Report of Time and Frequency Activities at NICT (2015-2017)

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

1. Introduction

The National Institute of Information and Communications Technology (NICT) 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 (STSL) as a part of the Applied Electromagnetic Research Institute. STSL comprises of four groups. Atomic Frequency Standards Group develops atomic clocks ranging in frequencies from microwaves to the optical region. Specifically, Cs fountain primary frequency standards, a Sr optical lattice clock, and a single ion optical clock are developed. In addition, studies in THz frequency standards and chip-scale atomic clocks have begun in 2011 and 2016, respectively. The second group is the Japan Standard Time Group, responsible for the generation and dissemination of Japan Standard Time, as well as a frequency calibration service as a national authority. A part of the Space-Time Measurement Group at Koganei develops precise time and frequency transfer techniques mainly using satellite links. The other part at Kashima specializes in VLBI research using antennas with a diameter of 34 m and smaller, and applies the VLBI technique to precision time transfer. Details of these activities are described in the following sections.

2. Primary clocks

NICT has been developing Cs atomic fountain primary frequency standards NICT-CsF1 and NICT-CsF2 for contributions to the determination of TAI and the calibration of Japan standard time. Our first fountain CsF1 had been in operation with a typical uncertainty of 1.4×10^{-15} since 2006 [1] . Aiming an operation at the 10^{-16} level, however, it has suspended operations for years and the system is currently being upgraded. First, the frequency reference based on cryogenic sapphire oscillator (CSO) was upgraded from the dewar-type to a “cryocooler”-type in 2014. The cryocooler CSO enables the long-term continuous operation without phase jumps due to frequent liquid helium transfer. To prevent acoustic noise of the pulse-tube refrigerator from disturbing the fountain operations, it is located well away from the fountains and the microwave signal is transferred to a fountain room via 100 meter optical fiber cable. This ultra-stable signal is converted to 9.192GHz and used in the microwave interrogation for both fountains. Additionally, for precise evaluation of the large collisional shift a rapid adiabatic passage method was installed in CsF1, enabling both high frequency stability and accuracy. Now we are re-evaluating the distributed cavity phase (DCP) shift.

In contrast to CsF1 which uses a (0,0,1) laser cooling geometry with quadruple magnetic field, the second fountain CsF2 (Fig. 1) adopts (1,1,1) geometry enabling many atoms to be captured without a magnetic field gradient in large diameter laser beams, resulting in a reduction in the atomic density and thus a smaller collisional shift. It realized a frequency stability of $3 \times 10^{-13}/\tau^{1/2}$ and completed evaluations of most systematic frequency shifts at an uncertainty below 5×10^{-16} for a while, but the vacuum problem occurred a few years ago. This issue is now resolved and we will evaluate the systematics again.

3. Optical clocks

3.1 Sr optical lattice clock

A lattice clock based on the ^{87}Sr $^1S_0$-$^3P_0$ transition has been in operation since 2011. In 2015, the absolute frequency measurement with reduced uncertainty was performed with respect to the International Atomic Time (TAI) [2]. Here, we proposed intermittent operations of an optical clock which are distributed homogeneously in the 5-day TAI grid. The fractional uncertainty of 1.1×10^{-15} is predominantly determined by a so-called dead time uncertainty, where the TAI-link suffers from additional uncertainty in assimilating the TAI frequency of five-day mean with that of one-month mean routinely available in Circular T. This additional uncertainty was evaded in a collaboration with BIPM by employing the estimation of TAI mean frequency with the estimation interval of five days of the experiment. The reevaluation of the frequency link in the measurement in 2015 reduced the total uncertainty below 1×10^{-15} [3]. Further reduction of total uncertainty down to 4.6×10^{-16} was achieved by extending the campaign to ten days in order to reduce the uncertainty in UTC(NICT)-UTC link [4]. Note that the Sr optical frequency standard contributes with 5.7×10^{-17}, which predominantly comprises of blackbody radiation shift, lattice Stark shift, and density shift. The absolute frequency agrees with latest measurements at PTB and SYRTE as shown in Fig. 1.

