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UPGRADING OF UTC(CRL)

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Abstract - **The problems in the current UTC(CRL) were solved. One problem was a large variation of frequency when a clock was withdrawn from the ensemble, which was caused by an inadequately predicted frequency of each cesium clock in the ensemble. We succeeded in solving this problem by changing the definition of the predicted frequency. Another problem was a variation in the daily-steering frequency of the UTC(CRL). We found that this problem was caused by a large variation in the measured time offset between the clocks. Improving the measured value was not easy, so we adopted a moderate adjustment and thereby succeeded in solving it. These solutions improved the frequency stability of the UTC(CRL).**
Keywords – ensemble time scale, UTC(CRL)

I. INTRODUCTION

The Communications Research Laboratory (CRL) has a long history as an institute, one that has been researching time and frequency standards. We also are responsible for the Japan Standard Time (JST) and UTC(CRL). In the early 1960's, an NH_3 maser and a hydrogen maser were developed at CRL and used as primary frequency standards. Crystal oscillators were used as a source of the UTC(CRL) at first, and cesium clocks have been used since 1969. In those days, the master-clock method was adopted. In 1985, an original GPS receiver was developed and the time comparison to the UTC became available, and then the clock data at CRL began to contribute to TAI. In 1986, the generative method of the UTC(CRL) was changed from the master-clock method to the ensemble-clock method. The current UTC(CRL) is generated from the ensemble of more than ten cesium clocks at CRL's headquarters and is used as the reference for the JST and for the national frequency standard. The generative system of the UTC(CRL) has been used since 1986, and some minor-changes in hardware have been made. However, the basic algorithm has not been changed for more than 15 years.

The UTC(CRL) described earlier has been operating well, but some problems have emerged as the progress of atomic clocks and measurement equipments. One is a large drift when a clock is withdrawn from the ensemble. It degrades the long-term frequency stability. Another problem is a large variation in the daily-adjusting frequency of the UTC(CRL). It degrades the short-term frequency stability. We have endeavored to solve these problems in achieving a highly stable UTC(CRL) and have succeeded in finding their causes and solutions.

In this paper, we introduce the current UTC(CRL) generative system in Section II and describe the causes of the problems and their solutions in Section III.

II. GENERATIVE SYSTEM OF UTC(CRL)

A. Outline of the system

Fig. 1 shows the occurrence process of the UTC(CRL) and its generative system. Twelve commercial cesium clocks of "HP5071A" are in the electromagnetic shielded room at CRL's headquarters. We obtain the time differences between these cesium clocks from one-shot measurements of 1 pps signals by the time interval counter. From those data, the ensemble time is calculated once a day by using the algorithm described in Section II-B. Because this ensemble time is from a paper clock, we need an "auxiliary output generator (AOG)" as a frequency adjuster to achieve this ensemble time. The AOG, referred to as a cesium clock, is automatically steered once a day so that it follows the ensemble time scale. The output 1 pps and 5 MHz signals from the AOG are used as the UTC(CRL). We have two equivalent systems, and one of them is used for a backup. The time differences between the UTC(CRL) and the UTC are monitored by the GPS-

