Report of Time and Frequency Activities at NICT

National Institute of Information and Communications Technology
Koganei, Tokyo, Japan

1. Introduction

The National Institute of Information and Communications Technology (NICT), an incorporated administrative agency, was established in 2004 with its large part inherited from the Communications Research Laboratory (CRL). The activity of time and frequency standards is conducted within the Space-Time Standards Laboratory of the Applied Electromagnetic Research Institute, this group itself comprises of four groups as follows. Firstly, the Atomic Frequency Standards Group develops atomic clocks ranging in frequencies from microwave to the optical region. Specifically, Cs fountain primary frequency standards, a single Ca^+ ion trap optical clock and a Sr optical lattice clock are originally developed. In addition, research in THz frequency standards has recently begun. The second group is the Japan Standard Time Group, which is responsible for generation of Japan Standard Time, its dissemination, and a frequency calibration service as a national authority. Thirdly, the Space-Time Measurement Group at Koganei develops precise time and frequency transfer techniques using optical fiber and satellite links. Lastly, the Space-Time Measurement Group at Kashima specializes in VLBI research using a 34 m antenna, and has recently begun research into VLBI precision time transfer. Details of these activities are described in the following sections.

2. Primary clocks

NICT has been developing Cs atomic fountain frequency standards for contribution to the determination of TAI, and are also used in frequency calibration of Japan standard time and calibration of optical frequency standards. The first fountain (NICT-CsF1) has been in operation since 2006 and accuracy evaluations with CsF1 have been carried out a few times per year. Construction of the second fountain (NICT-CsF2) attaining the goal of operation at the 10^{-16} level is fuelled by dual purposes. Firstly, two fountains allow vital inter-comparison evaluation of frequency shifts and their associated uncertainties. Secondly, another fountain provides redundancy necessary for guaranteed contribution to TAI. Both fountains are operated with a reference based on cryogenic sapphire oscillator (short-term) and hydrogen maser (long-term).

2.1 NICT-CsF1

Since 2006, twelve accuracy evaluations using CsF1 have been carried out with following the same procedure described in the first evaluation report circulated to the working group on the primary frequency standard in 2007 and also in [1]. So far, a typical frequency uncertainty is 1.4×10^{-15}. Recently, the optical system has undergone changes; firstly optics had to be realigned due to a vacuum system overhaul, and following this the Tohoku earthquake of March 2011 damaged parts of the optical setup. Repairs are complete and the vacuum is significantly improved and it is now possible to capture more atoms than before, resulting in a short term stability of $6 \times 10^{-14} / \tau^{1/2}$. However, this high atomic density is associated with a large collisional shift. To reduce the collisional shift CsF1 is currently operated with a reduced atomic density in normal operation, and has a short term stability of $2 \times 10^{-13} / \tau^{1/2}$. Installation of rapid adiabatic passage process [2] would enable both high frequency stability and accuracy. Additionally, following the new approach proposed in [3], we are currently re-evaluating the distributed cavity phase (DCP) shift.

2.2 NICT-CsF2

In contrast to CsF1 which uses a (0,0,1) laser cooling geometry with quadruple magnetic field, CsF2 adopts (1,1,1) geometry enabling many atoms to be captured without a magnetic gradient in large diameter laser beams, resulting in a reduction in the atomic density and thus a smaller collisional shift.

Currently CsF2 has a frequency stability of 3 x $10^{-13}/\tau^{1/2}$ and averages down to a statistic uncertainty at the 10^{-16} level. When used with the currently operational CsF1 this additional fountain clock allows accurate evaluation of frequency shifts and uncertainties between fountains. We have completed evaluations of most systematic frequency shifts and their uncertainties for CsF2 at a level below 5 x 10^{-16}, and the remaining measurements for microwave related shifts are currently underway.

3. Optical clocks

3.1 Ca^+ single ion trap

NICT has improved the experimental setup in several ways for the $^{40}Ca^+$ ion trap after our first report of the absolute transition frequency in 2008 [4]. Firstly, photo ionization is now used to increase production efficiency of $^{40}Ca^+$ ion trapping. Secondly, a two-layer magnetic shield has been installed on the vacuum chamber. Thirdly, mechanical and acousto-optic modulator shutters were installed to ensure thorough reduction in coupling of the cooling laser to the clock transition. Lastly, a fiber noise cancellation technique has been implemented. These improvements resulted in an observed spectral line width of the clock transition of about 30 Hz.

