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A1. Time and Frequency Standards and Time Transfer Technique

In Japan, the researches and developments on Time and Frequency (T&F) Standards and Time Transfer Technique are carried out in the National Institute of Information and Communications Technology (NICT), National Metrology Institute of Japan (NMIJ), and some Universities.

In April 2004, the Communications Research Laboratory (CRL) and the Telecommunications Advancement Organization of Japan (TAO) were merged and reorganized into a new organization, the National Institute of Information and Communications Technology (NICT), an incorporated administrative agency. The responsibility of CRL for the national frequency standard and time dissemination has been succeeded by NICT.

The accuracy evaluations of TAI unit by the optically pumped Cs primary frequency standard NICT-O1 have conducted about twice a year regularly. Papers on the accuracy evaluation of NICT-O1 were published [Hasegawa et al. 2004, Fukuda et al. 2004]. Development of Atomic fountain standard in NICT has been in progress. Ramsey fringe has been obtained with high signal to noise ratio, and the frequency stability of $5x10^{-13}$ at the averaging time of 1 second has been achieved [Kumagai et al. 2002, 2003, 2004 a, b].

Two Way Satellite Time and Frequency Transfer (TWSTFT) network in the Asia-Pacific region has developed under the collaboration with NICT and major T&F institutes in the region [Hongwei et al. 2003a, b]. A multi-channel TWSTFT modem has been developed in NICT [Imae et al. 2002]. Researches on GPS time transfer have been also conducted [Shibuya et al. 2002, Sekido et al. 2003, Fujieda et al. 2004a, b, Gotoh et al. 2004b]. On GPS carrier phase time transfer, precise orbit analysis software "CONCERTO" is applied to solve the ambiguity problem [Gotoh et al. 2004a].

At the headquarters of NICT, about 15 cesium atomic clocks with high-performance beam tube have been operated to generate UTC(NICT). The short term stability of UTC(NICT) has been also improved by optimizing the control gain of daily frequency adjustment [Hanado et al. 2002, 2003, 2004a]. A new UTC(NICT) generation system is under development [Hanado et al. 2004b]. Two standard time and frequency stations transmit the signals on the LF band [Kurihara et al. 2004]. These signals cover whole Japan during 24 hours [Wakai et al. 2004]. A calibration system for frequency standards certificated with ISO17025 is developed [Iwama et al. 2002, 2004]. NICT provides the Network Time Protocol (NTP) service through Internet Service Providers (ISPs) [Imamura et al. 2004]. The Japanese government has established the "Time Business Forum" (http://www.scat.or.jp/time/) 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 TAs. NICT is conducting research on trusted time-transfer method for safe use of Time Stamping based on Japan Standard Time [Iwama et al, 2004].

NICT has developed a precise time and frequency transfer system for ETS-VIII, a Japanese Engineering Test Satellite, which will be launched in FY 2005. Using a two-way time-transfer method and carrier-phase information, this precise time-transfer system is planned to attain a precision around 10 ps [Takahashi et al. 2002, Gotoh et al. 2004c]. A plan to develop a regional satellite navigation system called Quasi-Zenith Satellite System (QZSS) was recently announced. It makes use of three satellites on inclined orbits separated 120 degrees each other to improve the visibility of satellites particularly in urban canyons. NICT is to develop time and frequency technology for this system such as space-borne hydrogen maser atomic clock and time management system [Hama et al. 2004, Ishida and Araki, 2004, Kimura 2004a, b, Takahashi et al, 2004, Ito et al. 2002, 2004].

Various time and frequency standards related researches have been conducted in NICT, such as on atomic and molecular physics [Fukuda et al. 2002 a, b, 2003, 2004 a, b, Kajita 2002a, b, c, d, 2003, 2004a, b, Matsubara et al. 2002, 2003, 2004a, Li et al. 2004], Milli-second pulsar timing [Hanado et al. 2002, 2003b], Relativistic Effects in time and frequency standards [Kotake et al. 2002, 2004, Hosokawa et al. 2002, 2004b].