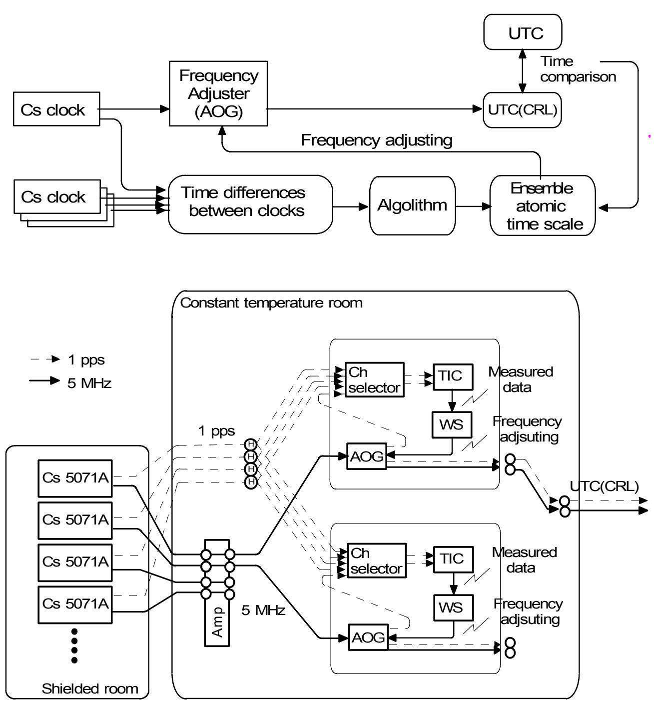

Fig. 1. Process of occurrence of UTC(CRL) and block diagram of generative system. "WS" is a work station, and "TIC" is a time interval counter.

common-view method and two-way-satellite-time-and-frequency-transfer method and are reported by the "Circular T" published by the Bureau International des Poids et Mesures (BIPM) [1]. If this time difference between the UTC and the UTC(CRL) increases, we sometimes adjust the AOG intentionally to trace the UTC.

Fig. 2 shows the UTC(CRL) relative to the UTC in 2001 and 2002 derived from the Circular T. The inserted comments show events such as the clock exiting and the intentional adjusting of the AOG.

B. Ensemble calculation method

The UTC(CRL) algorithm is similar to that of the real-time time scale AT1(NIST), of which the basic method is described by [2] and [3]. Our calculation method is described next.

The ensemble atomic time $TA(t)$ is theoretically defined as

$$TA(t) = \sum_{i=1}^{N} w_i(t)\, h_i(t), \qquad (1)$$

where $h_i(t)$ is the reading of the clock "i" (indicating the time offset of the clock "i" from the ideal time), and $w_i(t)$ is the weight. The suffix "i" represents each clock. $TA(t)$ is likely to change greatly in this definition if a clock exits from the ensemble. Therefore, the next definition is adopted in the real calculation:

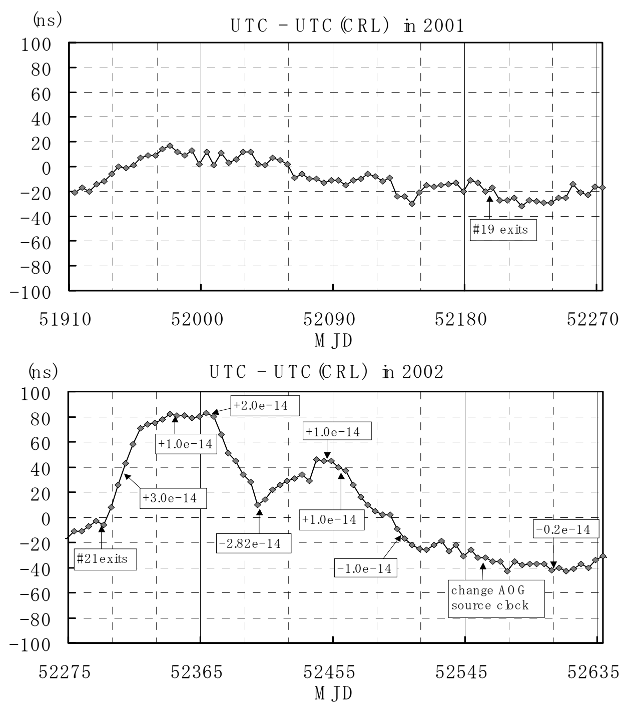

Fig. 2. UTC(CRL) relative to UTC in 2001 and 2002. Inserted comments show events and intentional adjusting of AOG to trace UTC.

$$TA(t) = \sum_{i=1}^{N} w_i(t)\{\, h_i(t) - x'_i(t)\}, \qquad (2)$$

where $x'_i(t)$ shows the predicted time offset of clock "i" from the past ensemble time. This equation indicates that the ensemble time scale consists of the accumulation of the time-offset-prediction-error. We define $x'_i(t)$ by using the predicted frequency $y'_i(t)$:

$$x_i'(t) = x_i\,(t_0) + y'_i(t)(t - t_0), \qquad (3)$$

where t_0 is the time of the previous ensemble calculation, $x_i(t_0)$ is the time offset of the clock "i" from the ensemble time at time t_0, and $y'_i(t)$ is the predicted frequency of the clock "i" estimated from the previous time interval. The calculation interval is T=86400 s (= 1day), and $t=t_0+T$.

