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FEATURE

Space-Time Synchronization Enabled by Three Core Technologies

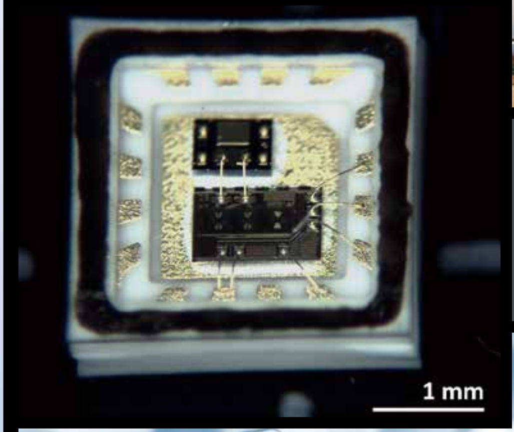
DIALOG

Director, Global Research and Development Center for Business by Quantum-AI Technology (G-QuAT)

Director of Space-Time Standards Laboratory,

MASU Kazuya × IDO Tetsuya

The Future of 6G and Quantum Networks Supported by Space-Time Synchronization



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(Middle Left)
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(Photo by Social-ICT System Laboratory, NICT)

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FEATURE

Space-Time Synchronization Enabled by Three Core Technologies

TOPICS

INFORMATION

Director, Global Research and Development Center for Business by Quantum-AI Technology (G-QuAT)

Director of Space-Time Standards Laboratory,

MASU Kazuya × IDO Tetsuya

The Future of 6G and Quantum Networks Supported by Space-Time Synchronization

It has been more than a century since Einstein introduced the concept of space-time, sparking a revolution in physics. Today, a new interpretation of space-time is emerging in the field of information and communications technology. Space-time synchronization technology, which enables precise determination of both time and position, can greatly enhance the accuracy and efficiency of information and communication systems. This technology is also indispensable for the rapidly advancing development of quantum computers and their networks.
In this feature, we present a dialogue between Kazuya Masu, Director of the AIST Global Research and Development Center for Business by Quantum-AI Technology (G-QuAT), and Tetsuya Ido, Director of the Space-Time Standards Laboratory at NICT.

MASU Kazuya (Left)

Director, Global Research and Development Center for Business by Quantum-AI Technology (G-QuAT), National Institute of Advanced Industrial Science and Technology (AIST)

Completed the doctoral program in Electronic Engineering, Graduate School of Science and Engineering, Tokyo Institute of Technology, in March 1982.
After serving as Research Associate and Associate Professor at the Research Institute of Electrical Communication, Tohoku University, appointed Professor at the Precision and Intelligence Laboratory, Tokyo Institute of Technology, in June 2000. Later served as Director-General of the Institute of Innovative Research, Tokyo Institute of Technology, among other positions. Since April 2018, has been President of Tokyo Institute of Technology.
Appointed Director of the AIST G-QuAT Center in October 2024.
Ph. D. (Engineering)

IDO Tetsuya (Right)

Director of Space-Time Standards Laboratory, Electromagnetic Standards Research Center, Radio Research Institute

After completing graduate studies, worked as a researcher for JST-ERATO, followed by a Research Associate position at JILA (NIST/University of Colorado) in the United States. Joined NICT in 2006.
Has conducted research on optical lattice clocks and precision optical measurement technologies, and their integration into standard time systems. In recent years, has also been actively promoting space-time synchronization technologies.
Ph. D. (Engineering)

—— To begin, could you both introduce yourselves by sharing your research backgrounds?

IDO I have been involved in the research and development of optical lattice clocks since their very early days. Compared to cesium atomic clocks, which are the devices that currently define the second, optical lattice clocks generate frequencies that are more than two orders of magnitude more accurate. They are now on the verge of practical implementation, and at NICT we already use them to verify once a week whether Japan Standard Time truly aligns with the correct one-second interval. We are also contributing to discussions at the General Conference on Weights and Measures regarding the potential redefinition of the second.

At the same time, as the Director of the Space-Time Standards Laboratory, I am working to ensure that space-time synchronization technologies can be put to use in society. Optical lattice clocks serve as ultra-high-precision timekeepers that underpin social infrastructure. Alongside them, our lab is also developing miniature atomic clocks, which are less precise than lattice clocks, but compact enough that individuals could one day carry them.

MASU As a teenager, I was fascinated by fundamental physics, such as relativity and quantum mechanics. At university, however, I majored in electronic engineering, and after graduation, I worked on integrated circuit design and development. Currently, at AIST's G-QuAT center, I manage research and development in quantum computers and quantum networks.

