ALBIN CZUBLA[1], JANUSZ KONOPKA[1], JERZY NAWROCKI[2]

[1] Central Office of Measures (GUM), Electrical Metrology Division, Time and Frequency Laboratory
00-950 Warsaw, Poland, e-mail: timegum@gum.gov.pl
[2]Astrogeodynamical Observatory at Borowiec (AOS), Time and Frequency Laboratory
62-035 Kórnik/k Poznania, Poland, e-mail: j.nawrocki@cbk.poznan.pl

REALIZATION OF ATOMIC SI SECOND DEFINITION IN THE CONTEXT OF UTC(PL) AND TA(PL)

In this paper, the problem of practical realization of atomic SI second definition is discussed from the metrological point of view. Special attention is devoted to the maintenance of UTC(PL) – Polish local physical realization of UTC, and to the determination of TA(PL) – the Polish independent atomic timescale. The role of such timescales , as well as local and international cooperation in time and frequency metrology is also considered. We share some Polish experience in this field.

Keywords: time and frequency metrology, timescale, UTC(PL), TA(PL), second unit

1. INTRODUCTION

Application of quantum phenomena to building caesium atomic time and frequency standards and consequentially adopting in 1967 a new definition of SI second, based on quantum transitions occurring in caesium 133 atoms, caused an about 10^5-fold increase in accuracy of time unit realization and of time measurements over a period of the last forty years. At the same time the very nature of time and the necessity of coupling quantum and mechanical oscillations make the realization of atomic definition of the second by an individual atomic clock unique and unrepeatable. The necessity to perform continuous comparisons of timescales generated by individual atomic clocks as well as the condition to maintain absolute continuity of their work became in this situation exceptionally important. It became necessary to determine and maintain physical and calculated atomic timescales, which replaced the too inaccurate astronomical 'standard' formed by Earth rotation. Such scales are currently international atomic timescales TAI (Time Atomic International) and UTC (Universal Time Coordinated) determined by the Time Section of BIPM (Bureau International des Poids et Mesures) in Sévres as well as local atomic time scales, e.g. UTC(PL) and TA(PL) determined in Poland. These scales are a basic reference for the evaluation of the accuracy and unstability of realization of time and frequency units by individual standards.

2. ATOMIC DEFINITION OF SI SECOND

In 1967, the currently standing definition of the SI second was accepted by the 13th Conférence Générale des Poids et Mesures (CGPM) as the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom, more precisely, to the transition between the hyperfine levels $F = 4$, $M = 0$ and $F = 3$, $M = 0$ of the ground state $^2S_{1/2}$, unperturbed by external fields [1]. In 1997 this definition was supplemented by a note that it refers to a caesium atom in its ground state at a thermodynamic temperature of 0 K. The assigned number of periods of the radiation corresponding to 1 second was in conformity with the value of 1 second following the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time (it refers to the division of the tropical year into days, hours, minutes and seconds respectively), in accordance with the previous definition SI second.

A good point of this definition is its independence of long-term astronomical observations and of irregularity in Earth rotation, the possibility of realizing a time unit with great precision in actual time (nowadays at the level 10^{-15}) as well as its invariability, with the assumption of time invariability of physical constants appearing in relations describing quantum phenomena. At the same time, in spite of its precision and uniqueness, this definition cannot be fully put into practice, because the temperature of 0 K cannot be achieved and total separation from the influence of external fields is impossible. It requires applying special correction for the shift due to ambient radiation [2]. Also, there is a problem with coupling quantum phenomena with the classical ones and all limitations following the way of realization of that coupling.

3. ATOMIC TIME AND FREQUENCY STANDARDS

The atomic definition of the SI second at the highest level of accuracy is directly realized mainly by caesium atomic time and frequency standards (commercial and laboratory) and by hydrogen masers. Atomic time and frequency standards of the new type, using quantum phenomena in the optical range occurring in other elements, are currently in the phase of research and experiments e.g.[3-5]. Caesium standards dominate in time and frequency laboratories of National Metrology Institutions (NMI) [6], because time and frequency standard signals generated by caesium standards are more stable and precise in the long term (usually for averaging periods longer than 1 day) than the signals generated by hydrogen masers. Due to this fact, caesium standards are used more frequently for conducting local atomic timescales. On the other hand, hydrogen masers are better at providing a source of reference signal to perform time and frequency measurements for short averaging periods (usually shorter than 1 day). Atomic time and frequency standards are interchangeably called atomic clocks.

