Report of Time and Frequency Activities at NICT

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1. Introduction

At National Institute of Information and Communications Technology (NICT) of Japan, research and developments related with time and frequency are currently conducted by the Space-Time Standards Group of the New Generation Network Research Center. The objectives of this group are to establish standards and reference of space and time as the fundamental basis for various fields of activities in science, engineering, and social activities, and to provide easy access to these foundations from wide range of communities. To carry out this concept, four research projects have been established in the group. Japan Standard Time Project is responsible for generation and maintenance of high quality Japan Standard Time (JST) and UTC (NICT), as well as dissemination of them by various methods. Atomic Frequency Standards Project is aiming to develop and operate primary frequency standard systems in the microwave and optical regions. Satellite Time Control Projects are performing precise time and frequency transfer experiments between a ground-reference clock and an atomic clock on the satellite such as ETS-8 and Quasi-Zenith Satellite System. Space-Time Measurement Project is conducting research and developments for precise time and frequency transfer and establishment of spatial reference frame by using two way satellite link methods, optical fiber transfer methods, and space geodetic techniques.
Recently, the Cesium fountain primary frequency standard system at NICT was reviewed by the Working Group of CCTF and the frequency accuracy of 2×10^{-15} was officially authorized. The ETS-8 satellite was launched into the gestational orbit and the precise carrier phase comparison between the on-board clock and a frequency standard system on the ground was successfully demonstrated. For the construction of UTC (NICT), Cesium clocks at remote sites were added and the contribution factor to the UTC is now routinely exceeding 10%.

2. Atomic Frequency Standards

2.1. Cesium Primary Frequency Standards

The optically pumped cesium primary frequency standard (NICT-O1) stopped an operation in June 2006. Instead of NICT-O1, the cesium atomic fountain primary frequency standard NICT-CsF1 is operational now. It obtained international official recognition in September 2007, and the results of accuracy evaluation with CsF1 have been used for TAI determination by BIPM since 2006. Currently, its frequency uncertainty is 1.9×10^{-15} [1].

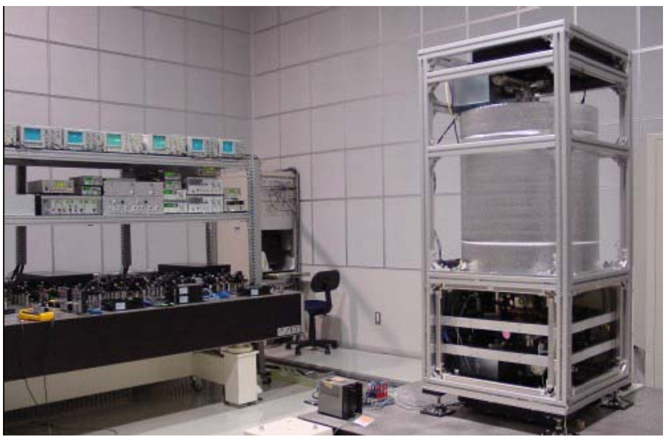

Figure 1. Cesium atomic fountain primary frequency standard (NICT-CsF1).

NICT have introduced a University of Western Australia built Cryogenic Sapphire Oscillator (CSO). Synthesis chains based on the CSO have been assembled without degradation of the frequency stability of the CSO. At present, the 1GHz and 9.192GHz signals, whose short-term stabilities are better than 2×10^{-15} at 1sec, are available as references for frequency standards.[2]

2.2. Optical Frequency Standards

NICT is developing two kinds of optical frequency standards. One is a single ion trap of $^{40}Ca^{+}$ (Figure 1). In June 2008, we reported the absolute frequency of clock transition of $^{40}Ca^{+}$ with an uncertainty of 10^{-14} level for the first time [3][4].The frequency is in good agreement with a result obtained in Innsbruck [5]. The other is an optical lattice clock using Sr atoms (Figure 3). Two-stage magneto-optical trap of bosonic as well as fermionic isotope has been produced and the bosonic atoms are further loaded into an optical lattice. Clock laser is under development. In theoretical research, possibility of a new clock using molecules' transition is suggested [6][7].