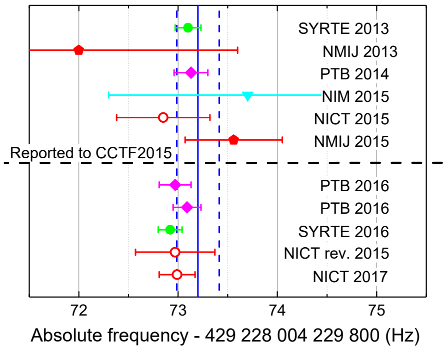

Fig. 1 Various absolute frequency measurement for ^{87}Sr lattice clock

Capability of stable intermittent operations has allowed us to realize a timescale by predicting the linear drift of a hydrogen maser frequency with respect to the Sr lattice clock. Following a feasibility study in 2015 which utilized the data of three five-day campaigns [5], we operated the lattice clock steadily for a half year in 2016 with operation rate of once in a week or more, by which the steering parameter set into a phase micro stepper was determined. The timescale TA(Sr) we obtained was as stable as UTC, and as accurate as TT(BIPM16). The UTC-TA(Sr) monotonically increased to 8 ns over five months, whereas TT(BIPM16)-TA(Sr) stayed in sub-ns, demonstrating a capability to steer the time signal as well as to calibrate TAI frequency using intermittent operations of highly accurate optical clocks. Using the optically steered signal, we achieved the evaluation of one-month mean TAI scale interval continuously for a half year.

3.2 Single ion-trap optical clocks

A single-ion optical clock based on $^{115}In^+$ is under development at NICT. The advantages of the $^1S_0$-$^3P_0$ clock transition at 237 nm are the ultimate relative frequency inaccuracy in the order of 10^{-18} and the prospective stability enhancement by use of multiple ions [6]. A new approach of using two $^{40}Ca^+$ ions in a linear trap for sympathetic cooling of the In^+ as well as for micromotion and the magnetic-field probe has been successfully employed to the observation of the clock transition [7]. The first frequency measurement since the last report with a single In^+ in a Paul-Straubel trap in 2007 has been demonstrated recently, using the UTC(NICT) and a Sr optical lattice clock as the frequency reference [7]. The clock transition frequency obtained by 36 measurements of the transition spectra (Fig. 2(a)) is 1 267 402 452 901 049.9 (6.9). The main contribution to the uncertainty is given by the first-order Zeeman shift due to the imperfect management of the residual magnetic field, and the uncertainty could be reduced by better control of the magnetic field. The comparison with the previously reported values shown in Fig. 2(b) exhibits the small frequency uncertainty obtained in our measurement.

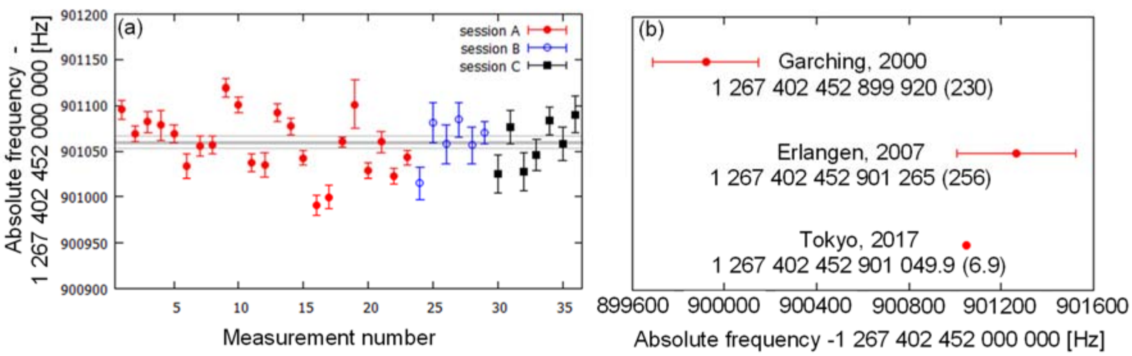

Fig. 2 (a) Plot of each frequency measurement, (b) comparison with the previously reported values. Reference [8] and [9] corresponds to 'Garching, 2000' and 'Erlangen, 2007', respectively.

