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Article

Compensation of Accuracy Error for Time Interval Measurements

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Abstract: A method of accuracy error compensation for the time interval is examined, allowing to eliminate the dependence of accuracy error on the duration of measured intervals and minimising the influence of destabilising factors - ambient temperature changes and the initial deviation of the meter clock generator frequency from the nominal value. The compensation method is based on a calibration procedure that measures precise time intervals under conditions of changing ambient temperature. Then the dependence of the accuracy error on temperature for a particular meter is recorded. Based on these data, a correction table is compiled containing correction factors and temperature values at which these factors were determined. Under real measurement conditions, the correction factor corresponding to the current temperature is determined from the table for measured results correction. The table with correction factor values could be stored in the memory of the meter or processing computer. Experimental verification of the method showed that applying a correction for a meter with a standard XO class clock generator (certificated instability of ± 50 ppm) can obtain an equivalent clock generator instability of ± 0.15 ppm. The application of the method is efficient in cases where the use of high-end clocking to ensure the required measurement accuracy is not economically feasible.

Keywords: measurement of time intervals; clock generator; accuracy error compensation; correction of measurement results

1. Introduction

Time measurements (time-to-digital conversion) [1–4] have always belonged to the class of the most demanded measurements since it is reasonable to reduce measurements of many heterogeneous physical quantities to time measurements. As modern methods and instruments for measuring time provide very high accuracy [5], these technologies are in demand in a wide range of fields and industries [6,7]. The most commonly used time measurements are measurements of time intervals (TI) between the start and stop input signals [8,9]. For a significant part of the experiments, the object of investigation is the time relations between initialising and secondary events [10,11].

In the analysis of measurement errors of time intervals, we assume that the result A_i of the i -th measurement is, in general, a random variable and can be represented as a sum of the measured quantity T_i and the absolute error of its measurement a_i

$$A_i = T_i + a_i$$

The absolute measurement error a_i can, in turn, be represented as the sum of the random Δ_{ir} , accuracy Δ_{is} and offset Δ_c components of the total error [12], therefore:

$$A_i = T_i + a_i = T_i + \Delta_{ir} + \Delta_{is} + \Delta_c \quad (1)$$

The random error (or precision error) Δ_{ir} has an unpredictable value and represents the scatter of the measurement results due to the influence of noises of different origins.

The accuracy error is determined by the repeatability of its value from measurement to measurement. However, the value of this error Δ_{is} itself depends on several parameters. The peculiarity of the accuracy error in TI measurement is its multiplicative character, i.e. the value of Δ_{is} is proportional to the duration of the measured TI.

The offset error is determined by the difference between the delays of the start and stop channels and is additive. Its value Δ_c is offset for a particular meter. The offset error can be determined and used to correct the measurement results accordingly.

Suppose the task is to test a meter. In that case, the value of T_i in (1) is generally unknown since the source (generator) of input signals possesses its errors (Accuracy, Offset, Jitter). T_i can be represented as the sum of the generator set value T_g , generator accuracy error Δ_{isg} , generator constant error Δ_{cg} and jitter of the TI generator Δ_{irg} . Therefore, the general equation of the measurement result is as follows:

$$A_i = T_i + a_i = T_g + \Delta_{irg} + \Delta_{isg} + \Delta_{cg} + \Delta_{ir} + \Delta_{is} + \Delta_c \quad (2)$$

A graphical interpretation of the generation and measurement errors is illustrated in Figure 1.

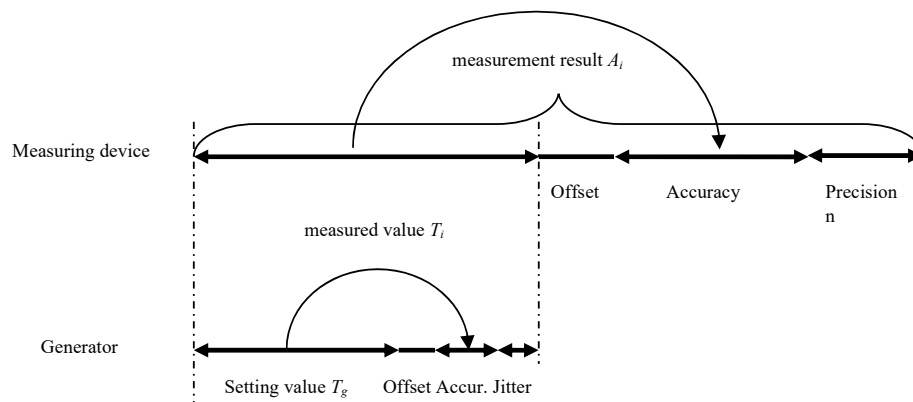


Figure 1. Graphical interpretation of the generation and measurement errors of the time intervals

The accuracy error Δ_{is} in the TI measurement is determined by the stability level of the clock generator (CG) of the meter and is caused by the fact that the period F of the CG differs from the nominal value F_0 by τ . The value of τ is not constant and depends on four factors: changes in ambient temperature, the value of the initial deviation from F_0 , variations in the generator supply voltage and ageing of its components.

