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Research Article

The New Generation System of Japan Standard Time at NICT

Yuko Hanado,[1] Kuniyasu Imamura,[1] Noboru Kotake,[1] Fumimaru Nakagawa,[1] Yoshiyuki Shimizu,[1] Ryo Tabuchi,[1] Yukio Takahashi,[2] Mizuhiko Hosokawa,[1] and Takao Morikawa[3]

[1] *Space-Time Standard Group, New Generation Network Research Center, NICT, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan*
[2] *National Institute of Information and Communications Technology, (NICT), 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan*
[3] *Incubation Department, Core Technology R & D Center, ANRITSU Corporation, 5-1-1 Onna, atsugi, Kanagawa 243-8555, Japan*

Correspondence should be addressed to Yuko Hanado, yuko@nict.go.jp

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NICT has completed a set of major upgrades in its systems for the realization of Japan standard time. One of the most significant 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 major change is the introduction of a newly developed 24-channel 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 has been in regular operation since February 2006.

1. 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 realization of coordinated universal time (UTC). NICT is continuously generating UTC(NICT) from its atomic clocks at the Koganei headquarters using a system we termed the "JST system."

Although improvements are necessary as technology progresses, any change in the JST system must be made with care since UTC(NICT) is a real-time product that must be continuous so as to satisfy the needs of its users. The JST system experienced changes three times since its first version became operational in 1976. These were in 1987, 1995, and 1999 [1]. Recently, a new building for time and frequency facilities was constructed, and the development of the fifth JST system was undertaken for the installation.

The design of this new system was begun in 2002. The main target of this system was the improvement of a short-term frequency stability of JST, and this required the introduction of hydrogen masers. Another important target was the improvement of the measurement precision. It was achieved by developing 24-channel dual mixer time difference (DMTD) systems. In addition, we aimed to improve the reliability of JST by new data processing, high redundancy, and enhanced monitoring. The transition to regular operations was made in February 2006 and the system has now run over one year without major problems.

The outline of the JST system is outlined in Section 2, with a more detailed description of the new system and its comparison with the former system in Section 3. The regular operation performance and a future target are introduced in Section 4, and a summary is given in Section 5.

2. JST SYSTEM, BASICS AND FORMER ONE

In this section, we present an outline of the JST system and also of the former system. The basic data flow is shown in Figure 1 and the block diagram of the former system is shown in Figure 2(a).

UTC(NICT) is a realization of an average atomic time calculated from an ensemble of Cs atomic clocks. We call this timescale "NICT ensemble atomic time" (NET), which is reported to the International Bureau of Weights and Measures (BIPM) as TA(NICT). In the former system, NET was

