Hardware and Software Realization of Time Error Measurements with Real-Time Assessment of ADEV, TDEV, and MTIE

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INTRODUCTION

Allan deviation (ADEV), time deviation (TDEV), and maximum time interval error (MTIE) are commonly used for describing the quality of synchronization signals in telecommunication networks [1, 2, 3]. Estimates of the parameters are computed for a series of observation intervals using the sequence of time error samples previously measured at some network interface. The evaluation of the synchronization signal is commonly a two-stage process: First, the time errors are calculated, and then the parameters are calculated. Dividing the evaluation process into two steps causes an obvious delay; therefore, calculating the parameters in real-time allows us to reduce the analysis time. Faster results enable faster reaction to undesirable states of operation of many devices, and fast reactions are becoming ever more essential in contemporary telecommunication networks.

This paper deals with the analysis of synchronization signals in the telecommunication networks and systems. The concept of the time-error measurement system and the analysis of the measurement results are described. The adaptation of an existing measuring system to a system with real-time assessment of ADEV, TDEV, and MTIE is presented. The system is the third version of the system designed by the authors 15 years ago for Polish telecom operator TP S.A. It is called the SP-4000 measuring system. The system consists of two separate units: a set of independent devices placed in one casing and an external computer controlling the measurement process. The same computer is used to compute different parameters of timing or synchronization signals. To acquire measuring signals from working telecom lines, a set of probes was also designed. We start with the description of hardware, software and basic functions of the SP-4000 system. Next, the solutions enabling real-time computations of ADEV, TDEV, and MTIE are described. The paper finishes with conclusions.

THE CONCEPT OF THE MEASURING SYSTEM

The SP-4000 was designed to measure the quality of timing and synchronization signals. It calculates values of parameters that characterize the long-term properties of these low frequency (less than 20 Hz) signals. The user can compare the numerical values with masks defined by ITU-T, by ETSI or by himself [1, 2]. The results of measurements and computations are stored on the computer that controls the measurements. They can also be sent via Internet or intranet to any place named by the telecom operator. The length of time of a single measurement is limited only by the hard-disc size of the computer used. For contemporary notebooks, this time exceeds 10 years. Adapting the proposed systems to future needs requires changing the notebook and its software. This is a basic reason why the first measuring systems, manufactured in 1995, are still used by TP S.A. The SP-4000 (Fig. 1) contains all devices necessary to evaluate the parameters describing long-term variations (in the range of frequencies from 0 Hz to 20 Hz) of a timing signal. It contains four time error meters, TE-1, TE-2, TE-3, and TE-4; a conversion/distribution module; a reference clock module with a built-in rubidium oscillator; digital processing phase-locked loop (DP-PLL) module, which automatically compensates the aging effects of the rubidium oscillator; and a digital/analog interface (Fig. 2).

The SP-4000 has two power supplies. The first one supplies all devices excluding the rubidium oscillator. The second one provides energy to the rubidium clock. It also supplies power to an internal accumulator, which prevents the retriggering error of the rubidium oscillator. The conversion/distribution module converts a signal with frequency 5 MHz into four signals with frequency 2048 kHz with parameters that meet the ITU-T G.703-13 recommendation. The same module can be used to standardize parameters of the periodic input signal with frequency 2048 kHz in accordance with the same recommendation. The reference module has 8 outputs. Four of them provide 2048 kHz signals that can be used by the four TE meters as reference signals for synchronization measurements. The next four signals have the following frequencies: 1 MHz, 5 MHz, 10 MHz, and 80 MHz. The aging effects of the rubidium oscillator can be compensated by an external 1 pps signal coming from an external GPS receiver or an external 2048 kHz signal. The built-in oscillator can replace the cesium source in synchronization measurements for up to 2 days (the accuracy of frequency is better than $1x10^{-11}$ for standard solutions of rubidium oscillators). All the modules shown in Fig. 2 are controlled by external computer. The DP-PLL has its own microprocessor that performs all computations. In the hold-over state of the DP-PLL, the control signal can be provided independently by the DP-PLL or by the external computer. The results of measurements, commands and parameters are sent via a dedicated module, digital/analog interface with USB ⇔ FIFO converter FT245. The data to or from the computer can be transmitted up to 8Mb/s.

