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MAINTENANCE OF TIME STANDARDS IN THE DEPARTMENT OF REFERENCE STANDARDS IN ZIELONKA. CONTRIBUTION INTO THE CREATION OF THE POLISH ATOMIC TIME SCALE TA (PL)

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Abstract. *The article includes information about time standards in the Department of Reference Standards in Zielonka. The department is part of the Central Military Calibration Laboratory, which performs tasks related to the calibration standards of the other military calibration laboratories in Poland. The first part discusses components of a time standards station, which is involved in the creation of an Independent Polish Atomic Time Scale TA (PL), and its maintenance process. The second part is related to the analysis of the benefits of the inclusion of standard time calibration laboratory into the TA (PL). Last part presents the method of determining the parameters of the Relative Frequency Deviation (RFD), the prediction and uncertainly estimate of RFD*

Keywords: time and frequency metrology, time and frequency standards, Time Atomic International

UTRZYMANIE WZORCÓW CZASU W ZESPOLE WZORCÓW ODNIESIENIA W ZIELONCE. UDZIAŁ WE WSPÓŁTWORZENIU POLSKIEJ ATOMOWEJ SKALI CZASU TA (PL)

Streszczenie. *W artykule zawarto informacje dotyczące wzorców czasu utrzymywanych w Zespole Wzorców Odniesienia (ZWO) w Zielonce. Zespół jest częścią Centralnego Wojskowego Ośrodka Metrologii, i realizuje zadania związane z kalibracją (wzorcowaniem) wzorców roboczych pozostałych jednostek metrologicznych w Wojsku Polskim. W pierwszej części omówiono elementy stanowiska wzorców czasu, które bierze udział we współtworzeniu niezależnej polskiej atomowej skali czasu TA (PL), oraz sposób jego utrzymania. Druga część związana jest z analizą korzyści jakie daje włączenie wzorca czasu laboratorium wzorcującego do TA (PL). W ostatniej części, przedstawiono sposób wyznaczania Odstrojenia Względnego Częstotliwości wzorca, prognozowanie odstrojenia i jego niepewność.*

Słowa kluczowe: metrologia czasu i częstotliwości, wzorce czasu i częstotliwości, Międzynarodowy Czas Atomowy

Introduction

Time and frequency are among most accurately reproduced quantities serving as a basic units of measurement in the International System of Units (SI). The second most precisely measured units is a meter. The definition and implementation of this unit is based on the passage of time. It is not only primary standards such as cesium fountains bases on the (SI) unit of time, but also cheaper solutions such as rubidium standards achieve excellent metrological parameters. Therefore, calibration laboratories, such as Central Military Calibration Laboratory (CMCL) built the calibration station based on atomic cesium time and frequencies standards (with high-performance cesium beam tube). In table 1 are shown two popular commercial time standards.

Table 1. Comparison two popular reference standards

Parameter	Type of standard		
	Rubidum 910(R)	Cesium 5071A standard	Cesium 5071A op. 001
RFD	2×10^{-12}	1×10^{-12}	5×10^{-13}
Allan dev (τ=1s)	3×10^{-11}	$1{,}2 \times 10^{-11}$	5×10^{-12}
Allan dev (τ=100s)	3×10^{-12}	$2{,}7 \times 10^{-12}$	$8{,}5 \times 10^{-13}$
Aging	2×10^{-12}/day	-	-

The Table 1 shows the low-cost rubidium calibration standard need to use the standard cesium from the highly stable frequency playback option. Unfortunately, using of this standard causes difficulties with the binding standard to the international system of units SI with satisfactory measurement uncertainty deviation frequency. Using the services of laboratories that do not have the primary standard is pointless, because calibration results will have a very large measurement uncertainty. Therefore, the best solution for laboratory having the aspiration to have in its offer calibration of atomic time and frequency standards, is linking to the local atomic time scale TA (k).

Participation in the creation of TA (k) and UTC (k) (where PL stands for Polish), brings both benefits and responsibilities as well. The benefits are linking standard involved in the creation of TA (PL) / UTC (PL) to the International System of Units SI, the ability to determine the time and frequency deviation, forecasting standard parameters and monitoring the standard's efficiency. Responsibilities are associated with maintaining the time standard in constant good shape in a stable climate condition and guaranteeing the continuity of comparisons.

