The New Generation System of Japan Standard Time at NICT

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***Abstract*— NICT has completed a new generation system for the realization of Japan Standard Time. There are various renewals in this system. One of the big changes is the introduction of hydrogen masers as signal sources for UTC(NICT) instead of Cs atomic clocks. This greatly improves the short-term stability of UTC(NICT). Another big change is the introduction of a newly developed 24ch dual-mixer-time-difference system (DMTD) as the main tool for measurements. The reliability of the system is also improved by enhanced redundancy and monitoring systems. The new JST system is in regular operation since February 2006.**

I. INTRODUCTION

Japan Standard Time (JST) is generated by the National Institute of Information and Communications Technology (NICT). JST is defined as UTC(NICT) + 9 hours, where UTC(NICT) is a local timescale generated by NICT so as to follow the UTC (Coordinated Universal Time). NICT is continuously generating UTC(NICT) from atomic clocks at the Koganei headquarters. It has been stably realized by a generating system of JST (JST system) with high measurement precision and high reliability.

A change of the JST system is a big effort because JST should be kept continuously any time. Some improvements of the system are, however, necessary as techniques progress. The JST system experienced changes three times since the first one became operational in 1976. They were in 1987, 1995, and 1999 [1]. Afterwards, a new building for time and frequency facilities was planed to be built, and development of the fifth JST system was decided on this occasion.

The project of developing this new JST system was started in 2002. Various renewals were implemented in the whole system. For example, hydrogen masers were introduced as the signal source of JST instead of Cs atomic clocks to improve the short-term frequency stability of JST. Newly developed 24-ch Dual Mixer Time Difference (DMTD) systems are effective for highly precise measurements. High redundancy of main units and a new monitoring system contribute to enhance the systems' reliability. A regular operation started on February 2006 and has been kept over one year without major troubles.

In this paper, the basic configuration of JST system is outlined in Section II, and details of the new system are described in Section III. The regular operation performance is introduced in Section IV.

II. HOW IS JST GENERATED?

Fig. 1 shows a basic configuration of the former and the new JST system. The basis of JST is an average atomic time calculated from an ensemble of Cs atomic clocks [2]. We call this time scale "NICT ensemble time" (NET) here. NET is calculated from the regularly measured time differences between the clocks. Since NET is merely a paper-clock, an oscillator is required as the source of actual signals. As the oscillator, we use the output of an atomic clock (we call it "source clock") steered by a Symmetricom's Auxiliary Output Generator (AOG). Two output 5 MHz and 1 PPS (pulse per sec) signals of the AOG are used as the actual signals of UTC(NICT). The former signal is used as the frequency reference and the latter is used as the timing reference. The AOG is regularly steered to make UTC(NICT) follow NET. The values of UTC - UTC(NICT) every 5 days are also published in a monthly report "Circular-T" by the Bureau International des Poids et Mesures (BIPM). The AOG is also adjusted occasionally so that the time difference between UTC(NICT) and UTC is kept within 10 ns.

III. NEW JST SYSTEM

The block diagram of the new JST system is shown in Fig. 2. The new system is based on the configuration in Section II. Though the structure is similar with the former system [1], devices and data processing are largely changed. We describe the details of the new system as compared with the former one.

A. Clocks

The new system has 18 Cs atomic clocks (5071A with high performance tube, Symmetricom) and 4 hydrogen

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masers (RH401A, Anritsu Corp.). The Cs atomic clocks are used for making NET, and the hydrogen masers are used as the source clock of UTC(NICT). This is the first attempt to use hydrogen masers in the JST system. In the former system, a Cs atomic clock was used as the source clock. This change of source clock improves a short-term frequency stability of UTC(NICT) of about a factor of 100. The long-term stability of UTC(NICT) is assured by NET.

Specifications of the Anritsu hydrogen maser RH401A are shown in Table 1, and its frequency stabilities measured by the new system are shown in Fig. 3.