4. THz frequency standard

NICT has started to establish a new frequency standard in THz (0.1 - 10THz, wavelength 30 um-3 mm) region. A wide- frequency-range and highly accurate THz frequency counter based on a photocarrier THz comb in a photoconductive antenna using a femtosecond-pulse mode-locked laser has been developed for measuring absolute THz frequencies. Its measurement accuracy has improved to 10^{-17} level over unprecedented wide range from 0.1 to 0.65 THz (Fig. 4) [10]. A THz-to-microwave synthesizer, which serves as a novel THz frequency divider, was demonstrated by employing a THz comb technology [11]. An ultra-stable and widely-tunable THz continuous-wave (cw) synthesizer was developed for THz frequency metrology by the photomixing of two lasers coupled into a uni-traveling carrier photo diode (UTC-PD). It generated cw radiation at an arbitrary frequency from 0.1 THz to 3 THz with the instability of less than 1 mHz in 1000 s averaging time. This method was extended to open a way for distributing a THz frequency reference to a remote site via an optical fiber link. New THz frequency reference transfer with higher 10^{-18}-level accuracy was developed by employing the THz comb and coherent optical carrier transfer technologies [12].

In theoretical research, THz quantum standards around 10 THz [13, 14, 15, 16] and mid-IR quantum standards [16, 17, 18], which are based on vibrational transition frequencies of trapped ultracold molecules, were proposed to attain the uncertainty level of less than 10^{-16}.

5. Japan Standard Time

5.1. Atomic timescale

UTC(NICT), the base of Japan Standard Time, is a realization of an atomic timescale comprising of an ensemble of 18 Cs commercial atomic clocks (Microsemi Corporation "5071A") at NICT headquarters in Tokyo [19]. In this ensemble timescale, rate of each clock is estimated from the last 30-day-trend and clock weigh is set by $1/\sigma_y(\tau = 10\text{ days})$. If any clock shows a sudden rate change more than 1×10^{-14}, its weight is recued to zero. 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 [20]. Phase data is measured in addition to the frequency data using one pulse per second (1 PPS) signals to prevent cycle-slip mistakes. For robustness, the main parts of the system have three redundancies; atomic clocks and other critical devices are supplied with a large UPS, a generator which has sufficient fuel to maintain power for three days; and the building itself incorporates quake-absorbing technologies. Fig. 5 shows the generation system of UTC(NICT) [21], and Fig. 4 shows the frequency stability of UTC(NICT) calculated from the data during 2011 - 2015.

To improve resilience against a disaster, a physically distributed system of Japan Standard Time is being developed.

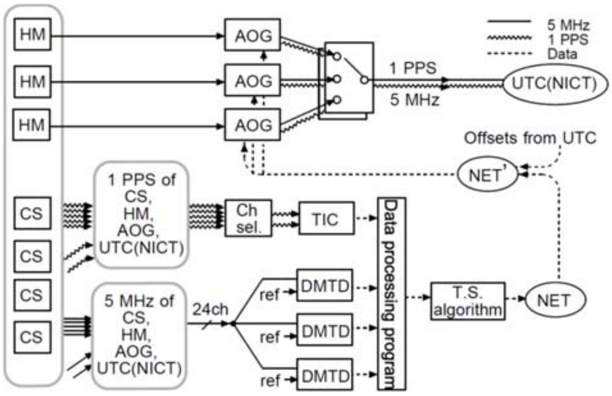

Fig. 3. Generation system of UTC(NICT).

