Report of Time and Frequency Activities at NICT (2012-2015)

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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 microwaves to the optical region. Specifically, Cs fountain primary frequency standards, a single ion trap optical clock and a Sr optical lattice clock are developed. In addition, research in THz frequency standards has begun in 2011. 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 mainly using satellite links. Lastly, the Space-Time Measurement Group at Kashima specializes in VLBI research using a 34 m antenna, and applies the VLBI technique to precise 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 contribution to the determination of TAI and the calibration of Japan standard time. Our first fountain CsF1 had been in operation with a typical uncertainly of 1.4×10^{-15} since 2006 [1]. Currently, toward an operation at the 10^{-16} level it is being upgraded. At first we introduced a cryogenic sapphire oscillator (CSO) developed by the University of Western Australia as an ultra-stable reference and a short term stability of $6 \times 10^{-14} / \tau^{1/2}$ was realized in high density operation mode. Additionally, for precise evaluation of the large collisional shift a rapid adiabatic passage method [2] was installed in CsF1, enabling both high frequency stability and accuracy. Now we are re-evaluating the distributed cavity phase (DCP) shift with following the approach proposed in [3]. In the case that the collisional shifts have the microwave power dependence [4], the rapid adiabatic passage method is effective in the microwave power elevating measurements for the 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 gradient in large diameter laser beams, resulting in a reduction in the atomic density and thus a smaller collisional shift. Once CsF2 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}, but the vacuum problem occurred a few years ago. Now the system reconstructions including the vacuum repair are complete and re-evaluations of the frequency shift are ongoing.

Fig. 1 NICT-CsF2

Toward a long-term continuous operation of the fountains for contributing to a time scale, the CSO was upgraded from dewar-type to “cryocooler”-type in 2014 [5]. 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 cycle cryorefrigerator from disturbing the fountain operations, it is located well away from the fountains and the only microwave signal is transferred to a fountain room via 100meter optical fiber cable. This ultra-stable signal is converted to 9.192GHz and used in the microwave interrogation for both fountains.

3. Optical clocks

3. 1 Sr optical lattice clock

A lattice clock based on the ^{87}Sr ^{1}S$_{0}$-^{3}P$_{0}$ transition has been in operation since 2011. Following a remote comparison using a fiber-link to Univ. of Tokyo [6], we performed an experiment of a satellite-based intercontinental link with the Sr lattice clock at Physikalishch-Technishe Bundesanstalt (PTB) [7]. See the section 6.4 of this report for the detail of the two-way satellite link that we employed for this experiment. The frequency difference was measured to be 1.1 (1.6) x 10^{-15}, indicating the frequency agreement of two lattice clocks in Japan and Europe. The absolute frequency of the transition was lately measured to be 429 228 004 229 872.85 (47) Hz [8] with reference to the International Atomic Time (TAI). The fractional uncertainty of 1.1 x 10^{-15} is smaller than any other absolute frequency measurements using the TAI link. The dead time uncertainty of a local transfer oscillator (hydrogen maser) was reduced by homogeneously distributed intermittent measurement over a five-day grid of TAI (Fig.2). This frequency agrees with previous measurements at other institutes. The Sr optical frequency standard contributes with 8.6 x 10^{-17}, which comprises of blackbody shift, lattice Stark shift, dc Stark shift, and density shift. We expect some straightforward improvements will soon reduce it further. Currently, we aim to evaluate the scale unit of UTC(NICT) using the lattice clock. A stable hydrogen maser and the rapid evaluation of its frequency based on an optical clock may allow a simple steering of the time scale.