B. Measurement system

In the former system, time intervals between 1 PPS signals of clocks were measured with a time-interval (TI) counter as the time differences between the clocks. One clock was settled as the reference clock. The signals of the other clocks were selected by a mechanical switch one after another, and their time differences from the reference clock were serially measured. The measured value was obtained after a one-shot measurement without averaging.

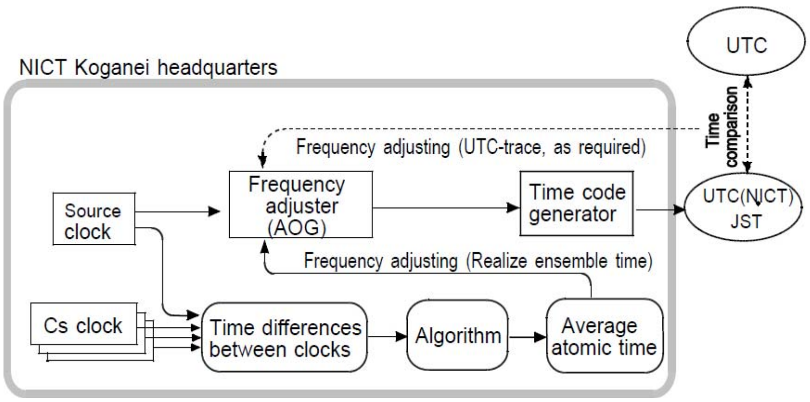

Figure 1. Configuration of the former and the new JST system.

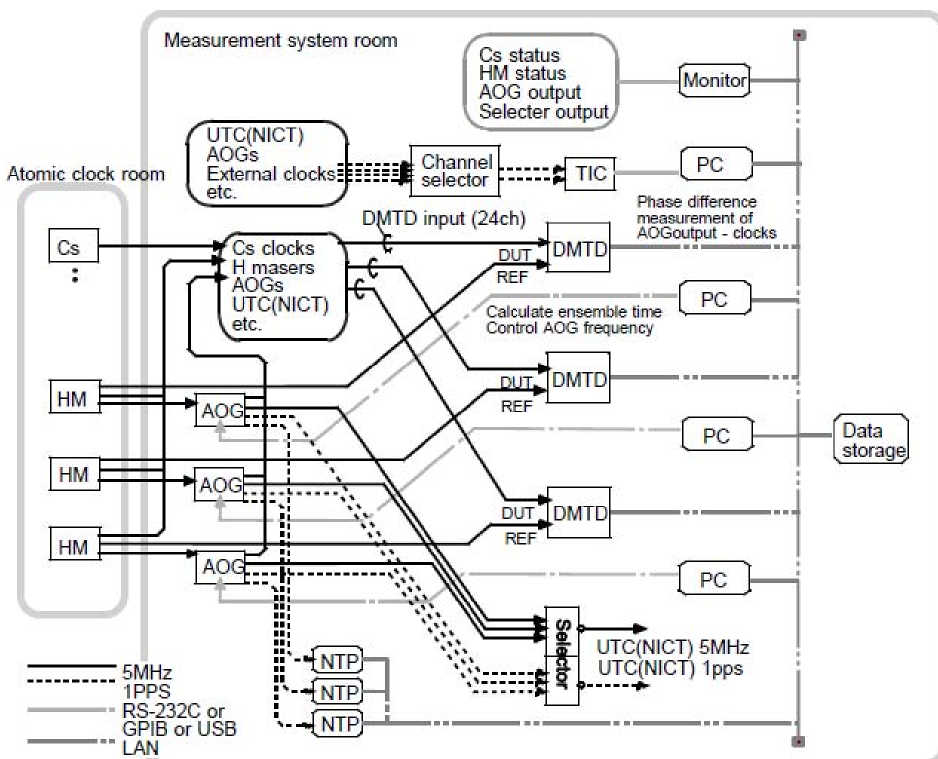

Figure 2. Block diagram of the new JST system.
"HM" is a hydrogen maser, "TIC" is a TI counter, and "PC" is a computer.

