Update of research activities on time and frequency at the National Institute of Information and Communications Technology (NICT)

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***Abstract*—The National Institute of Information and Communications Technology (NICT) in Japan has five time and frequency research and service groups. Those are, Atomic Frequency Standards Group, Time and Frequency Measurements Group, Japanese Standard Time Group, Quasi-Zenith Satellite System Group, and Time Applications Group. In this paper, we introduce the recent activities of these five groups.**

I. ATOMIC FREQUENCY STANDARDS

A. Optically Pumped Cesium Standard, NICT-O1

NICT-O1, an optically-pumped-cesium primary-frequency standard, formerly called as CRL-O1, has been in use since April, 2000 [1]. The accuracy evaluation data is sent to BIPM twice a year. The best accuracy among these data is $6x10^{-15}$. Since S/N became worse during the operation, we baked the whole system twice in 2004. The total uncertainty of the NICT-O1 is of the order of 10^{-15}.

Figure 1. Fountain type Cesium standard

B. Fountain-type Cesium Standard

Research and development on the atomic fountain Cs standard has been going on [2]. By using the first standard-size fountain system, a stability of $2x10^{-12}$ at 1 sec was achieved. Now the second fountain system, whose distance between the optical trap and the microwave cavity was reduced from 67 cm to 45 cm, was developed in 2005 as shown in Fig.1. In the second system the S/N and the total stability of the mechanical and optical systems are much improved.

C. EIT Resonance of Cs Atoms

Electromagnetically induced transparency (EIT) resonance experiments using a thin Cs vapor cell (Fig.2) are carried out. This Cs-vapor cell and the molecule trap are used for laser stabilization. As a result, a sub-Doppler 2-f spectrum is observed [3].

Figure 2. Pyrex glass cells for Cs vapor

D. Optical Frequency Standards

Aiming at measuring the spectrum of forbidden transition of single Ca^+ ion, we are now developing a new ion trap [4], [5]. To observe the $4s^2S_{1/2}$ - $3d^2D_{5/2}$ forbidden transition (729 nm), a narrow linewidth laser is being developed. So far, a few tens Hz linewidth and the stability of 10^{-13} for the laser is achieved [6]. To measure the optical frequency, we have used a femtosecond optical comb system Menlo FC 8003 and we have evaluated its performance [7].

II. PRECISE TIME SCALE GENERATION AND TIME TRANSFER

A. Two Way Satellite Time and Frequency Transfer

Regular operation of multi-channel TWSTFT modems developed in NICT has commenced since February 2005 between NICT and KRISS (Korea), NMIJ (Japan), NTSC (China), TL (Taiwan), SPRING (Singapore) via JCSAT-1B satellite, and between NICT and NMIA (Australia), KRISS via PAS-8 satellite together with GPS time comparison on those baselines.

Results of an inter-comparison of TWSTFT by the NICT modem, TWSTFT by the Atlantis modem and GPS common view (CV) in some links have been analyzed and evaluated. An example of the inter-comparison between NICT and KRISS is shown in Fig.3. Though JCSAT-1B has stopped the operation since the end of July, 2005, it is expected to recover at the end of 2005 (otherwise another satellite should be used).

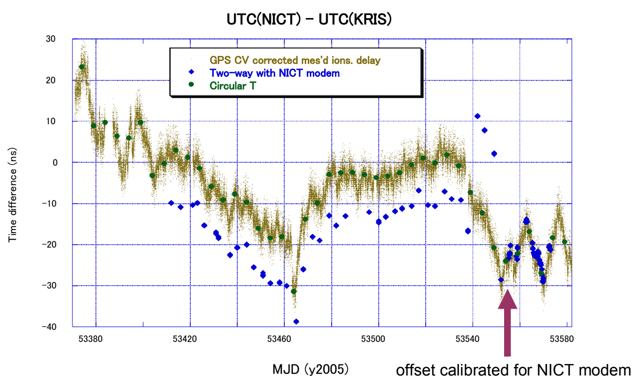

Figure 3. Time comparisons by various methods

A transportable TWSTFT station (Fig.4) is under development for calibration in the Asia-Pacific Rim region.