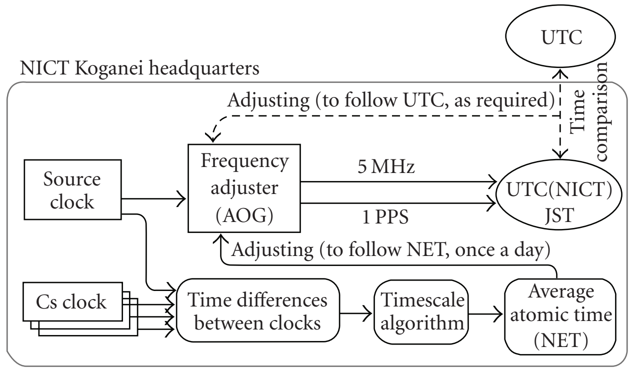
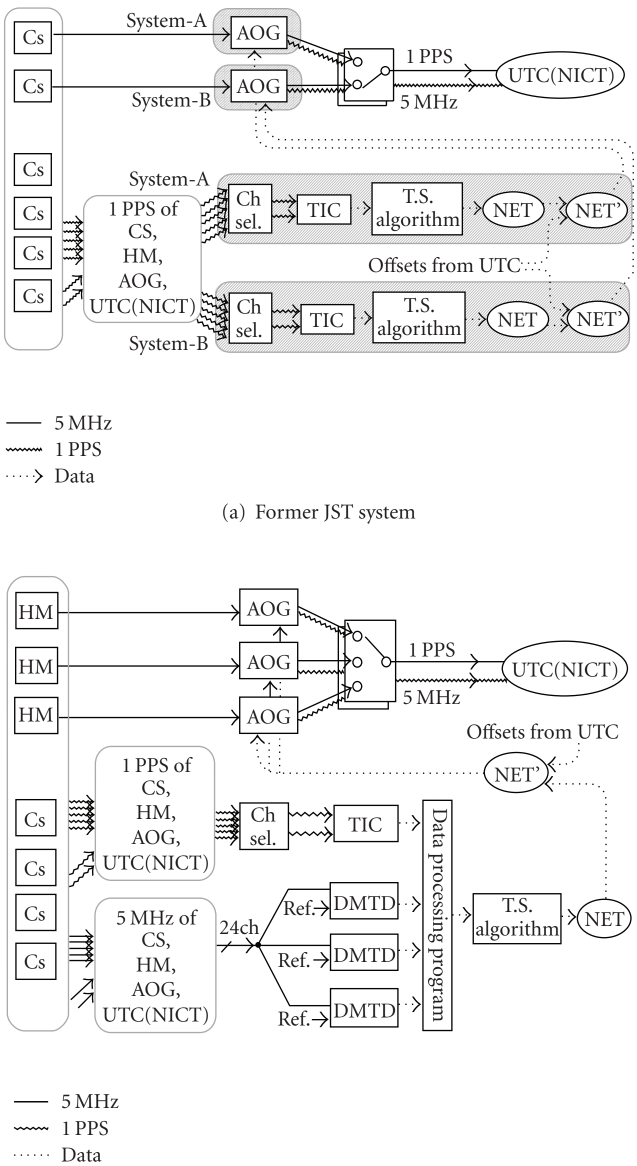


Figure 1: Configuration of the JST system.



(a) Former JST system

(b) New JST system

Figure 2: Comparison of the former and the new JST system. CS: Cs atomic clock, HM: hydrogen maser, TIC: Time interval counter, Ch Sel.: Channel selector, T.S. algorithm: Timescale algorithm.

made from maximum 14 Cs atomic clocks (5071A with high-performance tube, Symmetricom), which are maintained at the Koganei headquarters.

To calculate NET, we use the data of regularly measured time differences between clocks. In the former system, they were measured by using the 1 PPS signals of the clocks with a time-interval (TI) counter. One clock was chosen as the reference. The signals of the other clocks were selected sequentially by a channel selector, and the measured values were obtained by a one-shot measurement without averaging.

The algorithm for NET in the former JST system [2] was based on a standard theory of timescale algorithm [3, 4]. First, the rate of each Cs atomic clock at a moment is estimated from the past behavior. The clock reading is predicted by a linear extrapolation using this rate, and the discrepancy between the predicted phase and the actual one is treated as the prediction error of each clock. NET is made from a weighted average of these errors. In the former system, the rate was estimated from the frequency difference between the clock and NET during the last 30 days, and the weight was calculated from the Allan deviation at $\tau = 10$ days of this clock.

Since NET is a paper clock, an oscillator is required to realize the actual signals of UTC(NICT). The output of an atomic clock (we call it "source clock") is steered by a frequency adjuster used as the oscillator. In the former system, we used a Cs atomic clock as the source clock, and the Symmetricom's auxiliary output generator (AOG) as the frequency adjuster. The 5 MHz and 1 PPS signals from AOG were used as the frequency reference and the timing reference of UTC(NICT), respectively. The frequency and time differences between the AOG and NET were adjusted once a day.

The time difference of UTC-UTC(NICT) is reported in the "Circular-T," produced monthly by the BIPM. When the offset from UTC becomes large, additional adjustments to follow UTC are added to NET, to produce a steered timescale NET'. The AOG follows NET' so that UTC(NICT) should follow UTC. The AOG allows additional adjustments to be given as the frequency offset or phase changes. In the operation of former system, the frequency offset was mainly used to meet a 50-nanosecond target of synchronization with UTC. Time links between NICT and other institutes were performed by GPS common-view method by using the Topcon Euro80 multichannel receiver mainly.