The clock transition frequency was evaluated by microwave link to International Atomic Time (TAI) in more than ten measurement campaigns over the past year. The measured frequency of 411 042 129 776 398.4 (1.2) Hz [5] agrees with the CIPM recommendation [6]. Furthermore, using optical comparison against a Sr lattice clock locally available in NICT [7] enabled measurement of the frequency ratio of the $^{40}Ca^+$ transition to that of the Sr lattice clock. The result 0.957 631 202 358 0499 (23) with fractional uncertainty of 2.4 x 10^{-15} agrees with the frequency ratio separately evaluated by microwave links to the SI second [5].

3.2 Sr lattice clock

A lattice clock based on the ^{87}Sr $^1S_0$-$^3P_0$ transition started operation in 2011. A vertically oriented one-dimensional lattice is employed for recoil-free confinement. Referring the TAI, the absolute frequency of the transition was measured to be 429 228 004 229 873.9 (1.4) Hz [7]. This frequency agrees with those measured in other four institutes; JILA, SYRTE, U. Tokyo-NMIJ, and PTB. The systematic fractional uncertainty of 5 x 10^{-16} mainly comprises of blackbody radiation shift, collisional shift, 2nd order Zeeman shift and lattice stark shift. The agreement with the clock in University of Tokyo (UT) is also confirmed by an optical fiber link [8]. A 60 km-length of dark fiber between NICT and UT is used for the all-optical direct frequency comparison. The frequency difference of 3.7 Hz is predominantly due to the elevation difference of 56 m. The residual difference after the subtraction of the systematic corrections is smaller than the total systematic uncertainty of two clocks (7 x 10^{-16}) demonstrating the reproducibility of lattice-based clocks [9].

3.3 New approach

An optical frequency standard based on a single $^{115}In^+$ is being developed at NICT with an expected inaccuracy in the order of 10^{-18} for the $^1S_0$-$^3P_0$ transition at 237 nm [10]. Three new approaches will be employed to compensate the relatively small transition rate of its cooling and detection transition ($^1S_0$-$^3P_1$, 230 nm). They include (a) use of a clock laser stabilized to a Sr optical lattice clock [11], (b) detection by quantum logic spectroscopy and its derivatives, and (c) detection by excitation of the vacuum ultraviolet (VUV) transition ($^1S_0$-$^1P_1$,159 nm) by coherent pulses generated by high harmonic generation (HHG) of a femto-second laser. These three methods are applied to a $^{115}In^+$ that is sympathetically cooled with $^{40}Ca^+$ in a linear trap. Basic technologies for generating the ion chains consisting of $^{115}In^+$ and $^{40}Ca^+$ have been developed, and the first frequency measurement is planned for 2014.

4. THz frequency standard

NICT has started to establish a new frequency standard in THz (0.1 - 10 THz, wavelength 30 μm - 3 mm) domain. The THz frequency comb with a photoconductive antenna using 1.5 μm femto-second fiber lasers has been developed for the absolute THz frequency measurements. Its measurement accuracy has attained to 10^{-16} level around 0.3 THz, which corresponds to a frequency resolution of 30 μHz. The present accuracy is limited by the electric noise of a current-to-voltage conversion amplifier. In theoretical research, THz quantum standard based on vibrational transition frequencies of optically trapped molecules was proposed to attain the uncertainty level of 10^{-16} around 10 THz [12][13].

5. Japan Standard Time

5.1. Atomic time generation

UTC(NICT), the base of Japan Standard Time, is a realization of an average timescale comprising of an ensemble of more than 10 Cs atomic clocks (Symmetricom, Inc. "5071A") at NICT headquarters in Tokyo [14]. The ensemble timescale is calculated by a program that estimates the clock rate from the last 30-day-trend, and weighs each clock according to its Allan deviation at $\tau = 10$ days. If any individual clock suddenly changes more than 1 x 10^{-14} it is considered anomalous and its weighting to the average becomes zero. This Cs ensemble timescale makes the self-reliant timescale TA(NICT) by coupling with the Cs Fountain NICT-CsF1. For the realization of this Cs ensemble timescale, an Auxiliary Output Generator (AOG) phase-locked to a hydrogen maser is used. We have 4 hydrogen masers produced by Anritsu Corporation and one of them is used as the source of UTC(NICT). The AOG is automatically steered every 8 hours to trace the Cs ensemble timescale, and is manually steered to trace UTC if necessary.