Figure 4. A transportable TWSTFT station

The performance evaluation of the NICT modem data shows that they are consistent with those of the conventional model (Atlantis) and satisfactory for international time comparison. Differential delays between each station are determined and reported to BIPM [8]. We have been using the NICT modems for Asia-Pacific time comparison network from this June.

A plan to extend a TWSTFT link to PTB (Germany) by using PAS-4 satellite has been proceeded. We are also going to put a relay station in Hawaii for NICT-USNO baseline since current relay station Vandenberg (USA) has low elevation for the satellite to NICT. After establishing both PTB and Hawaii stations, a round-the-world closure TWSTFT link will be achieved. We are now surveying an appropriate site in Hawaii.

B. GPS Time Transfer with Geodetic Receivers

NICT makes research on precise time transfer using dual frequency geodetic GPS receivers. In carrier phase method, we achieved a precision to 100 ps for a short baseline such as NICT-TL by making use of the precise orbit analysis software "concerto" [9] developed by NICT. Since the number of visible satellites is not enough to resolve the carrier phase ambiguity for long baseline, we are trying to improve the precision by increasing the number of parameters to be estimated [10].

For P3 code time transfer, we are trying to improve precision of all-in-view method with IGS products in Asia Pacific region. All-in-view method is expected to have 1.5 times better precision than common-view method for a long baseline such as NICT-NMIA [11].

NICT has joined the GPS realtime network as "KGN1" since June, 2005.

C. Time-scale Algorithm

Some improvements have been achieved as the result of the research on the algorithm of UTC(CRL) system. The frequency change of UTC(NICT) resulted from an insertion or a deletion of a clock to/from the Cs ensemble has been greatly reduced. The short term stability of UTC(NICT) has been also improved by optimizing the control gain of daily frequency adjustment [12]. We have developed a system which predicts UTC-UTC(NICT) by using the data from Circular-T and Cs ensemble paper clock in NICT. We have been developing an algorithm for a new system which generates more stable time-scale by using hydrogen masers and Cs clocks.

III. TIME KEEPING AND DISSEMINATION

A. Daily Time Keeping and Time Transfer

At the headquarters of NICT, 15 cesium atomic clocks with high-performance beam tubes are operated to generate UTC(NICT) at present. UTC(NICT) is used for Japanese Standard Time (JST) and for the national frequency standard. UTC(NICT) was kept within 50 ns compared with UTC since January 2003. UTC(NICT) has been used as the reference value for the NICT's frequency calibration service.

A new JST system is under development. This system adopts a new algorithm using hydrogen masers as well as Cs clocks aiming for more stable UTC(NICT), keeping the time within 10 ns from UTC. Fig. 5 shows the measurement system for the new JST.

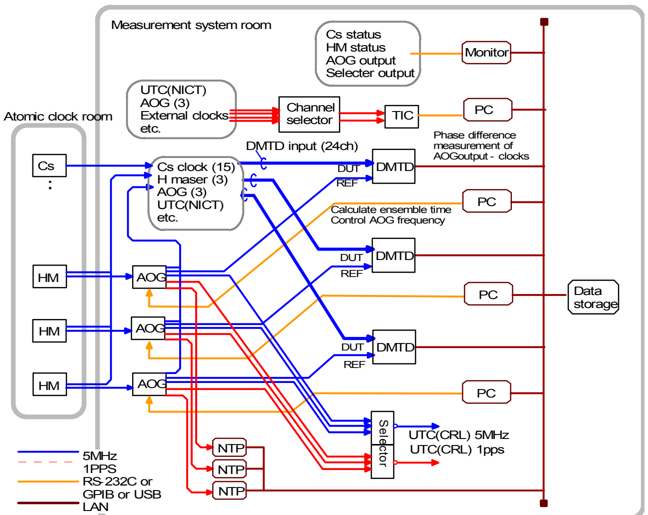

Figure 5. New Japanese Standard Time System

The main tool for the daily time transfer has been the GPS L1 single-channel common-view method. However, because its performance is lower than the clock's, it became insufficient for the daily time transfer for the contribution to the TAI. The time-transfer results for the TWSTFT (between NML, NTSC, AIST/NMIJ, and TL) have been adopted by BIPM as daily time transfer. Fig.6 shows the TWSTFT network in Asian and Pacific Rim.

