Interview

Time is born here!

Contributing to global time by the generation of Japan Standard Time

Space-Time Standards Laboratory

Space-Time Standards Laboratory (STSL) in NICT not only generates accurate timescale which is commonly used as Japan Standard Time, but also contributes to processing international standard time. Accurate time is one of fundamental infrastructures that sustain modern society. Most fields such as economy, industry, and academic research never work without an accurate time.

What kind of research is ongoing? Where is STSL heading? We asked Tetsuya IDO and Yuko HANADO, who are the Director of STSL and an Executive Researcher in Advanced Electromagnetic Research Institute, respectively.

Tetsuya IDO

Director of Space-Time Standards Laboratory, Applied Electromagnetic Research Institute

After completing a doctoral course and serving as Researcher at JST-ERATO, Research Associate at JILA (NIST/University of Colorado), and as a JST-PERSTO Researcher, IDO joined NICT in 2006. After his doctoral course, he has been engaged in laser cooling of Sr atoms and its application for optical lattice clocks. Ph.D. (Engineering).

Yuko HANADO

Executive Researcher, Applied Electromagnetic Research Institute.

Joined the Communications Research Laboratory (Currently NICT) in 1989 after completing a master's course at university. She is engaged in the research of time and frequency standards. Ph.D. (Engineering).

How has the definition of time been changed?

——Why did people begin to pursue more accurate time historically?

Hanado: The motion of the sun was the first method in which people measure the time. They first made a unit "day." One day was defined as a duration between two sequent sunrises. Then, hour, minute, and second were defined by dividing one day. However, the time of sunrise differs from place to place. It did not cause a problem when people moved in a limited area. As time goes, the progress in telegram and railway expanded the territory of their daily lives. Then, they felt an inconvenience since time depended on place, in other words, time was not shared among people.

People started to consider having common time which does not depend on locations. Universal Time (UT) was first defined in 1920s. It is a mean solar time on Greenwich meridian. Meanwhile, we noticed that the earth rotation is not stable.

Then, the standard of time was changed from the earth rotation to the orbital period of earth movement around the sun. One year is first obtained, and the division of the year makes day, hour, minute and second. This is the Ephemeris Time (ET) employed in 1960s. Time had been determined by astronomical observation.

——Do you mean that the astronomical time was not accurate?

Hanado: Yes, I do. The speed of earth rotation has fluctuations. It takes time to measure the earth's yearly rotation precisely. In 1955 at National Physics Laboratory in UK, however, the cesium atomic clock was invented. Employing the transition frequency of cesium atoms, they succeeded to measure time precisely. Conference Generale des poids et mesures (CGPM) in 1967 defined the second as the duration in which the electromagnetic wave resonant to the cesium 133 hyperfine transition oscillates for 9,192,631,770 times.

Procedure to generate standard time

——How is the standard time determined these days?

Hanado: BIPM (Bureau International des poids et mesures) is an international organization located in France, where world standard time is determined by collecting clock data of more than 400 atomic clocks in world and by calculating a weighted average of these clocks.

The averaging process certainly improves the stability, but never tells us if the scale interval is accurate. This is evaluated by primary frequency standards (PFSs). PFSs have a capability to evaluate the uncertainty of the

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one second by themselves. Thus, we often call PFS "God of clocks."

——How does it differ from ordinary cesium clocks?

Ido: Both are indeed cesium clocks, but the difference is found in the method to measure the atomic resonance. The heart of most PFSs are a fountain of cesium atoms. Cesium atoms are first laser-cooled and launched upward like a fountain. Then the atoms and microwave interact, telling us how the duration of one second obtained from microwave is identical to the definition. The uncertainty of PFS corresponds to the error of one second in 2.5 million to 200 million years. The number of PFS is less than twenty. One of them is in NICT and we are also developing another advanced one.

——Conventional atomic clocks will be replaced to fountains eventually, won't they?

Ido: No, they won't. Fountains are quite accurate, but do not work continuously. In addition, we cannot do the mass production of fountains. Thus, it is also difficult to maintain a redundancy.

