Preliminary Study of TA1000: Performance and Time-Keeping Application

Hongqiang Du[1], Jianjun Gong[1], Wenjun Wu[1,2], Shaowu Dong[1,2], Shougang Zhang[1,2]

[1] National Time Service Center, Chinese Academy of Sciences, Xi'an 710600, China

[2] School of Astronnomy and Space Science, University of Chinese Academy of Sciences, Beijing, 100049, China

***Abstract*—The time-keeping system of National Time Service Center (NTSC) has shown rapid improvement in the difference between coordinated universal time (UTC) and local realization of universal coordinated time UTC(NTSC). Cesium atomic clock plays an important role in time-keeping system. Cooperated with a company, NTSC has successfully developed a new optically-pumped cesium atomic clock TA1000. This paper makes a preliminary study of TA1000 from two aspects: performance and time-keeping application. Compared with 5071A cesium atomic clock of Microsemi, the results demonstrate that TA1000 and 5071A perform at the same level in terms of frequency accuracy and frequency stability. TA1000 is a great substitute for the 5071A.**

***Keywords*—cesium atomic clock; timescales; frequency stability; frequency accuracy**

I. Introduction

Coordinated universal time (UTC) provides an excellent reference for precise time-keeping worldwide. Local timescale UTC(NTSC) is one of the physical realizations of the coordinated universal time [1]. The accurate measurement of UTC(NTSC) is vital to the success of many fields of science and technology, e.g. navigation and positioning [2]. National time service center (NTSC) has made great progress in frequency stability, and the difference between UTC(NTSC) and UTC is maintained within $\pm 3ns$ at present.

An ensemble of clocks is the basic towards the realization of UTC(NTSC). Commercial cesium clocks for the most part, and some Hydrogen Masers form the clock ensemble. Both commercial cesium atomic clocks and Hydrogen Masers contribute to the realization of timescales. Specifically, the cesium atomic clocks and Hydrogen Masers improve the long-term and short-term stability of timescales, respectively. Both have their own advantages, and are indispensable parts of time-keeping systems.

For more than three decades, cesium atomic clocks have been the backbone for time-keeping. Currently, many 5071A cesium atomic clocks of Microsemi are applied for the calculation of UTC(NTSC). To further improve the performance of UTC(NTSC), NTSC has cooperated with company and developed commercial cesium atomic clock TA1000. For the following section, we will introduce the optically-pumped cesium atomic clock TA1000, then analyze the performance and apply it to time-keeping, and finally conclude this paper.

II. Optically-pumped cesium atomic clock TA1000

A. *Cesium atomic clock TA1000*

Fig 1 shows the diagram of the optically-pumped cesium atomic clock TA1000. Based on the laser pumping theory and the laser detection technology, laser pumping miniature cesium atomic clock TA1000 can avoid traditional complex beam optics and magnetically selected, and life-limited electron multipliers. TA1000 has high precision, high reliability performance, and long life characteristics, which represents the direction of the development of the atomic clock technology. TA1000 can be used in high precision time-keeping, digital communication, power synchronization, and time-frequency metrology.

Fig. 1. Diagram of the optically-pumped cesium atomic clock TA1000.

B. *Performance metrics*

Frequency accuracy and frequency stability are the key indicators for a cesium atomic clock. Frequency accuracy describes the degree of conformity of a measured frequency to its definition, which is related to the offset from an ideal value.

Frequency stability describes the degree of an oscillating signal that produces the same frequency for a specified interval of time, which indicates whether the frequency stays the same.

The formula of frequency accuracy is expressed as follows:

$$f = -\frac{\Delta t}{T} \tag{1}$$

where T is the phase measurement period, and Δt is the amount of phase deviation.

Allan variance [3] is an effective algorithm to evaluate the frequency stability. For the atomic clock, it is estimated on discrete samples of the phase deviation. τ_0 is the minimum observation intervals, let averaging time τ be a multiple of τ_0, $\tau = k\tau_0$, k is the averaging factor. The discrete-time Allan variance is expressed as follows:

$$\sigma_y^2[k] = \frac{1}{2\tau^2}\frac{1}{N-2k}\sum_{n=0}^{N-2k-1}(x[n+2k]-2x[n+k]+x[n])^2 \tag{2}$$

where N is the number of sampling data.