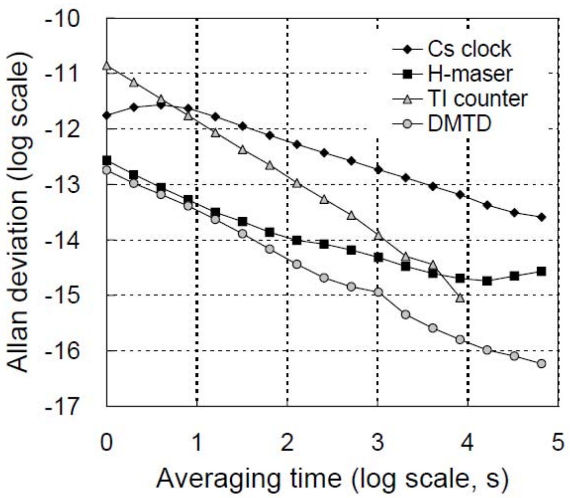

Figure 3. Frequency stabilities of atomic clocks and system noise of measurement devices.

This method was simple but had plenty room for improvement. Firstly, higher frequency signals are desirable for a precise measurement. Secondly, the simultaneous measurements are better for the construction of an average atomic time.

To solve the problems, 24ch-DMTD systems (DMTD5, Japan Communication Equipment Co., Ltd.) were newly developed for the new system [6]. They are main tools for the measurements. Though a DMTD system is a well known method for a precise measurement of time difference [3][4][5], multi-channel devices are not so wide spread. Our DMTD5 solved the time lag problem in the measurements of many clocks as well as the precision problem.

A specification of DMTD5 is shown in Table II and its block diagram is shown in Fig. 4. It measures the time intervals between the 5 MHz signal of a hydrogen maser and that of 24 clocks simultaneously. The hydrogen maser signal is used as reference. Input 5 MHz signals are down-converted to 1 kHz, so that the phase resolution is magnified 5000 times. The phase resolution of the 1 kHz signal is 10 ns because the sampling clock inside the DMTD5 is 100 MHz. It means that the relative phase resolution of 5 MHz signal is 2 ps. The average of sequential 100 measurements is output every second. The resolution of this final data is therefore around 0.2 ps. Details are described in [6].

A measurement of 5 MHz signals with a DMTD5 provides more precise data than that of 1 PPS signals with a TI counter. However, the measurements of 5 MHz tend to have phase ambiguities due to miscounting of cycles. The DMTD5 prevents this problem by shifting the signal phase by a half period when its phase is close to the phase of reference signal. The counted cycle number is output with each measurement.

TABLE I. SPECIFICATION OF THE HYDROGEN MASER RH401A.

Carrier outputs	Frequency	5, 10, 100 MHz, 1.4 GHz
	Level	13 dBm ±2 dB
Timing outputs	Format	1PPS
	Level	TTL
Stability σ y	1 s	less than 4 x 10^{-13} (auto-tuning off)
	10 s	less than 4 x 10^{-14} (auto-tuning off)
	100 s	less than 5 x 10^{-13} (auto-tuning off)
	10^3～10^4 s	less than 2 x 10^{-15}
	Long term	less than 2 x 10^{-15} / day
Sensitivity	Temperature	less than 4 x 10^{-13} / degree
	Magnetic	less than 2 x 10^{-13} / Gauss
Function	Freq. control	Range: 2 x 10^{-9} Resolution: 7 x 10^{-16}
	Auto-tuning	No ext. reference required

TABLE II. SPECIFICATION OF THE DMTD5

Input frequency	5 or 10 MHz
Beat-down frequency	1 kHz
Input channels	24
Period of output	1 s
Resolution	2 ps at 5 MHz (without averaging)
Averaging	1～100 samples

This method, however, cannot avoid the risk of cycle-miscounting when the measurements stop for a long time. In order to keep a phase continuity of measured data, we use TI counter 1 PPS measurements together with the DMTD5 5 MHz measurements. The 1 PPS measurements are done every hour in the same way as the former system. These data are not so precise but not ambiguous. We adopt the result of TI counter as the initial phase value of a clock when the operation starts. In the continuous operation, the accumulated phase calculated from the data of DMTD5 is used. Detail of this process is described in the next subsection.