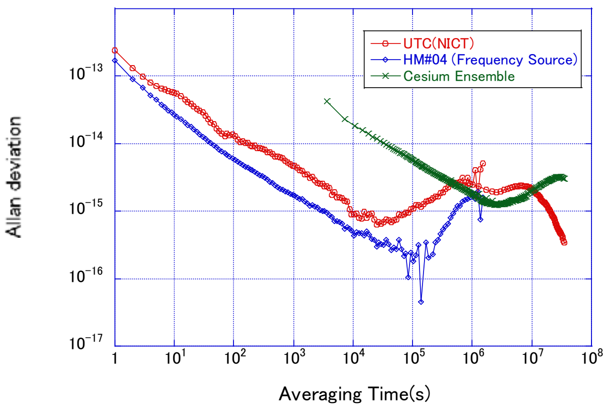

Fig. 4. Frequency stability of UTC(NICT) compared with H-maser and Cs ensemble time (TA). Here, "NET" is NICT-Cs-ensemble-time.

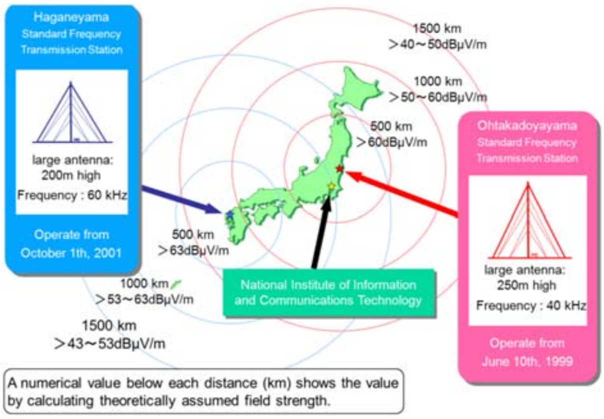

Fig. 5. LF time and frequency service stations in Japan.

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

In this system, atomic clocks at remote stations are planned to be connected via satellites or optical fibers, and an ensemble timescale at each station will be constructed independently from all these connected clocks. As these ensemble timescales at remote stations should become approximately the same, they can be used as back up timescales in emergency. This system will ensure a continuity of Japan Standard Time even if NICT headquarters suffers from a disaster. As the first remote station, JST sub-system that consists of atomic clocks and necessary components has been installed in Kobe branch. Furthermore, time link systems between NICT headquarters, Kobe branch and two LF stations have been installed and calibrated, and preliminary operation tests are in progress. Official operation at Kobe branch will start in 2018.

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 Fig. 5. The values under the distance (km) show the approximate strength calculated as the assumed electric field. Signals from the two LF stations, Ohtakadoya-yama and Hagane-yama, mostly cover Japan. Table 1 shows the characteristics of the stations, both of which operate 24 hours a day. As it has passed more than fifteen years since the two stations started their services, we renewed a part of the system including amplifiers and matching devices. This renovation in two stations were completed in March 2016.

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 merely initializes and checks 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 2 billion accesses per day in August 2016.

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 5×10^{-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 KCDB in August 2005. The revised CMC table was submitted to the KCDB and registered in November 2009. The latest CMC table was reviewed in the APMP TCTF Committee in July 2015. It was registered and published in the KCDB on October 3, 2016. The peer review once in 5 years was carried out in March 2016. It was conducted jointly with the examination for accreditation by IA Japan, the accreditation body of ISO/IEC 17025. After that, NICT received the latest certificate dated April 19, 2016 from IA Japan.

6. Time transfer

NICT has conducted precise time and frequency (T&F) transfer between atomic clocks in many sites including satellites using several methods such as GNSS, two-way satellite time and frequency transfer (TWSTFT) and optical fiber. Recent T&F transfer experiments using very long baseline interferometry (VLBI) are also described here.