An extremely important part of the system is built-in redundancy to identify and protect against a system trouble. In the former system, the measurement device (a channel selector and a TI counter) and a signal generating unit (a source clock and an AOG) were duplicated. A pair of these units was selected as the master system. If malfunction is detected in the master system, the system was quickly changed to the backup one.

3. MODIFICATIONS FOR THE NEW SYSTEM

A block diagram of the new system is shown in Figure 2(b). Though the basic configuration is similar with that of the former system, various upgrades were implemented in the

Table 1: 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 4×10^{-13} (auto-tuning off)
	10 s	less than 4×10^{-14} (auto-tuning off)
	100 s	less than 5×10^{-15} (auto-tuning off)
	$10^3 \sim 10^4$ s	less than 2×10^{-15}
Long term drift		less than 2×10^{-15}/day
Sensitivity	Temperature	less than 4×10^{-13}/degree
	Magnetic	less than 2×10^{-9}/T
Function	Frequency control	Range: 2×10^{-9} Resolution: 7×10^{-16}
	Auto-tuning	No ext. reference required

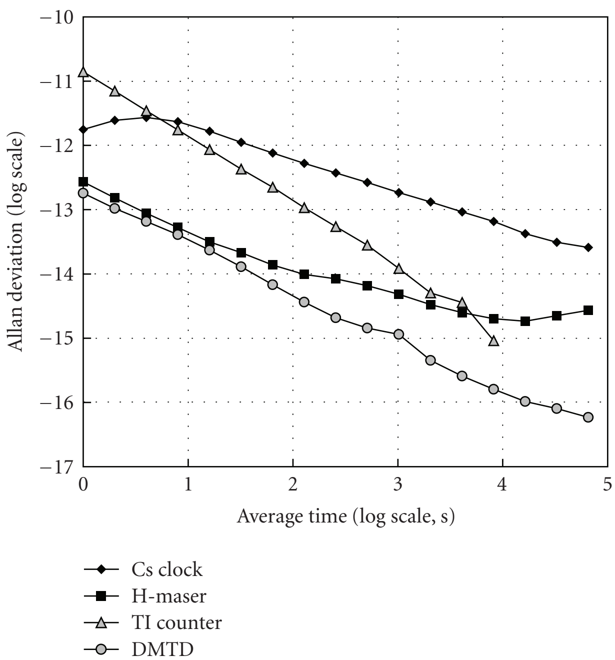


Figure 3: Frequency stabilities of atomic clocks and system noise of measurement devices.

whole system. We introduce the revised points in the new system as compared with the former system.

3.1. Clock

The new system has 18 Cs atomic clocks (5071A with high-performance tube) and 4 hydrogen masers (RH401A, Anritsu Corp., Atsugi, Kanagawa, Japan). Specifications of the Anritsu hydrogen maser RH401A are shown in Table 1, and its frequency stabilities as measured by the new system are shown in Figure 3. The Cs atomic clocks generate NET, and the hydrogen masers are used as the source clocks. The change of the source clock from a Cs atomic clock to a hydrogen maser improves the short-term frequency stability of UTC(NICT) about a hundred times. Though the long-term stability of hydrogen maser is not so good, the long-term stability of UTC(NICT) is assured by NET.

Table 2: 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

3.2. Measurement system

The measurement method in the former system was simple but had plenty of room for improvement. Firstly, for precise measurements higher frequency carrier signals are more desirable than the 1 PPS signals of the former system. Secondly, the simultaneous measurements of all signals are better for the construction of an average atomic time than the sequential measurements of the former system.

