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FEATURE

Toward the Ultimate of Time and Frequency

Interview

Time is born here!

Contributing to global time by the generation of Japan Standard Time

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FEATURE

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Cover photo:
Atom-trapping part of an optical lattice clock. A large number of atoms are first cooled down to several micro Kelvin with a combination of blue and red laser light combined with a magnetic field, and then trapped in an optical lattice. Subsequently, laser light is irradiated with its frequency tuned to the atomic resonance, yielding light that serves as an unchanging frequency standard. By referencing one second obtained from the standard frequency, the lengths of one second ticked by UTC and JST are measured and reported to maintain time more accurately.

Upper-left photo:
Japan Standard Time Measurement System (Headquarters: Koganei). The weighted average of eighteen cesium atomic clocks is calculated, and a standard real signal is adjusted to synchronize with the average.

Interview

Time is born here!

Contributing to global time by the generation of Japan Standard Time

Space-Time Standards Laboratory

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).

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.

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

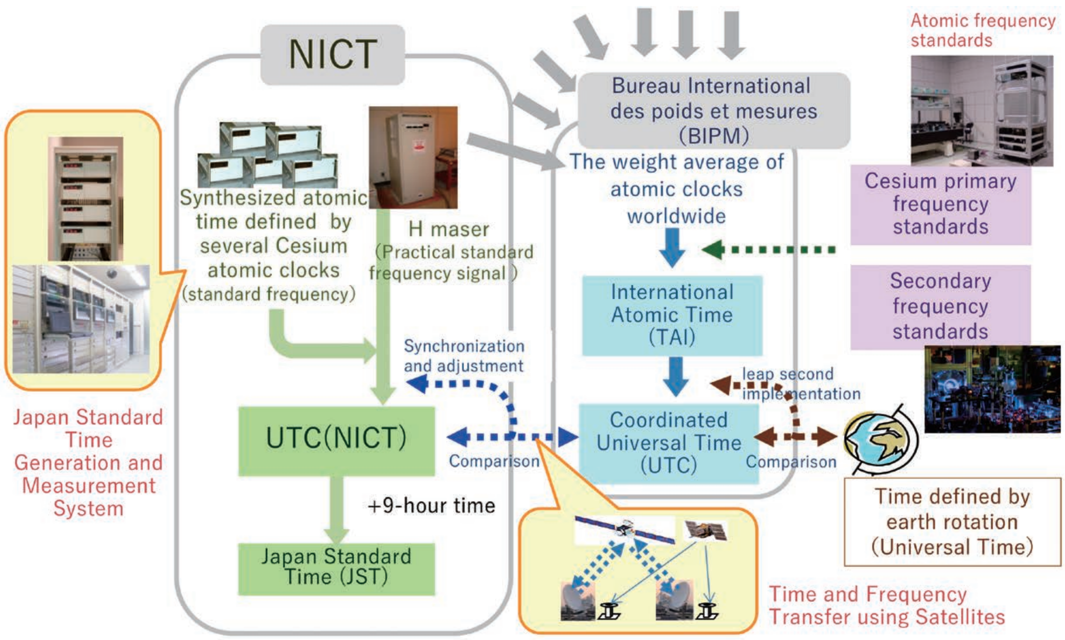

Figure　Generation of Japan Standard Time. Time, as an important social infrastructure, is generated and maintained not only by NICT but under collaboration and mutual cooperation with BIPM and research institutes worldwide.

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.

“Japan Standard Time” Leading to the Next Generation

Kensuke MATSUBARA

Research Manager
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Applied Electromagnetic Research Institute

After completing graduate school, joined the Communications Research Laboratory (CRL, currently NICT) in 2001. Engaged in research on single-ion optical clocks, high-precision frequency provision by standard radio waves and operation of Japan Standard Time, etc. Ph.D. (Science).

Fumimaru NAKAGAWA

Senior Researcher
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Applied Electromagnetic Research Institute

After completing graduate school, joined the Communications Research Laboratory (CRL, currently NICT) in 2002. Engaged in research on time and frequency transfer, the standard time system and construction of the atomic time scale. Ph.D. (Science).

With the sophistication of IT in recent years, the importance of the frequency standard that has long been defined as the national standard by the NICT, and the Japan Standard Time (JST) generated using it, is growing. In addition to providing the correct time and frequencies in Japan and around the world, the NICT makes a significant contribution to generating Coordinated Universal Time (UTC), which is the world standard. Moreover, in response to demands for the next generation, we have been conducting research and development on a new JST by introducing the high reliability of decentralization and high accuracy of optical clocks.

Generating Accurate and Stable JST

The current unit of time, the second, is defined as the duration of approximately 9.2 billion microwave periods, using the fact that a cesium atom absorbs an electromagnetic wave with a constant period. As Figure 1 shows, the Space-Time Standards Laboratory generates atomic time synthesized by weight-averaging up to eighteen commercial cesium atomic clocks. By adjusting the frequency of a hydrogen maser clock using this atomic time, JST and the frequency standard are generated. This makes it possible to generate time by taking advantage of a hydrogen maser clock, which has small fluctuations in time period in a short time (approx. 10 days or shorter) and of synthesized atomic time, which has small variations in time period in a long time (approx. 10 days or longer). The weighted average algorithm has been optimized based on the operational experience accumulated over the years. Even if some clocks stop due to failure, their effects can be sufficiently reduced.

