Development of Optical Frequency Standards and Their Remote Comparisons

Y. Koyama, T. Ido, K. Matsubara, Y. Li, M. Kumagai, S. Nagano, K. Hayasaka, H. Hachisu, N. Shiga, H. Ito, T. Iwama, K. Imamura, M. Fujieda, T. Goto, M. Sekido, T. Hobiger, and Y. Hanado

National Institute of Information and Communications Technology
4-2-1 Nukui-kitamachi, Koganei, 184-8795 Tokyo, Japan
koyama@nict.go.jp

Abstract—Recent developments of optical frequency standards are achieving stabilities and accuracies better than those of microwave frequency standards and are expected to improve the definition of the unit of second in the future. At National Institute of Information and Communications Technology (NICT), two different types of optical frequency standards have been developed, i.e. an optical lattice clock using ^{87}Sr atoms and an ion trap optical clock using a ^{40}Ca^{+} ion. It is also important to develop precise comparison methods to evaluate optical frequency standards located at different laboratories and such methods are also being developed. The overview of these developments will be presented.

I. INTRODUCTION

Recently, many research laboratories are trying to develop accurate and stable frequency standards using optical frequency transitions of ions and neutral atoms. The advancements of the developments are so rapid and it is becoming difficult to evaluate the absolute transition frequencies of optical frequency standards based on the current definition of the unit of second. Therefore, it is widely recognized that the development of optical frequency standards and their comparison are quite important for possible redefinition of the unit of second.

II. JAPAN STANDARD TIME

A. Japan Standard Time

UTC(NICT), the basis of Japan Standard Time, is a realization of an average timescale comprising of an ensemble of more than ten Cs atomic clocks (Symmetricom, Inc.“5071A”) at NICT headquarters in Tokyo [1] [2] [3]. UTC (NICT) is generated by using 18 high-performance Cs clocks and 3 H-masers. One H-maser is currently used as the signal source of UTC(NICT) and not included in weighted averaging of ensemble timescale. As a new approach, a distributed generation system of Japan Standard Time is under development.

B. Dissemination

UTC(NICT) is disseminated in various ways, such as LF frequency standard signal emissions from two broadcasting stations, a telephone-line service (Telephone JJY) and public NTP services. As for LF frequency standard signal emission, NICT operates two remote stations in north and south areas in Japan. Each LF broadcasting station generates and transmits time code by using locally installed Cs atomic clocks. Deviation from the JST at Koganei headquarter is monitored by a satellite time transfer method and it is corrected to keep the time difference become as small as possible. Frequency stability of LF frequency standard emission is better than $1\text{x}10^{-12}$, and ratio of air time is more than 99%. As for the Telephone-JJY, number of monthly access has been increasing and is currently exceeding $1.4\text{x}10^{5}$. For the public NTP service, FPGA-based NTP servers can accept up to 1 million requests/sec. Number of requests is currently exceeding 180 million/day (2013 Mar.). NTP-Repeater units can transmit a weak radio signal compatible with the LF frequency standard emission signal with the time-code referenced to the time synchronized by using the public NTP service. This system can transmit both 40 kHz and 60 kHz and cover up-to 10m in distance. Precision is less than 10ms.

C. Time-business service and calibration service

In addition to these dissemination services, NICT plays a role as a National Time Authority for the time stamp accreditation program in time-business services. The procedure established by NICT was approved as ITU-R TF recommendation in 2010. NICT is also providing the frequency calibration service both on-site and at remote site. The frequency calibration system was approved and registered in the international official database (KCDB) in 2005. In our remote frequency calibration services, GPS-CV is regularly used. New system using LF frequency standard emission signal was developed, and is under evaluation.

III. MICROWAVE ATOMIC CLOCKS AND APPROACH TO THZ REGION

A. Cs primary frequency standard

The cesium fountain primary frequency standard NICT-CsF1 has been operated to contribute to the determination of TAI since 2006 [4]. Typical frequency uncertainty is estimated as 1.4 x 10^{-15}. Now it is under refinement aiming at an uncertainty of 10^{-16} level. The 2nd fountain (NICT-CsF2) attaining the goal of operation at the 10^{-16} level is under development. Most systematic shifts are evaluated at a level below 5 x 10^{-16} uncertainty. The remaining measurement for distributed cavity phase shift is underway.

B. 171 Yb^+ frequency standard

A project to develop a 171 Yb^+ frequency standard system was started in 2010. The purpose of this project is to develop laser cooled Microwave frequency standard, aiming 1 x 10^{-13} fractional uncertainty in 100 sec. It is also aiming to be a proof-of-principle experiment for "atomic phase lock". Future extension of the system to a frequency standard in optical frequency is also in the scope in the future.

C. THz standard

NICT has started to establish a new frequency standard in the THz (0.1-10THz, 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 been evaluated as the level of 10^{-16} around the frequency of 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. Theoretical study about a THz quantum standard based on vibrational transition frequencies of optically trapped molecules are in progress to attain the uncertainty level of 10^{-16} at 4-10 THz [5, 6].

IV. OPTICAL CLOCK

NICT is developing two types of optical clocks: i.e., ion-trap optical clocks and optical lattice clocks.