6.1 GPS time transfer

NICT has been operating three receivers (Septentrio PolaRX2 TR and PolaRX4 TR, Dicom GTR50) for a network of international time links. The receivers were calibrated by BIPM portable calibration station "METODE" in spring 2014. For the JST distributed generation system under a development, we constructed a GPS real-time common-view (RTCV) time link between UTC(NICT) and Kobe branch. GPS RTCV is also used to monitor the clocks located at two LF stations.

We are now preparing a GNSS calibration system as a group-1 laboratory in APMP for a new international time link calibration network planned by BIPM. The system was installed at NICT headquarter and is evaluating with receivers for a network of international time links now. We are now planning to perform the G2 calibration trip using the system by March 2018. We have also confirmed the calibration procedure by calibration trips in NICT branches with this system.

Fig. 7. The rooftop of the NICT building.
Two platforms for MWL GT and some TWSTFT antennas are seen.

6.2 TWSTFT

NICT has organized the Asia-Pacific Rim TWSTFT link, currently utilizing the satellite Eutelsat 172A, to monitor atomic clocks located in three domestic stations. Time transfer is performed once every hour. Using the same frequency band, time transfers between NICT, TL, and KRISS are performed once every hour. An Asia-Hawaii link was terminated in the end of September 2016 due to the end of QZSS project.

The Asia-Europe TWSTFT link had been cooperatively constructed by major T&F institutes in Asia; NICT, TL, NIM, NTSC, KRISS, NPLI, and two European institutes; PTB and VNIIFTRI [22]. The link had been established by the satellite AM-2 until November 2014. The link was restarted by AM-22, however, due to the coverage NICT did not participate in the link. Since the end of the lifetime of AM-22 is approaching, alternative satellites are under review.

6.3 Quasi-Zenith Satellite

NICT conducted the demonstration experiments for the first Quasi-Zenith Satellite (QZS-1) "MICHIBIKI" with the Japan Aerospace Exploration Agency (JAXA). In the experiments, we were responsible for providing the time difference between GPS time and UTC(NICT) (GPST-UTC(NICT)) to the QZS-1. The QZS-1 broadcasts UTC parameters generated from the GPST-UTC(NICT). The operation of the QZS system (QZSS) was transferred from JAXA to the government of Japan on 28th February 2017. The second QZS satellite (QZS-2) will be launched on June 1st, 2017 by the government of Japan. NICT has already terminated the operation of the QZS timing system in the end of March, 2017. In the operational QZSS, UTC parameters will be generated using GPST-UTC(NICT) published in the NICT web-site.

6.4 Carrier-phase TWSTFT

For improvement of measurement precision, NICT has studied carrier-phase TWSTFT (TWCP) [23]. Under cooperation with KRISS, the TWCP measurement started in December 2016. The TWCP result was compared with PPP and IPPP (Integer PPP). Particularly, we confirmed a quite good agreement between TWCP and IPPP results, where the disagreement was less than 10^{-16} (Fig. 6). The demonstration of a direct frequency ratio measurement between a Sr lattice clock and a Yb lattice clock was successfully performed by TWCP technique between NICT and KRISS.

NICT has been developing a new TWSTFT modem which enables both code-phase and carrier-phase measurements since 2016. Two prototypes are currently under evaluation.

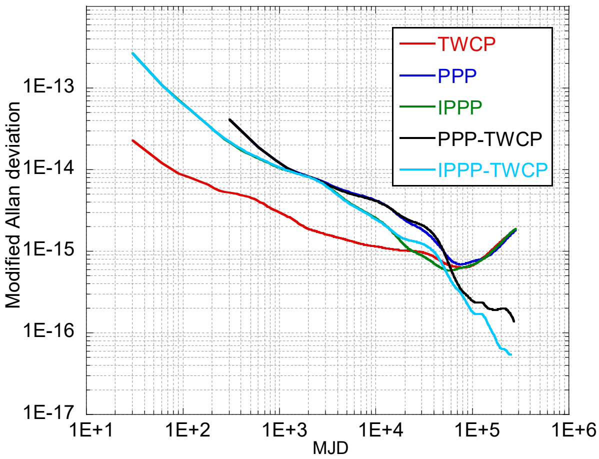

Fig. 6. Frequency stability of UTC(NICT)-UTC(KRIS) for 13 days starting from Jan. 19, 2017 shown in modified Allan deviation.