Fig. 1. The SP-4000 measuring system

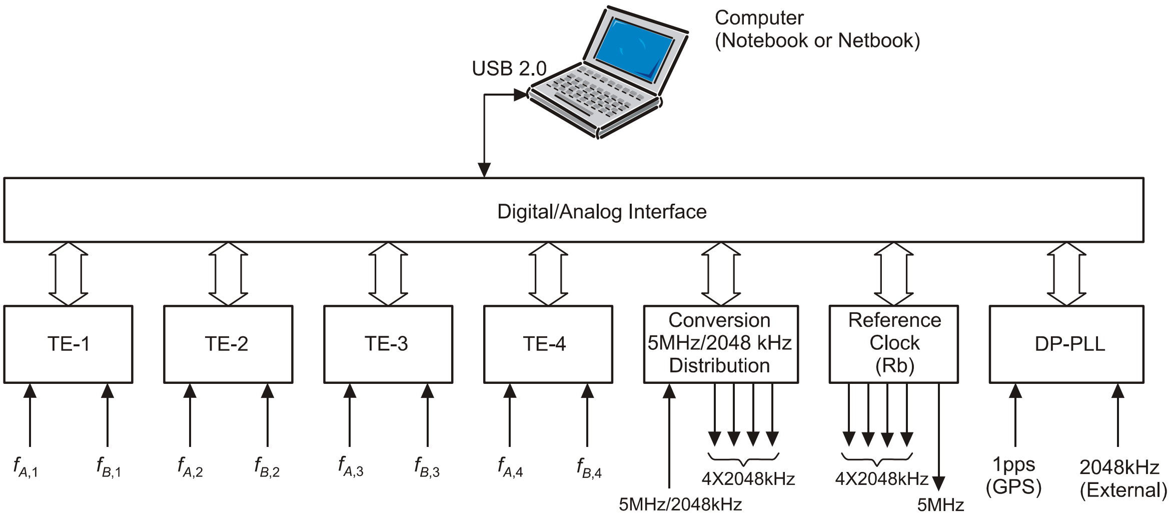

Fig. 2. The block diagram of the SP-4000 measuring system

TIME ERROR MEASUREMENT

One of the important advantages of the SP-4000 is its 4 independent measuring channels, TE-1, TE-2, TE-3, and TE-4. They are optional – i.e., a user can choose a smaller number of channels and exploit free slots for other modules, such as additional conversion/distribution modules or more specialized modules, like the time interval interpolation module for increasing the resolution of the time error measurement [10]. The time error meters can measure the time error between signals with the same or different nominal frequencies, e.g., 2048 kHz and 1 pps, 2048 kHz and 5 MHz, etc. The range of input frequencies extends from 1 Hz to 30 MHz. All the time-error meters use the same timing signal coming from the rubidium oscillator. The measuring channels are identical and the channel number can be programmed manually.

Signals from the two inputs of TE, denoted by A and B, are amplified and converted into digital signals. The measurement is performed by an FPGA circuit – we used a Virtex-5 (XC5VLX50) produced by Xilinx [4]. The block diagram of the time error meter is shown in Figure 3. The frequencies of signals from input A and B are divided to a common frequency established by the measuring software. The phase START-STOP detector measures the phase difference between both signals. The result is a time interval. To convert time into number, we used a method with a multiphase clock. It is simple to implement in an FPGA and provides a resolution sufficient for telecomm applications.

In our case, it was $1/1280\text{MHz} \approx 0.781\text{ns}$. A signal with frequency 40 MHz from the reference clock is provided to all time error meters. Its frequency is multiplied in the Virtex-5 by 8. Next, the clock 320 MHz is used to form a four-phase clock with the same frequency. Let us emphasize that the resolution of measurements can be significantly increased in the future without any hardware change by implementing another method of time/number conversion in the Virtex-5. We did not apply such a method because it was not necessary for telecomm applications and because it decreased the speed of computations. Fast computation is very important for real-time computations of ADEV, TDEV and MTIE. In other words, there is a trade-off between the length of the result of the time error measurement and the number of samples per decade for ADEV, TDEV, and MTIE that can be computed in real-time for contemporary notebooks.