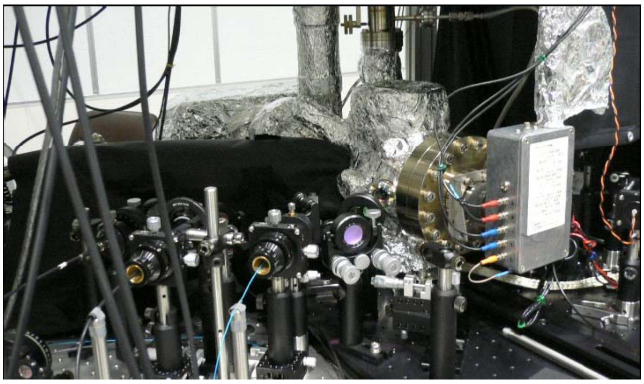

Figure 2. Optical frequency standard using an electric quadrupole transition in single, laser-cooled, trapped Ca+ ions.

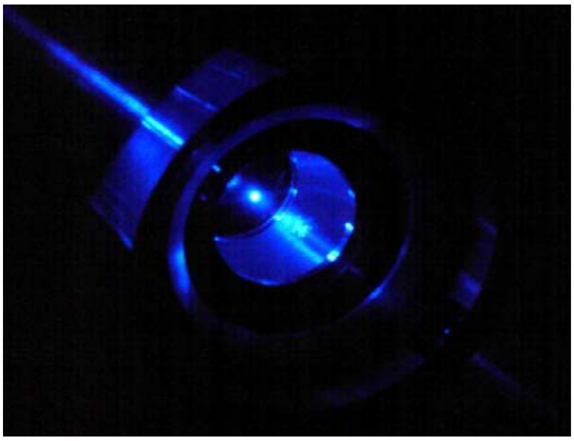

Figure 3. Emission of Sr atoms trapped by laser cooling technique.

2.3. Optical Measurement and Transmission Technique

Two optical frequency comb systems originally developed by using different lasers play an important role in evaluation of optical frequency standards under development. Their frequency stabilities of 2×10^{-16} were confirmed by mutual comparison.

3. Time Keeping

UTC(NICT), the base of Japan Standard Time, is a realization of an average timescale made by ensemble of 18 Cs atomic clocks at NICT headquarters. We have 4 hydrogen masers and one of them is used as the source of actual signal of UTC(NICT). The current generation system of Japan Standard Time started a regular operation in Feb. 2006 and works well since then [8]. UTC(NICT) has been synchronized with UTC almost within ±20ns. Frequency stability of the timescale becomes better by improved timescale algorithm [9]. We are going to link the Cs ensemble timescale with NICT-CsF1 and make a self-reliance timescale TA(NICT).

4. Precise Time and Frequency Transfer

4.1. GPS

NICT is collaborating with PTB to develop system, which is the potable frequency standard system composed of a passive hydrogen maser and a dual frequency GPS receiver, in this year. PTB plans to use the GPS carrier phase time transfer software developed by NICT for this system [10]. NICT and PTB performed GPS receiver calibration of both stations by using NICT Septentrio receiver from September 2007 to June 2008. The P1/P2 bias of both receivers consisted within 1 ns with respect to BIPM calibration result performed on April 2008. NICT is developing software GPS receiver using off-the-shelf Graphics Processing Unit (GPU). We confirmed that single-channel real-time software GPS receiver can generates similar results as obtained from a hardware receiver.

4.2. TWSTFT [11]

NICT and major T&F institutes in the Asia-Pacific region, NTSC in China, TL in Chinese Taipei, KRISS in Korea, are cooperatively constructing a TWSTFT network in this region using the satellite IS-8. To operate those links, we use multi-channel modem (NICT modem) developed by NICT. Time transfer is regularly performed and data/hour are reported to the BIPM.

A TWSTFT link between NICT and PTB has been conducted using NICT modem. Besides NICT modem observation, we introduced SATRE modem into this link December 2006. In addition, a time transfer operation with OP in France has been performed since March 2009. Their time transfers are hourly performed and the data are also reported to the BIPM. The TWSTFT link between NICT and USNO via VDB relay station was closed November 2006 because the link quality was very low. We plan to restart the observation with the relay station to in Hawaii.

NICT is developing a new TWSTFT system using dual Pseudo Random Noise (PRN). We carried out test observations with a satellite link, and confirmed that the short-term stability of less than 50 psec can be achieved.