System noise of the DMTD5 and the TI counter are compared in Fig. 3. It is confirmed that the system noise of DMTD5 is lower than the frequency noise of the hydrogen maser RH401A.

C. Redundancy

In the former system, a measurement unit (a mechanical switch and a TI counter) and a signal generating unit (a source clock and an AOG) were duplicated. One pair of these units was selected as the master system. As their combination was fixed, we could not exchange only the

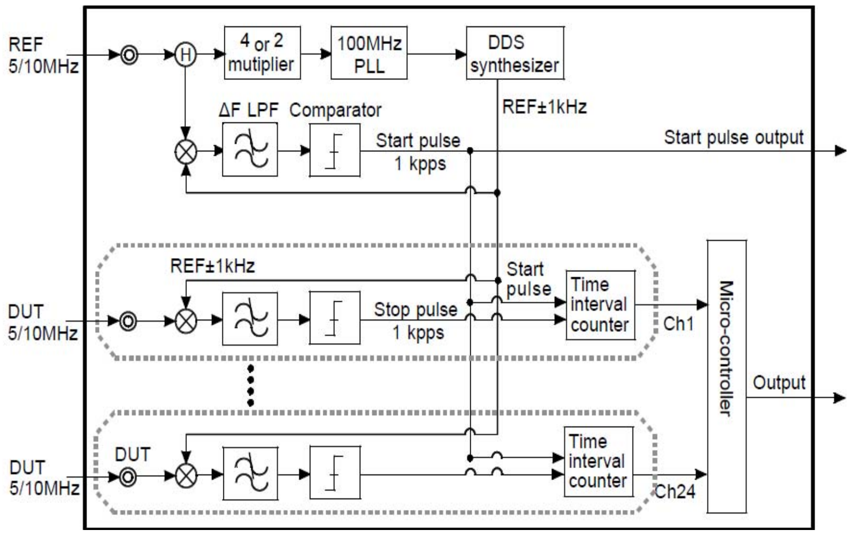

Figure 4. Block diagram of DMTD5.

measurement unit apart from the signal generating unit. This way was simple but not efficient for using the devices.

In the new system, the measurement unit consists of four groups (three DMTD5s, and a switch plus TI counter), and the generating unit consists of three equivalent groups (a source clock and an AOG). There is no fixed combination between the measurement unit and signal generating unit. One signal generation group is selected as the master system, and its outputs are used as the signals of UTC(NICT). If malfunction is detected in the master system, it is quickly exchanged. The exchange process needs a human decision for safety at present.

As for the measurement unit, one representative data set is obtained after data processing by using all four data sets. The details of this process are described in the next subsection.

D. Data processing

The measurement unit in the new system consists of three DMTD5s and a TI counter. They measure the same sources, so that their results should be almost same in a normal situation. If an anomaly appears in one device, its measurement differs from the others. The wrong device is identified by comparing the results of all groups. Bad data detection and removing are automatically done by the following procedure. The index i identifies each clock. The indexes A, B, C identify each DMTD5 and T the TI counter.

(1) Time difference between clock#i and clock#01 is obtained by each DMTD5 every second. Here clock#01 is a reference clock of the measurement.

(2) The time difference between clock#i and clock#01 every hour on the hour is determined as follows. The time difference of clock#i and clock#01 at x o'clock is determined by a linear fit of the data between $x-1$ o'clock and $x+1$ o'clock. Here we express this determined time differences as $p_{Ai}(t)$, $p_{Bi}(t)$ and $p_{Ci}(t)$ for the DMTD5-A, B, and C respectively. Fig. 3 shows that the frequency drifts of the clocks are small enough for such linear fit. The time difference measured by the TI counter every hour is denoted by $p_{Ti}(t)$.

(3) Frequency difference between clock#i and clock#01 is calculated every hour from the time differences described in (2). In the case of DMTD5-A, $f_{Ai}(t) = (p_{Ai}(t+T) - p_{Ai}(t)) / T$. Here T is 3600 s. The values of $f_{Bi}(t)$, $f_{Ci}(t)$, $f_{Ti}(t)$ are obtained in the same way.