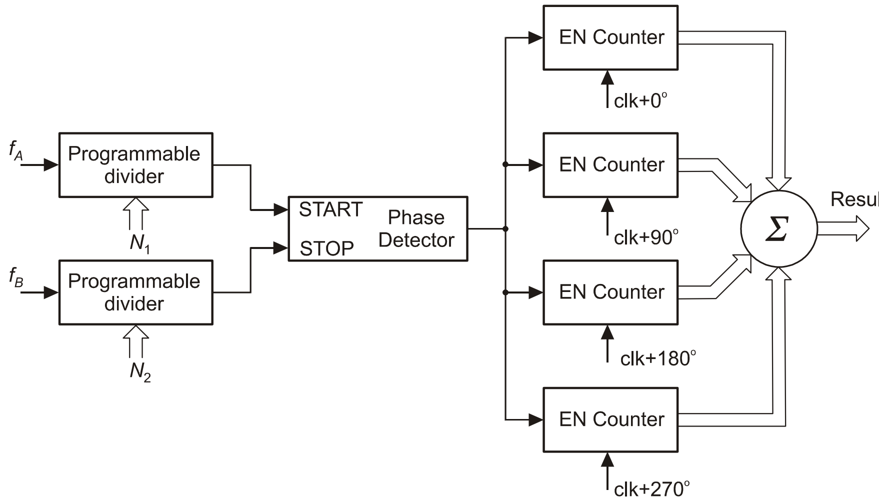

Fig. 3. The block diagram of a single time error meter from Figure 2

Structure and functions of measurement and analysis software

The software that controls the measurements and computes parameters that characterizes the timing signal has a hierarchical structure with three main windows. They correspond to the three steps of evaluating the timing signal. The first step is the measurement. The user interface for the measurement step is the Measurement Window (MW) (Fig. 4).

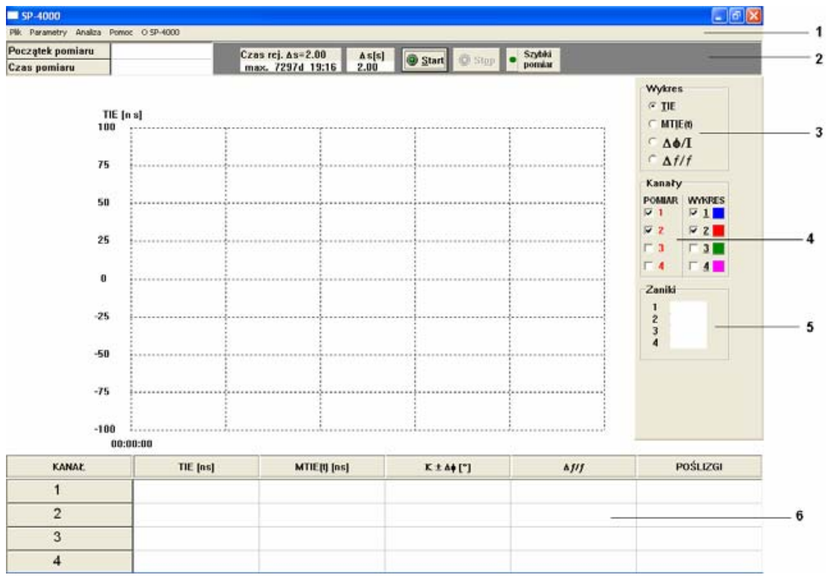

Fig. 4. The Measurement Window (MW); 1 – main menu, 2 – start/stop keys, 3 – selection of plotted parameter, 4 – channel selection, 5 – signal decay indicator, 6 – table with numerical results

To configure the measurement, we use the windows from area 1 of Figure 4. During the measurement a user can follow on-line the measurement of time error and time interval error, the values of maximum peak-to-peak time error for the current measurement instant, the phase difference modulo of a chosen number of periods of a signal from input A, and the current frequency accuracy $\Delta f / f$. The number of 125 µs slips is shown in the same table at the bottom of the MW.