The 5 MHz signals from all clocks in the Cs ensemble are measured using a 24-ch DMTD system with precision of 0.2 ps [15]. Phase data is measured in addition to the frequency data using one pulse per second (1 PPS) signals to prevent a cycle-slip mistakes. For robustness, the main parts of the system have three redundancies; atomic clocks and main devices are supplied with a large UPS, a generator which has sufficient fuel to maintain power for three days; and the building itself is incorporates quake-absorbing technologies.

Figure 1 shows the generation system of UTC(NICT) [16], and Figure 2 shows the frequency stability of UTC(NICT) calculated from the data during 2009 - 2011.

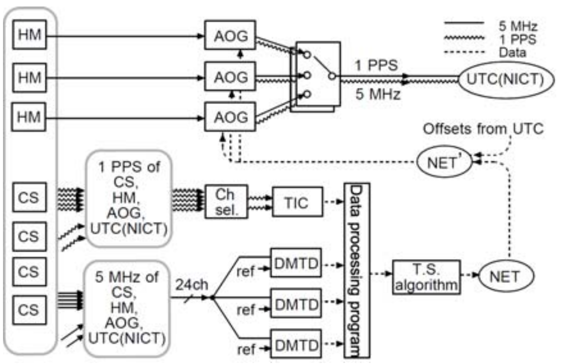

Figure 1. Generation system of UTC(NICT). Here, "NET" is NICT-Cs-ensemble-time.

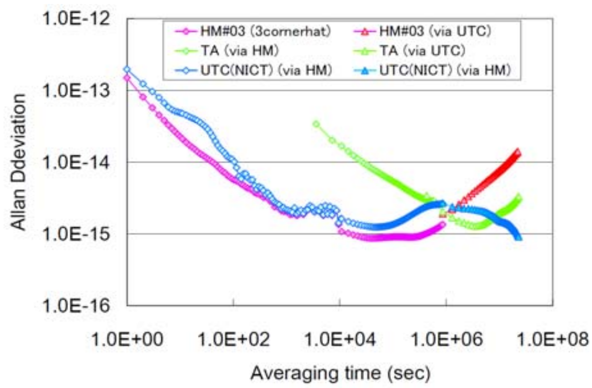

Figure 2. Frequency stability of UTC(NICT) compared with H-maser and Cs ensemble time (TA).

5.2. Disseminations

5.2.1. Standard-frequency and time-signal emissions

NICT provides a dissemination service of standard-frequency and time-signal via the LF band, as shown in Figure 3. The values under the distance (km) shows the approximate strength calculated as the assumed electric field. Signals from the two LF stations, Ohtakadoya-yama and Hagane-yama, entirely cover Japan. Table 1 shows the characteristics of the stations, both of which operate 24 hours a day. A consumer market of radio controlled watches and clocks have been developed.

The Ohtakadoya-yama station is located within 20 km from the Fukushima 1st nuclear power plant. When the power plant suffered damage from the tsunami resulting from the March 2011 earthquake staff were evacuated from Ohtakadoya-yama station and operation suspended for 40 days. Following this incident, remote control functions have been implemented to maintain operation.

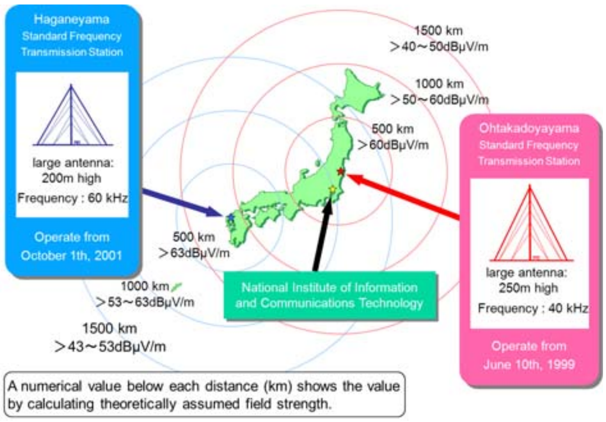

Figure 3. LF time and frequency service stations in Japan.