In NMIJ, following researches have been conducted.

Primary Frequency standards; An atomic fountain frequency standard is under development in NMIJ. The main factor that limits the accuracy of the frequency standard is collisional frequency shift. A simple technique was developed to minimize the collisional frequency shift while keeping the moderate frequency stability. Atoms collected by a magneto-optical trap were cooled to 800nK and launched to 40cm above the microwave cavity giving rise to Ramsey fringes with a linewidth of 0.85Hz. The frequency stability reached to 3-6x10^{-13} and the uncertainty level is expected to be 1.4x10^{-15} [Kurosu et al., 2003, Yanagimachi et al., 2004]. Control techniques of laser frequencies were also developed for the applications to cesium standards [Kwon et al., 2003].

Cryogenic Sapphire Oscillator and Low Noise Frequency Synthesis; NMIJ is developing a synthesized microwave local oscillator (LO) for a Cs atomic frequency standard using a cryogenic sapphire oscillator (CSO) under collaboration with the University of Western Australia and BNM-SYRTE [Watabe et al., 2003, Watabe et al., 2004a]. The CSO is a loop oscillator which is servo controlled by a Pound-type frequency stabilization scheme using a phase modulator and a phase corrector. The sapphire-loaded cavity (SLC) was cooled with liquid helium. A Whispering Gallery mode, $WGH_{15,0,0}$ at 10.812 GHz was chosen because it exhibited the highest Q-factor. The Cs hyperfine transition frequency of 9.192 GHz was synthesized from the 10.812 GHz oscillation frequency. A fractional frequency stability of 6×10^{-15} was obtained for integration times of 600 to 1200 s. At the integration times shorter than 300 s the result was limited by the H-maser. The stability is clearly superior to the hydrogen maser at short integration times and it is expected to be well below 10^{-14} for $1 \text{ s} \leq \tau \leq 100 \text{ s}$ [Watabe et al., 2004b].

Time Keeping and Time Comparison; In NMIJ, four cesium atomic clocks with high-performance beam tubes (Agilent 5071A) are operated for time keeping. One of them (Clock code and number 35 224 in BIPM report) was referred as UTC(NMIJ) before June 3, 2004(MJD= 53159). Since then, an AOG (Auxiliary Output Generator) has been used for steering UTC(NMIJ) much closer to UTC. The source clock for the AOG will be replaced by a hydrogen maser frequency standard to improve the short term stability in 2005 and the ensemble clock method will be introduced to improve the long term stability and reliability in 2006. For the contribution to the TAI, two types of GPS receivers, AOA TTR 6 (single-channel common-view method) and Ashtech Z12-T (Multi-channel carrier phase method) have been used. TWSTFT between NMIJ and NICT is continued to realize precise time comparison in the order of 10^{-15}. An optical fiber bidirectional time transfer system using Wavelength Division Multiplexing technology is investigated in NMIJ as future precise time and frequency comparison technique [Amemiya et al., 2004].

Frequency Calibration Services; A frequency remote calibration system is under development in NMIJ. A common-view experiment was carried out between Tsukuba and Okinawa whose distance was about 1600 km. The results show that the resolution of frequency comparison within Japanese islands will be better than 1x10^{-13} (k=1) with the averaging time of one day [Shibuya et al., 2004]. Frequency dissemination using optical fiber network is a promising method and NMIJ started the investigation about its performances.

In Kinki-University and Meiji University, time and frequency related atomic physics researchies are conducted [Otake et al. 2002, Hayashi and Tachikawa 2002, Izmailov et al. 2004, Nakagiri 2002, Nakagiri and Tanaka 2004].

A2. Laser Stabilization and Frequency Measurement

After an advent of an “optical frequency comb” technology at the end of the last millennium, which is introduced by Prof. Haensch group at MPQ in Garching and Prof. Hall group at JILA in Boulder, a direct comparison between microwave and optical frequencies has been realized by using an one-octave optical frequency comb generated by self-phase modulation in a photonic-crystal fiber. Since 2000, NMIJ also has started a project to realize a direct comparison between microwave and optical frequencies by using several types of ultra-fast mode-locked lasers.