A specific feature of synchronization measurements performed for telecommunication networks is their long period. A single measurement may take several days, or longer, if a telecom operator is interested in precise monitoring parameters of a given piece of synchronization equipment or a part of a synchronization network. The whole measurement process can be restored by means of the second main window – the Analysis Window (AW) (Fig. 5). We can look through the whole measurement screen by screen. We can also compress fragments of the measurement (using the zoom function) or even compress the whole measurement into a single screen. Some additional functions like cursor functions, difference cursor functions, eliminating the DC component of the plot, etc., known from digital oscilloscopes, are also available for this window. Numerical results are stored in tables. They can be opened from main menu (Fig. 5). The measurement data can be exported from an SP-4000 data file to the text file to make the analysis using other software.

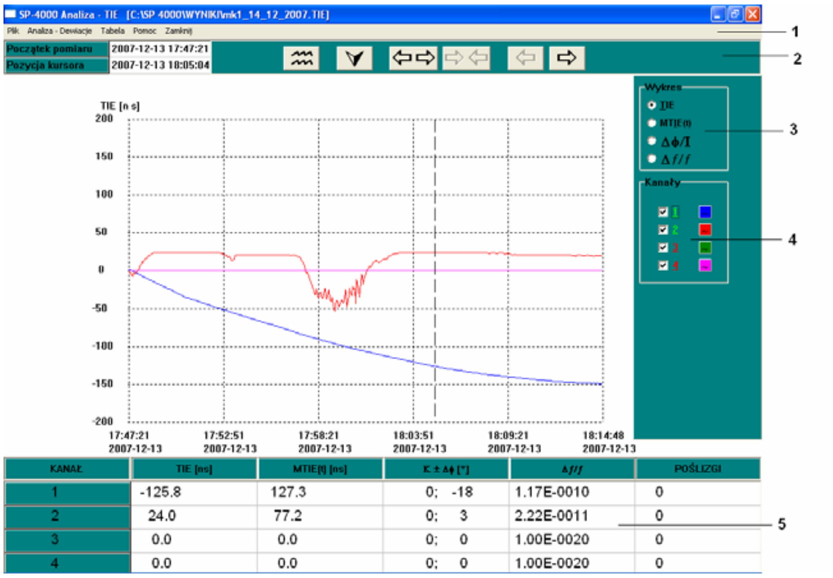

Fig. 5. The Analysis Window (AW); 1 – main menu, 2 – function keys and cursors, 3 – selection of plotted parameters, 4 – channel selection, 5 – table with numerical results

In the last step of evaluating the quality of a timing signal, we compute MTIE, ADEV, TDEV, frequency accuracy, and stability per a given period, e.g., per day. The results of the computations are available in the third window – the Computational Window (CW) (Fig. 6). A user can add to the plot ITU-T, ETSI or his/her own masks to check if the results satisfy recommendations prepared for digital telecommunication networks. The exact numbers are available in the table at the bottom of CW. They correspond to the current position of the vertical cursor. Numerical results for all width τ of windows defined for MTIE, ADEV and TDEV are contained in tables. The tables can be accessed from the main menu of Figure 6.

The computations of MTIE, ADEV and TDEV for long lasting measurements may take a lot of time. To accelerate the computations different methods are used. The software of measuring system SP-4000 exploits several time effective methods enabling short time of computation of the parameters [5, 6]. The algorithms are sensitive to short signal decays that may happen during long measurements. We also have to take into account that during long measurements, input signals can be disturbed by external signals that produce samples with values that differ significantly from the registered trend. The so-called “outliers” can significantly change the final result and, generally, should be eliminated during measurement or computations. The function of removing outliers is implemented in the system software. A user can choose a threshold above which a current sample is replaced by the previous one. Of course, the system can also work without detecting outliers, recording all values of time error. To avoid unexpected problems during long computations of MTIE, ADEV, or TDEV, the data file is verified before the start of the computations. Lack of data, insufficient number of time error samples, change of sampling interval or any signal decay can be detected and reported to the user.