The Space-Time Standards Laboratory reports to the International Bureau of Weights and Measures (BIPM) in France the time of more than 30 atomic clocks (cesium and hydrogen maser) including those at the LF Standard Transmission Stations and the Kobe sub-station. The BIPM regularly determines the Coordinated Universal Time (UTC) based on the time data from the frequency standards (primary frequency standards, optical clocks, etc.) and atomic clocks of more than 60 organizations around the world. The data from more than 400 atomic clocks are particularly conducive to determining more stable UTC. The atomic clocks of the NICT

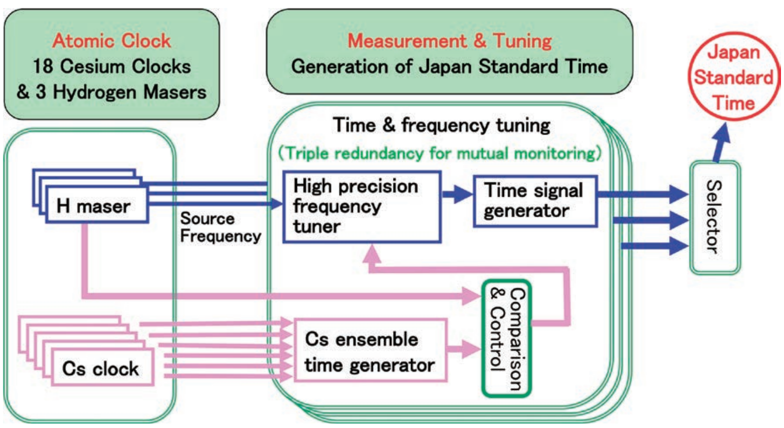

Figure 1 JST Generation System (Cs: Cesium; H: Hydrogen)

recorded the third largest contribution in the world on average last year. The NICT, which has advanced technology, is expected to play a leading role, for example, as the key organization in the Asia Pacific region in developing a technical review system for global mutual recognition of frequency calibration.

Providing a Reliable and Far-reaching Japan Standard Time

The main methods for the NICT to supply Japan Standard Time and frequency standards include the Standard Time and Frequency Radio waves, Telephone JJY, and Time Service by Network Time Protocol (NTP) (Figure 2). Of these, the Standard Time and Frequency Radio waves has the longest history, and its contents are stipulated by the Act for Establishment of the Ministry of Internal Affairs and Communications, etc. In 1999, transmission of the Standard Time and Frequency Radio waves at low frequency (LF) started, and more than a billion radio clocks in total have received signals of the JST. The transmitting equipment at the two stations in Japan were renewed by 2016. Today, the 20th year since the beginning of LF transmission, this has become the most familiar means to supply the JST.

The Telephone JJY provides JST through telephone lines, and it is accessed around 150 thousand times per month. It has millisecond accuracy, reliability, and high security, and is also widely used in the public sector including broadcasting and railway transportation. In response to the growing use of optical fiber telephone lines, Hikari Telephone JJY has been developed, which exploits the fast transfer speeds of optical lines. Since the number of accesses to the NTP is rapidly increasing and its importance is expected to rise, efforts are being made on speed enhancement and multiplexing of servers. In addition, we are contributing to the system of time stamp authentication for electromagnetic records (electronic files) required for administrative services incorporating electronic forms and are working on adapting our frequency calibration service to the newly published ISO/IEC17025:2017 standard.

Researches of Future JST Decentralization

To further improve the reliability and accuracy of Japan Standard Time (JST), research on the distributed arrangement of JST is under way. As a milestone, operation of the JST Kobe sub-station started on June 10, 2018 (Figure 3). Similar to the NICT Headquarters (Koganei), the Kobe sub-station has a JST generation system and Hikari Telephone JJY system. The system at Kobe is smaller than that at the Headquarters, and it constantly generates time. Using time comparison via communication satellites and GPS satellites, the time difference from the Headquarters is adjusted to be sufficiently small (nanosecond level). Therefore, even if the supply of JST from the Headquarters is interrupted, the sub-station immediately takes over and provides JST. Since the time difference between the two stations is constantly measured with high accuracy, which means that the sub-station has high traceability to JST, the application of the time and frequencies generated by the Kobe sub-station will be considered.

Research on the decentralization of JST is also expected to improve accuracy. In the current operation, the JST of the Headquarters is used as the master, and each of the time generated at the Kobe sub-station and the LF Transmission Stations is adjusted to the master by time comparison via satellites. Instead of using the Headquarters as the master, creating JST based on the atomic time synthesized from all atomic clocks spread to a sub-station and transmission stations is currently being studied. As more clocks are synthesized, the precision of the generated JST will increase. To realize such decentralization, stable operation of time comparison among atomic clocks, and development of a synthesis algorithm suitable for decentralization are required; this is now being studied.