These requirements seem to be a necessity with the possession of the standards in this class, therefore, they should not be an obstacle to joining the TA (PL), under the auspices of the President of the Central Office of Measures.

Additionally, participation in the creation Polish Atomic Time Scale means adds to the reputation of laboratory. This is because the data from the TA (PL) are taken to create of the International Time Coordinated UTC and the standards (identifiable by the type and piece of serial number) receive the weights which are calculated by the International Bureau of Weights and Measures (BIPM), which indirectly represent their metrological quality.

1. Station of time and frequency standards in Department of Reference Standards

Calibration measuring instruments as well time and frequency standards with a better class of oscillators OXCO was the purpose of building measuring station at the Central Military Calibration Laboratory. The station based on two standards: time and frequency. This solution increases the reliability of the measuring station. Additionally military laboratory has joined to the program of co-creation an independent Polish atomic time scale TA (PL), which also increases the reliability of measuring stand and ensures uninterrupted operability for several years (not taking into account the breakdown in the 2014).

1.1. Diagram of measuring station

Station for calibration time standard and participation in TA (PL) based on two highly stable cesium time standards HP and SYMMETRICOM 5071 op. 001 according to Figure 1.

Primary standard participates in the creation of TA (PL) using the method CV GPS (Global Positioning System Common-View). This method relies on observing GPS satellites at the same time by various laboratories and determining the differences between the indications of local clocks and GPS system clocks [1].

$$(z_{GUM} - z_{GPS}) - (z_{CMCL} - z_{GPS}) = z_{GUM} - z_{CMCL} \qquad (1)$$

where: z – clocks time signals

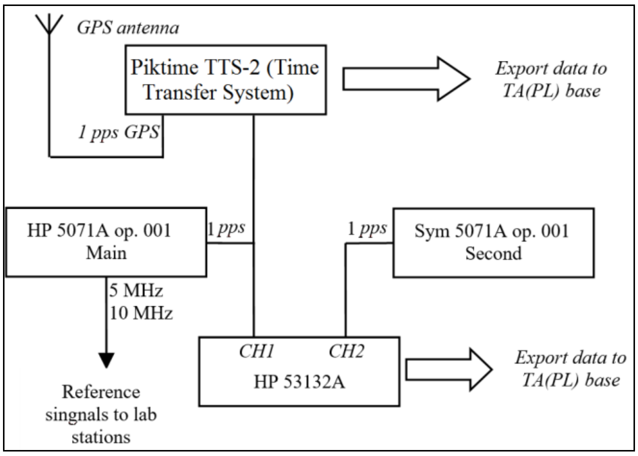

Fig. 1. Station to co-create TA (PL)

The time difference between two clocks being compared by GPS CV, is determined by simultaneous observation of a third clock on a GPS satellite. Thanks to this the accuracy of a third clock is not transferred to the measurement uncertainly budget. The uncertainty determined by the BIPM for UTC (PL) was estimated at around 5 ns for the five-period comparisons [2].

The second standard, in accordance with a practice established in laboratories, is compared with a primary reference using the frequency counter. This method increases the reliability of position, because in case the breakdown of the main/primary standard, the laboratory is in possession of extra reference, which through internal comparisons will be located in the database TA (PL) the Office of Weights and Measures. This is important because fully operational the time reference achieved after approximately 6 months of comparisons.

1.2. Environmental and housing conditions

The co-creation TA (PL) stand was separated using a thin wall of PVC and glass from a larger space laboratory. This was done to improve environmental conditions by reducing the air circulation and space in which the standards are working . To maintain temperature in the range of 22.5-23.5°C and the humidity between 40 - 50% RH, individual air conditioning system is used. These environmental parameters are sufficient to maintain the stability of standard on high level.

To protect against energy network failure laboratory uses UPS LanPro LP8-11 with a set of 20 batteries, giving a total of 40 Ah. It is the amount of power sufficient to maintain the TA (PL) working stand even for several days. Some laboratories, in case of failure the main UPS, make additional protection for the references by the network of DC 24V.

Leading time laboratories observed the relationship between stability of their clocks and local ground vibration. To eliminate this kind of disruptions affecting the stability of time standard's work, laboratory is located away from the traffic.

1.3. Monitoring of reference

Time references are monitored in two ways. The first is monitoring working parameters on a weekly basis. The most important working parameters (specified by the manufacturer), helps to indicate a worsening condition of the standard or ending of the element cesium in the tube. One of most important parameters are an ion pump amperage and the multiplier voltage.