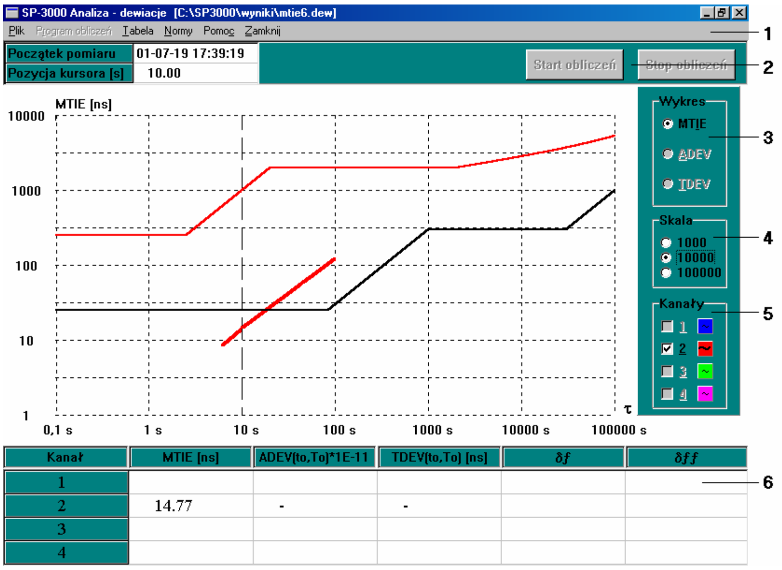

Fig. 6. The Computational Window (CW); 1 – main menu, 2 – cursor position and start/stop keys, 3 – selection of plotted parameters, 4 – scale selection, 5 – channel selection, 6 – table with numerical results

The computations can be performed for variable ranges of the observation interval τ chosen by a user. The range of τ is from 0.1 s to 100 000 s. The user can select the minimum interval τ_{min} and maximum interval τ_{max}. Results of the parameters' calculations are presented in the form of log-log plots. We can choose the number of points per decade in the scale of τ, i.e., the number of observation intervals τ in one decade for which the parameter will be computed. This number can be selected from the set: 1, 2, 5, 20, and 100. Fewer intervals per decade results in shorter computation times, but having more intervals enables more precise analysis and the ability to recognize some features affecting the signal that would otherwise be overlooked. If 100 points were selected, then each point of the curve on the plot is related to a computed value of the parameter. Before computations, the user can select the starting point of the analysis, t_0, and the length of the considered TE series, T, as a multiplier of the maximum widow width τ_{max}. The relation between τ_{max} and the minimal length of data series T necessary for the computation is different for each estimator (1 τ_{max} for MTIE, 2 τ_{max} for ADEV, and 3 τ_{max} for TDEV). So to avoid misunderstandings, the calculation for all parameters in one session is performed for the same data segment having the length selected from 4 τ_{max} to 100 τ_{max}. Note that, according to standards, the required relation between T and τ_{max} for TDEV is 12-15.

REAL-TIME COMPUTATION METHODS

A large number of time error samples (caused by small sampling intervals τ_0) and the formulae of the parameter's estimators may result in rather long computation times for the parameters. Long computation times performed after long-lasting measurements are not acceptable for many telecommunication applications. A current knowledge about MTIE, ADEV and TDEV also allows for the detection of on-line subtle disturbances in the function of many devices. A key purpose of our approach is to add the real-time assessment of ADEV, TDEV, and MTIE to the functionality of existing measuring system SP-4000.

The authors have already proposed the methods of real-time assessment of ADEV and TDEV deviation [8, 9], as well as the methods of real-time assessment of MTIE [7, 11]. These methods allow computation of the estimates of ADEV, TDEV or MTIE in real time during the measurement process, simultaneously for a set of observation intervals. To calculate the parameters' estimates simultaneously for several observation intervals in real time, all necessary operations should be performed in the time period between two sampling instants, i.e., during the sampling interval τ_0. Real-time ADEV or TDEV computation requires the rearrangement of indexes in the parameters' estimators, which enables proper data usage [8]. As a result we have obtained the ADEV estimator's formula for a current instant i in the form depending of the sum of squares of second differences computed for the previous sampling instant $i-1$

$$\hat{ADEV}_i(n\tau_0)=\sqrt{\frac{1}{2n^2\tau_0^2(i-2n)}\left(A_{i-1}(n)+\left(x_i-2x_{i-n}+x_{i-2n}\right)^2\right)} \quad (1)$$

were $A_i(n)$ is the sum of squares of second differences of time error samples

$$A_i(n) = \sum_{j=2n+1}^{i} \left(x_j - 2x_{j-n} + x_{j-2n}\right)^2, \quad i > 2n \tag{2}$$