Table 1. Characteristics of LF stations.

	Ohtakadoya -yama	Hagane -yama
Frequency	40 kHz	60 kHz
E.R.P	13 kW	23 kW
Antenna	250 m height	200m height
Latitude	37°22' N	33°28' N
Longitude	140°51' E	130°11' E

5.2.2. Public network time protocol service

In 2006 NICT began the public Network Time Protocol (NTP) service using a Field Programmable Gate Array (FPGA)-based NTP server which can accept up to one million NTP requests per second. Because this server is implemented on a PCI card, a host PC is required to initialize and check the server operation. In 2008 NICT introduced a stand-alone server which includes a Linux controller unit integrated on the FPGA together with the NTP server hardware. Using these NTP servers, NICT receives more than 140 million accesses per day in 2012.

5.3. Frequency calibration system for traceability

NICT has been conducting a frequency calibration service referenced to UTC(NICT). In order to fulfill the requirements of global MRA, NICT was certified in accordance with the ISO/IEC 17025 from the National Institute of Technology and Evaluation (NITE) in March 2001. NITE provided NICT with ISO/IEC 17025 accreditation for the frequency calibration system on January 31 2003, the frequency remote calibration system on May 2 2006 and the time scale difference on September 30 2011. Best Measurement Capability (BMC) of carried-in system was changed to 5 x 10^{-14} in April 2007. The measurement range of frequency calibration was expanded from 1 Hz to 100 MHz in September 2011.

The first CMC table was approved and registered in the Key Comparison Database (KCDB) in August 2005. A revised CMC table was also submitted and registered in the KCDB in November 2009. A springboard of guidelines for CMC tables was prepared for the discussion at the TCTF technical workshop held at NICT before APMP2011.

5.4. Trusted time stamping service

Accreditation program for time stamping services in Japan began in February 2005. In this program, the clock of the time stamping server is calibrated within the prescribed accuracy and traceability to UTC(NICT) for every issued time stamp is assured. The clock accuracy of the time stamping server is prescribed to be 1 second or better to UTC(NICT). NICT is the official time supplier for this accreditation program. NICT also contributes to standardization of Time Stamping Service. The NICT proposal "Trusted time source for time stamp authority" satisfied the approval procedures of ITU-R and was approved as Recommendation ITU-R TF, 1876 in April 2010.

5.5. New approach

To improve reliability we plan to develop a distributed generation system of Japan Standard Time. In this system, atomic clocks at some distant station will be connected using satellites or optical fiber links, and an ensemble timescale will be constructed at each station using all these distributed clocks. These ensemble timescales are expected to be approximately the same. In this manner even if NICT headquarters suffers a disaster and suspends operation atomic clocks and the continuity of Japan

Standard Time will be maintained. Preparation has begun this year 2012 on the first station at the Kobe branch of NICT. Another new theme is to make a generation system adaptable to higher frequencies. The operating frequency of current system is essentially 5 MHz, but this frequency is too low to match the system of optical clocks. As intermediate frequencies linking optical clocks should be at least GHz region we will develop a precise measurement system with 1 GHz operating frequency.

6. Time transfer

NICT has conducted precise time and frequency (T&F) transfer using several methods including GPS, TWSTFT, optical fiber, on-board atomic clocks of the eighth engineering test satellite (ETS-VIII), and the Quasi-Zenith Satellite System (QZSS). These activities at NICT will be discussed in this section. In the section following we describe recent T&F transfer experiments using very long baseline interferometry (VLBI).

6.1 GPS

NICT has been operating two Septentrio PolaRX2 TR receivers for TAI time comparison network, and GPS carrier phase observations are continuously provided for computation of TAI. Accurate troposphere delays were calculated in order to improve time transfer precision of GPS carrier phase. These troposphere delay computations are computed by Kashima Ray-tracing Tools (KARAT) for which we developed PPP software, concerto v4 [17]. NICT and Wuhan Institute of Physics and Mathematics (WIPM) performed the first optical clock comparison experiment using GPS PPP and directly compared both Ca^+ single ion trap clocks.