In the specifications of a CG, the maximum value of its relative stability is K_{max} , defined as ratio $K_{max} = \pm \tau_{max}/F_0$, where τ_{max} takes into account all destabilising factors. According to the methods of minimising the influence of destabilising factors, CGs are divided into stability classes [13,14]: standard XO (Crystal Oscillator), termo-compensated TCXO (Temperature Compensated Crystal Oscillators), thermo-stated OCXO (Oven Controlled Crystal Oscillators), microprocessor-corrected MCXO (Microprocessor Corrected Crystal Oscillator), and atomic standards.

Reducing the accuracy error is relatively easy to achieve by using high-end CG in the meter. However, for specific applications (e.g., space electronics), such a solution is not always feasible due to the high cost of high-class CGs, as the main cost component of space-level CGs are the testing procedures. In this paper, the problem of significant reduction of the accuracy error without increasing the CG class of the TI meter is solved.

2. Estimation of Accuracy Error

When measuring time intervals, the result of measurement A_i is proportional to the period of CG F , which determines the multiplicative nature of the accuracy error, and its value Δ_s increases

Evaluation of Δ_{smax} of a particular TI meter is based on measurement and accumulation of an array $[A]$ of n results of the TI measurement (Figure 2) for the case of measuring input TI of maximum duration T_{smax} when the ambient temperature t° changes in the operating temperature range of the meter. Based on (2), it can be assumed that the average value of the array of measurement results at temperature t° will be:

In this case, we assume zero values of the meter's random error and the TI oscillator's jitter. The influence of the accuracy error of the generator Δ_{sg} included in this expression can be neglected if the stability of its CG is 1-2 classes higher than the CG stability of the TI meter under study. Thus Figure 2 shows the use of an external OCXO (reference oscillator). In this case, expression (3) is simplified:

```

graph LR
    OCXO[OCXO Reference generator] --> TI[Time Interval Tg generator]
    TI --> TI_meter[TI meter Ai]
    TI --> TI_meter
    TI_meter <--> PC[PC]
    PC --> Climate_Camera[Climate Camera]
    subgraph Climate_Camera_System [Climate Camera]
        TI_meter
    end

```

Equation (4) used to evaluate the accuracy error Δt_c^{rc} is complicated due to the presence of unknown error constants Δ_{cg} and Δ_c in the expression. The value of Δ_c is determined by the difference in delays for the start and stop inputs of the TI meter. In turn, Δ_{cg} is determined by the difference in delays in the TI meter start and stop signal generation circuitry and the difference in the lengths of the connection wires.

$$\bar{A}_{min} = T_{g\ min} + \Delta_{cg} + \Delta_c$$
$$\bar{A}_{1min} = 2T_{gmin} + \Delta_{cg} + \Delta_c$$

This implies that:

$$\Delta_{cg} = \frac{\bar{A}_{1max} - \bar{A}_{2max}}{2}$$

$$\Delta_c = \frac{\bar{A}_{1max} + \bar{A}_{2max} - 2T_{g\ min}}{2}$$

Estimation of the error constant of the meter relative to its inputs Δ_c is an independent value, but at the same time, it provides the capability for estimation of Δ_{t° :

$$\Delta_{t^\circ s} = \bar{A} - (T_{g\ max} + \Delta_{cg} + \Delta_c) = \frac{1}{n} \sum_{i=1}^n A_{t^\circ i} - (T_{g\ max} + \Delta_{cg} + \Delta_c) \quad (5)$$

While testing the meter in a climate chamber within the meter's operating temperature range (Figure 2), a dependence of Δ_{t° on ambient temperature changes t° can be derived by TI measurement of maximum duration $T_{g\ max}$. The graphical representation provides a capability to estimate the value of $\Delta_{s\ max}$ for a particular TI meter and the actual stability of its clock generator $K_{max} = \pm \Delta_{s\ max} / T_{g\ max}$.