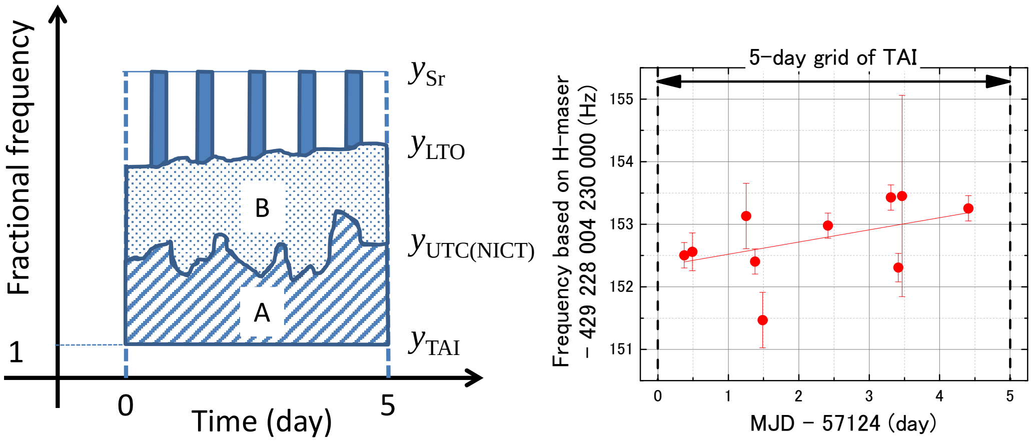

Fig. 2 Optical frequency measurement homogeneously distributed over a 5-day grid of TAI

3.2 Single ion-trap optical clocks

The most precise frequency of the ^{40}Ca^{+} single-ion optical clock at NICT remains as the previously reported value of 411 042 129 776 398.4 (1.2) [9]. Efforts are in progress to clarify the frequency difference of about 5 Hz between this value and those reported by University of Innsbruck [10] and by Wuhan Institute of Physics and Mathematics [11]. The efforts include frequency measurement at Osaka University, in which a novel system for remote optical frequency measurement without a flywheel microwave oscillator has been deployed [12].

A single-ion clock based on $^{115}\mathrm{In}^+$ 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 [13]. A new approach of using two $^{40}\mathrm{Ca}^+$ ions for sympathetic cooling of the In^+ as well as for micromotion probe has been successfully employed to the observation of the $^1S_0$-$^3P_1$ transition for the state detection (Fig. 3). Search for the clock transition is going on for the first frequency measurement by the new approach. A pulsed coherent vacuum ultraviolet (VUV) light source has been developed to excite the $^1S_0$-$^1P_1$ transition (159 nm) for faster detection of the quantum state [14]. This state detection method can extend the single-ion In^+ clock to a multi-ion clock, which is expected to break through the stability limit of single-ion clocks.

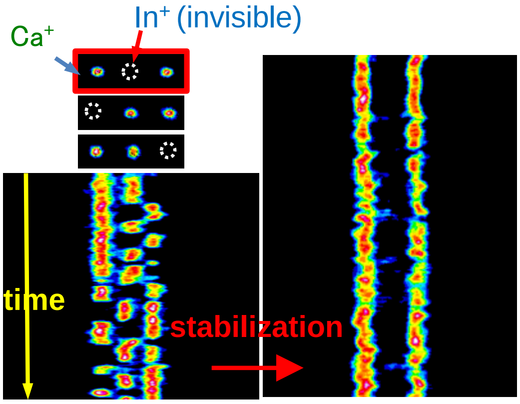

Fig. 3 Sympathetic cooling of In^+ by using Ca^+

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) [15]. A THz-to-microwave synthesizer, which serves as a novel THz frequency divider, was demonstrated by employing the THz comb technology [16]. 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 new way for distributing a THz frequency reference to a remote site via an optical fiber link.

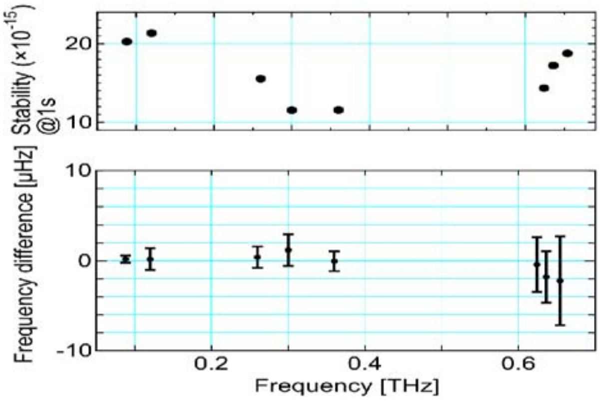

Fig. 4 Performance of THz counter based on a photocarrier THz comb

In theoretical research, THz quantum standards based on vibrational transition frequencies of optically trapped molecules were proposed to attain the uncertainty level of 10^{-16} around 10 THz [17–20].