6.2 TWSTFT

NICT has organized the Asia-Pacific Rim TWSTFT link, currently utilizing the satellite GE-23, to monitor atomic clocks located in two domestic low-frequency stations. Before March 2011 the satellite IS-8 had been used. In this link, time transfer is performed once every hour using the NICT modem. Additionally, in 2010 an Asia/Hawaii link was established using the same satellite. The Hawaii station is equipped with a hydrogen maser and two antennas for Asia and North America. Time transfers between NICT, TL and USNO are performed once every hour using the SATRE modem that joins the two links.

The Asia-Europe TWSTFT link is cooperatively constructed by major T&F institutes in Asia; NICT, TL, NIM, NTSC, KRISS, NMIJ, NPLI, and two European institutes; PTB and VNIIFTRI [18]. The link had been established by the satellite IS-4 until the beginning of 2010. However, due to the malfunction of IS-4 it was switched to the satellite AM-2 in October 2010. The working time of the transponder is limited from 13:00 UTC to 23:00 UTC. During this period time transfer is performed once every hour using the SATRE modem and the data are regularly reported to BIPM. NICT-PTB and TL-PTB links have been adopted for calculation of UTC(NICT) and UTC(TL), respectively. It is reported that satellite AM-2 is nearing the end of its operational lifetime, so we are considering the switch to another satellite.

6.3 Fiber transfer

An optical carrier transfer system was developed in NICT to improve the transfer stability over those systems using RF transfer in optical fibers [19][20]. To realize direct optical clock comparison, we developed an all-optical link system that consists of Ti:S optical frequency combs to bridge the frequency gap between the clock transition and telecom wavelength, fiber amplifiers, an active polarization control system

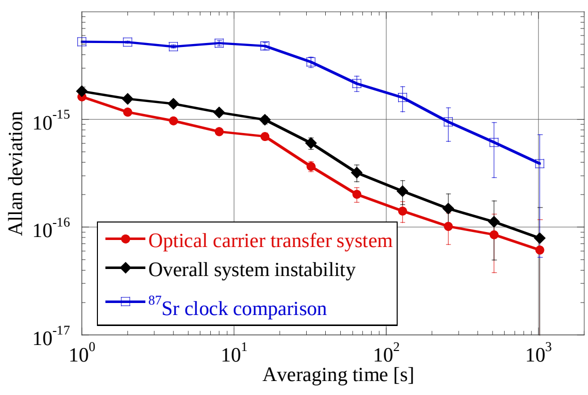

Figure 4. Frequency instability of direct clock comparison and system as measured by a λ-type counter.

and an optical carrier transfer system [21]. 1.5 μm light was stably transferred through a 90-km urban fiber link and fiber noise canceled to the theoretical limit. Transfer stability was 2 x 10^{-15} at 1 sec and 4 x 10^{-18} at 1000 sec by a Π–type frequency counter.

NICT was connected with the University of Tokyo (UT) through a 60-km urban fiber link. The ^{87}Sr lattice clocks developed at NICT and UT were compared [22]. Figure 4 shows the stability of two ^{87}Sr clocks (blue line) and instabilities of the all-optical link system (black line) and the optical carrier transfer system (red line) measured by a λ-type counter. It proved that the all-optical link system does not put any restrictions on the frequency comparison. The system included fiber amplifiers whose physical fiber length was not stabilized. When more stable optical clocks are to be compared, further improvement on the system and a noise-less optical fiber link will be necessary.

For RF transfer NICT developed commercially-available 10 MHz transfer system. The target transfer length was a few tens of km and transfer stabilities of 4 x 10^{-13} at 1 sec and 1 x 10^{-16} at 1 day were achieved. The system is appropriate for stable reference signal transfer, such as that demanded by VLBI systems.