Hanado: Thus, we use PFSs to regularly calibrate the scale interval of timescales, which are made by ordinary cesium clocks.

——How does BIPM synthesize the clocks which are physically distributed worldwide?

Hanado: Signal from satellites for example GPS (Global Positioning System) is used as a common reference in a time comparison. GPS satellites broadcast the information of their own clock and their position. For instance, if we simultaneously receive an identical signal in different places and compare each ground clock with respect to the GPS clock, we know the time difference of two ground clocks. Likewise, various atomic clocks on ground are compared. BIPM can calculate the weighted average of clocks using such data of clock comparisons.

——You instructed me how the accuracy of scale interval is maintained. Then, what is the start of the timescale?

Hanado: The SI second was defined by cesium in 1967. However, International Atomic Time (TAI) started in 1958, which is three years later than the invention of the cesium clock. Occasional insertion of leap seconds to TAI realizes the time scale roughly synchronized with the earth rotation. This is Coordinated Universal Time (UTC), which we use in daily life. Japan Standard Time (JST) is ahead of UTC for nine hours.

Generation and dissemination of Japan Standard Time

——How does NICT generate and disseminate JST?

Hanado: NICT has eighteen commercial cesium clocks. The weighted average of these eighteen of ticks becomes JST. Since this weighted average eventually deviates from UTC, JST is always compared with other atomic clocks worldwide and often adjustment to JST is made manually. The clock data in NICT is used in BIPM for the generation of mean free atomic timescale, to which NICT clocks has a high contribution.

One method to disseminate JST is a radio-wave clock. We radiate low-frequency radio wave from Ohtakadoya-yama in Fukushima and Hagane-yama in Fukuoka-Saga with its carrier frequency at 40 kHz and 60 kHz, respectively.

Another method is Telephone JJY using analog and optical telephone line, which is mainly used by broadcasting services. The others are, NTP (Network Time Protocol: for IT instrument via Internet) and offering time data to time-business companies in order to adjust and to prove their own time. We also calibrate frequency of instruments or oscillators.

——I heard Kobe substation was built in last year. What's the role of the substation?

Hanado: It is mainly the backup to prepare for a disaster at Koganei headquarters. The Kobe substation equips five cesium clocks and instruments for NTP and optical telephone JJY. The dissemination system in Kobe is in standby status. It provides signal to society only in an emergency in headquarters.

Efforts in Space-Time Standards Laboratory

——What kind of research is ongoing in STSL except for the generation and dissemination of JST?

Ido: Our laboratory has four groups. Frequency standards group mainly studies cesium PFS and optical frequency standards including an optical lattice clock. There also exists an activity of chip-scale atomic clocks (CSAC) and THz metrology. JST group generates and disseminates accurate time and frequency by using eighteen cesium clocks. Time and frequency comparison group compares time and frequency of clocks in physically separated places. This group always checks how much JST deviates from UTC. This group couples strongly with JST group. Space-Time measurement group studies Very Long Baseline Interferometry (VLBI). They maintain a large parabola antenna in Kashima, Ibaraki. They receive electromagnetic wave from quasars in universe, by which they measure the distance to other