Fig. 2. shows an example of characteristics for cesium tube installed in one of the standards with excellent metrological parameters and proper weight in the BIPM, but failed after less than a year of work.

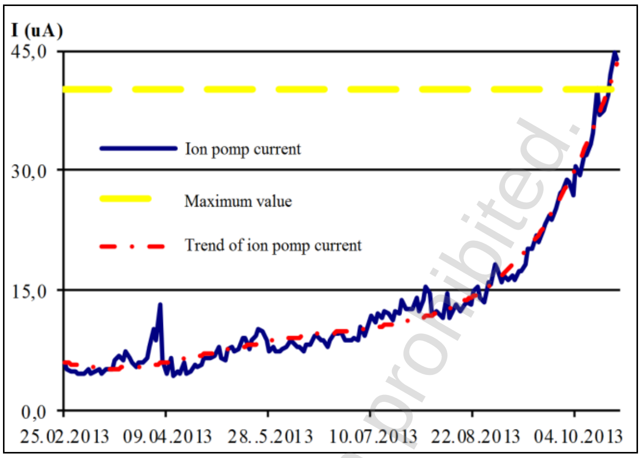

Fig. 2. Ion pomp current witch trend for cesium tube witch damage suspicions and well metrology parameters

Thanks to the supervision, laboratory ordered a replacement service in advance which resulted in shortening time in which the reference was out of order.

The second aspect is the verification the metrological parameters of reference. It is done with the determination of the relative frequency deviation by checking the Allan deviation ADEV (t = 5d) for five days periods of scale UTC and one day periods ADEV (t = 1d) for national data comparisons TA (PL).

Due to the fact that the UTC scale is charged with noise from all references involved in its creation, it is very hard to get the value ADEV(τ=5d) < 1×10^{-14} specified by the manufacturer of standard 5071.

For this reason, CMCL established proper operation standard for the calculated ADEV (t = 5d) <2×10^{-14}. This value is adopted conventionally based on the data from previous years of the standards work.

If calculated value of ADEV(t = 5d) is greater, then CMCL calculates additional value of ADEV(τ=1d) from TA (PL) data using "3-cornered hat" method [6]. The table below lists the values of these parameters for the three cases.

Table 2. Allan deviation calculated for the main clock in CMCL

Data	Comparable parameters	
	ADEV$_{UTC\text{-}CMCL}$(τ = 5d)	ADEV$_{CMCL}$ (τ = 1d)
Feb 2015	$2{,}04\times10^{-14}$	$2{,}66\times10^{-15}$
May 2015	$1{,}77\times10^{-14}$	$4{,}66\times10^{-15}$
Dec 2015	$1{,}21\times10^{-14}$	$2{,}77\times10^{-15}$

Analysis of the above data suggests the conclusion that there is no strong correlation between these two parameters, but due to the fact in the case of large swings in the pattern, it will move the value of ADEV(t = 5d) should be regarded as sufficient assumption described in the previous paragraph.

2. Contribution to maintaining independent Polish Atomic Time Scale TA (PL)

Cooperation agreement on maintaining independent Polish Atomic Time Scale TA (PL) was signed on 3 December 2004 between several polish laboratories, including CMCL. This fact lets CMCL acquire data from national time standards comparisons. The data, merged with information published by BIPM, gives CMCL ability to calculate Relative Frequency Deviation for its own time standards.

2.1. Acquiring data from comparisons

In order to analyze standard's metrological parameters, two sources of data are used – national and external.

National data (UTC(PL) – Clock) is available both on National's Institute of Telecommunications website http://timegum.itl.waw.pl/ and from Central's Office of Measures (GUM) e-mail timegum@gum.gov.pl. The data origins from 24-hour periods and is used to maintain TA (PL) and official time UTC(PL).

External data is obtained from the FTP server of the BIPM Time Department. BIPM provides whole data from all comparisons conducted by Department. For the purposes of laboratories determining RFD for own clocks, most useful data can be found under the path ftp://ftp2.bipm.org/pub/tai/publication/utclab.