A. Ion trap optical clock

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 [7]. The clock transition frequency was evaluated by microwave link to International Atomic Time (TAI) in more than ten measurement campaigns over the past years. The measured frequency of 411 042 129 776 398.4 (1.2) Hz [8] agrees with the CIPM recommendation [9]. Furthermore, optical comparisons with a Sr lattice clock locally available in NICT [10] enabled measurements of the frequency ratio of the $^{40}Ca^+$ transition to that of the Sr lattice clock. The result of 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 [8]. The measured absolute frequency has a disparity of more than three times as large as the measured uncertainty from two other previously published results. This result was reported and adopted in CCTF-GA 2012 and it contributed to update the recommended values of the standard frequency.

B. Optical lattice clock

A lattice clock based on the ^{87}Sr $^1S_0$-$^3P_0$ transition started its operation in 2011. By referring to the TAI, the absolute frequency of the transition was measured to be 429 228 004 229 873.9 (1.4) Hz [10]. 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} is mainly comprised of a blackbody radiation shift, a coalitional shift, the 2nd order Zeeman shift, and a lattice stark shift. The agreement with the clock at The University of Tokyo (UT) was also confirmed by an optical fiber link [11] described in Section V. 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 [12]. This result was reported and adopted in CCTF-GA 2012 and it contributed to update the recommended values of standard frequency.

C. New approach

A new optical frequency standard based on a single $^{115}In^+$ is being developed with an expected uncertainty in the order of 10^{-18} for the $^1S_0$-$^3P_0$ transition at 237 nm [13]. Three new approaches 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 [14], (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 an $^{115}In^+$ 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.

V. TIME AND FREQUENCY TRASFER

A. 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 [15, 16]. 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 and an optical carrier transfer system [17]. 1.5 μm light was stably transferred through a 90 km urban fiber link while canceling fiber noise to the theoretical limit. Transfer stability was 2 x 10^{-15} at 1 sec and 4 x 10^{-18} at 1000 s as measured by a Π type frequency counter.

NICT connected the ^{87}Sr optical lattice clocks developed at NICT and at the University of Tokyo (UT) through a 60 km urban fiber link [18]. 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 improvements on the system and a noise-less optical fiber link will be necessary.

For RF transfer NICT developed a commercially-available 10 MHz transfer system. The target transfer length was a few tens of kilometers 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 required for VLBI systems.

B. Sattelite Time and Frequency transfer for regular monitoring

In the GPS transfer, NICT has been operating two Septentrio PolaRX2 TR receivers for the 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 by using Kashima Ray-tracing Tools (KARAT) for which we developed PPP software, concerto v4 [19].

As for the Two Way Satellite Time and Frequency Transfer (TWSTFT), NICT has been organizing the Asia-Pacific Rim TWSTFT link, currently utilizing the satellite GE-23, to monitor atomic clocks located in two domestic LF standard frequency stations. An Asia/Hawaii link was established in 2010. 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 which are NICT, TL, NIM, NTSC, and NPLI, and two European institutes which are PTB and VNIIFTRI [20]. It is reported that satellite AM-2 will end its operational lifetime in the near future, and therefore, we are considering to replace the satellite with another satellite.

C. Advanced TWSTFT

NICT has developed a new two-way time transfer modem with an arbitrary wave form generator and a versatile A/D sampler. 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, by spreading the signals with a gap frequency, it is possible to obtain the equivalent time delay 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 [21]. NICT and TL have occasionally performed DPN TWSTFT by using the GE-23 North East Asia beam link [22].

For further improvements of measurement precision, NICT has started to develop carrier-phase TWSTFT [23]. The phase difference is derived from carrier phase information of the signals sent from the remote station and the local station. With a common clock measurement via a satellite link, a measurement precision of 0.2 ps was achieved, which is considered to be mainly limited by phase jitters induced by the frequency converters. In a long baseline with a length of 10000 km a measurement precision of 0.2 ps was achieved and the time variation showed good agreements with the results of GPS carrier phase. The evaluation is going to be reported soon.

D. VLBI for time and frequency transfer

For one of the tools for time and frequency transfer, NICT has been investigating potential capabilities of the Very Long Baseline Interferometry (VLBI) technique for T&F transfer. A T&F transfer inter-comparison experiment was performed between Kashima-Koganei over the 109 km distance for four days from 19 February 2012. This experiment was carried out to test the feasibility of VLBI with 11m diameter antennas. The clock difference between two hydrogen masers at both sites was compared by using VLBI, GPS, and TWSTFT (Code) in this experiment. The VLBI results demonstrated a smaller daily variation than TWSTF (Code) in this experiment. Additionally, increasing observation bandwidth in VLBI data from 500 MHz to 1 GHz showed an improvement of the precision of clock difference measurements. This encourages the plan to develop wideband VLBI system, which is under the development as the target of VLBI T&F transfer project.

E. New analys software

Otsubo et al. [24] have developed an analysis software package based on Java named CONCERTO4 which enables the user to consistently process GNSS, SLR, and other satellite tracking data. Driven by the need to update the software and to replace the existing Java code, VLBI was added as an additional module to this analysis package, which was renamed to “c5++” in 2010 [25]. The software complies with the latest IERS conventions [26] and provides state-of-the-art modules for a variety of geodetic, mathematical, and geophysical tasks. Modules of c5++ can be used for processing of single technique solutions or these modules can be combined for multi-technique analysis. In the multi-technique analysis, observed data are combined before the parameter estimation process and it ensures utmost consistent processing of space geodetic observations. Moreover, common parameters (clocks, troposphere, and orbits of satellites) between different techniques can be estimated in one single adjustment process. This makes it possible to utilize all the information from each observation technique and can cover the weak points that a single technique might have. As for frequency transfer applications, the combination of GPS and VLBI with c5++ is anticipated to provide high stability on both short-term and long-term time scales.

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