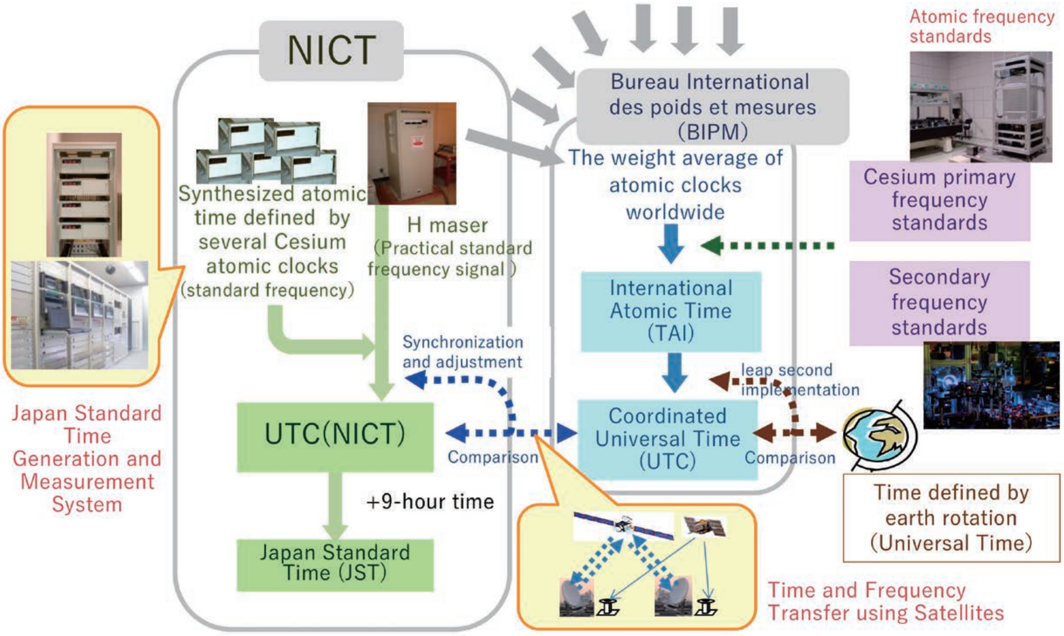

Figure Generation of Japan Standard Time. Time, as an important social infrastructure, is generated and maintained not only by NICT but under collaboration and mutual cooperation with BIPM and research institutes worldwide.

oversea stations with a small uncertainty of mm level.

——How is the VLBI related to the generation of standard time?

Ido: In order to insert a leap second, we need to know how the earth is rotating. The speed of earth rotation fluctuates, and it also possesses a complicated motion such as a nutation. VLBI enables a precision measurement of such motion of the earth. The uncertainty in measuring the one cycle is less than 1 ms. Normal optical observation never realizes such a high precision.

——What's the situation in international collaboration in research and development?

Ido: Institutes like NICT, which are responsible for national time, operate commercial atomic clocks such as Cs frequency standards or Hydrogen masers, send clock data to BIPM, and evaluate the scale interval of UTC using their own frequency standards. These activities are maintained by a fountain and a next generation frequency standard. We'd like to contribute to the international society through such activities. The real-time clock which we generated using a strontium lattice clock had a difference from TT(BIPM) for 0.8 ns in a half year. Such data is also sent to BIPM.

Time is becoming more important

Hanado: We also attend international committees, where the redefinition of the second and other international standards are extensively discussed. On the other hand, we assist emerging countries by instructing how to generate standard time. Mutual recognition agreement (MRA) is also important. Quality and capability need to be guaranteed internationally when we export instruments related to time and frequency. We standardize the method of characterization and also serve such mutual recognition process.

——What will be required for STSL from now on?

Ido: Our first mission is the stable provision of JST to real society. On the other hand, optical lattice clocks would soon improve the characteristics of time in a few orders of magnitude. We will provide such highly accurate time eventually. We also need to explore applications which make use of accurate time.

Redefinition of the SI second is approaching. The redefinition of mass (kg) was agreed last year, where it will be based on Plank constant as well as the unit second furthermore from May 2019. The role of second became more important in the definition of other units and various matters.

Reducing the size of atomic clocks is another effort that we are making. We hope the reduction allows an atomic clock installed in a smartphone. The availability of highly accurate time in smart phones will realize a novel application that we cannot imagine at this point.

——Time is an important social infrastructure, isn't it?

Ido: Yes, it is. Thus, we cannot take rest as a provider of JST. We keep a resolution that we never stop the provision of time, simultaneously with a passion to further study time and frequency metrology.

Developing an Atomic Frequency Standard in New Frontier

Toward the establishment of terahertz frequency standard and metrology

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Space-time standards laboratory
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Joined NICT in 2005 after completing a doctoral course at university. His research interests include femtosecond-laser frequency comb and terahertz frequency standard. Ph.D. (Science).