Thanks to this breakthrough, the concept of an optical frequency standard using such as single trapped ions or ultracold neutral atoms in free fall, which are aiming to realize the SI second or frequency standard at an optical region, has become much more feasible. Prof. Katori (University of Tokyo) proposed a different type of optical frequency standard, “an optical lattice clock”, in which atoms (for ex. Sr atoms) trapped in an optical lattice serve as quantum references [Katori, 2002, Katori et al., 2003]. Among many proposals for this challenging theme, this optical lattice clock is considered to be very promising, since it has narrower linewidth than neutral-atom clocks and better stability than single-ion clocks. Katori group and NMIJ have measured the transition frequency for the Sr lattice clock using an optical frequency comb referenced to the SI second [Takamoto et al., 2005, Hong et al., 2005].

NICT is developing a single Ca^+ ion trap standard. A trap with laser cooling system is completed and some theoretical investigations are made [Matsubara et al. 2004b, Kajita et al. 2004c]. To observe the 4s2S1/2 - 3d2D5/2 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 [Li et al. 2004].

NMIJ has been developing several stabilized lasers and optical frequency measurement systems by means of optical frequency combs generated from ultra-fast mode-locked $Ti{:}Al_2O_3$ (TiS) lasers and mode-locked fiber lasers. NMIJ has measured optical frequencies of several stabilized lasers by the frequency measurement systems and has reported results on an acetylene stabilized laser at 1542 nm [F.- L. Hong et al., 2003a], an iodine stabilized Nd:YAG lasers at 532 nm [F.- L. Hong et al., 2003b, 2004a, b] and a new optical standard at 660 nm and 1319 nm for optical telecommunication [R. Guo et al., 2004] at the working group of mise en pratique (MeP) in the Consultative Committee for Length (CCL) of the meter convention which was held at the BIPM (Bureau international des poids et mesures) in 2003.

To realize an optical frequency standard, it is very essential that an optical frequency comb can link microwave and optical frequencies for a day or a week to evaluate its accuracy referring to the SI second. As one of promising candidates for that purpose, a mode-locked fiber laser provides a very robust frequency comb and a frequency measurement system. NMIJ has developed frequency combs based on mode-locked fiber lasers [Hong et al., 2003c, Schibli et al., 2004]. The stability degradation of a mode-locked Ti:sapphire laser has been studied through phase noise measurement [Inaba et al., 2005]. The frequency measurement system combined with a sum frequency generation comb and a broadened comb by a photonic crystal fiber has been developed. In this system we need not to stabilized the CEO frequency, which makes the system robust for a long term operation.[Jiang et al., 2005]. Phase locking of a continuous-wave optical parametric oscillator to an optical frequency comb have been demonstrated as the first step for optical frequency synthesis [Inaba et al., 2004].

Prof. Tkahashi et al. (Kyoto University) have developed a stabilized laser system using a Yb atomic beam for the purpose of laser cooling experiments. They have also proposed a simple frequency offset-locking scheme by a double balanced mixer and a delay line [Komori et al. 2004]. Prof. Nishimiya et al. (Tokyo Polytechnic University) have developed a spectrometer for Doppler-free two-photon transition of Cesium ($6S_{1/2}$-$6D_{3/2,5/2}$). [Ohtsuka et al., 2005]. Prof. Musha et al. (University of Electro-communications) have studied a highly stable mm-wave synthesizer by two lasers locked to an optical frequency comb generator. [Musha et al., 2004]. Suzuki et al.(NTT Network Innovation Laboratory) have demonstrated a frequency-stabilized, 25 GHz-spaced optical comb over the S-, C- and L- bands. Using this frequency stabilized light source, they have calibrated several commercial available wavelength meters at the telecom bands [Suzuki et al., 2004].