The conversion of the time deviation estimator brought the formula dependent on the overall sum of squares and internal sum computed for the instant $i-1$ and four time error samples

$$T\hat{D}EV_i(n\tau_0) = \sqrt{\frac{1}{6} \cdot \frac{1}{i-3n+1} \cdot \frac{1}{n^2}\left[S_{ov,i-1}(n) + \left(S_{i-1}(n) - x_{i-3n} + 3x_{i-2n} - 3x_{i-n} + x_i\right)^2\right]} \tag{3}$$

where $S_{ov,i}(n)$ is the overall sum updated for each sample i, given in the form:

$$S_{ov,i}(n) = S_{ov,i-1}(n) + S_i^2(n) \tag{4}$$

where

$$S_i(n) = S_{i-1}(n) - x_{i-3n} + 3x_{i+2n} - 3x_{i+n} + x_i, \quad i > 3n \quad \text{and} \quad S_{3n}(n) = \sum_{j=2n+1}^{3n} \left(x_j - 2x_{j-n} + x_{j-2n}\right), \quad j > 2n \tag{5}$$

Real-time MTIE assessment requires the application of time-effective computation algorithms, which enable fast searching of extreme samples and protect the computation process against exceeding the limit of the computation time [11]. In the process of the MTIE search using the extreme fix (EF) method [6] some window's locations are excluded from inspection. The EF method is based on fixing the positions of minimum and maximum samples for a given window's location. The general rule is that the next window's location is originated at the first extreme previously found. The reviewing process is performed only for the new samples that come into the window's location. The review of the whole window at its new location is performed only in the case of one-sample shift (the first extreme is first sample in the window's location), when the new sample appearing in the window is not a new extreme. In the case of real-time calculation using EF method [7], the computation procedures for each observation interval run independently. Window's locations of longer observations intervals are analyzed after filling out by the samples without waiting for the analysis by the preceding shorter windows. All windows are activated after filling out their first locations by the samples. The number of samples reviewed in the course of the computation process performed within one sampling interval is tracked. If the review of the whole window's location have to be performed for some observation interval (critical case for the EF method), and the number of samples reviewed within this sampling interval will exceed assumed threshold, then the computation for this observation interval is suspended until the end of measurement. The computation for the suspended observation intervals will be completed after the end of measurement [11]. The example of this procedure is presented in Fig. 7. The extreme sample (8 at the position no. 10) leaves the current location of 10-sample window and the one-sample shift has to be done. Because the new sample coming to the window's location is not "more extreme" than the leaving sample – the review of the whole window at its new location is necessary. Therefore the analysis of the 10-sample window is suspended, because time of this review accumulated with the time of the operations done until now may exceed the length of sampling interval. The analysis of this window will be concluded after the end of time error measurement.