Effective utilization of the terahertz (THz) region, which is a valuable frequency resource, has attracted significant interest from a wide range of users. For a long time, this frequency region has been called an "undeveloped frequency band," and there have been no frequency standards to be used for allocation of the THz spectrum among users. NICT has been researching the establishment of a new THz frequency standard that is expected to yield a de facto international standard.

Research Background

The terahertz region (approx. 0.1 to 10 THz), which occupies the frequencies between light and microwaves, has resisted development by the application of electronic circuits and optical electronics technologies, which is why it is called an "undeveloped frequency band" (Figure 1). However, this region is recognized as an invaluable frequency resource for ultra-high-speed communication required for sustaining recent explosive increase in data traffic. In addition, since the absorption lines of various molecules (molecular fingerprint) exist in this region, spectroscopy and non-destructive analysis of many physical and chemical materials have already commenced; global THz technology markets are growing. Going forward, applications of the THz region will spread from science to many areas of everyday life.

At present, some conventional THz spectrometers have an accuracy of only three to four digits and exhibit poor reproducibility. This causes problems of decreasing reliability in the identification of original molecules with the fingerprint spectra. Therefore, it is important to define a common frequency reference (frequency standard) to prevent confusion among users. However, due to the difficulties in precision measurement specific to this region, there have been almost no studies by national metrology institutes in Japan or around the world on defining a THz frequency standard.

In response to expectations for us to establish a THz frequency standard based on the Radio Act, the Space-Time Standards Laboratory has not only been studying frequency standards but also associated technologies including frequency measurement and transfer in the THz region, viewing the three technologies as interlinked (Figure 2).

Creating a Frequency Ruler for the Terahertz Region

Developing a frequency standard requires precise frequency measurements. As the first step, we built a THz frequency counter using optical-comb technology. An optical comb consists of many laser modes, which are regularly spaced by constant frequency. Since it serves as a precise ruler for measuring optical frequencies, it has been widely used for absolute frequency measurement of optical atomic clocks, etc. Using a semiconductor photoconductive device for nonlinear frequency conversion, a comb structure in the THz region can be generated from an optical comb. We created a THz comb by converting an optical comb with a photoconductive antenna. This THz comb can be employed to measure the absolute frequency of target THz waves by stabilizing the frequency of its mode in-

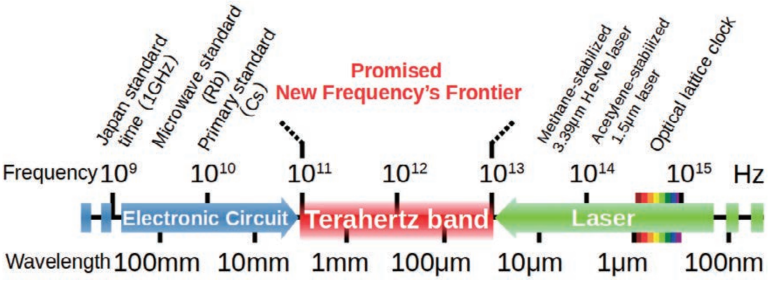

Figure 1 Current Status of the Frequency (or Wavelength) Standards and Terahertz Region

terval to Japan Standard Time, consequently becoming a THz frequency counter.

From the viewpoint of metrology, which deals with measurement itself, the measurement limitation of frequency counters built based on this method is a serious concern. Therefore, we measured the frequency of a THz oscillator with two counters simultaneously and evaluated their measurement limitations by checking the difference between the frequencies obtained by those counters. The results revealed that the frequency fluctuations of those counters were within 10 μHz, which corresponds to a measurement accuracy of 17 digits (Figure 3). These highly accurate THz counters are available for evaluating the THz standard currently under development and are also sufficient for the measurement of a theoretically proposed THz molecular clock that uses THz transition of ultracold molecules as a quantum reference.