6.4 Quasi-Zenith Satellite

The first Quasi-Zenith Satellite (QZS-1) "MICHIBIKI" was launched on September 11, 2010 by the Japan Aerospace Exploration Agency (JAXA) and Mitsubishi Heavy Industries, Ltd. NICT developed the time management system, which consists of on-board time transfer subsystem (TTS) and related ground systems such as time management stations (TMS) and also manages the TTS and TMS. The main purpose of TTS is to measure the time differences between the on-board clock and the atomic clock of TMS using a two-way time comparison method in the Ku-band. NICT has also operated a Ku-band transportable earth station for time and frequency comparison. We have successfully achieved a frequency stability over one second of the order of 10-11 for the time comparison experiments between TTS and TMS (see Figure 5).

In addition a narrow-band bent pipe (NBP) of QZS-1 is used for TWSTFT experiment. Two 3 MHz bandwidths separated in frequency by 20.46 MHz are used for clock comparison at the Okinawa earth station with respect to UTC(NICT). We evaluated the performance of NBP time transfer system compared with a conventional TWSTFT and GPS carrier phase time transfer. Figure 6 shows the NBP system has the most stable time transfer performance [23].

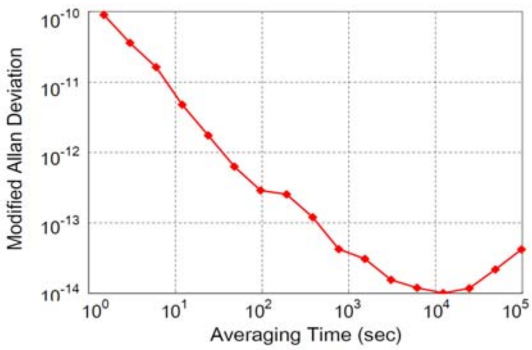

Figure 5. Time transfer stability of QZS on-board time transfer system related to the ground time management station.

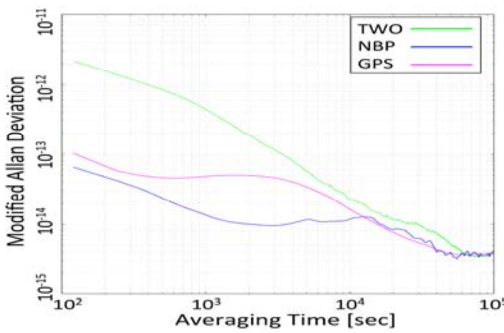

Figure 6. Time transfer stability of NBP TWSTFT (blue), conventional TWSTFT (green), and GPS carrier phase (purple).

6.5 Advanced TWSTFT (DPN and carrier-phase)

NICT has developed a new two-way time transfer modem with an arbitrary wave form generator and a versatile A/D sampler. Most of the digital-signal processing is done by graphics processing units (GPU) on the host computer. As a consequence, the modem is less expensive and has flexibility for the timing signal. Dual pseudo-random noise (DPN) signals were adopted for the modem, where two coded signals with a lower chip rate are used with separately-allocated frequencies. In this scheme, to spread the signals with a gap frequency is equivalent to using a wider chip rate signal. We achieved a measurement precision of 16 ps using 128-kbps coded signals with a frequency separation of 20 MHz in the first DPN TWSTFT experiments [24]. NICT and TL have occasionally performed DPN TWSTFT in the GE-23 North East Asia beam link, and the achieved time transfer stability is shown in figure [25].

For further improvement of measurement precision, NICT has started development of carrier-phase TWSTFT [26]. The phase difference is derived from carrier phase information of the signals sent from the counterpart station and one's own station. In a common clock measurement via a satellite link, a measurement precision of 0.2 ps is achieved, which may be limited by phase jitters induced by the frequency converters. In a short baseline with a length of 150 km a measurement precision of 0.4 ps is achieved and the time variation showed good agreement with the results of GPS carrier phase. Figure 7 shows the resultant frequency stabilities. The evaluation in a longer baseline is planned as a next step.