The predicted frequency $y'_i(t)$ is determined as

$$\begin{aligned} y'_i(t) &= y'_i(t_0), && \text{if } |y10'_i(t) - y'_i(t_0)| =< 10^{-12} \\ y'_i(t) &= y10'_i(t)/\{1 - w_i(t)\}, && \text{if } |y10'_i(t) - y'_i(t_0)| > 10^{-12}. \end{aligned} \qquad (4)$$

Hereafter, we call the drift rate relative to $TA(t)$ as "rate". The rate $y10'_i(t)$ is calculated from the last 10 days: $y10'_i(t)=\{x_i(t)-x_i(t-10T)\}/10T$, and $y'_i(t)$ is initially determined over the 60 days after the epoch when the clock "i" entered the clock ensemble.

The weight $w_i(t)$ is calculated as

$$w_i(t) = (1/\sigma_i^2) \,/\, \Sigma(1/\sigma_i^2), \qquad (5)$$

where σ_i is the unbiased Allan variance[4] at the averaging time of 10 days of the clock "i". The maximum weight is limited to 0.3 when more than 7 clocks exist in the ensemble.

We cannot know the ideal time scale, thus we cannot obtain the real value of $h_i(t)$. Therefore, we estimate $TA(t)$ by using $x_i(t)$, which is the time offset of the clock "i" from the ensemble time, as

$$TA(t) = h_i(t) - x_i(t). \qquad (6)$$

The time offset $x_i(t)$ cannot be obtained by a direct measurement. It is indirectly obtained from the time differences X_{ij} between the clocks "i" and "j".

$$X_{ij}(t) = h_i(t) - h_j(t) = x_i(t) - x_j(t). \qquad (7)$$

We select one clock as a measurement reference clock (MRC) that is expressed by the suffix "s". The following relation is obtained from (2), (6), and (7):

$$\begin{aligned} x_s(t) &= h_s(t) - \sum_{i=1}^{N} w_i(t)\{h_i(t) - x'_i(t)\} \\ &= \sum_{i=1}^{N} w_i(t)\{\, x'_i(t) + X_{si}(t)\}. \end{aligned} \qquad (8)$$

Meanwhile, the time offset $x_s(t)$ of MRC is obtained from (8), and $x_i(t)$ is obtained by using $x_s(t)$:

$$x_i(t) = x_s(t) - X_{si}(t), \qquad (9)$$

We now obtain the set of $x_i(t)$. This set of $x_i(t)$ is used in the calculation of the next time interval.

UTC(CRL) is the realization of the ensemble time $TA(t)$. UTC(CRL) is obtained from the output of AOG, and this signal is not completely equal to the calculated $TA(t)$. Therefore, we must adjust the AOG to cancel this small difference between the UTC(CRL) and $TA(t)$ once a day. $TA(t)$ is expressed by using the time difference $X_{sA}(t)$ between the MRC and the AOG:

$$TA(t) = h_A(t) - x_A(t) = h_A(t) - \{x_s(t) - X_{sA}(t)\}, \qquad (10)$$

where the suffix "A" expresses the AOG. $h_A(t)$ is the reading of the AOG, and at the same time, indicates the UTC(CRL). If we correct the AOG output $h_A(t)$ by the value of $\{x_s(t) - X_{sA}(t)\}$, the AOG output, that is, UTC(CRL) will achieve $TA(t)$. But this correction is not enough. We must keep UTC(CRL) until the next day because the AOG adjustment is only performed once a day. It means that UTC(CRL) on the next day should be equal to $TA(t)$. The AOG frequency drifts in accordance with the frequency of the referred source clock "a", and we add the adjusting frequency to the AOG. Therefore the AOG output on the next day is expressed as

$$h_A(t+T) = \{h_A(t) + y'_a(t)T\} + y_{adj}(t)T, \qquad (11)$$

where $y'_a(t)$ is the rate of the AOG referred source clock "a", and $y_{adj}(t)$ is the adjusting frequency set to the AOG. We define $y_{adj}(t)$ from (10) and (11) so as to $h_A(t+T)$ is equal to $TA(t)$:

$$y_{adj}(t) = \{X_{sA}(t) - x_s(t)\} / T - y'_a(t). \qquad (12)$$

To prevent the reckless running of the AOG due to abnormal events, The maximum of $y_{adj}(t)$ is limited to 8×10^{-12}.