A3. Realization of Electrical Units (DC & LF)

Based on Josephson voltage standard and Quantum Hall resistance (QHR) standard maintained as national standards, electrical standard division of National Metrology Institute of Japan (NMIJ) has been focused on to establish practical standards such as impedance standards in low-frequency and other standards in this term corresponding to urgent requirements from industry.

Effects of environmental conditions of four Zener voltage references units have been investigated in detail for using traveling standards of Japanese standard dissemination system [Nishinaka, H., et al., 2002-2003].

A voltage divider has developed in NMIJ to calibrate up to 1 kV. The ratio of the divider can be automatically self-calibrated in 1000 V/ 10 V and 100 V/ 10 V and participated to the international comparison [Sakamoto, Y., 2002-2004].

Resistance standards and Terra-ohm meter in the range from 1 MΩ to 1 TΩ in decade steps have been developed by using Cryo Current comparator (CCC) and resistance-bridge based on the QHR standard [Kiryu, S. et al., 2002-2004].

The capacitance standard derived from a DC resistance corrected by the QHR standard into ac-dc calculable-resistor, which is further converted to static capacity by means of a multi-frequency quadrature-bridge enables the measurement of the frequency dependence of the capacitor [Nakamura, Y. et al., 2001-2004].

We have expanded capacitance standard from small range [10 pF, 100 pF, and 1000 pF at 1 kHz] and [10 pF, 100 pF, and 1000 pF at 1.592 kHz] to medium range [0.01 μF, 0.1 μF, 1 μF at 1 kHz] and [0.01 μF, 0.1 μF, 1 μF at 1 kHz at 1.592 kHz] by using a capacitance-bridge system.

Several kind of Induced Voltage Divider (IVD) in the range of [0.1~1.0, 10 V at 1 kHz], [0.1~1.0, 100 V at 1 kHz], and [0.1~1.0, 10 V at 200 Hz and 400 Hz] have been developed in order to establish those capacitance standards [Nakamura, Y. et al., 2001-2004]. AC resistance standard (ac-dc calculable resistor) [10 k□ at 1 kHz] also has been developed for establishing capacitance standard [Nakamura, Y. et al., 2004].

Inductance standards in the range of [10 mH at 1 kHz], [10 mH and 1.592 kHz], and [100 mH at 1 kHz] have been developed based on the simple inductance measurement method using a commercial LCR meter [Yonenaga, A. et al., 2003-2004].

AC/DC difference standard in the range of [2-20 V, 10 mA at 10 Hz to 1 MHz] and [20-1000 V at 10 Hz to 100 kHz] based on TCs (thermal converters) have been developed
by using fast-reversed dc (FRDC) method [Fujiki, H. et al., 2001-2003].

AC current comparator in the range of [50 A, 1/1-1/100 at 45 to 65 Hz], and [50 A, 1/1-1/100 below 120 Hz] have been developed in order to establishing AC power standard [Yamada, T. et al., 2003].

A4. EM Field, Power Density and Antenna Measurement

In the field of precision measurements like EMC/EMI, a dipole antenna is used as a primary standard for wire antennas. The simplest structure enables us to evaluate its characteristics by some numerical methods and further a good agreement is obtained in the comparison between the numerical and measured results. In the frequency range from 30 to 1000 MHz, antenna factor (AF) is a popular parameter to indicate the antenna sensitivity to incident electric field. The measurement of the AF is usually carried out on an open-area test site (OATS), though it has height-dependency on a ground plane due to the coupling between the antenna and the ground-plane. The uncertainty associated with the dipole antenna calibration in NMIJ at 2.0 m high above the ground plane with horizontal polarization is reported in [Komiyama 2004].

However, in the method the accurate field-strength is not be realized namely by measurements. The field-strength is assumed as in the free-space condition. Therefore the uncertainty of the AF measurement will significantly increase at the condition of small electric field. To overcome the problem two approaches are proposed. One is to obtain the AF at an arbitrary height by a single site attenuation measurement [Morioka et al. 2004]. This is a kind of standard field method, but no field-strength should be explicitly evaluated instead of introducing a coefficient as a substitution.