Figure 3 shows an example of the plot of change of Δ_s as a function of temperature for a TI meter with a standard XO class clock generator (according to its specification $K_{max} = \pm 50$ ppm). The dependence character in the operating temperature range of the meter ($-40^\circ\text{C} \div +60^\circ\text{C}$) is of a pronounced non-linear nature and corresponds to the frequency-temperature characteristics of quartz AT-slice plates [5].

Based on Figure 3, $\Delta_{s\ max} = 740$ ps and $T_{g\ max} = 134$ μs , hence the estimate of $K_{max} = \pm 740 \cdot 10^{-12} / 134 \cdot 10^{-6} = 5.5 \cdot 10^{-6} = \pm 5.5$ ppm. The estimation of K_{max} obtained in this way is underestimated since it does not take into account the influence of instability of the generator supply voltage and the ageing of its components. Nevertheless, the difference between the specification listed and the actual component's parameter values is sufficient.

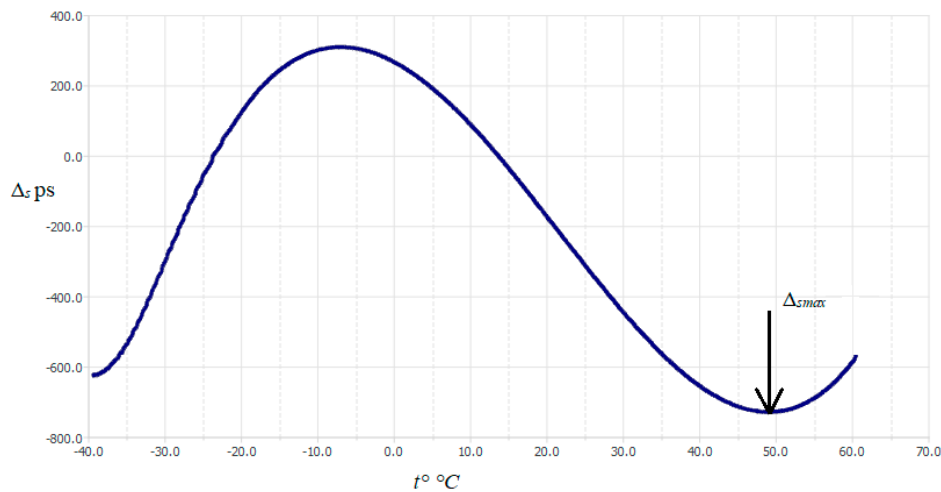


Figure 3. The temperature dependence Δ_s for an XO standard class TI meter when measuring TI with a duration of $T_{g\ max} = 134$ μs

3. Compensation for Accuracy Error

The investigation of the dependence of the accuracy error value Δ_s on the temperature for a particular CG provides the capability to perform a procedure for offsetting the influence of the accuracy error on the measurement result.

The compensation procedure is based on a special calibration, during which a series of high-precision TI measurements are carried out under changing ambient temperature t° . This is done by determining the average values of the TI measurement \bar{A}_{t° and the accuracy error $\Delta_{t^\circ s}$ for the current

temperature t° according to (5). The correction factors $K_{t^\circ} = \Delta_{t^\circ} / \bar{A}_{t^\circ}$ and the corresponding temperature calculated from this data are recorded as a table of K_{t° and t° values in the memory of the meter or processing computer.

Considering the non-linear nature of the relationship between the accuracy error and temperature (Figure 3), the choice of a table to record the relationship between the correction factors and temperature is the simplest method, although it requires memory resources.

Several conditions have to be met during calibration: the CG class of the TI generator must be higher than the CG class of the measured (compensated) meter, the results of the calibration measurements must be averaged to increase the accuracy of the table, and the T_{gmax} value must correspond to the maximum working range of the TI durations to be measured.

In general, calibration should be carried out under the real conditions of the meter's use or its equivalent. For example, if we are talking about space applications, then calibration must be carried out under thermo-vacuum conditions.

To implement the procedure for compensating for the accuracy error under actual measurement conditions, it is essential to monitor the current temperature t° . The algorithm for compensation of the i -th measurement result consists of extracting from the table the K_{t° coefficient corresponding to the temperature t° at the time of measurement and calculating the compensated measurement result $A_{t^\circ i} \text{ com} A_{t^\circ i} = A_{t^\circ i} (1 - K_{t^\circ})$.

In a general case, the measurement result $A_{t^\circ i}$ contains both an accuracy error and a constant error Δ_c , so $\text{com} A_{t^\circ i} = (A_{t^\circ i} - \Delta_c)(1 - K_{t^\circ})$. Figure 4 represents the dependence of the accuracy error Δ_s on the temperature after the compensation of the accuracy error shown in Figure 3. The value of Δ_{smax} decreased from 740 ps to 20 ps, and the equivalent stability of CG, in this case, reaches a value of ± 0.15 ppm.