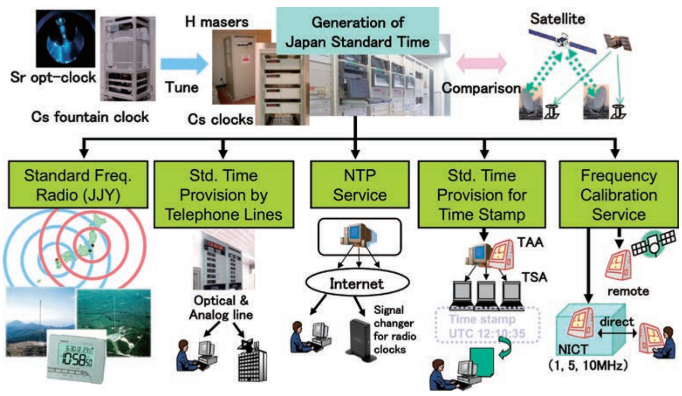

Figure 2 JST Supply (Sr: Strontium)

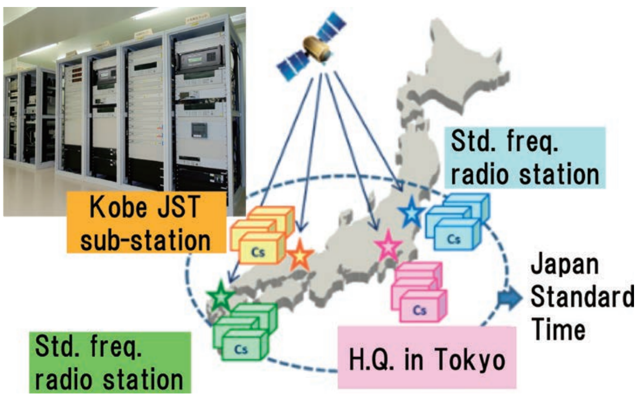

Figure 3 Kobe Sub-Station and JST Decentralization (Photo: Sub-station time and frequency measurement system)

Future Prospects

As described on pages 6 and 7 of this special issue, the re-definition of the second is currently being considered. The NICT is conducting experiments on time scale generation using optical clocks, with the aim of implementation as the next-generation system.

The NICT's JST and frequency standard are described at http://jjy.nict.go.jp/index-e.html. We will continue our efforts on the development and dissemination of next-generation time and frequencies that are more accurate and stable.

Next-Generation Frequency Standards in the Optical Domain

From the age of microwaves to the age of light

Hidekazu HACHISU

Senior Researcher
Space-Time Standards Laboratory
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After earning a doctor degree and working as a Post-Doctoral Fellow with JST-CREST, since 2010, he has been with the NICT, where he has been involved in the research and development of optical frequency standards, especially optical lattice clocks, and its applications. Ph. D. (Engineering).

Optical clocks employing a clock transition in the optical regime are more accurate than cesium frequency standards defining the SI unit of time—the second. To provide more accurate time information, we have been working on improving optical clock performance and applying it to time scale generation. By utilizing such highly accurate optical clocks, we have also investigated gravitational time dilation, which is described by the general theory of relativity. Recently, we teamed up with European and the U.S. groups to explore dark matter, which is indispensable for understanding the universe, but whose nature has not been identified.

Frequency Standard

The second, as a unit of time, is defined based on a clock transition of a cesium atom in the microwave regime. Primary frequency standards using this transition are internationally certified to calibrate Coordinated Universal Time (UTC). The best such standard has achieved an accuracy of one second in 300 million years. Expressed as a length, this accuracy corresponds to measuring the diameter of the Earth in nanometers (one billionth of a meter), which demonstrates the incredible accuracy of frequency standards. To further improve this, we, along with other research groups around the world, have been working on developing an optical frequency standard (an optical clock) using laser light, which is an electromagnetic wave with a much higher frequency than a microwave signal. Just as a ruler with finer marks can measure length more accurately, an electromagnetic wave oscillating with a higher frequency can help measure time periods with higher accuracy. In fact, an optical clock with an accuracy of one second in 16 billion years has already been realized, and it has been suggested that the definition of the second be changed from the microwave transition of cesium to optical transition in an atom.

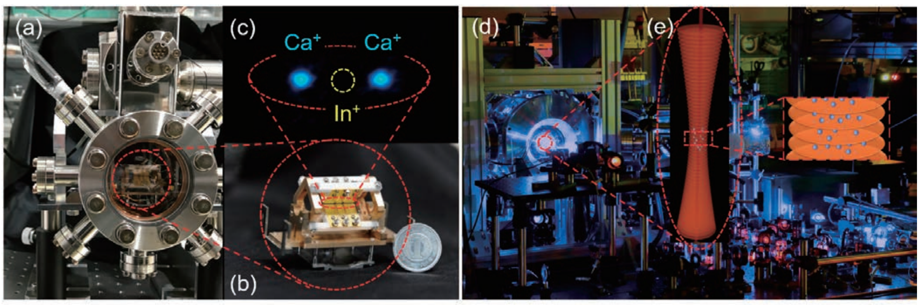

Figure 1 (a) Part of an Optical Single-Ion Clock, (b) Photo of the Trap Electrodes, and (c) CCD Image of Actual Trapped Ions. In (c), one indium ion (In^+), which is used for optical spectroscopy, is trapped between two calcium ions (Ca^+) glowing in blue. (d) Part of strontium-based Optical Lattice Clock Equipment and (e) Conceptual Scheme of an Optical Lattice. (e) A large number of atoms are trapped in the optical lattice.