The other approach is to adopt a free-space measurement. Nowadays, the measurement in a full anechoic chamber becomes common. Thus the field-strength measurements require free-space AF in the free space. [Matsumoto et al, 2003] proposed a method to obtain free-space AF by scanning an antenna above the absorber-attached OATS. As the input impedance of the antenna is affected by the mutual coupling with its image, this effect can be removed by using numerical method. A method proposed in [Fujii et al. 2004] also provides free-space AF by using the measured input impedance.

The complex antenna factor (CAF) of a dipole antenna with a balun can be determined from the effective length and the input impedance of the antenna element and the S-parameters of the balun. The effective length and the input impedance are calculated by a numerical method such as the method of moments. The S-parameters are measured using a network analyzer with its TRL calibration. Alternatively, the CAF can be determined by a modified three-antenna method on a ground plane. In the present paper, the systematic uncertainties of the two methods are estimated in the frequency range of 30 - 1000 MHz in order to clarify the potential for application of the two methods and to determine areas for improvement. The CAF values determined by these two methods are compared, and the results of this comparison indicate the validity of the uncertainty estimations. In the measured balun method, the TRL measurement should be improved in the low-frequency range (30-100 MHz), and in the three-antenna method, the antenna positioning should be improved [Iwasaki et al. 2004a].

A continuous antenna factor in a wide frequency range is convenient to be used and such a broad-band antenna as a log-periodic antenna was evaluated for a metrology standard. A new method was proposed for evaluating a free-space antenna factor continuously through a wide frequency band. The method is based on a technique of a time-domain analysis and a pulse-compression technology for reducing the influence by the reflected waves from surrounding obstacles [Kurokawa et al. 2003]. The method was examined for calculating the free-space antenna factor of a log-periodic antenna widely used for EMI measurement [Kurokawa et al. 2004].

The development of calibration techniques for standard loop antennas was carrying out by ETL and CRL in these 30-40 years. Recently both of these organizations changed to AIST and NICT, respectively. The AIST started to develop the calibration method again since 2002. Basically the methods depend on “3-Antenna technique” [Ishii et al. 2003] and “Reference Antenna Method”. They are also studying another new calibration method “Measuring Impedance Method [Ishii et al. 2004]”. They are taking part in the International Comparison in 2002-(in progress) and started a calibration service for small loop antennas from 2005 as a member of NMI’s.

On the other hand, NICT and Tohoku University are engaged in the development of “Standard Field Method” [Koike et al. 2002]. A vacuum thermocouple is used on the Standard Field Method. But that is easy to be broken, so they are developing an another method without any thermocouple now [Nakajima et al. 2004].

There appeared a new technique to measure standard horn antennas. The technique was combined with a photonic sensor and several near-field measurement techniques, where the photonic sensor was used as a probe that is small, light-weight and broad-band (below about 10 GHz). The technique was also used to measure other antennas such as micro-strip antennas and the log-periodic antennas. Since these were prototypes, there was about 1 dB difference between the results by the technique and by conventional antennas and methods. The technique is promising to measure various standard antennas without the influences by metal probe and metal cables in the field of metrology. [Hirose et al. 2002, Hirose et al. 2003a, Hirose et al. 2003b, Hirose et al. 2004a, Hirose et al. 2004b, Hirose et al. 2004c, Hirose et al. 2004d]

A novel method for measuring microwave reflection coefficients without the open and load standards is proposed. In this method, a single probe is inserted into an air line and the output wave is detected by a vector detector. Offset shorts are used for the calibration. The measurement system is constructed using 7 mm coaxial line and APC7 connectors. The result of the measurement in the frequency range 1 - 9 GHz shows the possibility of the proposed method. All the major systematic errors can be estimated from the data that is easily obtainable [Iwasaki et al. 2004b].