2.2. Calculating and predicting Relative Frequency Deviation

Measurement model of UTC standard's phase deviation x is defined as follows:

$$x = (UTC - UTC(PL)) + (UTC(PL) - Clock) = \\ = UTC - Clock[ns] \qquad (2)$$

It should be mentioned, that equation above excludes UTC(PL) time scale, so the result is referenced to the realization of SI unit by UTC. It is done because Central Office of Measures maintains UTC(PL) with slight deviation to UTC. The deviation is introduced because there is necessity of UTC(PL) phase-tuning. Phase adjustment is performed by the 5071A standard's femtosteper.

Attempt to determine RFD, using only the data provided by GUM is presented below.

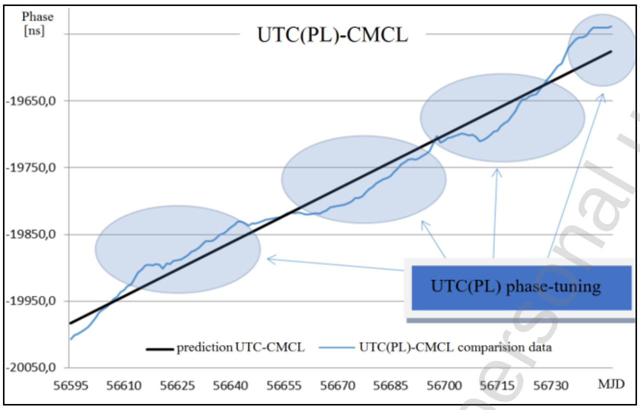

Fig. 3. UTC(PL)-CMCL comparison example

Frequency deviation oscillations present on figure above are caused by UTC(PL) phase-tuning. The oscillations should not be taken into consideration during determining standard's metrological parameters. Combining the data from GUM and BIPM gives proper sample which can be used to analyze x parameter.

Calculating standard's phase deviation x allows to determine historical operational parameters. In order to calculate factors needed to transfer measurement unit to CWOM, the X value is predicted using least squares linear regression method:

$$X = a \cdot MJD - b \qquad (3)$$

A and b coefficients are computed using equations below:

$$a = \frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{\sum_{i=1}^{N}(MJD_i - \overline{MJD})(x_i - \bar{x})} \qquad (4)$$

$$b = \overline{MJD} + a \cdot (\overline{MJD} - MJD_1) \qquad (5)$$

where: *MJD* - Modified Julian Day, *a* - denotes computed phase deviation and *b* - denotes phase computed for MJD_1.

The mentioned method is very simple. However, if there is not considerable distortion of standard's operation, it is very efficient and the dependency between prediction and historical data is significant. Pearson product-moment correlation coefficient r = 0,9997 calculated between May 2015 and January 2016 prove that there is total positive correlation between them.

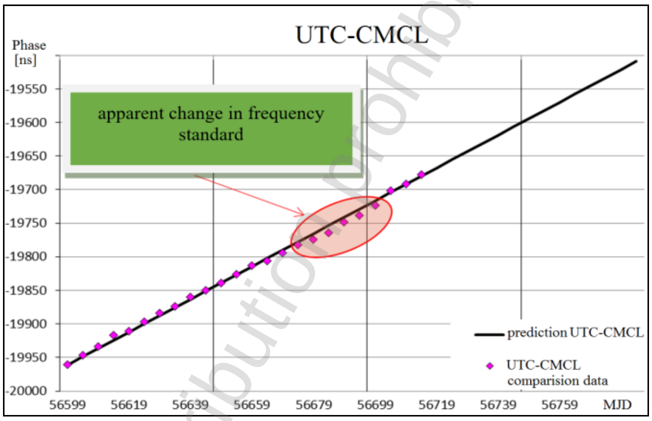

Fig. 4. UTC - CMCL example

Both data and prediction are transposed from absolute values to relative values by the equation:

$$\frac{\Delta f}{f} = (X_n - X_{n-1}) \cdot \frac{10^{-9}}{5 \cdot 86400} = a \cdot \frac{10^{-9}}{5 \cdot 86400} [Hz/Hz] \qquad (5)$$

Obtained result is predicted Relative Frequency Deviation, essential for laboratory operation. Instead of predicted RFD, phase prediction is more useful, because if results were transformed to no dimensional domain before making prediction it would give two parameters:

- predicted RFD – parameter b
- standard's ageing – parameter a

This information wouldn't be credible, as cesium standards are unaffiliated to ageing processes.

2.3. Uncertainty budget

In order to link predicted RFD to International's System of Units time and frequency unit, it is necessary to evaluate measurement uncertainty. Measurement model consist of both historical data and prediction method components.