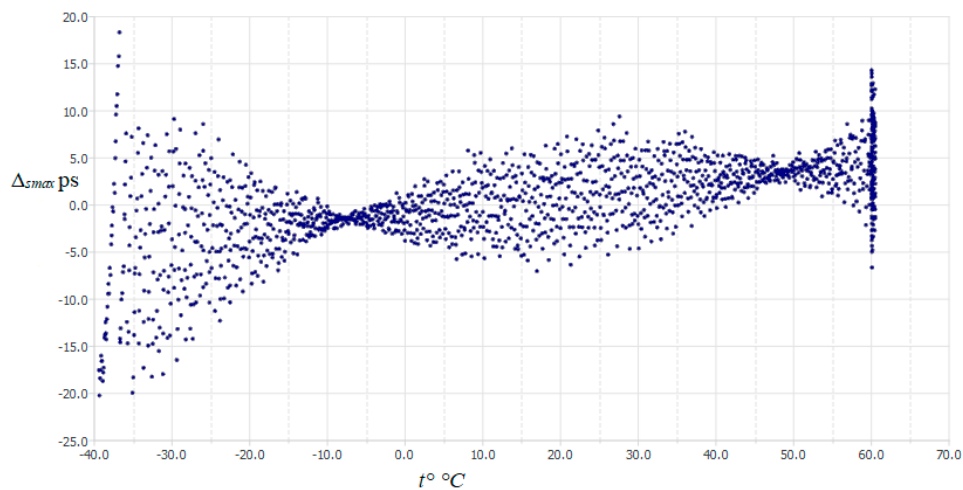


Figure 4. Relationship of the accuracy error value Δ_s to the temperature after compensation.

The compensation procedure also has its limitations since it does not consider the influence of instability of TG supply voltage and the ageing of its components.

As in the proposed solution, a variant of accuracy error minimisation implying a pre-calibration procedure is presented in [15]. This option is based not on the correction of measurement results but on microprocessor correction of frequency of VCXO class CG, the frequency of which is controlled by DAC voltage.

The microprocessor performs the calibration by the user. As a result of this procedure, the coefficients of the 4th-degree polynomial are determined and stored. This coefficient is used to calculate the DAC codes, which compensate the VCXO frequency deviation for the current temperature value t° . The CGs based on this principle belong to the CCXO (Coefficient Corrected Oscillator) class and can ensure the stability of the CG at the level of 0.1 ± 0.3 ppb. In its application,

there is no need to manually correct measurement results, but the cost of such CGs is high, and at this time, it is not manufactured for the space-level ready version.

4. Conclusions

The accuracy error at measuring time intervals (IT) is determined by the relative stability of the clock generator (CG) used in a meter and the duration of the measured time interval. The discussed method of accuracy error compensation eliminates the dependence of accuracy error on the duration of measured TI. It reduces to a minimum the influence of such destabilising factors as changes in ambient temperature and initial deviation of the clock frequency from its nominal value.

To implement the compensation method, three procedures have been developed: a procedure for registering an accuracy error, a calibration procedure in which a correction table is generated, and a procedure for correcting measurement results in real conditions of the meter's application. The main expenditures of implementing the method consist primarily in correctly conducting the meter's calibration, and hardware support for temperature monitoring and performing relatively straightforward computational operations is also required. The main costs of the method implementation primarily consider the correct calibration of the meter, as well as the required hardware support for temperature monitoring and relatively simple computational operations performance.

Experimental validation of the method demonstrated that an equivalent instability of ± 0.15 ppm can be achieved for a standard class XO meter (specification instability of ± 50 ppm), which reduces the accuracy error to the equivalent degree. The accuracy error compensation procedure has its limitations related to the replicability of the field conditions in which the calibration procedure has been performed.

5. Patent

The patent application of the Republic of Latvia LVP2023000010 has been filed (filing date: 02.02.2023) in perspective of the study conducted and the consequent conclusions.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, V.B. and A.L.; methodology, V.B. and V.S.; software, V.K.; validation, V.B., V.S. and V.K.; formal analysis, V.B.; investigation, V.B., V.S. and V.K.; resources, V.L.; data curation, V.S.; writing—original draft preparation, V.B., V.L. and A.L.; writing—review and editing, V.B., V.L. and A.L.; visualisation, V.S.; supervision, V.B.; project administration, A.L.; funding acquisition, A.L. and V.K. All authors have read and agreed to the published version of the manuscript."

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