B. LF Broadcasting Services

NICT transmits the standard time and frequency wave signal on the low frequency (LF) band by using two LF stations to cover whole Japan since 1999. The basic characteristics of the LF stations are listed in TABLE I. Now more than 15 million (estimated) wave watches and wave clocks are used in Japan. Nation-wide measuring of the electric field strengths of these LF waves was made and the observed diurnal variations of the received strengths showed fairly good agreement with the theory.

TABLE I. Characteristics of the LF

	#1	#2
Frequency	40kHz	60kHz
E.I.R.P	15kW	23kW
Antenna	250m high	200m high
Latitude	37° 22' N	33° 28' N
Longitude	140° 51' E	130° 11' E

C. NTP

NICT, possessing stratum-1 NTP servers, has provided Network Time Protocol (NTP) service not directly to public users but only to stratum-2 NTP servers operated by Internet Service Providers (ISP) through a common-carrier leased line or an ISDN line. But we will extend the service also to public users in 2006.

D. Trusted Time

As the national time authority (NTA) of Japan, NICT has researched a trusted time-serving system for time authorities (TA) as shown in Fig.7. The Japanese government has established the "Time Business Forum" [13] to promote and study the trusted time service system in Japan. For this activity, NICT is contributing a technical field to provide a secure UTC(NICT) to TA.

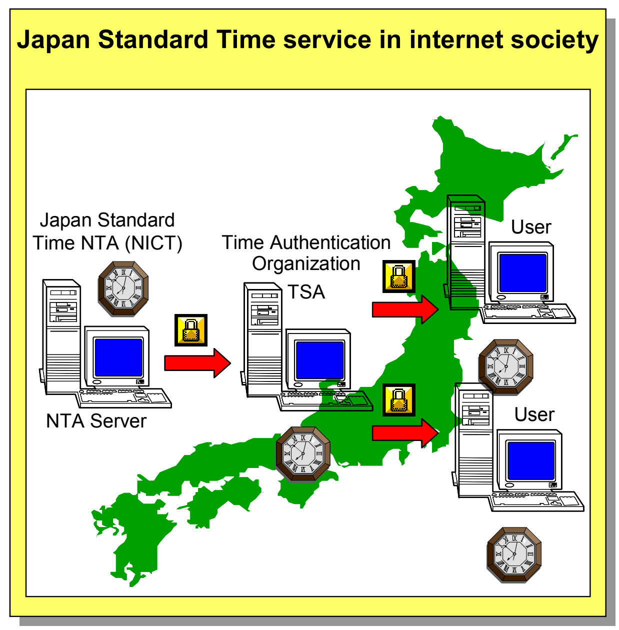

Figure 7. Electronic Time Authentication System

IV. R&D OF SATELLITE POSITIONING SYSTEM

A. Precise Time Comparison Using ETS-VIII

ETS-VIII (experimental Test Satellite 8) is a Japanese geostationary satellite, to be launched in FY2006, which has missions of mobile communications and positioning/ navigation. NICT and Japan Aerospace Exploration Agency (JAXA) plan to conduct a precise time and frequency transfer experiment between an atomic clock on the satellite and a ground-reference clock by using an on-board precise time and frequency comparison equipment (TCE), which conducts two-way time transfer using both code and carrier phase [14]. It also calibrates internal delays and delay variations in both uplink and downlink. By using these methods, we expect to obtain a measurement precision of approximately 10 ps. The flight model of the TCE went through electrical tests. We are also constructing the ground stations.

B. Quasi-Zenith Satellite System

Japanese government and private sectors decided to develop QZSS to provide navigation/positioning service and communication/broadcasting service with a high elevation. QZSS makes use of three satellites on inclined orbits separated 120 degrees each other to improve the visibility of satellites particularly in urban canyons in mid-latitude area.