To solve the problems, 24-channel DMTD system (DMTD5, Japan Communication Equipment Co. Ltd., Yamato, Kanagawa, Japan) was developed for the new system [5]. Three DMTD5s are used in the new system, and they are the main tools for the measurements. Though a DMTD system is a well-known method for a precise measurement of time difference [6–8], multichannel devices are not so widespread. Our DMTD5 solved the time lag problem in the measurements of multiple clocks as well as the precision problem.

A block diagram of DMTD5 is shown in Figure 4 and its specification is shown in Table 2. It measures the time

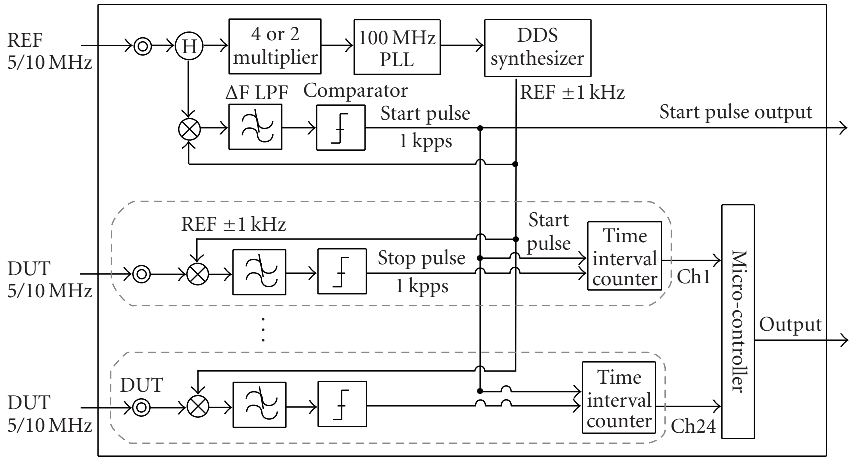


Figure 4: Block diagram of DMTD5.

intervals between the 5 MHz signal of a reference hydrogen maser and that of 24 clocks simultaneously. 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 nanoseconds because the sampling clock inside the DMTD5 is 100 MHz. It means that the relative phase resolution of 5 MHz signal is 2 picoseconds. An average of sequential measurements is output every second. Currently, we use the average of 100 samples. The resolution of the final data is therefore around 0.2 picosecond. Details are described in [5].

The measurements of 5 MHz signals with a DMTD5 provide more precise data than those of 1 PPS signals with a TI counter. The measurements of 5 MHz, however, have a risk of 200-nanosecond phase ambiguities due to the miscounting of cycles. The DMTD5 prevents this problem by shifting the signal phase by 2 nanoseconds when the phase difference between the clock and the reference becomes less than 1 nanosecond. The limit of the frequency offset to measure the signal without cycle slip is 1×10^{-9}. The cycle count number is output with each measurement.

This function of DMTD5, however, cannot avoid the risk of cycle miscounting if the measurements are temporarily halted. In order to keep a phase continuity of measured data in such cases, we use the TI counter 1 PPS measurements together with the DMTD5 5 MHz measurements. The 1 PPS measurements are made every hour in the same manner 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 restarts. In the continuous operation, the accumulated phase calculated from the DMTD5 data is used. Details of this process are provided in the next subsection.

The system noise of the DMTD5 and the TI counter are compared in Figure 3. While the TI counter shows much higher noise than that of hydrogen maser RH401A in the short term, the noise of the DMTD5 is lower than that of the RH401A in all regions.

3.3. Processing of measured data

The combination of DMTD5 and TI counter in the measurements requires special data processing. A newly developed computer program carries out an anomaly detection and data synthesis by using the data of three DMTD5 and one TI counter. The anomaly detection algorithm attempts to identify both bad clocks and bad measurement devices. This program selects the data of two good devices among four. There was no such function in the former system. The details of the procedure are described as follows:

In the new system, the measurement unit consists of four devices (three DMTD5s, and a TI counter). These four devices 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 malfunctioning device is identified by comparing the results of all devices. Bad data detection and removal are automatically achieved by an algorithm to be described next. In this description, the index #i indicates each clock. All clock#i are Cs atomic clocks, where $i = 01, \ldots, 18$. The clock#01 is a reference clock of the measurement. The indexes A, B, C, and T indicate triplicated DMTD5s and a TI counter, respectively.