Irrespectively of the type of the atomic clock, the physical sources of time and frequency standard signals are usually high stability thermostabilized quartz generators, which are continuously precisely adjusted to the frequency of quantum transitions occurring in atoms or molecules of chosen elements or chemical compounds. The mechanism of coupling quantum phenomena with oscillations of a quartz generator guarantees the maintenance of output frequencies within the defined range of accuracy, but at the same time it introduces additional interference. Furthermore, the dynamics of the process of oscillation generation, the influence of external conditions, in particular temperature and external magnetic field, Doppler effect, temperature broadening of energy levels, technological unrepeatability of each copy of atomic clock, different sensitivity of individual components and a number of other factors cause that there are no two ideal atomic clocks working synchronically. Also the same clock restarted again or moved to another place does not generate signals in the same way and does not return to the state before the change. What is more, there occur effects of the Special and General Theory of Relativity, which make the flow of time dependent on the movement relative to the reference systems and on gravitational field strength.

4. ATOMIC TIMESCALES

In order to make a time and frequency standard signal generated by individual atomic clocks credible, it is necessary to maintain continuous comparisons between them, which in practice boils down to comparisons of phases of 1 Hz pulse signals generated by them. The comparisons are conducted with direct methods in a given laboratory as well as with remote methods between timescales realized by spatially separated laboratories, located even on different continents (GPS CV method, TWSTFT (see e.g. [7])). The total change of time phase $\Delta x(t)$ during a given period Δt allows to determine the average relative frequency difference y_{12} of the compared signals $f_1(t)$ and $f_2(t)$ for that period:

$$y_{12} = \int \left(f_1(t) - f_2(t) \right) dt = \frac{\Delta x(t)}{\Delta t}. \qquad (1)$$

Considering the changeability, unrepeatability and dependence of the work of a given clock on a number of external and internal conditions, it was necessary to establish in the international environment a common, systematically calculated, reference timescale which would be more stable and more accurate than that of any individual clock. In 1971, the international atomic timescale TAI was adopted as a reference timescale, measured with atomic SI second and calculated as a weighted average of corrected indications of presently above 200 atomic clocks all over the world (including about 10 Polish atomic clocks), which enables to guarantee the uniformity of realization of a time unit. Additionally, in 1980, due to the Special and General Theory of Relativity, the rotating geoid was adopted as a reference system to the SI second realization within TAI [1].

Some countries additionally determine their own independent atomic timescales TA(k), where k stands for the country or laboratory, on the basis of comparisons within the group of their own atomic clocks. Such an independent atomic timescale is determined also by Poland. Obtaining as stable as possible the independent atomic timescale TA(k) supports the process of the realization of a repeatable and accurate time unit.

The basis for determination of local (legal) time is the calculated atomic timescale of universal coordinated time UTC, shifted in relation to TAI by an integer number of seconds in such a way that the difference between UTC and the time obtained from precise observations of reciprocal movements of Earth, Sun and Moon shall not be greater than 0,9 s. Since 1 January 2006, the difference TAI-UTC amounts to 33s. Individual countries maintain local, usually physical, realizations of UTC timescale, denoted as UTC(k), where k stands for a given laboratory. UTC(k) timescales are used for realization of local (legal) time by adding or subtracting usually an integer number of hours. In Poland such a role is performed by UTC(PL), determined in the Central Office of Measures (GUM), to which, during standard time, one hour is added, and during summer time, two hours are added.

Atomic timescales TAI and UTC are determined monthly by the BIPM Time Section for every fifth day. As a result of calculations, corrections of UTC(k) relative to UTC as well as corrections of TA(k) relative to TAI are published in the form of differences UTC-UTC(k) and TAI-TA(k) respectively [8]. The published corrections are the base to examine the stability and accuracy of standards contributing in TAI and UTC.