Sending a Terahertz Frequency Standard to Distant Places

Since microwaves and light are only slightly absorbed in the atmosphere and/or optical fibers, and are thus suited as carriers of long-distance communication. In contrast, the THz wave suffers from strong absorption of water vapor, making it difficult to use for transmission in the atmosphere. Moreover, THz waveguides have not yet reached a sufficient level for practical use. Considering these limitations, we developed a THz-frequency transfer technique with comb technology. This method copies the phase information of a THz standard onto a laser light using comb technology, transfers the laser light through an optical fiber, then reconstructs the original information in the THz region. A demonstration experiment with a 20-km optical fiber indicated a THz standard transfer accuracy of 18 digits (Figure 3). In the future, application to remote calibration of THz-frequency-related equipment via an optical fiber network is expected.

Stabilizing the Frequency of a Terahertz Light Source

The principle of a frequency standard is to stabilize the frequency of an electromagnetic wave using the absorption lines of atoms or molecules as a reference. Therefore, in addition to the availability of a light source that can be easily controlled and a high-resolution spectroscopy technique, the selection of atoms or molecules is important. As a result of detailed theoretical reviews, we chose carbon monoxide (CO) molecules as a reference. Their absorption lines widely lie in the THz region at approximately 0.1 THz intervals, which makes it possible to implement spectroscopy using a commercially available THz light source. In addition, since they are a diatomic molecule with a simple structure, it is relatively easy to calculate the frequency shift due to an external electromagnetic field. We have already succeeded in the frequency stabilization of a quantum cascade laser with an oscillation frequency of approximately 3.1 THz into an absorption line of a CO molecule (Figure 4). Although further performance evaluations are required for this THz standard, we are conducting research to achieve a target frequency uncertainty of around seven digits.

Future Prospects

There are still many challenging issues in the research of a THz frequency standard and metrology, and we are constantly focusing on solving them. In view of the social needs, the NICT will develop both new standard and precise measurement technology in the THz region, aiming to establish a de facto international standard.

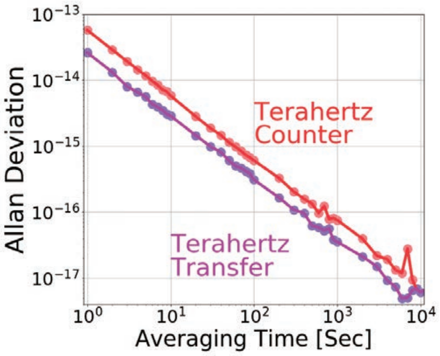

Figure 3 Measurement Accuracy of a Frequency Counter (Red) and Transfer Accuracy of the Frequency Transfer Technique (Purple). Both are the results of an experiment at 0.3 THz.

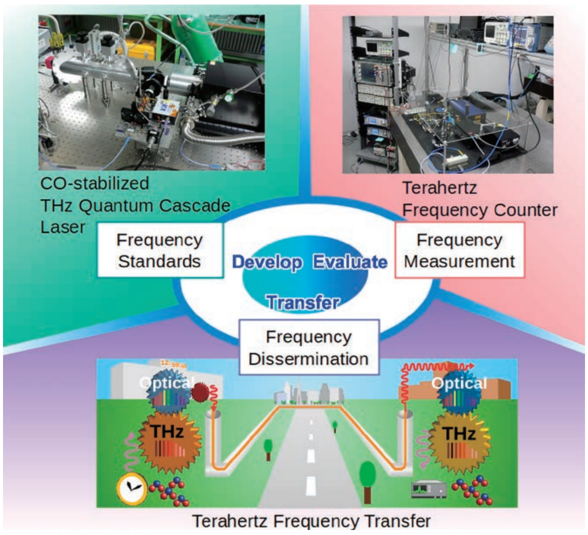

Figure 2 Essential technologies for the establishment of a Terahertz Frequency Standard and Metrology

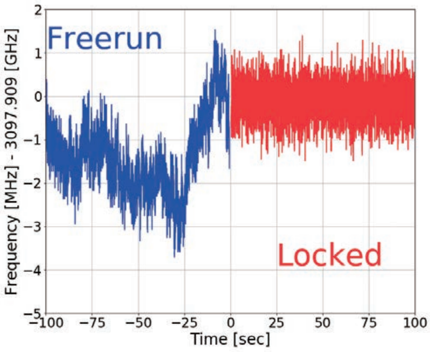

Figure 4 Frequency Fluctuations of a 3.1 THz Quantum Cascade Laser. (Blue) Free Running, (Red) Stabilized to a CO Molecule.