(1) Time difference between clock#i and clock#01 is measured by each DMTD5 every second.

(2) The time difference between clock#i and clock#01 every hour is determined as follows. In the case of DMTD5, 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 $p_{\mathrm{A}i}(t)$, $p_{\mathrm{B}i}(t)$, and $p_{\mathrm{C}i}(t)$ for the DMTD5-A, B, and C, respectively. Figure 3 shows that the frequency drifts of the clocks are small enough for such linear fit. As for the TI counter, the hourly measured value itself is used as the time difference denoted by $p_{\mathrm{T}i}(t)$.

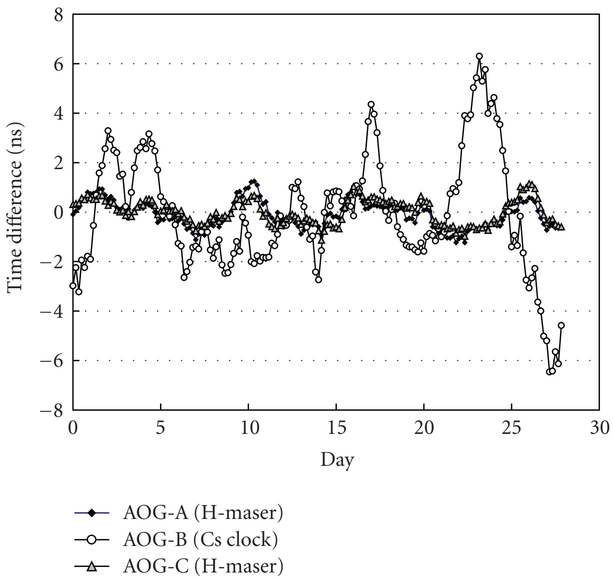


Figure 5: Time differences between the AOG outputs and NET'.

(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, $f_{Ai}(t) = (p_{Ai}(t+\tau) - p_{Ai}(t))/\tau$. Here, τ is 3600 seconds. The values of $f_{Bi}(t)$, $f_{Ci}(t)$, $f_{Ti}(t)$ are obtained in the same way.

(4) For each device, the sum of the frequency differences from the other devices is calculated. In the case of DMTD5-A, the difference is $S_{Ai} = |f_{Ai} - f_{Bi}| + |f_{Ai} - f_{Ci}| + |f_{Ai} - f_{Ti}|$. Similarly, S_{Bi}, S_{Ci}, and S_{Ti} are calculated for other devices.

(5) Two devices among four are selected by using the S values in (4). If DMTD5-A is out of order, the value of f_A is different from f_B, f_C, f_T. As a result, S_A becomes the biggest value among all S values. We select those who have the smallest and the next smallest S values as two reliable devices.

(6) The representative frequency difference between clock#i and clock#01 is calculated from the data of the two selected devices. In the case that S_B and S_C are selected in (5), the average $f_i(t) = (f_{Bi}(t) + f_{Ci}(t))/2$ is used as the representative frequency difference between clock#i and clock#01.

(7) By using $f_i(t)$, representative time difference between clock#i and clock#01 is obtained as follows: $p_i(t) = p_i(t_0) + \Sigma_k f_i(t_k) \cdot (t_k - t_{k-1})$. The initial phase $p_i(t_0)$ is obtained from the data of the TI counter when the regular measurement starts.

In the above procedure, one representative data set is made from the four data sets. We can obtain a measurement result if at least one measurement device works properly. If only one device remains, we would adopt its data. This process is used for the definition of initial phase. The result of TI counter is adopted if there are no DMTD5 data. Usually, the data of TI counter are not selected because their errors are larger than those of DMTD5.

The anomalies of the clock are detected in the above process. If a phase datum in the process (1) is larger than a limit, the datum is removed. Currently, the limit is set to the 10 times of the standard deviation. Any clock with a larger frequency deviation than 5×10^{-10} against the reference signal is also removed in the process (3). The software allows simple variation of the parameters for these limits.