Optical Single-Ion Clocks and Optical Lattice Clocks

Common to all current frequency standards is that they use the property that atoms absorb electromagnetic waves at specific frequencies. As Figure 1 shows, optical clocks come in one of two types: One is the optical single-ion clock, which was proposed in the 1980s in Europe and the U.S. This type employs a single ion that is trapped by a time-dependent inhomogeneous electric field. The other type is the optical lattice clock, which was proposed in 2001 by Hidetoshi KATORI, who was an Assistant Professor of the University of Tokyo at that time. This type uses a large number of atoms trapped in the standing wave formed by the interference of laser beams. The resulting periodic structure is the origin of the term "optical lattice." An atom-light interaction called the Stark effect allows neutral atoms to be attracted to the position of maximum intensity, where they occupy volumes that look like pancakes stacked one above the other (see Figure 1 (e)). Using many atoms simultaneously provides a stronger signal and allows reduced measuring times. My personal responsibility is the continued development of the optical lattice clock. However, our laboratory is also working on an optical single-ion clock. Both teams are proceeding with their research by cooperating with and motivating each other.

Generating More Accurate Time scale with an Optical Clock

In the real world, where global financial transactions are carried out at ever faster rates and the 5th-generation mobile communication system is being introduced, accurate time information is critical. In such a world, the international standard time UTC serves as a reference. To generate UTC, the Bureau International des Poids et Mesures (BIPM) collects time data of more than 400 microwave atomic clocks around the world and computes their weighted mean. The rate at which this atomic time scale advances is regularly evaluated by the primary frequency standards in the world to make sure it agrees with the defined period of one second. In order for the evaluation to be used for calibration, the capacity of the frequency standards needs to be recognized internationally. Among optical clocks, only the optical lattice clocks of the NICT and LNE-SYRTE were the first to obtain these certifications. Our evaluations are now used for calibrating UTC*[1] alongside those of the conventional frequency standards.

On the other hand, UTC comes as a set of numbers reported once a month by the BIPM; it is not an actual signal and therefore is not available for practical use. Therefore, each country generates and maintains their local time scale as an actual signal that is synchronized with UTC. The signal generated and maintained by our institute, with a +9-hour time difference added,*[2] is widely provided as Japan Standard Time. In recent years, we successfully generated a more accurate actual time scale signal using an optical lattice clock for the first time in the world.*[3] As shown in Figure 2, after adjusting the time difference between the generated time scale TA(Sr) and UTC to 0 ns (one nanosecond = one billionth of a second), the difference remained at less than 9 ns even after a period of five months. In fact, we found this discrepancy to be largely due to the imperfections of the UTC time scale itself: When we look at the time difference of TA(Sr) from the realization of terrestrial time, TT(BIPM), it is 0.8 ns or less after five months. TT(BIPM) is a more accurate time scale, with a rate closer to the definition, that is calculated and reported once a year based on all available data for the evaluation of UTC. This allows TT(BIPM), which is intended for academic use, to be more accurate than UTC, which cannot be corrected after its monthly publication. The agreement of our results with TT(BIPM) shows that TA(Sr) indeed ticked at a rate closer to the definition than even UTC itself.

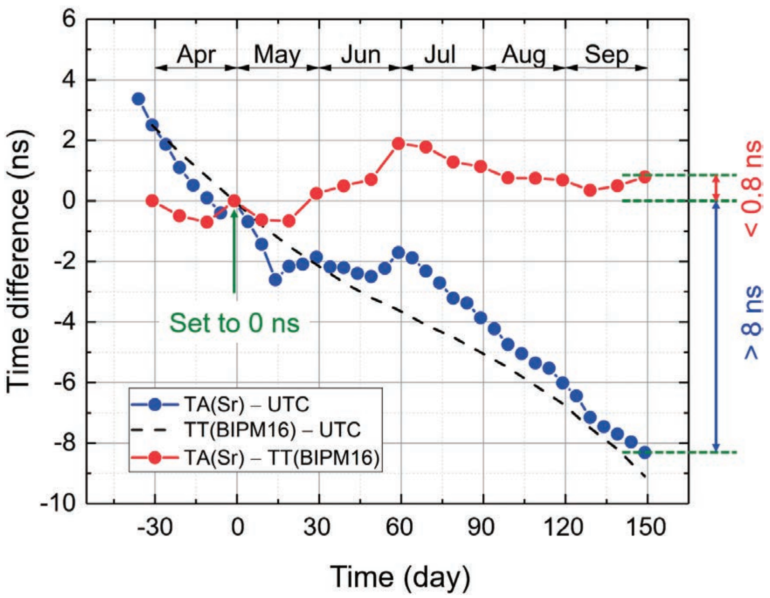

Figure 2 High-Accuracy Test Time scale TA(Sr) steered with an Optical Lattice Clock (2016). The blue and red lines indicate the time difference of TA(Sr) from UTC and TT(BIPM) respectively. The unit (ns) is nanoseconds. The time difference was adjusted to 0 ns at the beginning of May. The black broken line shows the time difference between TT(BIPM) and UTC.