Latest Trends in the Future of the UTC Time Scale (Leap Second Issues)

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After completing graduate school, joined the Radio Research Laboratory (currently NICT) in 1985. He engaged in research on 1-3 GHz band radio propagation characteristics, cell combination method for mobile systems, time transfer applications, frequency calibration method and trusted time stamping systems, etc. Ph.D. (Engineering).

The Instant a Leap Second was Applied on January 1, 2017.

Last fall, the news that the definition of weight had been drawn up, hit the media. At the 26th General Conference on Weights and Measures (CGPM) held in November 2018, which is the supreme authority established under the Metre Convention, the standard of mass was changed from the International Prototype of Kilogram (IPK) to the definition of mass based on the Planck constant.

The same conference also yielded recommendations on the definition of time scales in Resolution B.

The first recommendation considers the current upper limit of UT1 - UTC. The other recommendation concerns the improvement of the estimation accuracy of UT1 - UTC and its publication method.

UT1 is one of the types of Universal Time (UT), which is an astronomical time scale based on the rotation of the Earth. UTC is an abbreviation for Coordinated Universal Time, which is an atomic time scale that is adjusted to ensure approximate agreement with UT1. However, since the Earth's rotation is not constant, there are deviations between UT1 and UTC.

At present, Recommendation TF.460-6 by the International Telecommunication Union Radiocommunication Sector (ITU-R) defines that the upper limit of UT1 - UTC shall be within ±0.9 seconds. If it is estimated that UT1 - UTC will exceed this limit, one second is inserted or deleted so that the deviation of UTC from UT1 is kept within ±0.9 seconds. This one-second adjustment is a leap second. Since a special adjustment of inserting ten seconds in 1972, a leap second has been applied 27 times to maintain UT1 - UTC within ±0.9 seconds.

In today's highly computerized society, there are concerns about the various effects of a leap second shift in time scale on communication and other infrastructure. For example, after the leap second adjustment conducted in 2012, various incidents were reported. Japan supports suppressing leap seconds from the viewpoint of maintaining the safety of communications.

The ITU-R has been discussing suppressing leap seconds in the future of the UTC time scale. Although active discussions were held at the Radiocommunication Assembly (RA) in 2012, no agreement was reached. The argument was not settled at the World Radiocommunication Conference 2015 (WRC-15) in 2015, and it was decided that the current UTC (with leap second adjustments) will be maintained until WRC-23. It was also approved that various opinions from international organizations other than the ITU-R should also be collected before a recommendation is made at WRC-23.

Following the WRC-15 resolution, Resolution B by this CGPM states that the CGPM shall work towards the future of the UTC time scale.

If the upper limit of UT1 - UTC is set to one minute, an adjustment will be required approximately every 100 years based on the results of the adjustments conducted in the last 60 years (a total of 37 seconds were adjusted). If an upper limit of one hour is accepted, the adjustment interval will be more than 5,000 years, which is in effect equivalent to suppressing leap seconds.

From now on, in response to the CGPM resolutions, discussions will be held at the International Committee for Weights and Measures (CIPM) and its Consultative Committee for Time and Frequency. The results will be reflected in WRC-23 in 2023 through the CGPM, which will contribute to solving the future of the UTC time scale.

Draft Resolution B

On the definition of time scales

The General Conference on Weights and Measures (CGPM), at its 26th meeting,
considering that

(omitted)

and **recommends** that

- all relevant unions and organizations consider these definitions and work together to develop a common understanding on reference time scales, their realization and dissemination with a view to consider the present limitation on the maximum magnitude of UT1–UTC so as to meet the needs of the current and future user communities,
- all relevant unions and organizations work together to improve further the accuracy of the prediction of UT1–UTC and the method for its dissemination to satisfy the future requirements of users.

Excerpt from the Convocation of the General Conference on Weights and Measures (26th meeting)