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

The various upgrades described above required many changes in the system. The software, however, was designed so that the parameters for calculating the clock rate and weight are easily modified. At present, we use the same values as the former system except the rate of a source hydrogen maser is estimated from the last 5 days' frequency difference between the hydrogen maser and NET.

There are two changes in the way of making UTC(NICT) from NET. One is in the clock data archive. In the former system, NET' was used as the reference of archived clock data. The time differences between clocks and NET were not stored, which was very inconvenient for analyzing NET. In the new system, the clock data using NET as the reference are also archived. The other change is the adoption of a unique NET. The former JST system had two redundant systems (system A and B in Figure 2(a)). Each system made each NET from each measurement data and steered each AOG. It means that the NET used for making UTC(NICT) was changed and a time jump occurred in UTC(NICT) when the master system was changed. In the former system, this time jump was not considered as a serious problem because the steering errors of AOG were large and masked the time jump. Strictly speaking, this method of operation caused discontinuities in UTC(NICT). In the new system, only one NET is made from the representative measurement values described in Section 3.3.

For redundancy, there are three AOGs in the new system. They have different source clocks but are steered so that all the outputs follow the same NET'. The steering to cancel the time offset between AOG output and NET' is adjustable in the new system. Currently, we set the parameter of adjustment so that the time offset will disappear in two days. It makes a frequency change of UTC(NICT) in the adjustment gentle and smooth. In the new system, we aim to synchronize UTC(NICT) with UTC within 10 nanoseconds.

TA(NICT), an atomic timescale generated by NICT, was reset at the timing of starting the regular operation of new JST system. Currently, the NET is used as TA(NICT) and the data are sent to BIPM.

The time differences between the AOGs and NET' are shown in Figure 5. This graph shows the steering errors of AOG. To show the difference due to the source clocks, we set two hydrogen masers and a Cs clock as the source clocks. 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 3: 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 5 MHz & 1 PPS of UTC(NICT) Phase jump of each clock Frequency instability of each clock cycle slip of each clock

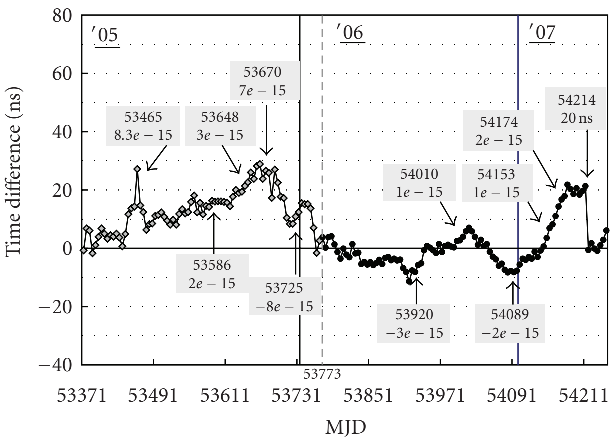


Figure 6: Phase stability of UTC-UTC(NICT).

3.5. Control systems, monitoring systems and facilities

In the former system, a workstation handled all tasks of device controls and calculations. These tasks are distributed to several computers in the new system to avoid the task concentration. In each task, the computers are duplicated or triplicated. All systems clocks are synchronized with UTC(NICT) via network time protocol (NTP) in a triply redundant manner.

The check points of the system are increased compared with the former system. They are listed in Table 3. We have found the real-time monitoring of 5 MHz and 1 PPS signals of UTC(NICT) with oscilloscopes to be effective for rapid troubleshooting. The outputs of DMTD5 are also useful to check the precise timing of clock anomalies. The staff are notified by email if an anomaly exists, and they can check the system condition on the internet with a newly developed monitoring program.