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 [21]. In this ensemble timescale, rate of each clock is estimated from the last 30-day-trend and clock weigh is set by $1/\sigma_y\,(\tau=10$ days). If any clock shows a sudden rate change over 1 x 10^{-14}, its weight becomes 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

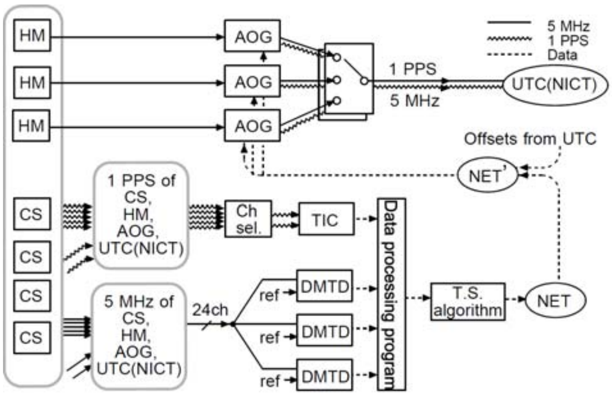

Fig. 5. Generation system of UTC(NICT).

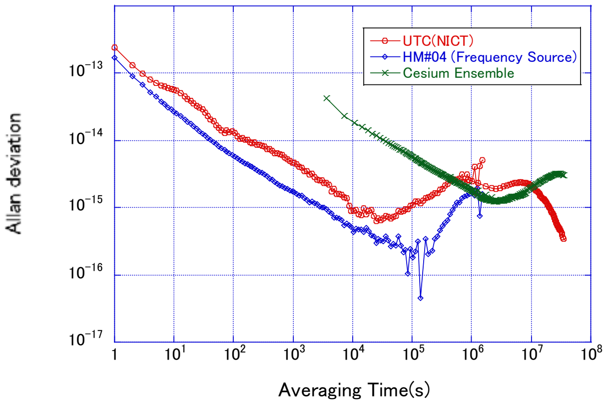

Fig. 6. Frequency stability of UTC(NICT) compared with H-maser and Cs ensemble time (TA). Here, "NET" is NICT-Cs-ensemble-time.

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 [22]. 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 main 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) [23], and Fig. 6 shows the frequency stability of UTC(NICT) calculated from the data during 2011 - 2015.

To improve reliability, a distributed generation system of Japan Standard Time is being developed. In this system, atomic clocks at remote stations will be connected together 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 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.

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. 7. 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, 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 has been developed.

The Ohtakadoya-yama station has been remote controlled from NICT headquarters since it temporarily suspended operation in 2011 just after East Japan earthquake. The renewal work of transmitting equipment of both the two stations is ongoing due to their aging deteriorations. It will be completed in FY2015.

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. In 2015, NICT

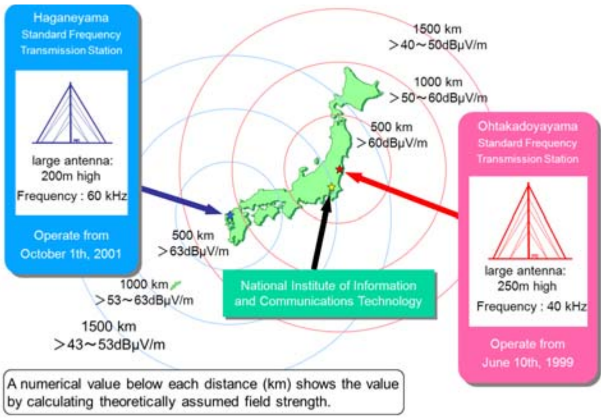

Fig. 7. LF time and frequency service stations in Japan.

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

introduced new PCI card servers with a new FPGA. Using these NTP servers, NICT receives more than 1.7 billion accesses per day on July 2015.

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 newest CMC table is just reviewed on July 2015. In the newest CMC, NICT plans to start a calibration of time-scale difference.

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. Based on the Rec. ITU-R TF. 1876, NICT planned to conform to the ISO standard, and this "traceability of the time source" was published as the ISO/IEC 18014 part 4 (18014-4) on April 2015.