NICT is to develop time and frequency technology for this system such as space-borne hydrogen maser (SHM) atomic clock and time management system [15].

As QZSS works as a supplement of GPS, the difference between QZSStime (referred to UTC(NICT)) and GPStime (referred to UTC(USNO)) will be measured with the precision of a few nano seconds and will be broadcast to users via navigation message of QZSS.

1) Spaceborne Hydrogen Maser

Development of a space-borne hydrogen maser (SHM) is one of the basic research and development themes for QZSS. So far, we have succeeded in developing a Bread Board Model (Fig.8) whose stability is better than 10^{-14} at 10,000 seconds, with the weight and power consumption of less than 60 kg and 100 W, respectively [16]. The approach to obtain ten-year life time in space was also confirmed. We are currently designing and developing an engineering model (EM) to meet space-use requirements.

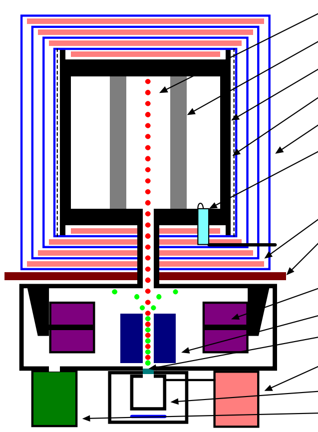

Figure 8. BBM physics part of Spaceborne H-Maser

2) Time Management System

Precise time comparison between on-board clocks (SHM, Rb and/or Cs), and between an on-board clock and ground stations (time management station (TMS) and monitor stations), are performed by using the on-board time comparison unit (TCU) via Ku-band. Two-way time transfer between TMS and the monitor stations will be also conducted by using a geostationary satellite to conduct precise orbit determination of the QZS and provide interoperability with GPS (modernized). We have carried out the basic design for the on-board equipment, and have started making an EM and designing the ground system for it.

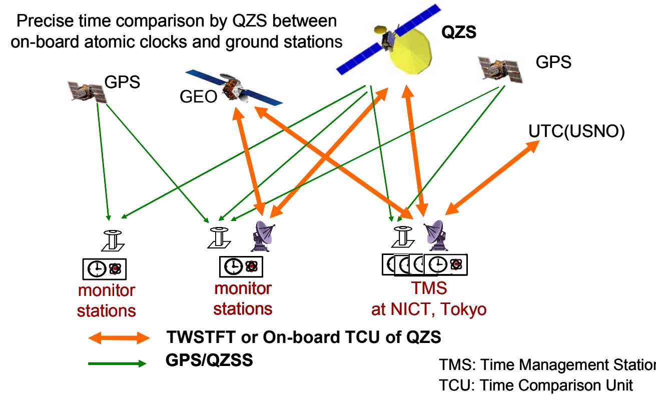

Figure 9. Time Management System of QZSS

V. TIME APPLICATIONS

Accurate and trusted time is indispensable for safe use of electronic commerce or other important information exchange. NICT has started research on standard time applications and related technologies including trusted time-stamping and Internet time distributions.

A. Internet Time-Transfer Technique

NICT has developed a high-precision hardware Simple Network Time Protocol (SNTP) server which can put timestamps with the precision of 8 ns in "wire-speed" of Gigabit Ethernet. This hardware can also assist SNTP clients to improve their accuracy.

We have measured the packet delay of about 40 km Gigabit link using these time-stampers and cesium clocks, and the results show that the high-speed IP network can be used for clock synchronization within one micro second.

We also developed a cascadable passing through time-stamper which can put timestamps with accuracy of 8 ns on UDP packets in "wire-speed" of 10 Gbit Ethernet [17][18].

B. Trusted Time-Transfer Technique

NICT is conducting research on trusted time-transfer method for safe use of time-stamping based on Japan Standard Time. As one method for realizing the safety, we are developing a hardware-accelerated trusted time-stamper which can process long electronic signatures at sufficient speed. Improvement in the speed by hardware-izing is planned.

