Metrol. Meas. Syst., Vol. 32 (2025) No. 2, pp. 1–12
DOI: 10.24425/mms.2025.154669

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

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

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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) time scale is very important due to the fact that the 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 that has 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, which indicates 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 are sent to the Time Department of the International Bureau of Weights and Measures (BIPM), which, on their basis, calculates the *coordinated universal time scale* (UTC) according to a specific complex algorithm every month. UTC is the main reference in realization

Article history: received November 5, 2024; revised January 15, 2025; accepted January 28, 2025; available online June 3, 2025.

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 references for establishing national measurement standards of length (based on the optical frequency comb) and DC voltage (based on the Josephson effect). They are also used, among others, in scientific and metrological laboratories, satellite navigation and astrogeodynamic observations, synchronization of telecommunications services, information technology, and banking.

The imperfection of atomic clocks is their instability and frequency drift and jumps [2], 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 [3] around the 12th day of the following month. Until July 1, 2013 (the beginning of the regular publication of UTC Rapid), they had 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 [4]. In a few cases, stochastic differential equations [5] and Allan deviations [6] 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 was also provided with data prepared for each day. The research was carried out using first the *multilayer perceptron* (MLP) and *radial basis function* (RBF) type NNs. The obtained research results showed achieving higher prediction accuracy in a shorter time for the RBF type NN [7] in comparison with 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, the IMEI UZ team proposed *group method of data handling* (GMDH) type NNs which belong to the group of self-organizing networks. A significant advantage of using this type of network is 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 with the previously used methods [8]. However, the problem of maintaining the best possible consistency of UTC(PL) with UTC resulting 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 sent to the BIPM from clocks and time transfer systems 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 [9]. When determining the UTCr scale in the current month, the corrections and weights of individual clocks are assigned with the same values that had been used for the UTC in the previous month. The obtained research results [10] 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 [11]. All the research results cited above has 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 has been 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 implemented such changes to their UTC(k)s. The paper [12] 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 was 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 the 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) [3]), where the hydrogen maser is supervised by a caesium fountain. So far, there has been no known application of GMDH-type NNs for time scales realized in other UTC(k) labs to be found in the literature.

The active hydrogen maser is characterized by high short-term frequency stability and dominated frequency drift [13–18], 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 precisely correct the frequency value of the signal fed to its input and on whose outputs UTC(PL) is defined (10 MHz and 1 pps) as 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.

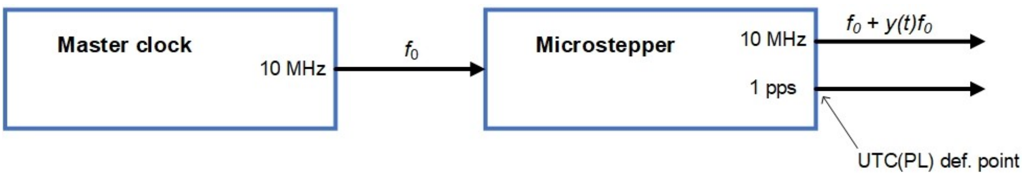

Fig. 1. UTC(PL) generation diagram in GUM (f_0 – standard frequency of the master clock violated by offset and frequency drift, $y(t)$ – a total value of fractional frequency deviation currently corrected by the microstepper).

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

Stage 3 – determination of 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 the IMEI UZ team). In order to maintain continuity and avoid sudden changes in UTC(PL) frequency and phase, the value of a 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, the control is carried out according to the formula:

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

where: $y(t)$ is a current total value of fractional frequency deviation corrected by the microstepper, y_1 and y_3 are corrections of frequency offset determined in Steps 1 and 3 respectively, and Δy_2 – is a frequency drift correction determined in Step 2 and fed into the 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 2$^{\text{nd}}$ 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 results from the fact that accumulated phase time changes of the 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.* [19, 20]. Because of frequency and phase variations are very small or relatively slow, then the first two terms of a Taylor series expansion are usually sufficient to correctly approximate clock phase time evolution *e.g.* [19, 21]. Therefore, the linear and 2$^{\text{nd}}$ 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