As shown in the next section, the definitions of $y'_i(t)$ in (4) and $y_{adj}(t)$ in (12) used in the UTC(CRL) algorithm had caused the problems.

III. Improvements of the Problems

A. Large drift by a clock-exit from the ensemble

We experienced a large drift in UTC–UTC(CRL) in 2002 (Fig. 2), which was caused by a clock exiting from the ensemble. Such a problem sometimes occurred while the UTC(CRL) was operated for a long term, but the reason was not clear. We checked the calculation process carefully and found it.

When a clock "k" exits from the ensemble, $TA(t)$ will change by $w_k(t)\{h_k(t) - x'_k(t)\}$ from (2). If the predicted value $x'_k(t)$ is not suitable, the error $h_k(t) - x'_k(t)$ increases, and the absence of the clock "k" causes a large drift in $TA(t)$. The predicted value $x'_k(t)$ is defined by (3) using the predicted rate $y'_k(t)$. According to (4), $y'_k(t)$ is not renewed by the latest value if the difference from the previous value does not go over the limit of 1×10^{-12}. As a matter of fact, this definition of $y'_k(t)$ is not suitable. The limit of 1×10^{-12} is too large for the cesium clock HP5071A, thus $y'_k(t)$ hardly reflects the latest suitable value.

Instead of $y'_i(t)$, we put the rate estimated over the last 30 days, $y30'_i(t)$, to trial.

$$y30'_i(t) = \{x_i(t) - x_i(t - 30T)\} / 30T \qquad (13)$$

We selected this time span because commercial cesium clocks usually show the best frequency stability in around 30 days. By using $y30'_i(t)$, we calculated a test time scale named RTA30. By using this time scale and UTC, we investigated the influence of the clock exiting from the ensemble. Fig. 3 shows the comparison of their simulation results. The lines of the $\mathrm{UTC(CRL)}_{\text{without-k}}$ and $\mathrm{RTA30}_{\text{without-k}}$ were obtained after removing the clock "k" from the ensemble. The difference between the RTA30 and $\mathrm{RTA30}_{\text{without-k}}$ are much smaller than that of the UTC(CRL) and $\mathrm{UTC(CRL)}_{\text{without-k}}$. We changed the removing clocks and obtained the same tendencies. We also tested $y10'_i(t)$ and $y60'_i(t)$, which are the 10-day and the 60-day rates respectively. However, $y30'_i(t)$ is the best among them.

From these results, we conclude that the use of the new rate $y30'_i(t)$ instead of $y'_i(t)$ is very effective in suppressing the influence of the withdrawal of a clock from the ensemble.

B. Large variation in the daily adjusting frequency of AOG

Another problem is associated with the daily adjusting frequency $y_{adj}(t)$ of the AOG. Fig. 4 shows the variation in $y_{adj}(t)$ from the previous day. The value of $y_{adj}(t) - y_{adj}(t_0)$ was sometimes larger than 1×10^{-13}, which is over the

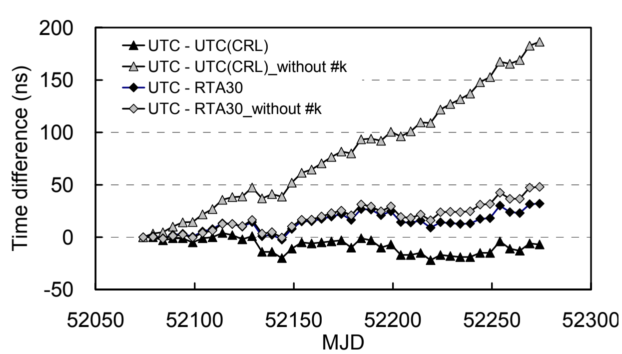

Fig. 3. Simulation of clock exiting about the current UTC(CRL) and test time-scale RTA30. The reference time scale is UTC. The suffix "without-k" indicates clock "k" is removed from ensemble.

frequency stability of HP5071A at one day. If this change becomes much smaller, we can improve the frequency stability of UTC(CRL) at one day.