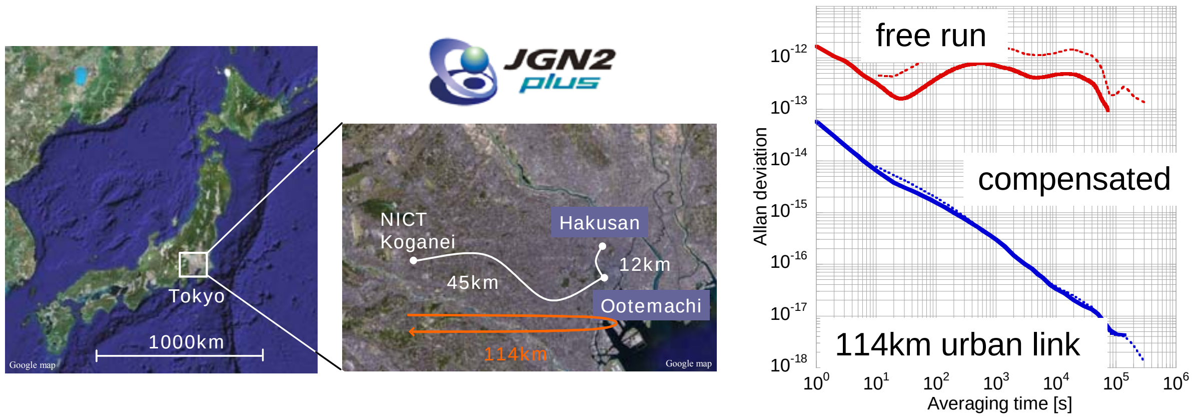

Figure 4. The fiber link used for the frequency transfer experiment and the achieved frequency stability.

4.3. Frequency Transfer Using Optical Fiber [12]

We have developed an RF dissemination system using optical fibers. The phase noise induced during the transmission is actively cancelled by the compensation system with a voltage-controlled crystal oscillator.

A performance test was conducted on an urban telecom fiber link of length 114 km, and a transfer frequency stability of $6x10^{-18}$ was achieved at an averaging time of 1 day (Figure 4).
As an application of ultra-stable frequency dissemination, a 1-GHz signal based on the CSO was transferred through a 25-km fiber and used as a microwave reference for an optical frequency comb. A fractional frequency stability of an ultra-narrow clock laser for a Ca-ion optical frequency standard was measured by the comb as $9x10^{-15}$ at 1 s, which included both the laser stability and transferred reference stability.

4.4. ETS-VIII

NICT is conducting a precise time and frequency transfer experiment between a ground-reference clock and an atomic clock on the satellite ETS-8 (Engineering Test Satellite -8). ETS-8, which was launched in late 2006, is a Japanese geostationary satellite equipped with cesium-beam frequency standards. NICT developed an equipment to carry out two-way time transfer with S-band by using both code and carrier phase measurement. The precision of the code phase reaches one ns for one second measurement and that of the carrier phase is of the order of 10^{-12} for one second, which is better than the traditional method by two orders [13]. The stability of the on-board atomic clock was evaluated in an averaging time of one second.

4.5. QZSS

Japan has started a project of Quasi-Zenith Satellite System (QZSS) since 2003 (Figure 5). QZSS will be highly useful for supplement to the modernized GPS in urban canyon and mountainous area with its high visibility brought out by its inclined orbits. In this project, NICT is developing a time management system [14]. By conducting two-way time transfer between the on-board clock and the clock on ground station by using Ku-band link, the management of the QZSS system time, which links to UTC (NICT), is expected to achieve nano second level. The proto-flight model (PFM) of the on-board equipments and the ground system has been developed. Three monitoring stations with TWSTFT and two time management stations are being built. The first satellite is planned to be launched in 2010.