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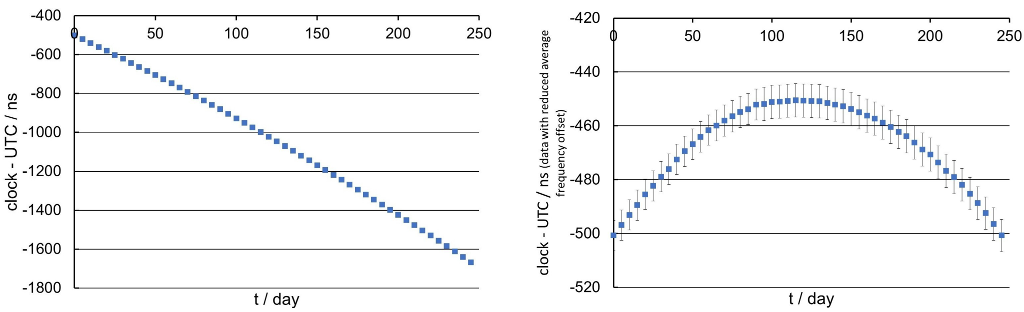
DOI: 10.24425/mms.2025.154669

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, are 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 (the 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. 2), 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: $a_2 = -0.0034$ ns/day^2 = −3.94E–17/day; $a_1 = -3.9461$ ns/day; $a_0 = -500$ ns.



(a) (b)

Fig. 2. Exemplary observed clock – UTC differences for the master clock for UTC(PL) a) and exemplary observed clock – UTC differences 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:

$$y(t) = \frac{\mathrm{d}x}{\mathrm{d}t} = 2a_2 t + a_1, \tag{3}$$

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 $-7.9 \cdot 10^{-17}$/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.

The feature above was 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.

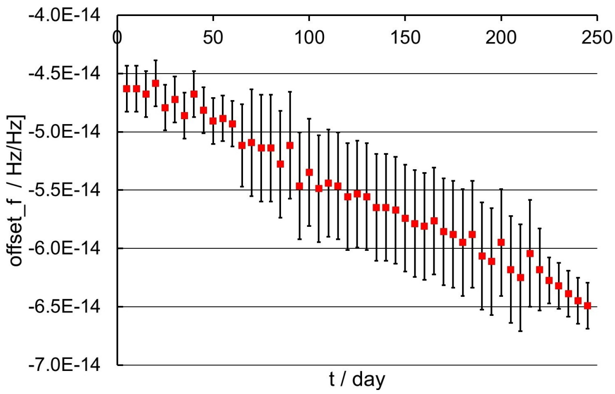


Fig. 3. Exemplary observed frequency offset for the master clock for UTC(PL).
(the bars correspond to the expanded uncertainties derived from the "Circular T" bulletin – based on the uncertainty u_A for UTC – UTC(PL) and for 5-day intervals, following the CCTF WGMRA guideline [22]).

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 were 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:

$$xa(t) = \mathrm{UTC}_{\mathrm{PL}}(t) - \mathrm{clock}_{\mathrm{PL}}(t), \tag{4}$$

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

where: $xa(t)$ – phase time values between 1 pps signals from UTC(PL) and the clock ($\mathrm{clock}_{\mathrm{PL}}$) 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 [11], is determined from the relationship:

$$x(t) = xa(t) + xb(t) = \mathrm{UTC}(t) - \mathrm{clock}_{\mathrm{PL}}(t) \tag{6}$$

The method of creating input data is additionally presented in Fig. 4 [11]. 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 ($xb(t)$) data published by BIPM presenting the divergence of a given UTC(k) in relation to UTC.