6.5 Preparation for ACES mission

ACES (Atomic Clock Ensemble in Space), which is one of ESA space missions, is scheduled for flight onboard the international space station in summer of 2018 [24]. It aims several precision tests in fundamental physics such as a measurement of Einstein's gravitational frequency shift. The measurement will be performed by a frequency transfer link in the microwave domain (MWL). MWL compares the ACES frequency reference with respect to a set of ground clocks. For the mission accomplishment, total seven MWL ground terminals (GTs) will be distributed to metrological institutes which have an accurate frequency standard and a frequency transfer link. NICT was selected as one of the deployment sites for the MWL GT and will contribute to ACES in cooperation with University of Tokyo, RIKEN and NMIJ. The construction of two platforms for MWL GT was finished on the rooftop of the NICT building in 2015 (Fig. 7). The MWL GT installation at NICT is tentatively scheduled in the early 2018.

7. VLBI for Time and Frequency Transfer

7.1 Status of Frequency Comparison with VLBI

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 concept of 'GALA-V' project, which is VLBI system for frequency comparison between transportable small diameter antennas. Under the collaboration with National Metrology Institute of Japan (NMIJ), 1.6m diameter VLBI station is placed at NMIJ Tsukuba. Joint use of this 1.6 m and 2.4 m diameter (upgraded from 1.5m in Mar. 2016) VLBI station at NICT Koganei are used for comparison of UTC(NMIJ) and UTC(NICT). By VLBI observations performed with these two small antennas and 34m radio telescope at Kashima, difference of clock behaviors of UTC(NMIJ) and UTC(NICT) has been measured. A series of VLBI experiments to evaluate the performance of this technique have been conducted in 2016. Fig. 9 shows a behavior of clock difference between UTC(NMIJ)-UTC(NICT) measured by broadband VLBI (5.9 – 10.6 GHz frequency range) and that of GPS observation. Alan standard deviations of the time series of these data and difference of them are indicated in Fig.10. This plot shows potential of precision frequency comparison of broadband VLBI observation. Improvement in measurement precision can be expected by expansion of observation frequency range, and it is to be

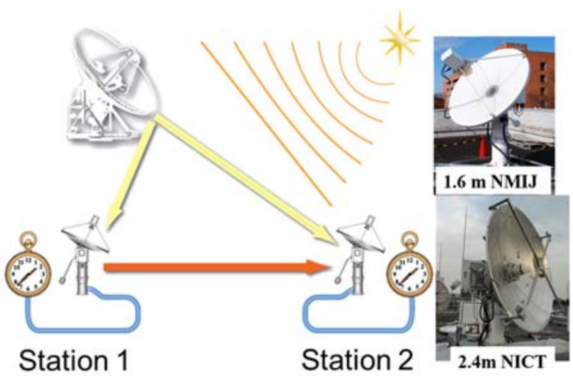

Fig. 8. GALA-V project measures difference of clocks connected small diameter radio telescopes via broadband VLBI observations. Left pictures are two small diameter VLBI antennas located at NMIJ and NICT.

verified in following experiments.

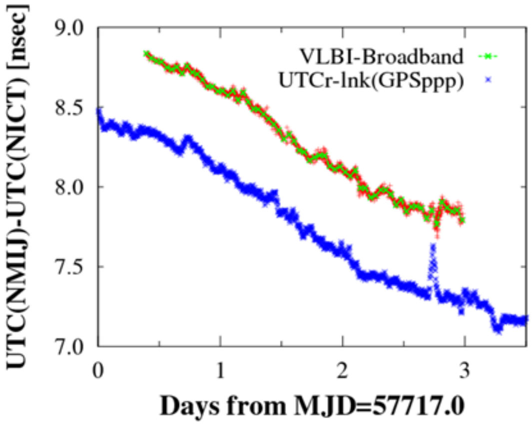

Fig. 9. An example of measurement results of clock behavior of UTC(NMIJ) – UTC(NICT) for 3 days since 25 Nov. 2016 obtained by broadband VLBI(GALA-V) and GPS observations.