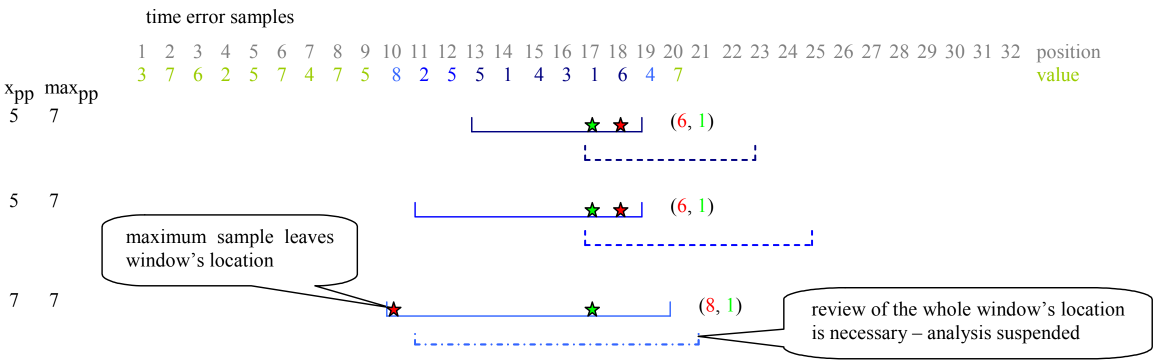

Fig. 7. Suspension of the analysis for the real-time MTIE computation using EF method

A general procedure for the real-time computation of MTIE, ADEV, or TDEV for a series of observation intervals is as follows:

1. Measure a new time error sample and store it in a data file.

2. For ADEV or TDEV: compute the appropriated differences for a given n (observation interval $\tau = n\tau_0$) using the current sample, and the samples measured n, $2n$ or $3n$ sampling intervals earlier, and then update the appropriated sums and compute current averages and their square roots.
   For MTIE: compare the new sample with current maximum and minimum.
   If current window's location is filled out with samples, fix the extremes for this location.
3. Execute Step 2 for successively greater observation intervals (greater n).
4. Return to Step 1 (measure a new sample).
5. When the measurement is finished, continue the computation for the remaining locations of each longer observation interval and suspended computations to complete the MTIE assessment; the values of ADEV or TDEV estimate for the observation intervals considered are known immediately.

The methods proposed were tested in experiments performed off-line, with real-time process simulation [7, 8, 9, 11]. The results obtained proved the ability of real-time simultaneous computation of the parameters for a set of observation intervals. To test these methods in a real measurement process, a special time error measurement test module using FPGA technology was made. This device, which allowed for single-channel time error measurements, was created using a Virtex-5 evaluation module [4]. The data storage and computation was accomplished by an external PC connected by the USB interface. The real-time computations of MTIE were performed using the EF method with a flexible control of the computation process [11] implemented especially for the test module [12]. The values of MTIE were computed for 21 simultaneously considered observation intervals from the range of 0.1 s to 1000 s. An example of the working process of real-time MTIE assessment is presented in Fig. 8. The values of currently computed MTIE for observation intervals values of 0.1 s, 1 s, 10 s, 100 s, and 1000 s are displayed on the screen in the text mode. Zero value of MTIE displayed on the screen denotes that the computation for this observation interval does not started yet because of insufficient number of samples measured until now. Negative value of MTIE denotes that computation for this observation interval is suspended until the end of the measurement and then concluded [11]. The results of the MTIE assessment successively obtained during the time error measurement process are presented in the three-dimensional plot in Fig. 9. The first segments of the MTIE plot are shorter than the others because the parameters' values for longer observation intervals were not computed for these instants of the time error measurement process. Last segment represents final MTIE curve obtained at the end of the measurement.

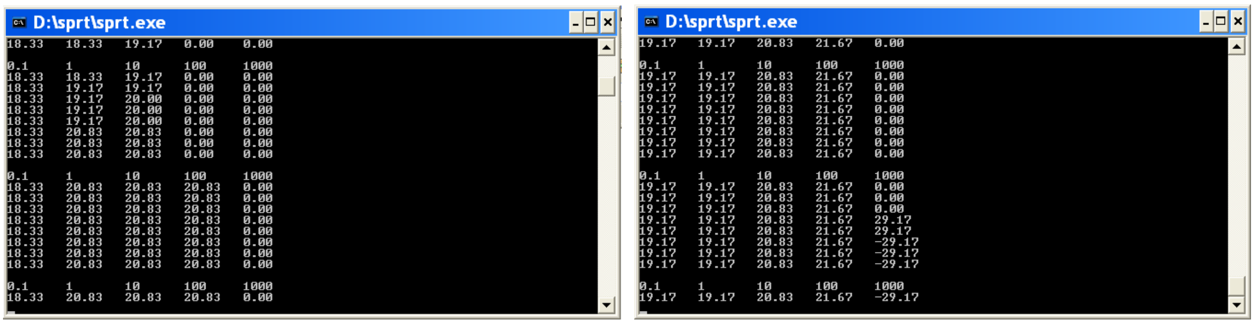

Fig. 8. The screenshots of the real-time MTIE computation, early stage (left) and late stage (right)