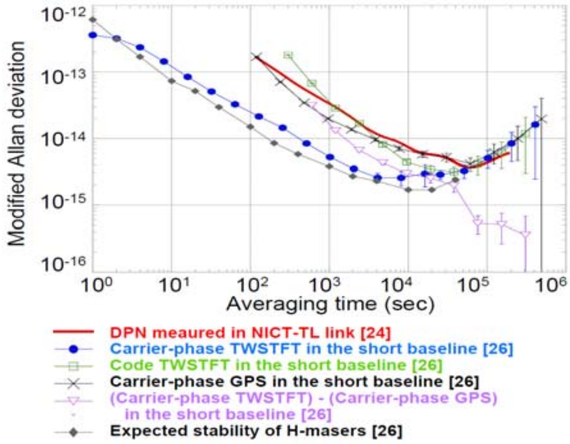

Figure 7. Frequency stabilities of DPN and carrier-phase TWSTFT.

7. VLBI for Time and Frequency Transfer

7.1 Feasibility test VLBI experiments with 11m diameter antenna

As one of the tools for time and frequency transfer, NICT has been investigating potential of VLBI in application to T&F transfer. Figure 8 shows the results of T&F transfer inter-comparison experiments performed between Kashima-Koganei 100 km distance on 19-23 Feb. 2012. Clock difference between two hydrogen masers at each site was compared with GPS, VLBI, and TWSTFT (Code) in this experiment. In this plot, each point of TWSTFT (Code: green cross) is the value obtained by taking the average of every one second raw data for 1 min. Those of GSP (red cross) are the data at every minute. In case of VLBI (blue closed circle and black open square), each point is obtained by averaging for 30 sec. Arbitrary offsets are removed from each measurement data and parabolic behaviors of the clocks are commonly removed from all the data in this plot. VLBI result demonstrates a smaller daily variation than TWSTF(Code) in this experiment. The clock jump at each day boundary is due to the discontinuity of the orbital information on the GPS satellite. It is notable that the increasing observation bandwidth in VLBI data from 500 MHz (blue closed circle) to 1 GHz (black open square) causes an increase of precession of clock difference measurements. This encourages the plan to develop wideband VLBI system, which is the target of our VLBI T&F transfer project.

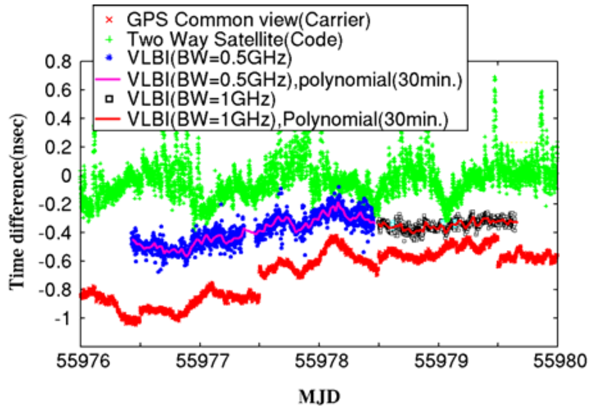

Figure 8. Inter-comparison of multiple time and frequency transfer techniques on Kashima - Koganei 100km distance.

Table 2. Specification of New wideband VLBI system and comparison with conventional one.

VLBI specification	Conventional	VLBI2010
Number of channel	16	4
Bandwidth	16 MHz	1 GHz
Effective band width	~300 MHz	~4 GHz
Delay measurement precision(target)	~30 ps	~3 ps

7.2 Development of wide-band VLBI system

For using VLBI technique in T&F transfer, we are developing small antennas in diameter with wideband VLBI system. The new wideband VLBI system is semi-compliant with next generation VLBI specification "VLBI2010", which is promoted by International VLBI community. Table 2 shows the comparison of specification between a current conventional and a new system.

References

[1] M. Kumagai, H. Ito, M. Kajita and M. Hosokawa; "Evaluation of Caesium Atomic Fountain NICT-CsF1" *Metrologia* 45 (2008) 139-148.

[2] F. Dos Santos, H. Marion, S. Bize, Y. Sortais, A. Clairon and C. Salomon; "Controlling the Cold Collision Shift in High Precision Atomic Interferometry" *PRL*, 89, (2002) 233004

[3] R. Li and K. Gibble; "Evaluation and minimizing distributed cavity phase errors in atomic clocks" *Metrologia* 47 (2010) 534-551

[4] K. Matsubara, K. Hayasaka, Y. Li, H. Ito, S. Nagano, M. Kajita and M. Hosokawa, 2008, App. Phys. Express, 1 067011, (2008).