5. UTC(PL)

UTC(PL) is the main Polish physical realization of the international Coordinated Universal Time (UTC), determined and maintained by the Time and Frequency Laboratory of Central Office of Measures (GUM - Główny Urząd Miar). The source of UTC(PL) is the national time and frequency standard – a set of atomic time and frequency standards with measuring systems for direct and remote comparisons of time scale as well as with supporting systems to ensure full functionality of the national standard, its uninterrupted work and supply maintenance . UTC(PL) is used not only to determine the legal time all over Poland, but it also constitutes the main reference scale for comparisons of atomic time and frequency standards maintained at Polish laboratories and participating in international atomic timescales TAI and UTC. It also constitutes the reference scale for the determination of metrological characteristics of the national time and frequency standard.

Firstly, for each clock compared to UTC(PL), you can calculate the value $z(t)$ = (UTC - *Clock*) for a given day on the basis of the difference $Z(t)$ = (UTC(PL) - *Clock*) obtained from measurements and the correction $x(t)$ = (UTC – UTC(PL)) determined for that day, according to the formula:

$$z(t) = x(t) + Z(t), \tag{2}$$

where $z(t)$ is the phase time of signal from the clock being compared with reference to UTC. Next, using the Eq. (1) you can determine the relative frequency deviation of its signals from nominal values, according to the formula:

$$y = \frac{z(t_1) - z(t_2)}{t_2 - t_1}. \tag{3}$$

Owing to that, every standard referred to UTC(PL) can also be directly referred to UTC, independently of the fact whether it contributes in TAI and UTC or not. In this way the traceability and high accuracy of these standards are maintained. The above solution is possible only for these measurement days for which the values UTC – UTC(PL) were published in [8]. Currently these are the days expressed in MJD (Modified Julian Date) which finish with the digit ‘4’ or ‘9’. Another disadvantage is that the results UTC – UTC(PL) are known with a delay of up to 45 days.

Secondly, very often referring the results of comparisons of the examined standard only to UTC(PL) should be satisfactory or applying such a reference is only possible, when quick information on the examined standard is necessary, when short-lasting measurements referred to UTC(PL) are being performed, when measurement days do not cover the days with values of correction or when the analysis has to be made before the corrections of UTC(PL) relative to UTC are known. Thus it is necessary to maintain UTC(PL) at an appropriate level of accuracy with reference to UTC (relative to value and slope), in addition the accuracy of UTC(PL) is monthly verified on the basis of published UTC – UTC(PL) corrections.

Due to the abovementioned facts, absolute continuity of realization, continuity of availability and high level of accuracy are required from UTC(PL). The continuity of UTC(PL) realization is ensured by continuous maintenance of at least 3 atomic clocks operating simultaneously. It allows to diminish the risk of losing the source of UTC(PL) signals in case of failure of the master clock as well as to continuously evaluate the quality of operation of the master clock (and remaining clocks), identifying abnormalities in their work. With only 2 atomic clocks it would not be possible to identify the clock whose signals became worse. The continuous availability of UTC(PL) at the highest level of accuracy is ensured by 24-hour-maintenance of the system to timescales comparisons using the GPS CV method and exchanging the measurement data. A significant role in this respect and in the improvement of stability and accuracy of UTC(PL) is performed by TA(PL) and the metrological cooperation connected with it. A very important role is also played by UTC(AOS), the second Polish physical realization of UTC, determined by the Astrogeodynamical Observatory (AOS) of the Polish Academy of Sciences at Borowiec. UTC(AOS) is the basis for conducting observations of Earth’s geodynamics and scientific researches into the development of time transfer systems. Corrections of UTC(PL) relative to UTC are also published in [8].