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 two Septentrio PolaRX2 TR receivers 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 also prepare 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 also confirming the calibration procedure by actual calibration trips in NICT branches with this system..

6.2 TWSTFT

NICT has organized the Asia-Pacific Rim TWSTFT link, currently utilizing the satellite Eutelsat 172A, to monitor atomic clocks located in two domestic low-frequency stations. Time transfer is performed once every hour. 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, KRISS and USNO are performed once every hour by combination of the two links: Asia-Hawaii, USNO-Hawaii.

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 [24]. 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. Due to the end of lifetime of the AM-2 satellite, the link finished in November 2014. The schedule of the launch of a successor satellite is unknown. The search for an alternative satellite is going on.

6.3 Quasi-Zenith Satellite

NICT has conducted the demonstration experiments for the first Quasi-Zenith Satellite (QZS-1) "MICHIBIKI" with the Japan Aerospace Exploration Agency (JAXA). In the experiments, we are 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). Japanese government plans to launch additional three space vehicles to establish a practical QZS system by the late 2010s. NICT will terminate the demonstration experiments when operation of the practical QZS system is started. In the practical QZS system, 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) [25]. Under cooperation with Physikalisch-Technische Bundesanstalt (PTB), the TWCP measurement was performed in the very long baseline of 9000 km [26]. We obtained a short-term instability for frequency transfer of 2 x 10^{-13} at 1 s, which is at the same level as previously confirmed over a shorter baseline within Japan. Additionally, we confirmed the agreement between TWCP and GPSCP results. A double difference between GPSCP and TWCP shows that the measurement frequency stability reaches to the 10^{-16} region (Fig. 8). The demonstration of a direct frequency comparison of two Sr lattice clocks was successfully performed by TWCP technique between NICT and PTB [27]. The frequency agreement of the two Sr clocks was confirmed on an intercontinental scale.

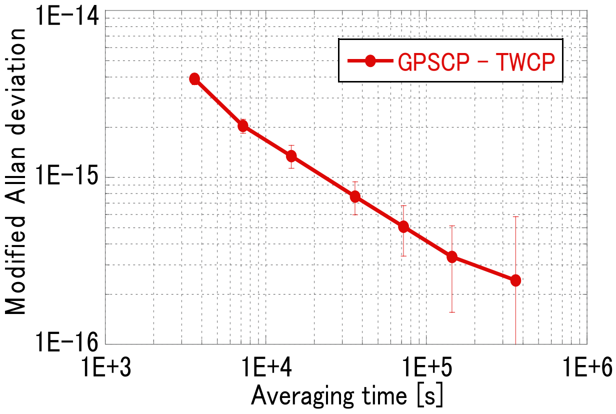

Fig. 8. Modified Allan deviation of double difference, GPSCP-TWCP, of NICT-PTB link..

NICT developed a remote frequency measurement system of optical clocks without a flywheel oscillator, which enables to evaluate optical frequencies even in laboratories with no stable microwave reference such as a Rb clock, a Cs clock or a hydrogen maser [12]. The system consists of a portable TWCP station and a microwave-signal-generation system from an optical clock. We confirmed the system uncertainty and instability to be at the low 10^{-15} level using a Sr lattice clock.

6.5 For the ACES mission

Fig. 9. The rooftop of the NICT building. Two platforms for MWL GT and some TWSTFT antennas are seen.

ACES (Atomic Clock Ensemble in Space) is the ESA space mission, which is scheduled for flight onboard the international space station in early 2017 [28]. 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 just finished on the rooftop of the NICT building (Fig. 9).

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. Fig. 10 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 and 1.5m diameter VLBI station is installed at NICT Koganei for comparison between 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) was measured and it was confirmed to be consistent with results measured by GPS observation. Fig. 11 shows the modified Allan standard deviation for UTC(NMIJ)-UTC(NICT) measured by VLBI(1 GHz

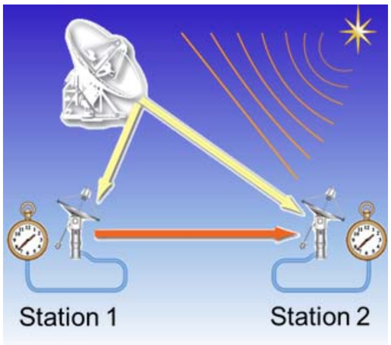

Fig. 10. Concept of 'GALA-V' project, which is VLBI system for distant frequency comparison between small diameter antennas.