C. Data and results analysis

There are four cesium atomic clocks TA1000 in the NTSC, marked as TA-A, TA-B, TA-C and TA-D respectively. We compare TA1000 with the 5071A cesium primary frequency standard in terms of frequency accuracy and frequency stability. The phase comparison data between clock and UTC(NTSC) is chosen from the modified Julian date (MJD) 59990 to 60064. The UTC(NTSC) is used as the reference to evaluate the TA1000.

TABLE I
THE FREQUENCY ACCURACY OF EACH CESIUM ATOMIC CLOCK

	TA-A	TA-B	TA-C	TA-D	5071A
Avg	1.43E-14	2.61E-13	1.89E-13	2.00E-14	1.10E-13

Table I shows the frequency accuracy results of each cesium atomic clock. In terms of frequency accuracy, TA-B and TA-C perform on the same level as 5071A, TA-A and TA-D are better than 5071A. The results demonstrate that TA1000 is on the same level of frequency accuracy as 5071A.

TABLE II
THE ALLAN DEVIATION ESTIMATIONS OF EACH CESIUM ATOMIC CLOCK

	TA-A	TA-B	TA-C	TA-D	5071A
1h	9.95E-15	1.37E-13	1.16E-13	1.25E-14	1.33E-13
1d	1.11E-15	3.00E-14	2.36E-14	1.12E-15	2.67E-14
5d	7.99E-16	1.60E-14	1.20E-14	4.66E-16	1.06E-14

Table II reports frequency stability results of each cesium atomic clock with overlapping Allan deviation. The Allan deviation of clock with respect to UTC(NTSC) at 1 hour shows that TA-B and TA-C perform similarly as 5071A. TA-A and TA-D are better than 5071A, which indicates that TA1000 is comparable with 5071A at 1 hour. Similar results are observed at 1 day and 5 days respectively. The frequency stability results demonstrate that TA1000 is on the same level of frequency stability as 5071A.

III. TIME-KEEPING

The atomic time scale is calculated with clock readings through an algorithm designed to optimize the frequency stability and accuracy. ALGOS [4, 5] is one of the typical time scale algorithms. We use an ALGOS-like algorithm to calculate time scale.

A. ALGOS-like algorithm

The general equation for defining local free atomic time scale (TA) [6] is given by the equation:

$$TA(t) = \sum_{i=1}^{N} w_i[h_i(t) + h_i^{'}(t)] \tag{3}$$

where N is the number of participating clocks during the interval of calculation, w_i is the relative weight of clock i. $h_i(t)$ is the reading of clock i. $h_i^{'}(t)$ is the prediction of the reading of clock i that serves to guarantee the continuity of the time scale at time t.

As the data take the form of time differences between readings of clocks, the data used is written as:

$$x_{ij}(t) = h_j(t) - h_i(t), i = 1, 2, \cdots N, i \neq j \tag{4}$$

The solution of TA is

$$x_j(t) = TA(t) - h_j(t) = \sum_{i=1}^{N} w_i[h_i^{'}(t) - x_{i,j}(t)] \tag{5}$$

where

$$h_i^{'}(t) = a_i(t_0) + B_{ip}(t - t_0) \tag{6}$$

$$w_i = \frac{{}^{1}\!/\!{}_{\sigma_i^2}}{\sum_{k=1}^{N} {}^{1}\!/\!{}_{\sigma_k^2}} \tag{7}$$

where $a_i(t_0)$ is the time correction relative to TA of clock i at date t_0, $B_{ip}(t - t_0)$ is the frequency of clock i relative to TA, predicted for the period $[t_0, t]$. σ^2 is individual classical variance computed from its frequency relative to TA.

B. Results analysis

The data of the clock ensemble are transferred to the bureau international des poids et mesures (BIPM) to calculate the rapid coordinated universal time(UTCr) [7] on each modified Julian date (MJD), and this makes it an excellent reference for time and frequency in scientific applications. We select four 5071A clocks as a clock ensemble, similarly for four TA1000 clocks, and compare frequency stability of the free local atomic time scale (TA) calculated with different clock ensembles. Both the UTCr and the UTC(NTSC) are used as the reference to evaluate the TA1000 clocks.

