The supervisor and main performer of many research projects for the industry. His areas of interests include, electrical measurements, methods of artificial intelligence and its application in instruments and measuring systems.

Albin Czubla received the MS degree in theoretical physics, in 1994, and the Ph. D. degree in physics, in 1999, at Maria Curie-Skłodowska University in Lublin, Poland. Since 2002, he works in Time and Frequency Laboratory at Central Office of Measures, Warsaw, Poland.

Actually, he is a head of Time and Frequency Laboratory, a representative of Poland in TCTF EURAMET and CCTF of CIPM, technical expert in time and frequency metrology for accreditation body. His research interests are maintenance of atomic time scales, stability analysis of time and frequency signals, precise time interval measurements, development of measurement methods and measurement uncertainty analysis.

Maciej Gruszczyński is a head of Time and Length New Technology Laboratory in Central Office of Measures. Ph.D. from satellite geodesy, since 2018 works at GUM. In his work, he deals with the development and improvement of satellite time transfer methods and with procedures for incorporating data from optical clocks into local implementation of the UTC time scale (k). He is the co-author of several feasibility studies and functional specifications of integrated systems using data from satellite navigation systems for the functioning and operating of critical infrastructure and everyday usage.

Roman Osmyk is a Senior metrologist at the Time and Frequency Laboratory of the Time and Length Department of the Central Office of Measures. He graduated in physics from the University of Opole in 2006. Specialist in the field of maintaining atomic time and frequency standards, realization of time scales, comparisons of clock readings over long distances.