To find the reasons for this problem, we investigated the components of $y_{adj}(t)$. As shown in (12), $y_{adj}(t)$ consists of three components: $X_{sA}(t)$, $x_s(t)$, and $y'_a(t)$. Fig. 5 shows the variations in these terms. Among them, we found that $X_{sA}(t)$ is most unstable and is the main cause of the variation in $y_{adj}(t)$. It is reasonable that $X_{sA}(t)$ has large measurement noise and short-term instability because $X_{sA}(t)$ was obtained by the one-shot measurement of 1 pps. However, improving the quality of $X_{sA}(t)$ directly is not easy because the hardware and operation processes need to be changed. Therefore, we tried to find another solution.

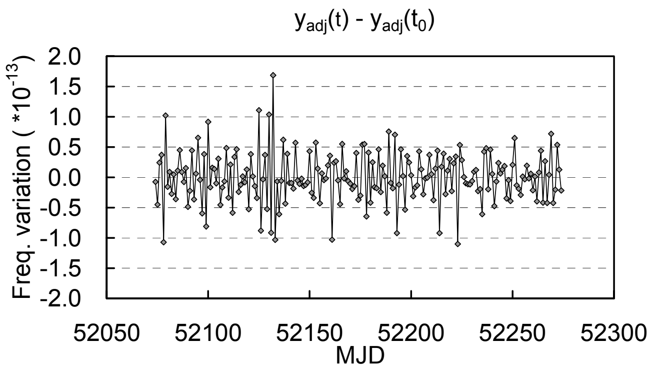

Fig. 4. Variation of adjusting frequency of AOG. Difference from value of previous day is plotted.

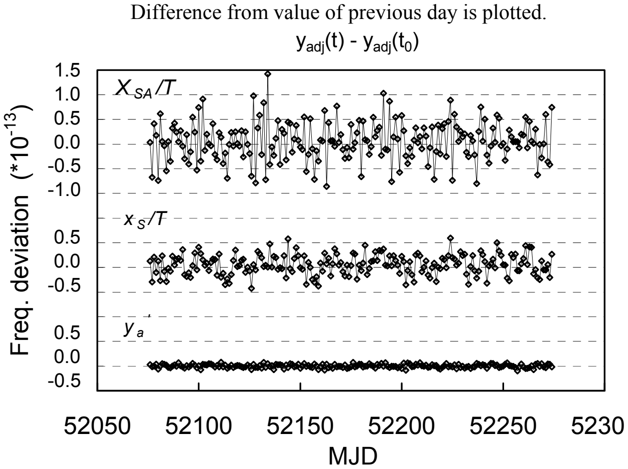

Fig. 5. Variation of components of adjusting frequency of AOG. Difference from value of previous day is plotted.

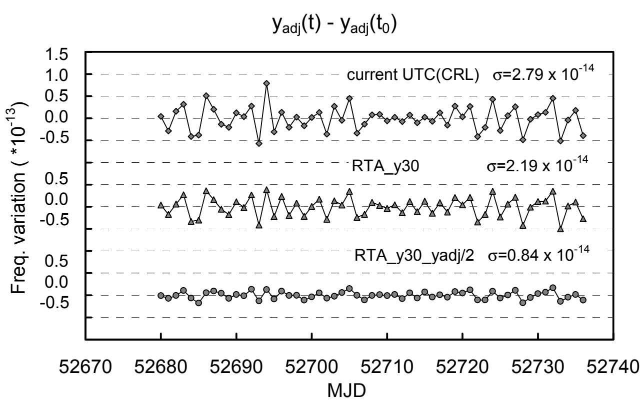

Fig. 6. Variation of adjusting frequency of AOG in UTC(CRL) and test time scales RTA30 and RTA30_yadj/2. The difference from the value of the previous day is plotted.

First, we tried to improve the instability in $X_{sA}(t)$ by smoothing them. The measurement is carried out every four hours, and we take six samples of data in one day. We used the linear-fitted $X_{sA}(t)$ from these six samples instead of the one-shot $X_{sA}(t)$, but the results was not improved. We tried to use a lot of data for the fitting, the results were worse. It seemed the measured $X_{sA}(t)$ did not behave like white noise, and the instability was enhanced in this method. Therefore we gave up smoothing of $X_{sA}(t)$ and sought another way.