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

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

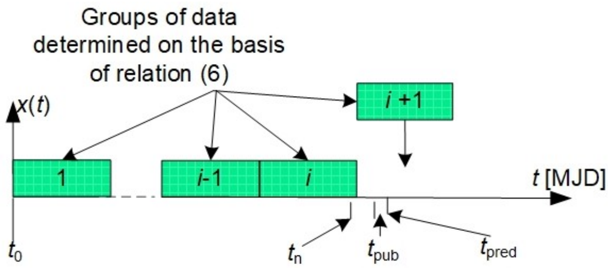


Fig. 4. Method of time series TS1 preparation.

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:

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

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, which is achieved 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 have 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 [23] 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

Figure 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 digits 4 and 9.

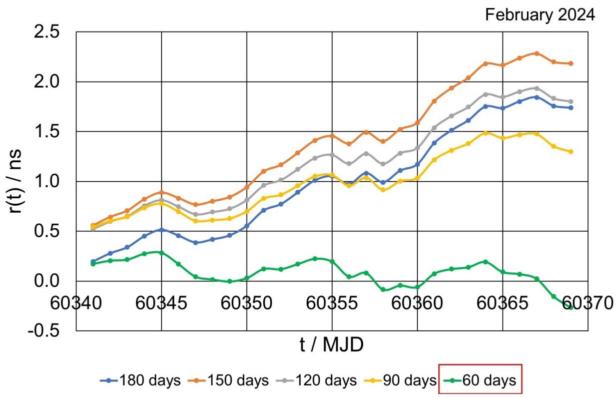


Fig. 5. Obtained residual values when determining the optimal length of data period for prediction method taking into account frequency drift.

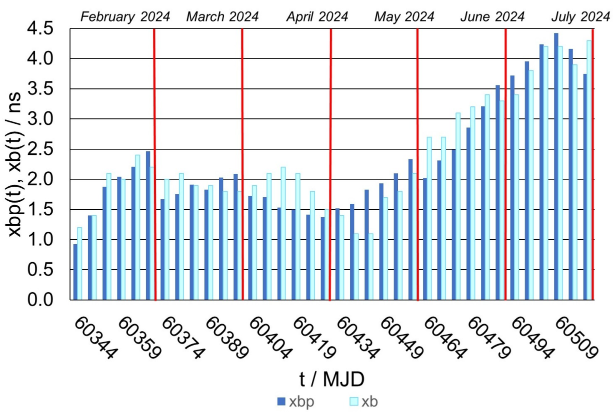


Fig. 6. Obtained values of forecast $xbp(t)$ for all prediction months for most favourable input data ranges compared with $xb(t)$ values for UTC(PL).

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 better is the accuracy characterizing the UTC(k) time scale. 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, when compared 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.

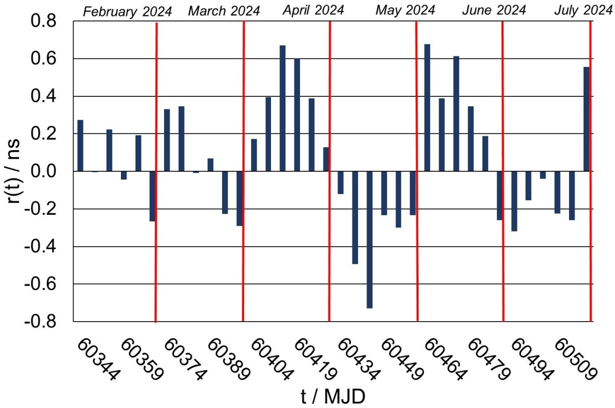


Fig. 7. Obtained residual values for all prediction months for most favourable input data ranges.

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 $xbp(t_{\text{pred}})$ and the values of $xb(t_{\text{pred}})$, $i.e.$ the values of residuals (r), which are also the basis for determining selected prediction quality measures (Table 2), presented in the literature [23, 24]. 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.

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

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).

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 [10] and [11] 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).

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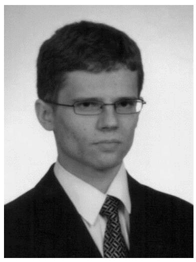

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