—— To clarify, what exactly do you mean by “space-time synchronization”?

IDO Simply put, it means that two objects in distant locations share the same coordinates in both space and time. In wireless communication networks like B5G and 6G, machine-to-machine (M2M) communication will play an increasingly important role. This requires the exchange of information about

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space and time, which is achieved by synchronizing space and time; in other words, by sharing the same temporal and spatial reference axes.

MASU The fact is, both semiconductors and quantum computers rely on time synchronization. An integrated circuit is about 1.5 cm square, containing multiple circuit blocks that operate using bits—1, 0, 1, 0. But unless those blocks operate in perfect timing with each other, the computation would not work.

It is essentially the same principle as sharing space and time in communication networks. And as we begin connecting quantum computers, which we are studying, to networks, discussions naturally move into the realm of “quantum time” and “quantum time synchronization.”

IDO What I think is important here is that in the past, as science advanced, the assumption was that having a single ultra-precise reference would cover everything, that even in cases where only modest precision was required, you could simply use the highest-precision resource available. But going forward, this includes risks of becoming wasteful. Needs are diversifying, and I believe the era we are entering is one where we must provide levels of precision tailored to the specific requirements at hand.

The Three core technologies of Space-Time Synchronization

—— What core technologies are necessary to realize space-time synchronization?

IDO At the Space-Time Standards Laboratory, we envision future networks built on space-time synchronization, as illustrated in Figure 1. To achieve this, we are developing what we call the “Three Pillars of Space-Time Synchronization.”

The first pillar is the compact atomic clock chip, CLIFS (Chip-Level Integrated Frequency Standard). By embedding highly stable time into all kinds of devices, a wide variety of services can be enabled. At present, atomic clocks about the size of an eraser have been commercialized, but they remain very expensive; we hope to reduce the cost by nearly two orders of magnitude. Looking further ahead, such clocks could eventually become small enough to be built into smartphones.

The second pillar is a short-range wireless two-way time transfer technology called Wi-Wi (Wireless Two-Way Interferometry). This technology makes it possible to determine time and position using only terrestrial radio signals, without relying on Global Navigation Satellite Systems (GNSS).

The third pillar is a technology called the cluster clock, which generates a stable, drift-free time signal by calculating the weighted average of clocks located at physically separated sites.

Today, much of our social infrastructure, including mobile communications, depends on GNSS-provided timing. If GNSS were to be disrupted, for example, due to natural disasters or conflict, our infrastructure would face severe disruption. By combining these three technologies, however, it becomes possible to deliver accurate timing even without GNSS, thereby safeguarding critical infrastructure.

MASU Adding time information to spatial information (location) greatly enhances the value of that information. By sharing both space and time, data shifts from being about objects to being about events, creating synchronous networks with much higher added value.

Looking further ahead, in the era of ultra-fast communications such as B5G and 6G, latency will effectively disappear, all information will become real-time, and signal propagation delays will no longer matter. The more precise the timing, the greater the real-time performance, and consequently, the higher the value of the information.

One area of research I am particularly interested in is time synchronization across interconnected computer networks. As illustrated in Figure 2, AI applications, such as those used to realize cyber-physical systems (CPS), rely on massive computing resources behind the scenes. In the past, when processors were slower, it was sufficient to synchronize clocks within a single chip. But today, even within a chip, signal delays can no longer be ignored. Moreover, synchronization is also vital when integrating quantum computers with conventional computers. As the use of quantum computers expands, space-time synchronization among devices separated in both space and time will become an essential technology.

Standardization of Space-Time Synchronization

—— It is clear that space-time synchronization will be a crucial technology in the future networked society. To ensure it can be used reliably and securely anywhere in the world, standardization will also be essential, would it not?

IDO Exactly. Space-time synchronization is essentially about sharing reference axes. But if the methods differ, sharing becomes impossible, so standardization is indispensable. We are actively engaged in international mobile communication standardization through the Third Generation Partnership Project (3GPP). In particular, we are working to standardize the “Three Pillars” I mentioned earlier. These three technologies are also included in the International Telecommunication Union Radiocommunication Sector (ITU-R) Report IMT-2030 Future Technology Trends, which identifies technologies expected to be used in 6G.