Prediction process can be conducted both for phase deviation X and relative values $\frac{\Delta f}{f}$.

Measurement model for prediction can be written as follows:

$$\Delta X = (X_i - X_{i+1}) + p(UTC - UTC(PL)) + p(UTC - CMCL) + \\ + p(predict) + p(CMCL)[ns] \qquad (6)$$

where $i \in \langle 2, N \rangle$.

Particular input quantities and tables with the data crucial for evaluating uncertainty budget are presented below [3].

1) $\boldsymbol{X_i}$, $\boldsymbol{X_{i-1}}$ are two consecutive values of predicted phases for MJD_i and MJD_{i-1} dates. These values are treated as „accurate values", and their uncertainty is considered in further part of equation. According to expression (3) X values should be consecutive, so part $(X_i - X_{i-1})$ in equation (6) can be replaced with parameter a.

Table 3. X quantity parameters

Quantity	Xi, Xi-1 or a
Estimate	Predicted values
Standard uncertainty	„accurate value"
Probability distribution	–
Sensitivity coefficient	–

2) ***p(UTC-UTC(PL))*** is correction of the computed UTC(PL) phase deviation relates to the UTC phase. The correction is determined by BIPM [2], and published in Circular-T bulletin. Uncertainty provided from Bureau consists of Type A and B evaluations, nevertheless only Type B is major. It results from fact, that GUM standard's phase fluctuations are inconsiderable. Major component origins from UTC(PL) participants' testbeds, such as GPS antennas or TTS systems inaccuracy. Due to the fact that uncertainties u_1, $u_2,\ldots$, u_n evaluated by Bureau for consecutively calculated phases x_i have different values, equation for the combined variance should be used (assuming all measurements have the same sample size):

$$S_p^2 = \frac{\sum_{i=1}^{N}(n-1)\cdot u_i^2}{\sum_{i=1}^{N}(n-1)} \tag{6}$$

Table 4. p(UTC-UTC(PL)) quantity parameters

Quantity	*p(UTC-UTC(PL))*
Estimate	0
Standard uncertainty	$u_1 = \sqrt{S_p^2}$
Probability distribution	rectangular
Sensitivity coefficient	$c_1 = 1$

3) ***p(UTC-CMCL)*** is correction derived from deviation of historical data phase differences between standard and UTC time. This parameter is estimated by mean standard deviation of variable *x* with zero expected value.

Table 5. p(UTC-CMCL) quantity parameters

Quantity	*p(UTC-CMCL)*
Estimate	0
Standard uncertainty	$u_2 = \frac{S(x)}{\sqrt{N}}$
Probability distribution	normal
Sensitivity coefficient	$c_2 = 1$

4) ***p(predict)*** is correction derived from applied prediction method. Its estimator is standard deviation of values calculated from expression:

$$y_i = X_i - x_i \tag{7}$$

Table 6. p(predict) quantity parameters

Quantity	*p(predict)*
Estimate	0
Standard uncertainty	$u_3 = \frac{S(y)}{\sqrt{N}}$
Probability distribution	normal
Sensitivity coefficient	$c_3 = 1$

Furthermore, because strong correlation between variables *x* and *y* appears, covariance uncertainty factor *u(p(predict), p(UTC-CMCL))* should be taken into consideration.

5) ***p(CMCL)*** is a second correction with estimator which represents rectangular probability distribution uncertainty (calculated by Type B evaluation). The correction is related to long term stability main standard in CMCL. Correction value is calculated from the specifications of the manufacturer standard [4].

Table 7. p(CMCL) quantity parameters

Quantity	*p(CMCL)*
Estimate	0
Standard uncertainty	$u_4 = 4{,}98\,ns/5\,days$
Probability distribution	rectangular
Sensitivity coefficient	$c_4 = 1$

Predicted Relative Frequency Deviation uncertainty evaluated in Zielonka using method described in this article stands at 5,5 to 6,5 ns per 5 days. Achieved uncertainty of phase is only a little bigger than UTC-UTC(PL) uncertainty, what proves CMCL's clock high stability.

In addition, comparison of the historical RFD data witch prediction, should be reconsidered to include in the equation parameters uncertainty type B. As far as the determination of uncertainty detuning of the phase they are necessary for the proper estimation of the result, whereas the estimate RFD tend to overestimate the value of uncertainty. This case will be discussed in CMCL in future.

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