[5] K. Matsubara, H. Hachisu, Y. Li, S. Nagano, C. Locke, A. Nogami, M. Kajita, K. Hayasaka, T. Ido, and M. Hosokawa, submitted to Opt. Express.

[6] CIPM recommendation (C2-2009), updates to the list of standard frequencies http://www.bipm.org/cc/CIPM/Allowed/98/REC_CIPM2009_C2_LIST_OF_ST_FREQUENCIES_18_DEC_2009.pdf.

[7] A. Yamaguchi, N. Shiga, S. Nagano, Y. Li, H. Ishijima, H. Hachisu, M. Kumagai, and T. Ido, Appl. Phys. Express **5**, 022701 (2012).

[8] M. Fujieda, M. Kumagai, S. Nagano, A. Yamaguchi, H. Hachisu, and T. Ido, Opt. Express **19**, 16498 (2011).

[9] A. Yamaguchi, M. Fujieda, M. Kumagai, H. Hachisu, S. Nagano, Y. Li, T. Ido, T. Takano, M. Takamoto, and H. Katori, Appl. Phys. Express **4**, 802203 (2011).

[10] M. S. Safronova, M. G. Kozlov, C. W. Clark, Phys. Rev. Lett., **107**, 143006(2011).

[11] K. Hayasaka, Appl. Phys. B **107**, 965(2012).

[12] M. Kajita, G. Gopakumar, M. Abe, and M. Hada, Phys. Rev. A84, 022507 (2011).

[13] M. Kajita, G. Gopakumar, M. Abe, and M. Hada, Phys. Rev. A85, 062519 (2012).

[14] Y. Hanado and M.Hosokawa, Japanese Journal of Applied Physics, Vol.47, No.4, pp.2294-2298, April, 2008.

[15] F. Nakagawa, M. Imae, Y. Hanado and M. Aida, IEEE Transactions on Instrumentation and measurement,vol.54, No.2, pp.829-832, April, 2005.

[16] Y. Hanado, K. Imamura, N. Kotake, F. Nakagawa, Y. Shimizu, R. Tabuchi, Y. Takahashi, M. Hosokawa and T. Morikawa, International Journal of Navigation and Observation, Article ID 841672, pp.1-7, January, 2008.

[17] T. Gotoh, T. Hobiger and R. Ichikawa, Proc. of International Symposium of GPS/GNSS, PS04, 2009.

[18] M. Fujieda, H. Maeno, D. Piester, A. Bauch, S. H. Yang, T. Suzuyama, W. H. Tseng, L. Huanxin, Y. Gao and J. Achkar, Proc. of EFTF 2011, 655-660, 2011.

[19] M. Kumagai, M. Fujieda, S. Nagano and M. Hosokawa, Opt. Lett., 34, 19, 2949-2951, 2009.

[20] M. Fujieda, M. Kumagai and S. Nagano, IEEE TUFFC, 57, 1, 168-174, 2010.

[21] M. Fujieda, M. Kumagai, S. Nagano, A. Yamaguchi, H. Hachisu and T. Ido, Opt. Exp., 19, 17, 16498-16507, 2011.

[22] A. Yamaguchi, M. Fujieda, M. Kumagai, H. Hachisu, S. Nagano, Y. Li, T. Ido, T. Takano, M. Takamoto and H. Katori, Appl. Phys. Exp., 4, 082203, 2011.

[23] T. Gotoh, J. Amagai, Y. Takahashi and S. Hama, IEICE Technical Report, SANE2011-100, 201-205, 2011.

[24] T. Gotoh, J. Amagai, T. Hobiger, M. Fujieda and M. Aida, IEEE IM, 60, 7, 2495-2499, 2011.

[25] W. H. Tseng, Y. J. Huang, T. Gotoh, T. Hobiger, M. Fujieda, M. Aida, T. Li, S. Y. Lin, H. T. Lin, K. M. Feng, IEEE TUFFC, 59, 3, 531-538, 2012.

[26] M. Fujieda, T. Gotoh, F. Nakagawa, R. Tabuchi, M. Aida and J. Amagai, submitted to IEEE TUFFC.