Omitting the initial period of realization of UTC(PL) in the 70-ties of the 20th century, when UTC(PL) was determined as a weighted average of the indications from atomic clocks placed in the Time and Frequency Laboratory of GUM, UTC(PL) is realized with a master clock and the 1 Hz pulse of UTC(PL) and is physically available on-line. Until October 2004, UTC(PL) had a reference point as a defined output of 1 Hz pulse of the atomic clock chosen as the master clock – usually taking into account the stability of its signals, operational reliability and predicted lifetime. When it was necessary to correct the signal of UTC(PL), one had to introduce the appropriate offset of frequency and/or time step of the 1 Hz pulse of the master clock. So, in the case of deterioration of the master clock operating parameters or because of the approaching end of its work caused by wear and tear of the caesium tube, the master clock had to be changed; prior to this a new master clock had to be synchronized, i.e. such a correction of its frequency and time phase of its 1 Hz pulse had to be performed as to ensure continuity and accuracy of determination of UTC(PL). However, introduction of the change of frequency offset may disturb the action of internal systems of the clock, so that the effect can be different from expected. The available resolution of correction is an additional difficulty (it amounts to 6.331991×10^{-15} for the HP5071A [9]).

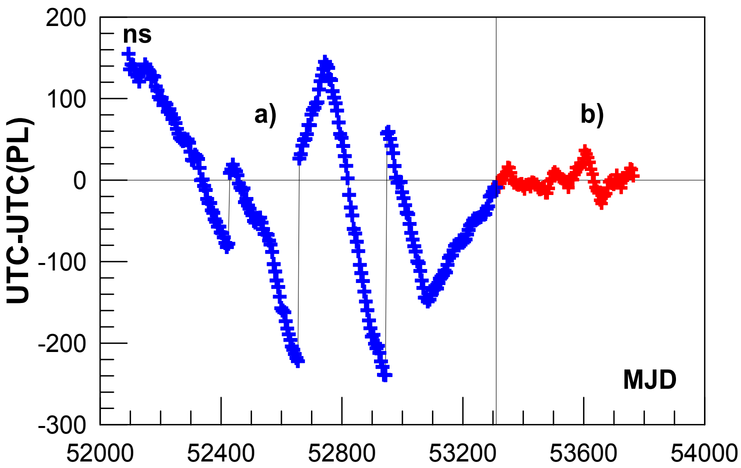

Fig. 1. UTC-UTC(PL) differences for UTC(PL) realized:
a) without micro-phase-stepper (curve with blue crosses),
b) with micro-phase-stepper (curve with red crosses).

A better solution is to apply a micro-phase-stepper (precise time phase shifter) and to perform the correction of UTC(PL) with such a device which has been realized since November 2004. In this configuration, the external 5 MHz sinusoidal signal taken from the master clock is being corrected with the micro-phase-stepper. This signal is being passed onto a frequency divider that generates a 1 Hz pulse signal on its output, and the reference point of UTC(PL) is defined at the output of this divider. The change of quality of UTC(PL) can be clearly observed in Fig. 1. Systems of physical realization of UTC(k) based on the micro-phase-stepper are used by most of laboratories [6].

UTC(k) should be maintained as closely to UTC as possible and a big problem with realization of timescale UTC(k) is its prediction, because due to the schedule of UTC calculation, the corrections (UTC – UTC(k)) are known with a delay of several to several dozen days. Different possibilities of UTC(PL) prediction are currently being considered [10]. One of them is assumed to consist of two stages. In the first stage, after publishing the corrections $x(t)$ = (UTC – UTC(PL)) for the previous month, the predicted value $x_p(t)$ = (UTC – UTC(PL))$_{pred}$ for the current day is calculated, according to the formula:

$$x_p(t) = at + b, \tag{4}$$

where a and b are the coefficients of the regression line fitted to the pairs of numbers $\{t_i, x(t_i)\}$ read from Circular T [8] allowing for reduction of possible time steps and frequency corrections of UTC(PL) introduced in that month, t - expressed in MJD day (or a fraction of a day) for which the predicted value is to be calculated.

On the basis of the slope of the regression line and the calculated predicted value $x_p(t)$ the current frequency correction of UTC(PL) can be established and introduced into the micro-phase-stepper, so that the predicted difference (UTC – UTC(PL)) is approaching zero.