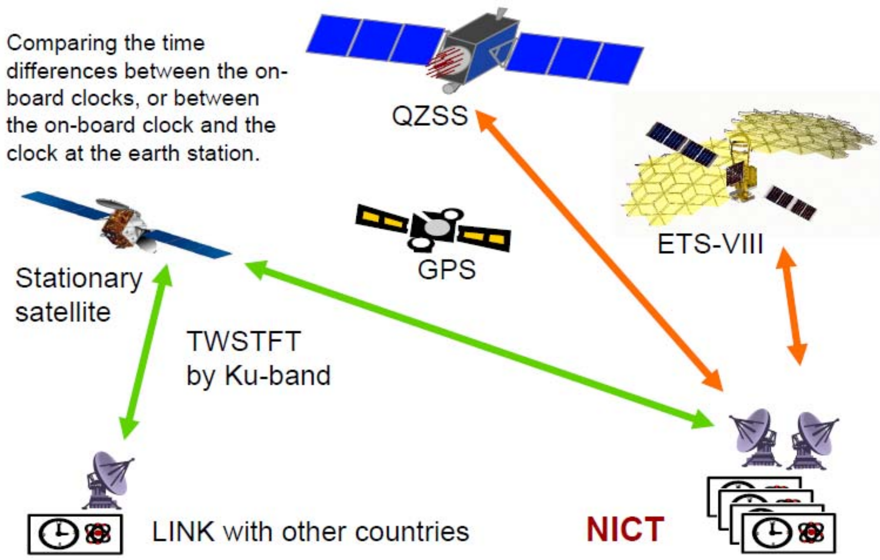

Figure 5. Time transfer systems at NICT.

4.6. VLBI

In the usual geodetic analysis using Very Long Baseline Interferometry (VLBI), clock offsets and their rates of change at each station are precisely estimated with respect to a selected reference station. The averaged formal error (1 sigma) of the clock offsets is typically about 20 picoseconds when analyzing geodetic VLBI experiments which are regularly conducted by the International VLBI Service for Geodesy and Astrometry (IVS). This precision is nearly one order better than other techniques like GPS or two-way satellite time transfer. We primarily evaluated the ability of VLBI frequency transfer by comparing with GPS carrier phase frequency transfer. We selected the two stations (Onsala, Wettzell) which belong to IVS and the International GNSS Service (IGS) network. These two stations have in common that at each site VLBI and GPS are sharing the hydrogen maser. VLBI is more stable at averaging periods longer than 10^3sec as shown in Figure 6. In addition, the VLBI frequency transfer stability follows a 1/tau law very close when averaging up to 10^4sec and it has reached about $2x10^{-11}$sec (20ps) at 1 sec.

In order to evaluate a capability of VLBI frequency transfer in more detail, we are carrying out geodetic VLBI experiments using Kashima-Koganei baseline (about 110km). GPS measurements are also simultaneously performed to compare with VLBI analysis. We have a plan to investigate longer stability of VLBI frequency transfer up to one week based on the experiments. In addition, we are now developing a compact and transportable VLBI system for providing reference baseline lengths to validate surveying instruments such as GPS and EDM. We are going to assess the compact VLBI system is feasible or not for the purpose of the precise frequency transfer.

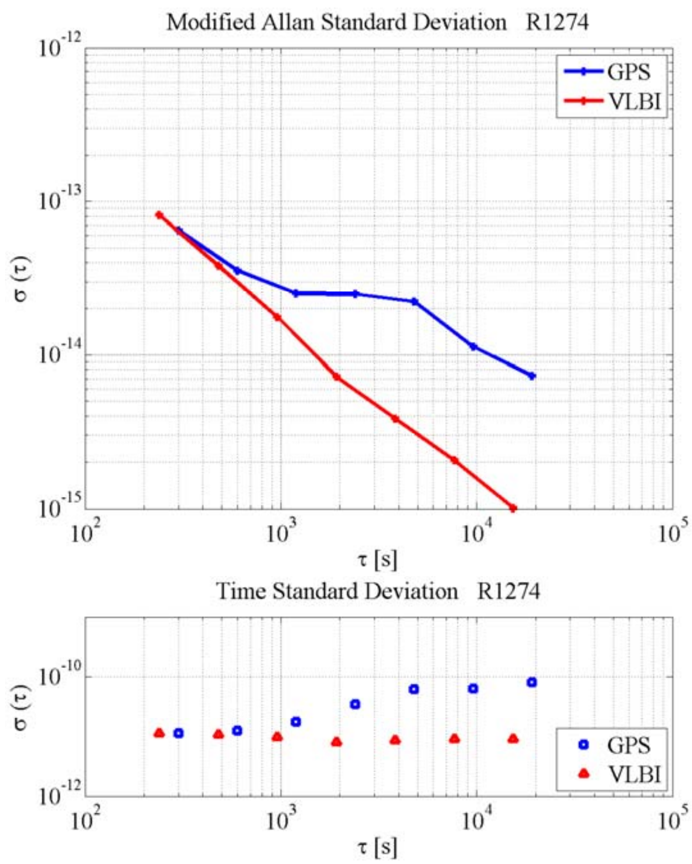

Figure 6. Modified Allan deviation (top) and Time Standard Deviation (bottom) of VLBI and GPS carrier phase results from an IVS session.