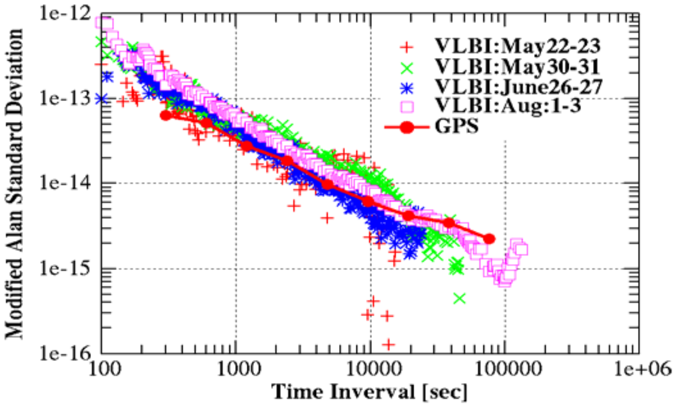

Fig. 11. Modified Allan Standard Deviation of UTC(NMIJ) – UTC(NICT) measured by VLBI observation of 1GHz bandwidth and GPS observation.

bandwidth) and GPS. This plot indicates that VLBI observation of 1GHz bandwidth has comparable performance with GPS observation. We are expecting further development of broadband VLBI observation will improve the results.

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 being developed to be compliant with the VGOS system, which is the next generation geodetic VLBI system promoted by International VLBI Service for Geodesy and Astrometry (IVS). Since all commercially available broadband receivers have wide beam width around 120 degrees, they cannot be accommodated to standard Cassegrain optics antenna and VGOS stations being constructed have special optics so called "Ring focus". To enable broadband observation with NICT's 34m radio telescope, we have developed low loss broadband feed by original design. Fig. 12 shows the broadband feed mounted on Kashima 34m radio telescope. Geospatial Information Authority of Japan (GSI) has built new VGOS station in 2014 at Ishioka in Japan, and this station became the domestic counterpart to Kashima 34 m antenna for broadband observation. The first broadband observation at 6-14 GHz frequency range was conducted on this baseline in Jan. 2015, and quite high delay resolution was achieved by super broadband bandwidth synthesis of 8 GHz bandwidth. Fig. 13 depicts the VLBI delay observable obtained by the observation. The precision was theoretically about 30 femto-second in 60 seconds of integration, and practically root-mean-square (RMS) of delay scatter of 1 second of integration was 0.6 pico-seconds with 8 GHz bandwidth. This new broadband observation technique will be used in the GALA-V, and improvement of precision on frequency comparison is expected.

Fig. 12. Picture of the broadband feed mounted on NICT Kashima 34m radio telescope. The first prototype broadband feed (IGUANA-H for 6.5-15GHz) in the right and the second prototype (NINJA for 3.5-14GHz) in the left.

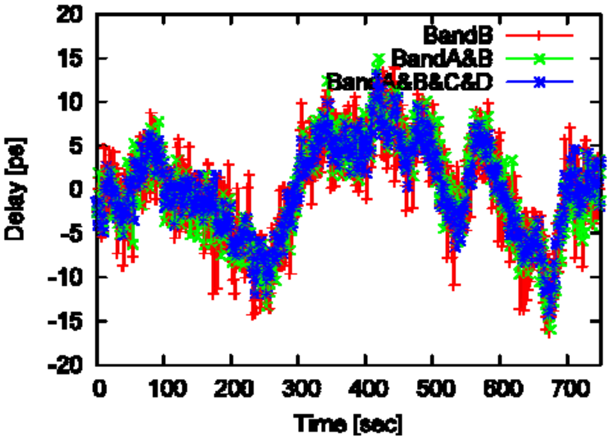

Fig. 13 Delay observable measured by VLBI observation on Kashima 34m – Ishioka 13m baseline. Observed signals in 6 – 14GHz frequency range were synthesized with 1 sec. integration for each points, and precise delay changes were clearly detected. Marks of red, green, and blue are indicating delay observable derived by 2GHz, 4GHz, and 8GHz band widths, respectively.

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