In the second stage, for every clock contributing in comparisons with reference to UTC(PL), differences $z(t)$ = (UTC – Clock) for the previous month are determined according to the Eq. (2). Next, on the basis of linear predictions $z_p(t)$ = (UTC – Clock)$_{pred}$ calculated in an analogous way as $x_p(t)$ as well as current values $Z_p(t)$ = (UTC(PL) – Clock) obtained from comparisons, predicted values on the current day $x_{p\_Clock}(t)$ = (UTC – UTC(PL))$_{pred}$ are calculated according to the formula:

$$x_{p\_Clock}(t) = z_p(t) - Z(t). \tag{5}$$

As the final predicted value of (UTC – UTC(PL)) an arithmetic average taken from predictions $x_{p\_Clock}(t)$ is accepted. This value is obtained on the basis of several (e.g. 2, 3 or 4) chosen clocks with the lowest uncertainties of predictions during previous 3 months (Eq. (6)) which were not rejected as incredible in the current month. Assuming that the prediction error is the difference between the predicted value for a given day and the actual value on that day, the uncertainty of predictions for a given period is calculated according to the formula:

$$u(x_{p\_Clock}) = \sqrt{\frac{\sum_i \left(x_{p\_Clock}(t_i) - x(t_i)\right)^2}{n-1}}, \tag{6}$$

where n is the number of compared values $x_{p\_Clock}(t)$ and $x(t)$, t_i - moments for which actual values $x(t_i)$ are known within the analysed period. The reliability of prediction for a current month performed on the basis of a single clock is evaluated by determining the difference between the predicted values of this prediction and the arithmetic average taken from all predictions with the lowest uncertainties in the previous 3 months. If the absolute value of this difference exceeds the double value of the uncertainty of the prediction determined for that clock for the period of previous 3 months, such a prediction is rejected as incredible.

On the basis of arithmetic averages of predicted values $x_{p\_Clock}(t)$ calculated on the basis of chosen clocks, the new current frequency correction of UTC(PL) can be established and introduced into the micro-phase-stepper in such a way as to maintain the predicted (UTC – UTC(PL)) difference close to zero. Such a calculation of predicted UTC(PL) values for a current day and verification of effectiveness of the applied frequency corrections of UTC(PL) should be performed in one-week or two-week intervals. However, the effectiveness of this kind of prediction depends strictly on the stability of the master clock and even the very complex calculations do not guarantee success.

6. TA(PL)

Poland holds its own independent atomic timescale TA(PL). It has been determined since

August 1999 as a weighted average of indications currently from above 10 atomic clocks, including caesium clocks and hydrogen masers maintained and compared by some Polish public, scientific and commercial institutions and additionally by one Lithuanian institute. This timescale is determined on the basis of a scattered network of atomic clocks and timescale comparisons, which consists of the abovementioned laboratories equipped with atomic time and frequency standards as well as with time transfer systems with the use of the GPS CV method. These laboratories possess multi-channel time transfer system TTS-2 or its newer version TTS-3, developed at AOS Borowiec in cooperation with BIPM [11]. The systems enable to achieve standard uncertainty of type A at the level below 4 ns for remote comparisons of atomic clocks with reference to UTC(PL) and allow to link the clocks of these laboratories to contribute in TAI and UTC.

TA(PL) is calculated monthly by AOS Borowiec, but unlike the case of TAI and UTC, it is determined for every day. The exchange of measurement data is made every week and on initial days of every month. First, for every day of the analysed month the differences between UTC(PL) and indications of particular clocks contributing in TA(PL) are calculated at the defined moment of the day by use of regression line fitted to measurement data for the same day. Next, the differences (UTC(PL) – Clock) are recalculated allowing for the known slope of UTC(PL) and the rate of clock relative to TA(PL) for the previous month and for the known (TA(PL) – UTC(PL)) differences and (TA(PL) - Clock) for the last day of the previous month. On the basis of the analysis of clock's stability with reference to TA(PL) for the previous period, the weights are attributed to clocks following the accepted weighting procedure. Finally, the differences between TA(PL) and UTC(PL) are calculated as weighted averages for every day of the analysed month and corrections of clocks relative to TA(PL) are determined. A detailed description of the algorithm of determining TA(PL) is contained in paper [12].