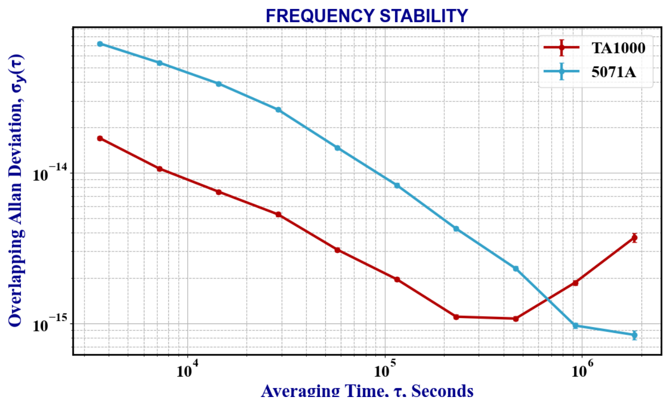

Fig. 2. The frequency stability analysis of UTC(NTSC)-TA with data-sampling interval of 1 hour.

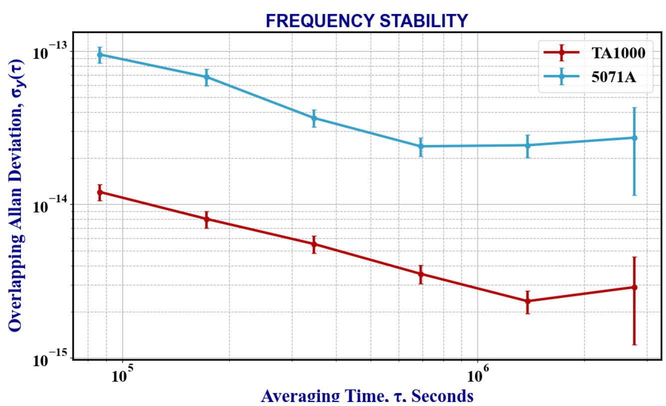

Fig. 3. The frequency stability analysis of UTCr-TA with data-sampling interval of 1 day.

Fig 2 shows the frequency stability analysis of UTC(NTSC)-TA with a data-sampling interval of 1 hour. We observe that the clock ensemble consisting of TA1000 clocks performs better than 5071A clock ensemble. When the data-sampling interval increases to 1 day, shown in Fig 3, the clock ensemble with TA1000 also performs better than that with 5071A. The results validate that TA1000 and 5071A are on the same level in terms of frequency stability.

IV. CONCLUSIONS

Cooperated with company, NTSC has successfully developed optically-pumped commercial cesium atomic clock TA1000, which represents the direction of the development of the atomic clock technology. This paper makes a preliminary study on its performance and time-keeping application. The results demonstrate that TA1000 and 5071A perform similarly in terms of frequency accuracy and frequency stability. TA1000 is a great replacement for the 5071A cesium atomic clock of Microsemi.

REFERENCES

[1] P. B. Whibberley, J. A. Davis, and S. L. Shemar, "Local representations of utc in national laboratories," *Metrologia*, vol. 48, no. 4, p. S154, 2011.

[2] S. Dong, W. Wu, and S. Zhang, "Construction and application of beidou time system," in *China's e-Science Blue Book 2018*. Springer, 2020, pp. 187–204.

[3] D. W. Allan and J. Levine, "A historical perspective on the development of the allan variances and their strengths and weaknesses," *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 63, no. 4, pp. 513–519, 2016.

[4] G. Panfilo, A. Harmegnies, and L. Tisserand, "A new prediction algorithm for the generation of international atomic time," *Metrologia*, vol. 49, no. 1, p. 49, 2011.

[5] G. Panfilo, A. Harmegnies, and L. Tisserand, "A new weighting procedure for utc," *Metrologia*, vol. 51, no. 3, p. 285, 2014.

[6] G. Panfilo and E. F. Arias, "Algorithms for international atomic time," *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 57, no. 1, pp. 140–150, 2009.

[7] G. Petit, F. Arias, A. Harmegnies, G. Panfilo, and L. Tisserand, "Utcr: a rapid realization of utc," *Metrologia*, vol. 51, no. 1, p. 33, 2013.