(4) To check the data of a device in bad condition, sum of the frequency differences from the other systems is calculated; $S_A = |f_A - f_B| + |f_A - f_C| + |f_A - f_T|$. Similarly S_B, S_C and S_T are obtained. If DMTD5-A is out of order, the value of f_A is different from f_B, f_C, and f_T. As the result, S_A becomes the biggest value among all values.

(5) The smallest and the next smallest S values are selected. When S_B and S_C are selected, the average frequency $f_i(t) = (f_{Bi}(t) + f_{Ci}(t)) / 2$ is obtained. This $f_i(t)$ is used as the representative frequency difference between clock#i and clock#01.

(6) By using $f_i(t)$, representative time difference between clock#i and clock#01 is obtained as follows; $p_i(t) = p_i(t_0) + \Sigma_{k=1} f_i(t_k) \cdot (t_k - t_{k-1})$. Initial phase $p_i(t_0)$ is obtained from the data of the TI counter.

Fig. 5 shows the differences between two DMTD5s. The differences are within almost only 2 ps. The data of TI counter are not selected usually because their errors are larger than that of DMTD5. If only one device remains, we would adopt its data. This procedure allows us to obtain a

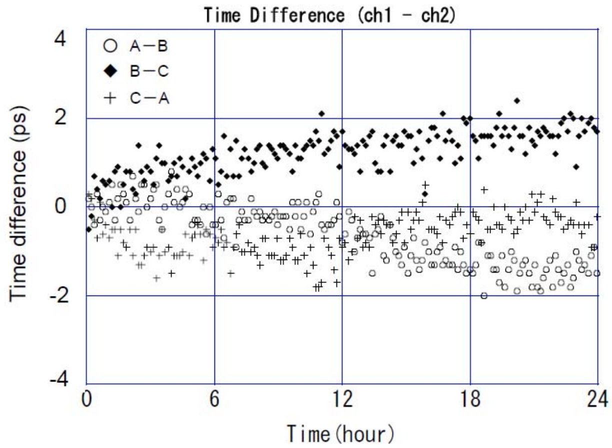

Figure 5. Time differences between two DMTD5s.
The value at 0 nour is set to be zero.

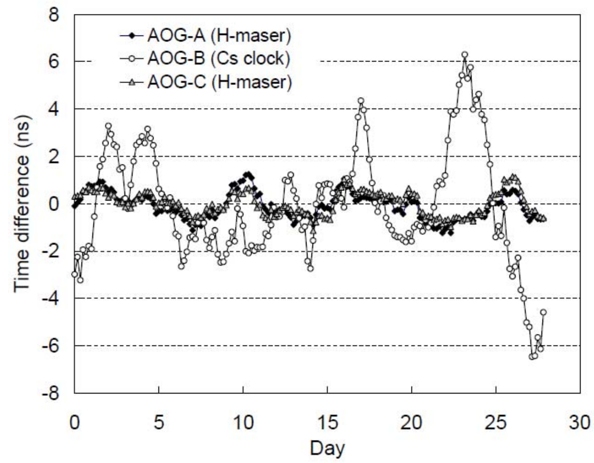

Figure 6. Time differences between the AOG outputs and NET '.

measurement result if at least one measurement device works correctly.

E. NET, TA(NICT) and UTC(NICT)

NET is calculated by using the time differences $p_i(t)$ of clocks as explained in subsection D. At present, NET is calculated from only the Cs atomic clocks. The algorithm is almost same as that of the former system [2]. The rate of a Cs atomic clock is estimated from the data of the last 30 days. A weight of a clock is calculated from the Allan deviation at τ=10 days of this clock. These method may be changed if we find more suitable ways. We are investigating a better algorithm now. Currently, NET is used as TA(NICT) and the data is sent to BIPM.