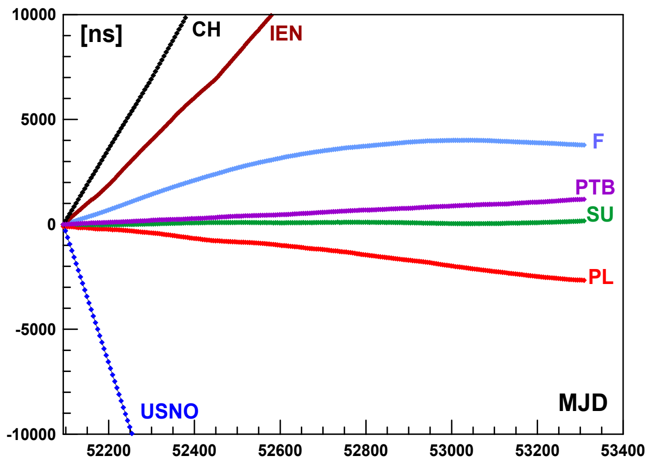

Figure 2. Illustration of the lack of accuracy of the independent atomic timescale (TAI-TA(k) differences shifted to 0 ns for MJD = 52094).

The basic feature of TA(PL), as well as of the remaining independent atomic timescales TA(k), is the long-term continuity of their determination and maintenance of their high stability, and the lack of their accuracy is an effect of their independence (Fig. 2 and 3). In this way, TA(PL) is a supplementary reference for clock stability analysis already at averaging period equal to 24 hours, and above all it systematizes and improves the quality of Polish atomic time and frequency standards' comparisons as well as unites the community and brings about the development of time and frequency metrology in Poland. It also enables the improvement of the stability and accuracy of UTC(PL) due to access to the wide set of measurement data, as mentioned in section 5.

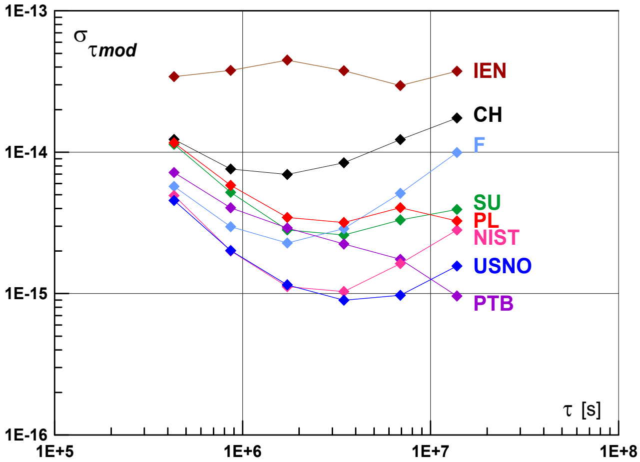

Figure 3. Comparison of stabilities of chosen independent atomic timescales (Modified Allan deviation calculated on the basis of TAI-TA(k)) differences.

It is also important that the contribution in TA(PL) obliges the contributing laboratories to ensure appropriate working conditions for their atomic clocks, to conduct appropriately their own clocks and systems to remote comparisons, to send regularly measurement data from remote and direct comparisons of their clocks to the remaining laboratories, as well as to pass information about the performed frequency corrections and time steps. In return, wide access to measurement data is ensured as well as the regular revision of accuracy and stability of every clock contributing in comparisons, the exchange of information about conducting atomic time and frequency standards and systems to comparisons and the support of specialists.

7. CONCLUSIONS

In order to realize precisely the SI second definition it is not enough to have caesium atomic time and frequency standards and hydrogen masers. It is also necessary to take part in creating the international atomic timescales TAI and UTC and to maintain physical realizations of coordinated universal time as closely to UTC as possible. It also requires conducting continuous comparisons of atomic clocks and timescales as well as cooperation among many laboratories. In Poland this is realized by the wide contribution in international atomic timescales TAI and UTC, generating physical realizations of coordinated universal time UTC(PL) and UTC(AOS) as well as by creating a scattered network of atomic clocks and timescales comparisons using the GPS CV method and calculating the Polish independent atomic timescale TA(PL). Many laboratories are involved in this process, which is still developing and requires constant improvements.