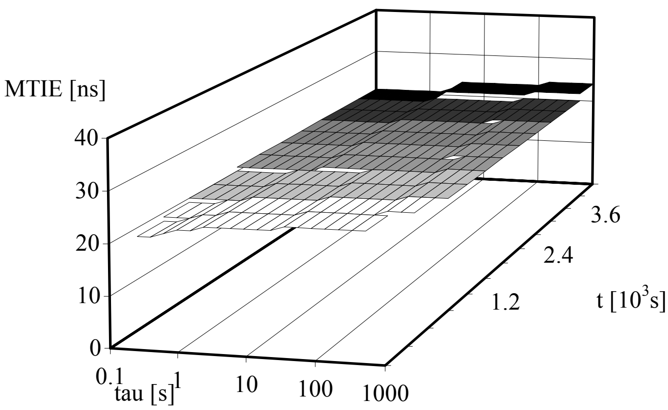

Fig. 9. Results of the MTIE real-time computation successively obtained

CONCLUSIONS

In this paper, the measuring system SP-4000, which allows for the analysis of timing signals in telecommunication networks, has been described briefly. The solutions that make possible the cooperation between time error meters of this system and the real-time assessment of the parameters have been described. Because of the limitations of computer technology, the user can choose real-time computation for only a single channel. The current version does not allow simultaneous traditional computations and real-time computations. We expect that in the future such computations will be possible for channels that are not chosen for real-time assessment of ADEV, TDEV, and MTIE. We also plan to increase the number of channels capable of real-time computations.

ACKNOWLEGMENTS

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REFERENCES

[1] ETSI EN 300 462, "Generic requirements for synchronization networks" (1998).

[2] ITU-T Rec. G.810, "Considerations on timing and synchronization issues" (08/96).

[3] ANSI T1.101-1999, Synchronization interface standard.

[4] http://www.xilinx.com/support/documentation/virtex-5.htm.

[5] M. Kasznia, "Some Approach to Computation of ADEV, TDEV and MTIE", Proc. of the 11th European Frequency and Time Forum, pp. 544-548, Neuchatel 4-6 March 1997.

[6] A. Dobrogowski, M. Kasznia, "Time effective methods of calculation of Maximum Time Interval Error," IEEE Trans. Instrum. Meas., vol. 50, No. 3, pp. 732-741, June 2001.

[7] A. Dobrogowski, M. Kasznia, "Testing of the methods of real-time MTIE calculation", Proceedings of 2005 Joint IEEE Frequency Control Symposium and Precise Time and Time Interval Systems Application Meeting, pp. 397-403, 29-31 August 2005, Vancouver, Canada.

[8] A. Dobrogowski, M. Kasznia, "Real-time assessment of Allan deviation and time deviation," Proc. of the 2007 IEEE International Frequency Control Symposium Jointly with the 21st European Frequency and Time Forum, pp. 887-882, Geneva, 29 May – 01 June 2007.

[9] A. Dobrogowski, M. Kasznia, "Joint Real-time Assessment of Allan Deviation and Time Deviation", Proc. of 22nd European Frequency and Time Forum, 22-25 April 2008, Toulouse, France.

[10] K. Lange, M. Kasznia, "Application of Vernier interpolation for digital time error measurement", Proc. of Poznan Telecommunications Workshop PWT'2008, 11 December 2008, Poznan, Poland.

[11] A. Dobrogowski, M. Kasznia, "Real-time MTIE Assessment with Flexible Control of Computation Process", Proc. of European Frequency and Time Forum and IEEE Frequency Control Symposium Joint Conference EFTF'09 IEEE-FCS'09, pp. 1102-1107, 20-24 April 2009, Besancon, France.

[12] P. Michocki, "Methods of assessment of Maximum Time Interval Error of timing signals", B.Sc. Eng. thesis, Poznan University of Technology, 2010.