The atomic clocks are operated in the four special rooms. They are shielded against static and AC electromagnetic fields and kept in the constant temperature and humidity at 24+/−0.5 degrees and at 40+/−10%, respectively. For protection against external power failure, the atomic clocks and the main devices are supplied with a large UPS and a generator. The generator has sufficient fuel to maintain power for three days. The building itself is equipped with a quake-absorbing structure.

3.6. Time links

Time transfer method for the link of UTC(NICT) was also upgraded [9]. When the new JST system started, February 2006, the Septentrio PolaRX2 was newly adopted as the main GPS receiver instead of Euro80. By this replacement, both P3 and multichannel CCTF data can be obtained from the same receiver. Since March 2007, two-way satellite time and frequency transfer method has been used for the time link between NICT and PTB. These improvements decreased the time link uncertainty.

4. CURRENT STATUS AND NEXT TARGET

The regular operation of the new system was initiated on February 7, 2006 (MJD 53773). Figure 6 shows the time difference of UTC-UTC(NICT) reported by the Circular-T. In the new system, we have so far made 5 additional frequency adjustments to follow UTC. Though the number of adjustments was the same as that in 2005, the magnitudes of the adjustments were much smaller.

In 2006, UTC(NICT) by the new system was stable and synchronized with UTC to within almost 10 nanoseconds peak to peak. The frequency stability in one year period between February 6, 2006 and February 6, 2007 is shown in Figure 7. The stabilities in 2001, 2003, and 2005 are also shown for a comparison. The stability in the new system is clearly improved with respect to the former system.

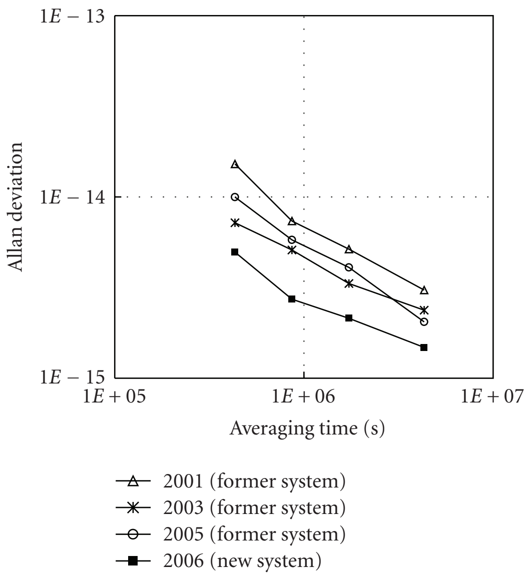


Figure 7: Frequency stability of UTC-UTC(NICT).

In 2007, UTC(NICT) showed a large drift in February and March (around MJD 54153), and the time difference from UTC reached almost 20 nanoseconds. Then we made a phase adjustment on April 24, 2007 (MJD 54214). This phase adjustment is rarely used because it causes a rapid change of frequency in UTC(NICT). Usually, only a frequency adjustment is enough for canceling a small phase offset. This time, the large offset of 20 nanoseconds was a good opportunity to test a performance of phase adjustment. The result agreed with what was expected.

The drift in 2007 was caused by unexpected large drifts of some Cs clocks. We are now trying to solve this problem. Some anomaly checks should be added to the timescale algorithm. Several methods were tested with simulations, and some of them show promise of reducing the frequency drift of NET to almost half of the present value. We are further investigating these methods for their appropriateness improving the long-term frequency stability of UTC(NICT).

5. SUMMARY

In the new JST system, better short-term frequency stability of UTC(NICT) and more precise measurement were achieved by the hydrogen maser and the newly developed multichannel DMTD system. The reliability was improved through upgraded monitoring, increased redundancy and improved data processing.

Since the start of a regular operation of the system in February 2006, the frequency stability of UTC(NICT) in 2006 was better than that in the former system. In 2007, however, a frequency drift of UTC(NICT) occurred because of the drifts of some Cs atomic clocks. This provided an opportunity to test a phase adjustment and reconsider the timescale algorithm. Together with the reliable regular operation of the system, an investigation on improvements to the algorithm to make UTC(NICT) more stable is in progress.

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