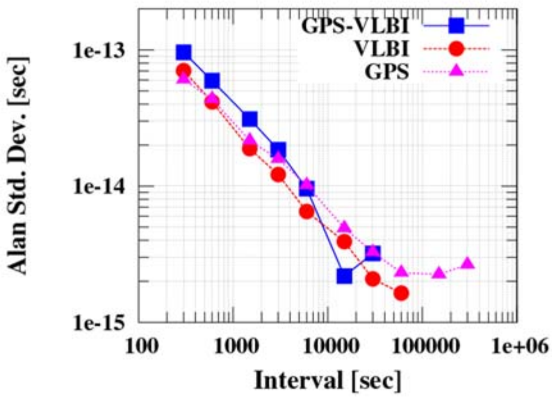

Fig. 10. Alan standard deviations of UTC(NMIJ) – UTC(NICT) measured in 25-27 Nov. 2016 via GALA-V system and GPS observations are indicated closed circle '●' and riangle '▲'. That of difference 'GPS-VLBI' is plotted with closed rectangle '■'.

7.2 Development of broadband VLBI system

To improve the performance of frequency transfer with VLBI, we are developing a broadband VLBI observation system, which captures four 1GHz bandwidth signals in 3-14GHz frequency range. This new VLBI system is designed to be compatible with the VGOS (VLBI Global Observing System) , which is the next generation geodetic VLBI system promoted by International VLBI Service for Geodesy and Astrometry (IVS). Since commercially available broadband receivers does not fit to standard Cassegrain optics antenna due to their broadband beam angle, we have developed original broadband feed [25] for NICT's 34m radio telescope. RF-Direct sampling technique, which enables stable broadband phase measurement, is another feature of our GALA-V system. Geospatial Information Authority of Japan (GSI) has built a new VGOS station in 2014 at Ishioka in Japan, and we have made some R&D VLBI experiment for broadband GALA-V system. A new broadband bandwidth synthesis software for precise group delay determination [26] has been developed, and sub-pico second delay resolution measurement has been achieved. Fig. 11 shows Alan standard deviation computed from time series of group delay at every second obtained by 1 second of integration of VLBI data on Kashima34 – Ishioka 13m baseline. The frequency comparison results described in the section above is obtained by these developments.

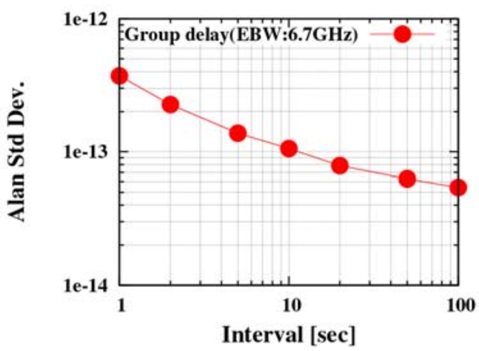

Fig. 11. Alan standard deviation of delay observable obtained by broadband (3.2-12.6GHz) VLBI observation. The plot indicates the broadband delay has sub-ps delay precision at 1 sec.

References

[1] M. Kumagai, H. Ito, M. Kajita and M. Hosokawa, "Evaluation of caesium atomic fountain NICT-CsF1," *Metrologia,* vol. 45, p. 139, 2008.

[2] H. Hachisu and T. Ido, "Intermittent optical frequency measurements to reduce the dead time uncertainty of frequency link," *Jpn. J. Appl. Phys.,* vol. 54, p. 112401, 2015.