Next we tried a moderate adjustment. We found that $y_{adj}(t) - y_{adj}(t_0)$ tended to repeat a plus/minus every other day. It meant that the daily adjusting value was overestimated (due to the instability of $X_{sA}(t)$). Therefore, we made $y_{adj}(t)$ half. Fig. 6 shows the results of this test. RTA30 was the test time-scale using the new rate $y30'$, and RTA30_y_{adj}/2 was the test time-scale using the new rate $y30'$ and half y_{adj}. The value of $y_{adj}(t) - y_{adj}(t_0)$ was smallest in RTA30_y_{adj}/2, which meant this moderate adjustment was effective in suppressing the variation in $y_{adj}(t)$.

C. Frequency stability of the improved time scales

To test the effects of the two aforementioned solutions, we calculated the Allan deviations of the following three time scales; current UTC(CRL), RTA30, and RTA30_y_{adj}/2. The reference frequency was derived from a hydrogen maser. Fig. 7 shows the results. The frequency stability of RTA30 was better than that of the current UTC(CRL) in the whole range. The frequency stability of RTA30_y_{adj}/2 was better than that of RTA30 in one day, and the same as that of RTA30 in a longer range. These results are reasonable. We adopt a new rate definition for RTA30, which makes the predicted error small and decreases the frequency stability in both the short and long terms. We adopt a moderate adjustment in the daily

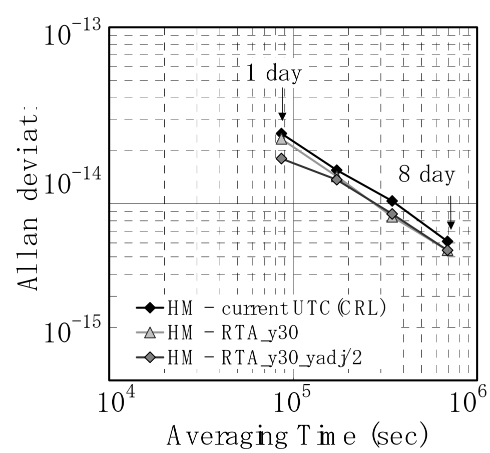

Fig. 7. Allan deviation of UTC(CRL) and test time scales RTA30 and RTA30_yadj/2 relative to hydrogen maser.

steering of the AOG for RTA30_y_{adj}/2, which suppresses the instability at one day but does not affect the frequency stability in the other range. We conclude that both solutions are effective for upgrading the UTC(CRL).

IV. Summary and Future Plan

We had two problems in the current UTC(CRL): one was a large drift when a clock exits from the ensemble, and the other was a large variation in the daily adjusting frequency of the AOG. The former problem occurred because of an inadequate definition of predicted frequency. We changed the definition to reflect the latest status of clocks, and succeeded in suppressing the influence of the clock exiting. The latter problem involved instability in the measured time differences of the clocks used for the calculation of the adjusting frequency. However, improving the quality of the measured value directly was not easy. Thus we adopted a moderate adjustment, which made the adjusting frequency half. We successfully suppressed the large variation in the adjusting frequency. It was shown that the frequency stability of the UTC(CRL) was improved in the averaging period from one to eight days by adopting these solutions. If both solutions are adopted in the UTC(CRL), the frequency stability will be better in both the short and long term. The upgraded UTC(CRL) is being tested in the backup system and is going to be applied soon to the working system.

In addition to the upgrades in the current system, we have commenced the construction of a new generative system for the UTC(CRL). A few hydrogen masers are going to be introduced as the source of the standard frequency, which will improve the short-term stability of the UTC(CRL). A multi-channel DMTD system is also going to be used for simultaneously measuring clocks, which will be effective in suppressing measurement errors. A frequency drift of the UTC(CRL) relative to the UTC will be automatically adjusted by using the data published in the Circular-T report. To realize such adjustment, a good way of UTC(CRL)-prediction with a high stability during one month should be developed. As the first step, we have started an investigation to estimate the drift of a hydrogen maser using a cesium ensemble time as a reference.

Acknowledgments

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