Using High-Precision Optical Clocks

The general theory of relativity describes how time ticks faster at high altitudes. Our laboratory verified this effect 20 years ago when commercial cesium atomic clocks were moved to the Standard Time and Frequency Transmission Stations.*[4] In recent years, the same effect was verified with shorter measuring times and with higher accuracy using optical clocks. In 2011, we transferred the signal from the strontium-based (Sr) optical lattice clock at the NICT Headquarters (Koganei) to the Katori Laboratory at the Hongo Campus of the University of Tokyo through an optical fiber to measure the frequency difference from the Sr optical lattice clock located there. The results clearly showed that the time at NICT, located 56 m higher, ticks faster than at the University of Tokyo.*[5] Since the way time ticks depends on gravitational potential, it may soon be possible to investigate the existence of underground caves and natural resources by utilizing the difference in the ticks of time between two points. We are also exploring the nature of dark matter using optical lattice clocks in a collaboration with European and U.S. groups led by researchers at Nicolaus Copernicus University in Poland. Evolving from table-top research on the interaction between atoms and laser light, optical clocks now test the effects of the theory of relativity and tackle research exploring the grand mysteries of the universe. This is one of the fascinations of research on the frequency standard, in which we continue to pursue ultimate accuracy.

We are working on increasing the precision of UTC by using optical clocks, and on upgrading the system to offer more accurate JST in cooperation with the JST group. We will also contribute to leverage the sophistication of optical clocks towards a deeper understanding of nature.

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*1 Press release on March 2019: https://www.nict.go.jp/en/press/2019/03/04-1.html

*2 This Issue, P4-5

*3 Press release on March 2018: https://www.nict.go.jp/en/press/2018/03/20-1.html

*4 Journal of NICT Vol. 50 Nos. 1/2 P211

*5 Press release on August 2011：https://www.nict.go.jp/press/2011/08/04-1.html (in Japanese)

Intercontinental Time and Frequency Transfer Techniques

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Miho Fujieda joined in the Communications Research Laboratory (currently NICT) in 2003. She engages in the time and frequency transfer via a satellite and by using optical fibers. Ph. D. (Science).

Mamoru SEKIDO

Associate Director
Space-Time Standards Laboratory
Applied Electromagnetic Research Institute

Mamoru Sekido joined in the Communications Research Laboratory (currently NICT) in 1991. He engages in engineering research with very long baseline interferometry for geodesy, astrometry, spacecraft navigation, and e-VLBI. Ph.D. (Arts and Sciences).

The frequency is defined as a number of events repeatedly happened during one second. And period of the cycle is time interval between the events. A clock is a device equipped with a mechanism to generate such repeating events, for instance a pendulum, and with that for counting the number of events. It expresses the time by products of the period and accumulated number of counts. Coordinated Universal Time (UTC) is generated by averaging slowing and advancing (time difference) atomic clocks operated all over the world, and it is used as the reference of national standard time of each country. For the purpose to measure the differences of national standard time between countries and to confirm the reproducibility of frequency of national frequency-standards, very precise measurement of clock and frequency comparison is essential. For example, time and frequency (T&F) transfers have been regularly performed to measure time difference between UTC and JST (Japanese Standard Time) by using satellites with wide viewing angle such as GPS.

Status of time and frequency transfer techniques

Current regular T&F transfer have been performed by observation of GPS satellites or by two-way signal exchanges via geostationary satellite. Measurement precision of these techniques (blue line and black one in Figure 1) is lower than that of atomic clocks to be compared. Consequently, it will take hundreds of days for comparison measurement to achieve the same precision with that of optical atomic clock (green line in Figure 1), which is thought to be used for re-definition of the second in future. To improve this situation, ultra-high precision T&F transfer with optical fiber link has been conducted inside the European continent. However rental fee of optical fiber is expensive, and submarine cable is required for connection between oversea countries. Due to those difficulties, optical fiber link for T&F transfer is not realized yet for intercontinental baseline. Thus, we are extensively investigating T&F transfer technique using satellite link and VLBI (very long baseline interferometry). Figure 2 shows parabolic antennas for two-way satellite link and small antenna for VLBI placed at the roof of the 2nd building of NICT Headquarters (Koganei). Figure 3 shows 34m diameter antenna used for VLBI. The antenna for two-way satellite link is fixed for direction of a geostationary communication satellite. VLBI antennas make observations many celestial radio sources distributed in the wide range of the sky. Observation is made more than 24 hours by changing radio sources in a few minutes' interval automatically by computer control.