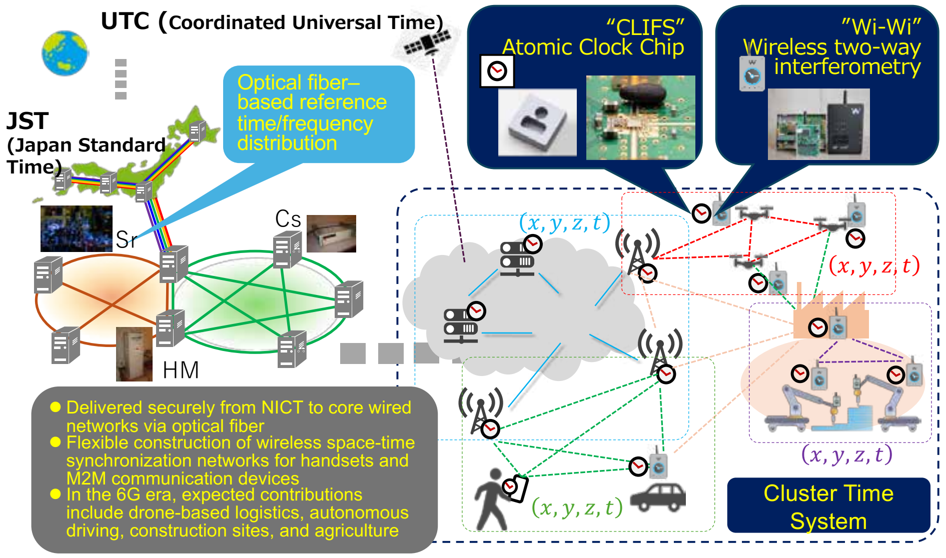


Figure 1 Future network enabled by space-time synchronization technology
With the “Three Pillars” — CLIFS, Wi-Wi, and Cluster Clock — network participants can share common temporal and spatial coordinates, enabling diverse forms of automation. By adding timestamps and location data to information, its value and range of applications expand significantly.

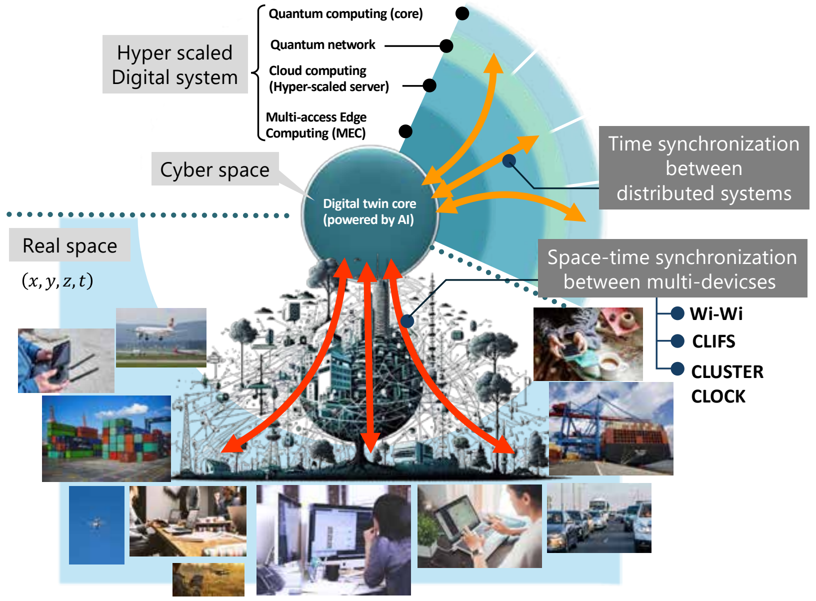


Figure 2 Digital twin (cyber space) as a mapping of the physical world and digital systems:
Bringing together all types of information in a coherent and unified way requires a robust space-time information network.

At present, 3GPP is also discussing possible 6G use cases. For example, a smartphone application that detects a pedestrian’s walking speed and location, such as an elderly person at a crosswalk, and warns them if it looks unsafe to cross in time; monitoring the gradual deformation of infrastructure such as bridges over long periods; and automated construction using robots.

MASU More generally speaking, standardization is always important, especially in communications, where it is absolutely necessary. This is because the radio spectrum used in communications is a limited resource shared by all humanity. Unless we agree on how to use it, no one can use it effectively. Standardization may seem like a low-profile activity, but it is indispensable for industrial development and for ensuring that people everywhere in the world can conveniently make use of these technologies.

Future Prospects of Space-Time Synchronization Technology

—— Space-time synchronization technology seems certain to continue advancing. Could you share your outlook for the future?

MASU In the past, even when fascinating physical phenomena were discovered, it was difficult to quickly gather the related research and technical information needed to turn them into practical applications. Today, however, the internet allows us to collect as much information as we need. We can also test promising approaches right away, which means that the pace of progress in basic science has been accelerating dramatically.