Based on NET, we generate a real-time timescale UTC(NICT). The reference point of UTC(NICT) is the input connector of TI counter. The signals of UTC(NICT) are generated from a hydrogen maser steered by an AOG. The frequency shift given by the steering is estimated from the latest 5 days data of the frequency difference between the hydrogen maser and NET. Not only the frequency but also the phase of the AOG is controlled by the steering. When a phase offset appears between the AOG output and NET, the offset is decreased by the steering. The decreasing rate is variable in the new system. Currently we chose the rate that the offset will disappear in two days. The frequency of AOG is adjusted at 1:20 UTC, every day.

The time differences between the AOGs and NET ' are shown in Fig. 6. NET ' is a timescale that includes an additional frequency shift to keep the synchronization with UTC. This graph shows the steering errors of AOG. To show the difference due to the source clocks, we set a Cs clock as source clock in a back-up system. In the cases of using hydrogen masers (AOG-A and C), the steering errors are clearly smaller than that in the case of a Cs clock (AOG-B).

TABLE III. Check points of the new system.

Health check	Cs clocks
	H-masers
	AOGs
	Data logger for monitoring temperature and humidity
	Oscilloscopes for monitoring of UTC(NICT) signals
Status of Regular measurements and Calculations	DMTD measurements
	TI counter measurements
	Temperature & humidity
	TA(NICT) calculation
	AOG adjusting
Quality of signals	Figures of 5MHz & 1PPS of UTC(NICT)
	Phase jump of each clock
	Frequency instability of each clock
	cycle slip of each clock

F. Control systems, monitoring systems and environments

In the former system, a workstation took all tasks of device controls and calculations and it was duplicated. In the new system, various tasks are distributed to several computers to avoid a concentration of tasks. We use Linux computers as servers, and Windows computers to control devices. Each computer is duplicated or triplicated. The time of the system is synchronized with UTC(NICT) via network time protocol (NTP).

The check points of the system are increases as compared with the former system. They are listed in Table 3. The every second outputs of DMTD5 are useful to check the clock anomalies. The real time monitoring of 5 MHz signals and 1 PPS signals of UTC(NICT) with oscilloscopes are also useful to detect the troubles in UTC(NICT) rapidly. Detected anomalies are notified to staffs by e-mails. We can check the system condition on web by a newly developed monitoring program.

As for environments, there are four magnetic and electromagnetic shielded rooms for atomic clocks. Temperature and humidity in those rooms are kept at 24+/-0.5 degree and at 40+/-10 % respectively. The new building is equipped with a dynamo and a large UPS. The main devices in the new system are supplied with them. The dynamo keeps their electricity for three days when the commercial supply is stopped. This building also has a high security and a quake-absorbing structure.

G. *Attentions in the system design*

Additional attentions in designing the new system are introduced here. The outputs of UTC(NICT) are supplied to many rooms. If some of the cables for supplying signals are not connected, reflections occur by them. In the former system, such reflections affected the other outputs of the original distribution amplifier. To avoid this problem, we use distribution amplifiers with high isolation between ports in the new system. In addition, a distribution amplifier for various applications is independently provided. Clearness of a system configuration is important for a regular operation in long term. Though fewer junctions are better for signal quality, some junction panels are inserted for clearness. To find the causes of troubles quickly, various check-points exist in the path of signal transmission and data processing.

IV. PROCESS OF A DEVELOPMENT AND CURRENT STATUS

The project of the new system development started in 2002. The development of DMTD5 and tests of a preliminary system were carried out in the first two years. After the new building was completed in 2004, the new system was assembled there and total operation tests started. As the Cs atomic clocks were used for the former system in the old building and for the new system in the new building, they were carefully moved to the new building step by step. After the total operation tests were finished, various simulations of troubles were carried out for more than one year. Some improvements were added during this test phase. After that, propriety of the results of the new system was confirmed by comparison with the former system. Finally, a regular operation started since February 7, 2006.

Fig. 7 shows the time difference of UTC - UTC(NICT) reported by the Circular-T after the regular operation was started. We did frequency adjustments five times to follow UTC until the end of April in 2007. UTC(NICT) was stable in 2006 and synchronized with UTC within almost 10 ns. The frequency stability in the one year period between Feb. 7 in 2006 and Feb.7 in 2007 is shown in Fig. 8. The stabilities in 2001 and 2003, stable two years in the latest five years, are also shown for a comparison. The improvement of the stability of the new system is clearly shown by comparing it with that of the old system.