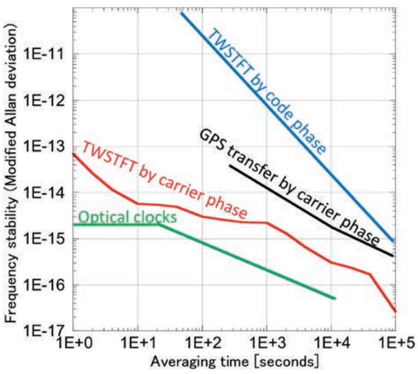


Figure 1 (Left) Precision of frequency transfer by using satellite. (Right) Newly developed modem.
Measurement precision of each techniques, Red: Two-way satellite carrier phase transfer, Blue: Two-way satellite code phase transfer, Black: GPS transfer with carrier phase. Only red line is measurement data. Lines of others indicate typical performance of each method. Green line shows typical frequency stability of optical clock.

Future of two-way satellite T&F transfer by using carrier phase

Above mentioned T&F transfer with GPS satellite is a method of receiving signal transmitted from navigation satellites with a reference signal supplied from atomic clock. Precisions of each methods are about 5 nano second and 50 pico second by using code phase and by using carrier phase (Black line in Figure 1), respectively. In case of two-way satellite transfer, signals are exchanged simultaneously between atomic clocks to be compared through a communication satellite. This method can improve the precision by cancelling influences effectively caused by atmospheric excess paths and changes of satellite orbit, which are error sources of the technique using GPS. Normally 500 pico second of precision is gained by using code phase of 2.5 Mbps chip rate (Blue line of Figure 1). This precision is inversely proportional to the chip rate, thus higher precision is obtained by using higher chip-rate modulation signal. Though, expensive rental fee for transponder of commercial communication satellite is limiting factor in this case.

We have investigated using carrier phase for two-way satellite T&F transfer, and have achieved world highest precision 0.1 pico second for the first time. And we have performed optical clock comparison experiment with institutes at overseas distances. However, that technique did not get popular among national metrology institutes because only we possessed the instruments enabling carrier-phase measurement. At the beginning the number of instruments and their specifications were not enough. The reproducibility of internal instrumental delay was insufficient then it could not be used for absolute time comparison. Then we started a development of instrument so called modem to solve the issues by using digital devices. Prototype of the modem has completed by a firm in FY2017, and its performance has been confirmed to clear the specification. We have been conducting an experiment with oversea institute with this modem since late FY2018.

Our final target is promotion for utilization of two-way satellite carrier phase technique to be used regularly in the UTC comparison network. Consequently, we wish to improve the stability of UTC. We are just on the stage where we got tool for that. We wish to move forward to the goal with learning way of efficient popularization of our technology by help and supports from related parties.

Figure2 Antennas at the roof of 2nd building of NICT Headquarters (Koganei)

Intercontinental frequency comparison with VLBI

VLBI is one of the space geodetic techniques which can make precise frequency comparison of atomic clock over earth diameter scale. VLBI is a technique to measure precise arrival time difference of radio signals coming from distant celestial radio sources to multiple radio telescopes on the earth. Observing radio sources are so called quasar at bllions year away from the earth, and they consist of celestial reference frame. By the analysis of the arrival time differences, baseline vector between the radio telescopes and clock differences are obtained. VLBI has complementary characteristic with respect to the other T&F comparison technique (GPS and two-way satellite link), that is passive technique just observing celestial radio sources, thus no need of radio transmission and free from availability of satellites. We have developed broadband (3-14 GHz) VLBI technique, which drastically improves VLBI measurement precision than conventional. We are investigating technique to realize precise frequency comparison via broadband VLBI observation with small (2.4 m) diameter antenna (Figure 2). After domestic test experiments with National Metrology Institute of Japan (NMIJ), we have exported the small VLBI station to Italy in 2018. From fall of 2018, a series of experiments to compare Yb optical lattice clock operated by National Institute of Metrological Research (INRiM) and Sr optical lattice clock operated by NICT has started (Figure 4). Instead of microwave signal emitted by Cs atom, optical signal emission is supposed to be replaced as new definition of the time interval of one second. Although still discussion on an issue, which atom is to be used for definition, is being continued. Thus, inter-comparison of optical clock is an important subject. We think it is important from viewpoint of four-dimensional reference frame of space-time coordinates that VLBI, which contribute to the definition of the space coordinate system, will make contribution to determination of time coordinates.