To observe transient radiation fields, a technique for reconstructing electromagnetic (EM) waveforms using the complex antenna factor (CAF) have been developed. However, the CAF is originally defined assuming plane wave incidence, while the waveforms are measured in a vicinity of the radiating source. In order to examine the reconstruction technique using the CAF in the near-field measurements, the EM fields radiated from a monopole antenna excited by pulsed input voltage was reconstructed and compared with calculated results. For the geometry of the experiment, the waveforms of the reconstructed and calculated EM fields have shown good agreement. Therefore, the reconstruction technique using the CAF can be used for similar dimensions or at a greater distance when sufficient sensitivity is provided [Hamada et al. 2002].

A5. Power, Attenuation and Impedance Measurement

In the year 2000, a new national standard infrastructure plan for attenuation was mapped out at NMIJ to meet the increasingly growing demands for accurate, traceable, and broad-band standards which have a high attenuation range. The measurement capability was planned to cover the frequency range of 10 MHz to110 GHz and the attenuation range of greater than 50 dB. The first developed measurement system was for an attenuation standard from 10 to 100 MHz [Widarta et al. 2002a, 2003a]. The system uses an inductive voltage divider (IVD) operating at 1 kHz as a reference standard and employs dual-channel intermediate frequency (IF) substitution method. The IVD is used for direct traceability of the Japan national standard for a low-frequency voltage ratio. The dual-channel type is employed to achieve high-precision measurements via the well-known high accuracy null detection method. Uncertainties better than 0.001 dB for an attenuation range up to 20 dB, and 0.04 dB for 80 dB were achieved.

Based on the developed system’s design, a broadband attenuation measurement system working in the frequency range of 10 MHz to 18 GHz was also successfully developed [Widarta et al. 2002b, 2003b, 2004a]. Some unique techniques such as usages of interpolation technique, double step measurement technique, etc., were introduced in order to improve the uncertainties. The system is used as a national standard of attenuation and provides the attenuation calibration to several service systems including Japan Calibration Service System (JCSS). The calibration and measurement capabilities are up to 100 dB in frequency range of 100 MHz to 12 GHz, and up to 60 dB at 18 GHz. Enhancing to the frequency range up to 40 GHz is being developed now.

A study on analysis of the linearity of heterodyne detection and an important property in applying the IF substitution method in attenuation measurements, is carried out and the results show that the linearity check by the dependence of measured attenuation on measuring levels is mostly reasonable [Kawakami et al. 2004].

Implementing optical fiber assemblies was proposed to obtain extremely high isolation between the channels of dual channel measurement system in RF and microwave frequency range [Widarta et al. 2002c, 2003c]. The isolation effects were demonstrated in attenuation measurement systems and satisfactory results were shown. The assemblies also gave good flexibility to the structure of the system and minimized earth loop problems.

As for the noise standard, National Meteorology Institute of Japan (NMIJ) has developed a new microwave radiometer system for the measurement of noise sources with PC7 coaxial output connector in the frequency range from 2 GHz to 18 GHz. It is a type of total-power radiometer which employs a null-balanced method in order to reduce an instability and non-linearity [Nakano et al. 2002a].

NMIJ has been also developing the original cryogenic standard noise source with PC7 coaxial connector by using the auxiliary transmission line method which is cooled by liquid nitrogen. The measured value of the noise temperature of the original noise source is good agreement with the noise temperature which is calculated by the loss measurement of each auxiliary transmission line [Nakano et al. 2002b, 2003].

A survey on precision thermal noise power measurement techniques in RF region and the thermal noise standards established in the leading national metrology institutes are reviewed by NMIJ. The noise temperature measurement system developed by NMIJ is also described. Performance of the measuring instrument of noise temperature is evaluated to verify the measurement system. The uncertainty of the noise measurement system is discussed by the radiometer equation [Shimada 2003].

NMIJ has established the calibration system of the noise temperature for the coaxial noise sources with PC7 and PC3.5 coaxial output connectors. The noise temperature calibration systems and the uncertainty analysis of the calibration of coaxial noise sources are reviewed [Shimada 2004].

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