5. Dissemination

5.1. Standard-Frequency and Time-Signal Emissions

NICT provides the dissemination service of standard-frequency and time-signal via LF band, as shown in Figure 7. The signals from the two LF stations, namely Ohtakadoya-yama station and Hagane-yama station, cover whole Japan. Table 1 shows the characteristics of the stations, Both stations operate 24 hours a day. A market of radio controlled watch and clock have been developed.

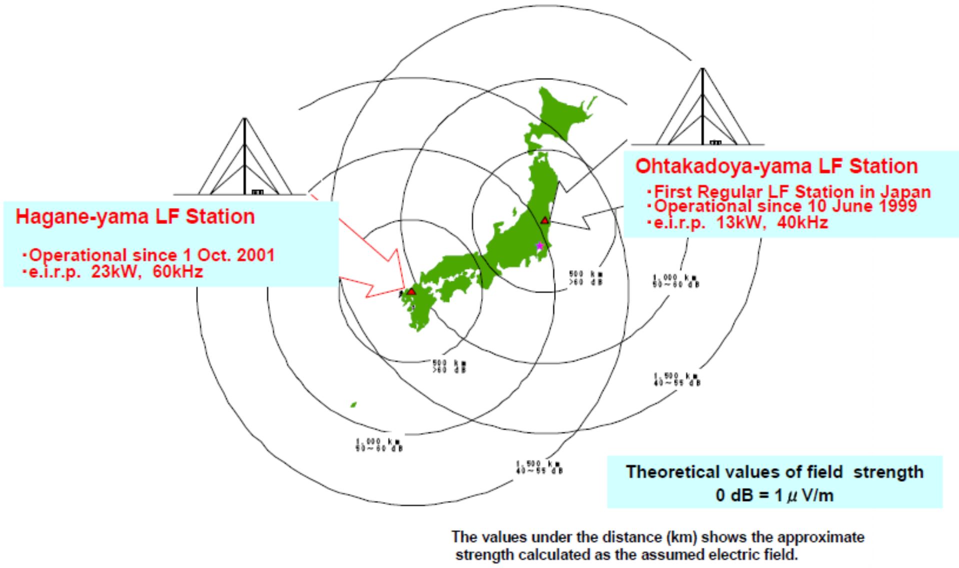

Figure 7. LF time and frequency service stations in Japan. The values under the distance (km) shows the approximate strength calculated as the assumed electric field.

Table 1. Characteristics of LF stations.

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

5.2. Frequency Calibration System for Traceability

NICT have been conducting a frequency calibration service referenced to UTC(NICT). In order to fulfill the requirements of global MRA, NICT have established a quality system for the frequency calibration service, which was assembled by the accreditation body, National Institute of Technology and Evaluation.

The conformity to ISO17025 was certified at the end of March 2001. The NITE (National Institute of Technology and Evaluation) provided an accreditation of ISO/IEC 17025 to NICT on 31 January, 2003, and also provided an accreditation of ISO/IEC 17025 of the frequency remote calibration system to NICT on 2 May 2006 BMC of the system is 5×10^{-14} Since April 2007.

5.3. Public Network Time Protocol Service

NICT has started public Network Time Protocol (NTP) service since 2006 using Field Programmable Gate Array (FPGA)-based NTP server which can accept NTP requests up to one million per second.

Because this server is implemented on a PCI card, a host PC is required to initialize and check the server operation. NICT recently developed a stand-alone server which includes a Linux controller unit integrated on the FPGA together with the NTP server hardware, and started use of this stand-alone server from 2008. Using this server, we expect to improve the availability and to reduce the operation cost of the public NTP service.

6. Trusted Time Stamping

Accreditation program for time-stamping services in Japan has started since Feb. 2005. In this program, the clock of the time-stamping server is calibrated within the prescribed accuracy and traceability to UTC(NICT) for every time stamp issued is assured. The accuracy of the clock 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.

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