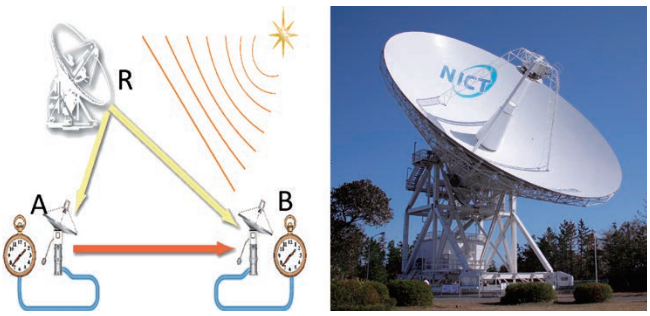
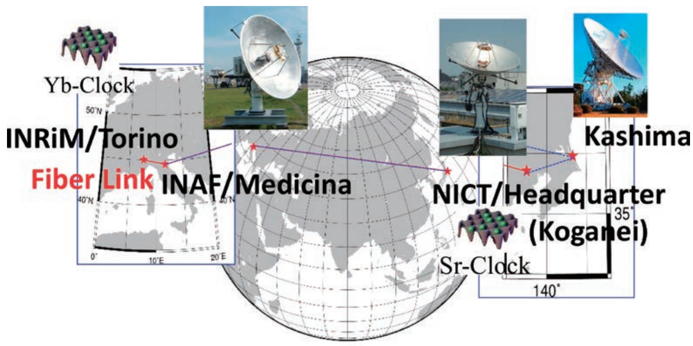


Figure 3 (Left) Node-Hub style VLBI with small diameter antenna. (Right) Kashima 34m antenna.

Small diameter antennas as node (A, B) and large diameter antenna as hub station (R) form RA and RB baselines. Then AB baseline data is composed from RA and RB baseline data. Large diameter antenna compensates the disadvantage of less sensitivity of small antenna, and influence of large diameter antenna, which is suffered from deformation and larger delay variation, is eliminated in the final AB baseline data. Kashima 34m antenna works as the hub station in this experiment.



INRiM: National Research Institute of Metrology, Italy
INAF/IRA: National Institute for Astrophysics/Institute of Radio Astronomy, Italy
NICT: National Institute of Information and Communications Technology, Japan

Figure 4 Frequency transfer experiment of optical clocks between Italy and Japan by VLBI

Optical clock signal of Yb generated by National Institute of Metrological Research(INRiM) is provided to National Institute for Astrophysics (INAF). Precise frequency comparison between Yb atoms at INRiM and Sr atoms at NICT are conducted by means of VLBI network observations with the small broadband antennas installed at INAF/Medicina observatory, the one at the roof of 2nd building of NICT/Koganei, and Kashima 34m antenna.

Developing an Atomic Frequency Standard in New Frontier

Toward the establishment of terahertz frequency standard and metrology

Shigeo NAGANO

Senior Researcher
Space-time standards laboratory
Applied Electromagnetic Research Institute

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).

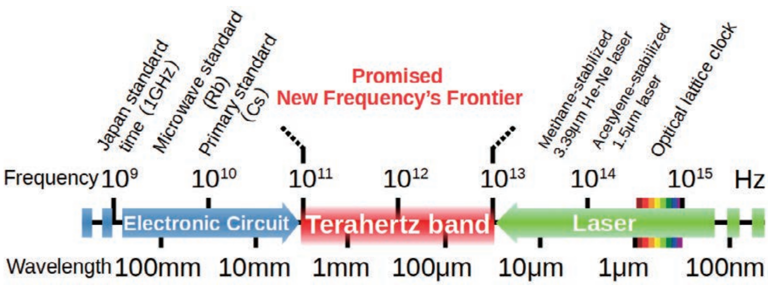


Figure 1 Current Status of the Frequency (or Wavelength) Standards and Terahertz Region

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 interval 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.

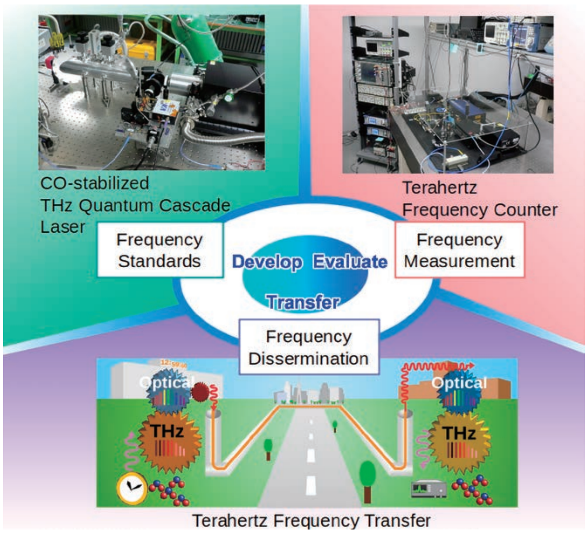


Figure 2 Essential technologies for the establishment of a Terahertz Frequency Standard and Metrology

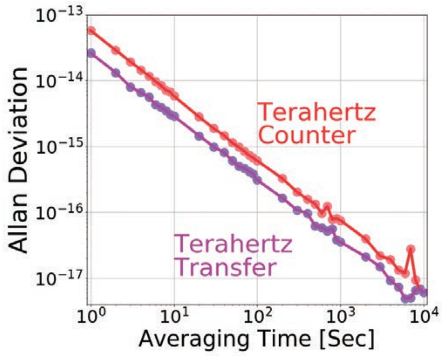


Figure 3 Measurement Accuracy of a Frequency Counter (Red) and Transfer Accuracy of the Frequency Transfer Technique (Purple). Both are the results of an experiment at 0.3 THz.