C. Demonstration Experiments on Trusted Time Stamping

NICT is constructing the demonstration system of trusted time-stamping for finding out possible problems through real operations. We have already prepared most of important subsystems including the trusted time stamper and the time stamping authority (TSA) software. Demonstration experiments are planned in collaboration with TA/TSA service providers in 2005.

VI. RELATED RESEARCH ON TIME AND FREQUENCY STANDARDS

A. Milli-second Pulsar Timing

Millisecond pulsars are expected to supply a source of new time and frequency standard. NICT is carrying out weekly timing observations in S-band by using the 34m antenna at Kashima since 1997. The data of PSR1937+21 and PSR1713+07 show precisions 2 μs and 6 μs, respectively [19]. A new digital system was developed and is going to have a test observation.

B. Relativistic Effects in T&F Standards

Research on relativistic effects in the space-time references and standards has been conducted. Gravitational red shift of atomic clocks transported from NICT headquarters to LF stations was measured [20].

Theoretical investigation on applying gravitational lensing effect to measurements of galactic structure and stellar mass is carried out [21].

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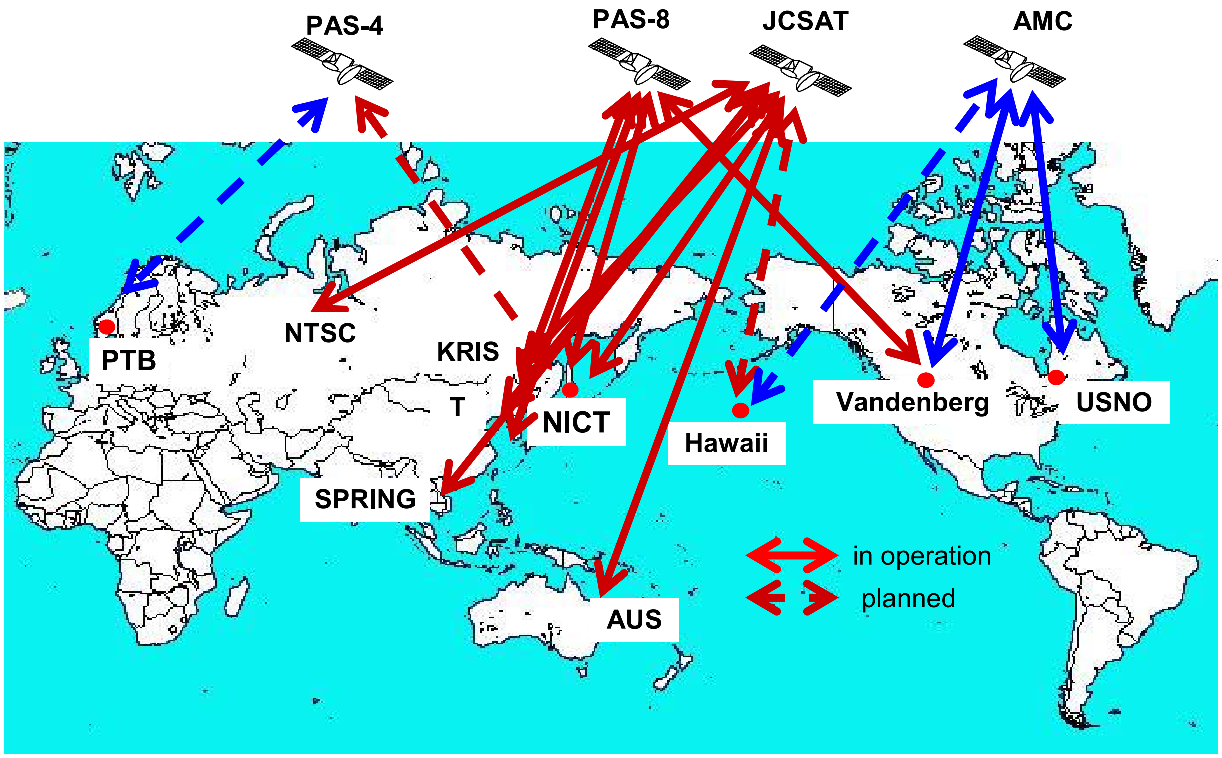

Figure 6. TWSTFT network related with NICT