REFERENCES

1. *The International System of Units (SI)*. 7th edition, BIPM 1998, available on-line from www.bipm.org.
2. *The International System of Units. Supplement 2000: addenda and corrigenda to the 7th edition (1998).* BIPM 2000, available on-line from www.bipm.org.
3. Gill P., Barwood G.P., Klein H.A., Huang G., Wetster S.A., Blythe P.J., Hosaka K., Lea S.N., Margolis H.S.: *Trapped ion optical frequency standards*. Measurement Science and Technology, vol. 14, 2003, pp. 1174-1186.

4. Oskay W.H., Itano W.M., Bergquist J.C.: *Measurement of the* $^{199}Hg^+$ $5d^9 6s^2$ $^2D_{5/2}$ *Electric Quadrupole Moment and a Constraint on the Quadrupole Shift*. Physical Review Letters, vol. 94, 2005, pp. 1630001(4).
5. Peik W., Schneider T., Tamm Ch.: *Laser frequency stabilization to a single ion*. Journal of Physics B: Atomic, Molecular and Optical Physics, vol. 39, 2006, pp. 145-158.
6. *Annual Report of the BIPM Time Section*, vol. 17, Sevres, BIPM 2004.
7. Levine J.: *Time and frequency distribution using satellites*. Reports on Progress in Physics, vol. 65, 2002, pp. 1119-1164.
8. *BIPM Circular T* (monthly), available on-line from www.bipm.org.
9. *Operating and Programming Manual. HP5071A Primary Frequency Standard*. Hewlett-Packard Company, 1997.
10. Czubla A., Gadomski P., Konopka J.: *Realization of time and frequency units within measuring system of the national standard.* Podstawowe Problemy Metrologii. Prace Komisji Metrologii Oddziału PAN w Katowicach. Seria: Konferencje nr 8, Ustroń 2005, pp. 417-424 (in Polish).
11. Nawrocki J., Lewandowski W., Azoubib J.: *Time Transfer with GPS Multi-channel Motorola Oncore Receiver Using CCDS Standards*. Proc. of PTTI, vol. 29, 1997, pp. 319-328.
12. Azoubib J., Nawrocki J., Lewandowski W.: *Independent atomic timescale in Poland – organization and results*. Metrologia, vol. 40, 2003, pp. S1-S4.

REALIZACJA ATOMOWEJ DEFINICJI SEKUNDY SI W KONTEKŚCIE UTC(PL) I TA(PL)

Streszczenie

Przy realizacji atomowej definicji sekundy na najwyższym poziomie dokładności samo posiadanie atomowych wzorców czasu i częstotliwości nie wystarcza. Wymagane jest również prowadzenie szerokiej lokalnej i międzynarodowej współpracy laboratoriów czasu i częstotliwości. W celu zachowania wysokiej dokładności zegary atomowe powinny być w sposób ciągły ze sobą porównywane i niezbędny jest ich udział w tworzeniu międzynarodowych i lokalnych atomowych skal czasu. Z tego względu atomowe skale czasu UTC(PL) i TA(PL) pełnią istotną rolę w zachowaniu wysokiej dokładności pomiarów czasu i częstotliwości w Polsce. UTC(PL) stanowi główną skalę odniesienia dla porównań zegarów atomowych i skal czasu w Polsce i umożliwia im dowiązanie do UTC. Dlatego bardzo ważne jest utrzymywanie UTC(PL) jak najbliżej UTC, co jest procesem złożonym i wymaga prognozowania skali czasu UTC(PL) względem UTC. Z kolei wyznaczanie TA(PL), możliwe dzięki utworzeniu w Polsce rozproszonej sieci porównań zegarów atomowych przy użyciu metody GPS CV, stymuluje rozwój wyznaczania i prognozowania skal czasu, zobowiązuje laboratoria biorące udział w TA(PL) do prowadzenia regularnej współpracy na odpowiednio wysokim poziomie merytorycznym oraz gwarantuje regularną ocenę stabilności wzorców atomowych. Wszystkie te działania prowadzą do podnoszenia dokładności odtwarzania jednostek miar czasu i częstotliwości i są one w Polsce ciągle rozwijane i doskonalone.