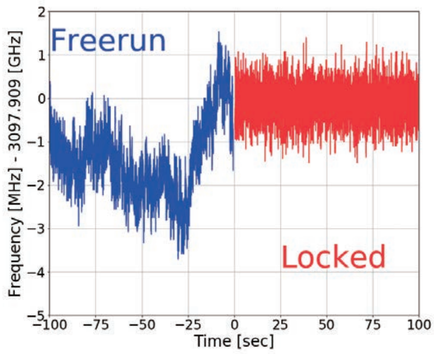


Figure 4 Frequency Fluctuations of a 3.1 THz Quantum Cascade Laser. (Blue) Free Running, (Red) Stabilized to a CO Molecule.

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

Tsukasa IWAMA

Research Manager
Space-Time Standards Laboratory
Applied Electromagnetic Research Institute

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)

Integrating an Atomic Frequency Standard in a Microchip

Motoaki HARA

**Senior Researcher
Space-Time Standards Laboratory
Applied Electromagnetic Research Institute
Ph.D. (Engineering).**

Biography

1977: Born in Hyogo Prefecture.
2005: Received Ph.D. in engineering from Tohoku University.
2005: Joined Fujitsu Laboratories Ltd.
2011: Became an assistant professor of the Graduate School of Tohoku University.
2013: Became an associate professor of Tohoku University.
2016: Appointed to present position.

Awards, etc.

The 35th Symposium on Ultrasonic Electronics: Young Scientist Award (2014)
The 35th Sensor Symposium: Excellent Technical Paper Award (2018)

Q&As

Q What are you currently interested in outside of your research?

A Although not just a current interest, I have always read many books. I try to choose ones in various fields, not limited to science and engineering, such as fiction, business, philosophy, and autobiographies by politicians and bureaucrats, etc.

Q If you were reborn, what would you like to be?

A I would like to be reborn as a large organism such as a big tree or whale because I have been studying microscopic objects in this world.

Q What advice would you like to pass on to people aspiring to be researchers?

A Since it's not possible to produce good research outcomes and create suitable research environments only by oneself, I think researchers need mental toughness to keep a balanced attitude and positive thinking.

When electronic equipment such as chronometers and mainframes that were for public infrastructure become widespread as consumer products, many of them were rapidly miniaturized and made into wearable sizes. This trend correlates with the downsizing of electronic devices such as memory, sensors, and microphones, as their scale of integration increases dramatically.

The atomic frequency standard managed by the NICT, which generates Japan Standard Time (JST), will definitely follow the downsizing trend. The atomic frequency standard is a large rack-mount unit, but atomic clock modules of just a few centimeters per side have been marketed in recent years. The next-generation mobile phone standard requires efficient linkage by synchronization between communication terminals including sensors. The same is true for next-generation vehicles, which are driven by the trend toward smart and autonomous cars. Against this backdrop, there is a growing need for more accurate time synchronization and positioning. We may be at the dawn of mass-production and significant downsizing of electric frequency standards, which are clocks of ultimate accuracy.

My research career started with a steampunk-like project to miniaturize a gas turbine into a palm-size one using silicon micromachining technology. Next, I worked on developing technology using mechanical resonators for processing high-frequency signals, which cannot be realized only with an electronic circuit. While I was teaching at university, I also worked on developing on-chip power-generation elements and on-chip fluid devices.

Miniaturization and on-chip integration of an atomic frequency standard, which involves a cluster of advanced technologies such as microfabrication of a high-frequency control system, optical control system, and micro gas cell, are an extension of my expertise. It is a demanding but worthwhile subject. Finally, the high-frequency control system for an atomic clock, which has been developed in advance, is shown in the figure below. I hope it clearly reveals the scale of downsizing.

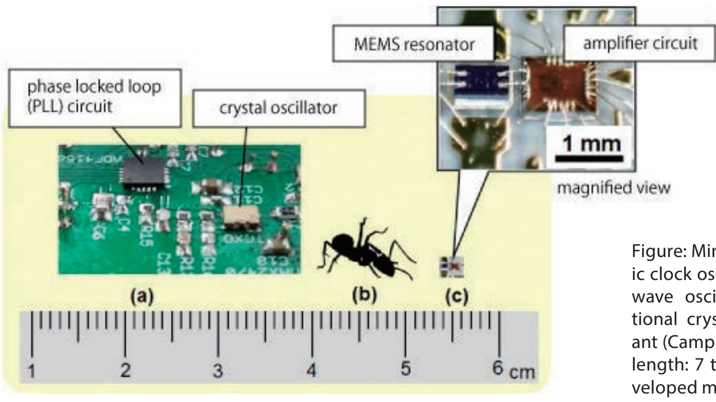


Figure: Miniaturization of an atomic clock oscillator circuit. (a) Microwave oscillator using a conventional crystal resonator. (b) Black ant (Camponotus japonicus) (body length: 7 to 12 mm). (c) Newly developed microwave oscillator

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