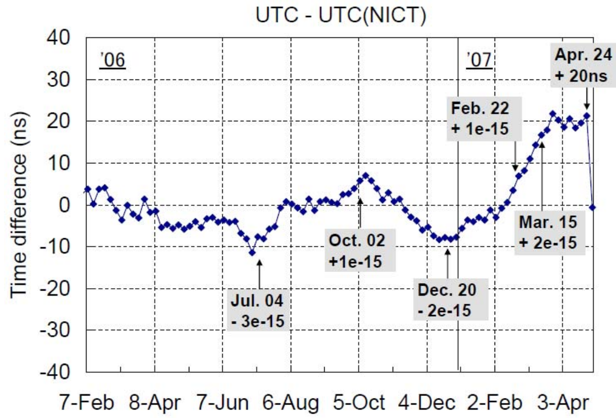

Figure 7. UTC-UTC(NICT) in the new system.

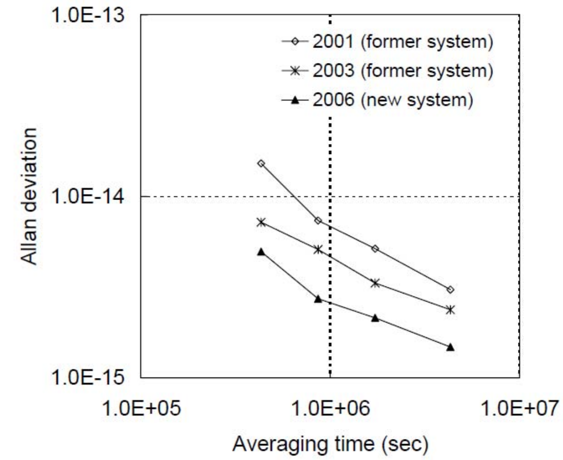

Figure 8. Frequency stability of UTC- UTC(NICT).

In 2007, UTC(NICT) showed a large drift, and the time difference from UTC reached almost 20 ns. To decrease this time difference, we did a phase adjustment at the end of April in 2007. As described in III-E, the frequency is steered every day and the frequency shift is chosen so that the phase offset would disappear in two days. It means that the offset of 20 ns becomes 10 ns, 5 ns and 2.5 ns day by day if NET is stable enough. This adjustment is not usually used for steering UTC(NICT), because it largely changes the frequency. We, however, adopted it this time for a performance test of this function. The result of the adjustment agreed with what was expected.

The drift in 2007 was caused by large drifts of some Cs clocks. We found a tendency that when a clock was removed from or entered in a room, other clocks in that room showed large drifts. We are now trying to solve the problem in two ways. One is to improve the environment condition of the clocks. The other is to improve the algorithm to detect clock anomalies rapidly and make an appropriate correction.

V. SUMMARY

There are many improvements in the new system. The hydrogen masers were introduced as source clocks instead of Cs atomic clocks. This change improves a short-term frequency stability of UTC(NICT) about 100 times better than that in the former system. The newly developed DMTD5, main tool of the measurement, improves a measurement precision to the hydrogen maser level. The 5 MHz measurement by DMTD5 is effective for improving the precision, but tends to loose phase continuity when a measurement stops for a long time. We solved this problem by combination of the DMTD5 5 MHz measurements and the TI counter 1 PPS measurements. Though the algorithm of NET is almost the same as that of the former system, the steering way of UTC(NICT) was changed because the source clock was changed to a hydrogen maser. The redundancy of main units in the system, task distribution for computers, and enhanced monitoring system improved reliabilities. Regular operation of the new system started on Feb. 7 in 2006. We found a drift of UTC(NICT) caused by the drifts of some Cs clocks. The adjustments for it showed the system performance as it was designed. Though the hardware renewal was completed, there remains the room for improvements of algorithm. We will improve the environment of Cs clocks and the algorithm of NET to make the new JST system better.

ACKNOWLEDGMENT

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