[3] H. Hachisu, G. Pètit and T. Ido, "Absolute frequency measurement with uncertainty below 1 × 10−15 using International Atomic Time," *Appl. Phys. B,* vol. 123, p. 34, 2017.

[4] H. Hachisu, G. Petit, F. Nakagawa, Y. Hanado and T. Ido, "SI-traceable measurement of an optical frequency at low 10-16 level without a local primary standadard," *Opt. Express,* vol. 25, no. 8, p. 8511, 2017.

[5] T. Ido, H. Hachisu, F. Nakagawa and Y. Hanado, "Rapid evaluation of time scale using an optical clock," *J. Phys. Conf. Ser.,* vol. 723, p. 012041, 2016.

[6] K. Hayasaka, *Appl. Phys. B,* vol. 107, p. 965, 2012.

[7] N. Ohtsubo, Y. Li, K. Matsubara, T. Ido and K. Hayasaka, *Opt. Express,* vol. 25, p. 11725, 2017.

[8] J. von Zanthier, T. Becker, M. Eichenseer, A. Yu, C. Schwedes, E. Peik and H. Walther, *Opt. Lett.,* vol. 25, p. 1729, 2000.

[9] Y. H. Wang, R. Dumke, T. Liu, A. Stejskal, N. Y. Zhao, Y. N. Zhang, Z. H. Lu, L. J. Wang, T. Becker and H. Walther, *Opt. Comm.,* vol. 273, p. 526, 2007.

[10] H. Ito, S. Nagano, M. Kumagai, M. Kajita and Y. Hanado, *Appl. Phys. Express,* vol. 6, p. 102202, 2013.

[11] S. Nagano, H. Ito, M. Kumagai, M. Kajita and Y. Hando, *Opt. Lett.,* vol. 38, p. 2137, 2013.

[12] S. Nagano, M. Kumgai, H. Ito, M. Kajita and Y. Hanado, *Appl. Phys. Express,* vol. 10, p. 012502, 2017.

[13] M. Kajita, G. Gopakumar, M. Abe and M. Hada, *Phys. Rev. A,* vol. 84, p. 022507, 2011.

[14] M. Kajita, G. Gopakumar, M. Abe and M. Hada, *Phys. Rev. A,* vol. 85, p. 062519, 2012.

[15] M. Kajita, G. Gopakumar, M. Abe and M. Hada, *J. Phys. B,* vol. 46, p. 025001, 2013.

[16] M. Kajita, *Jpn. J. Appl Phys.,* vol. 53, p. 128001, 2014.

[17] M. Kajita, G. Gopakumar, M. Abe, M. Hada and M. Keller, *Phys. Rev. A,* vol. 89, p. 032509, 2014.

[18] M. Kajita, *Phys. Rev. A,* vol. 92, p. 043423, 2015.

[19] Y. Hanado and M. Hosokawa, *Jpn. J. Appl. Phys.,* vol. 47, pp. 2294-2298, 2008.

[20] N. Nakagawa, M. Imae, Y. Hanado and M. Aida, *IEEE Trans. Inst. Meas.,* vol. 54, no. 2, pp. 829-832, 2005.

[21] Y. Hanado, K. Imamura, N. Kotake, N. Nakagawa, Y. Shimizu, R. Tabuchi, Y. Takahashi, M. Hosokawa and T. Morikawa, *International Journal of Navigatio and Observation,* vol. Arcticle ID 841672, pp. 1-7, 2008.

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

[23] M. Fujieda, T. Gotoh, F. Nakagawa, R. Tabuchi, M. Aida and J. Amagai, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control,* vol. 59, no. 12, pp. 2625-2630, 2012.

[24] L. Cacciapuoti and C. Salomon, *Eur. Phys. J. Special Topics,* vol. 172, pp. 57-68, 2009.

[25] H. Ujihara, *Radio Sci.,* vol. 52, pp. 479-489, 2017.

[26] T. Kondo and K. Takefuji, *Radio Sci.,* vol. 51, pp. 1686-1702, 2016.