A concrete example is quantum mechanics, a fundamental science that is now directly linked to a tangible product, the quantum computer. That is the era we live in.

IDO In B5G and 6G, communication will extend beyond human-to-human and human-to-machine, to include machine-to-machine interactions. Until now, it has been difficult to let machines make independent decisions because the available temporal and spatial position data were not reliable enough. But with space-time synchronization providing trustworthy information, machines will be able to make accurate judgments, enabling more advanced and efficient automation. I believe this can help address major social challenges such as labor shortages due to declining birthrates and the need for optimal allocation of resources.

MASU In the past, research and development followed what was called a linear model, in which the government would fund basic research, engineers would then turn it into prototypes, and manufacturers would eventually commercialize it. Today, however, basic science and business development proceed almost in parallel.

I call this the Agile Dynamic Society. As you know, “agile” refers to development methods that can quickly adapt to changes in technology and social needs.

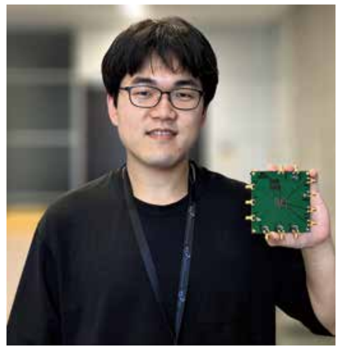
That is the kind of era we are entering. For this reason, national research institutes must also collaborate more closely. Since many of our technological domains overlap, we should push each other to excel, cooperate where possible, and accelerate the pace of research and development. I hope today’s dialogue can serve as a step in that direction.

—— Thank you very much for your time today.

＊For further technical details on space-time synchronization technology, please refer to the June 2022 issue of NICT NEWS.

First Arrow：Atomic Clock Chips

Advancing Technologies toward Atomic Clock Chips: Current Progress and Future Directions



FUKUOKA Masahiro

Researcher,
Space-Time Standards Laboratory,
Electromagnetic Standards Research Center, Radio Research Institute

Dr. FUKUOKA joined NICT in 2024. He has been engaging in research of compact atomic clock. Ph.D. (Engineering)

HARA Motoaki

Senior Researcher,
Space-Time Standards Laboratory,
Electromagnetic Standards Research Center, Radio Research Institute

After receiving Ph.D. in engineering, Dr. HARA Joined Fujitsu Laboratories Ltd. He became an associate professor at the Graduate School of Tohoku University in 2013. Then he joined NICT in 2016. He has been engineering in devise development by applying semiconductor microfabrication. Ph.D. (Engineering).

Have you heard of chip-scale atomic clocks? An atomic clock is a clock based on the transition frequency of an atom, and a device that reduces the size of an atomic clock to the scale of an IC chip is called a chip-scale atomic clock. A device that serves as a clock can be mounted on all sorts of systems, and replacing that with an atomic clock can dramatically improve performance. However, existing chip-scale atomic clocks are still about the size of an eraser, so there is a need for even smaller devices with high-performance, power-saving, and low-cost features. At NICT, we aim to achieve truly IC-size atomic clocks through research and development as part of our Chip-Level-Integrated Frequency Standards (CLIFS) project.

■About Atomic Clocks

An atomic clock is an oscillator that uses a property of atoms that each element has a different transition frequency, so a time interval of one second can be measured by counting up the waves for that frequency. An atom is considered to be immutable, so its transition frequency likewise does not change. In short, an atomic clock, theoretically speaking, is a clock that never loses time. In addition, atomic clocks using the same element can divide up time into completely identical intervals, which means that exact replicas of those clocks can be created.

However, counting atomic waves is not a simple matter, so an atomic clock creates duplicates of atomic waves and counts those waves. Specifically, a laser is used to create duplicates of atomic waves. As shown in Figure 1 (a), this system directs the laser at an atom and observes the brightness of the laser transmitted through the atom. Here, an oscillator is used to create duplicate waves. The system connects the oscillator to the laser and modulates the laser light. If the system sets the frequency of the oscillator near the transition frequency and gradually increases the frequency, the brightness of the laser transmitted through the atom changes as shown in in Figure 1 (b) and becomes brightest at a certain frequency. This brightening phenomenon is called resonance, and the frequency at which resonance occurs is the transition frequency of the atom. An atomic clock is controlled so that the frequency of the oscillator is always at resonance. In this way, the frequency of the oscillator functions as a duplicate of the atom's transition frequency. Consequently, if the waves of the oscillator serving as a duplicate of the transition frequency can be counted, the result is a clock that produces one second based on an atom. At NICT, we are oriented toward lowering costs so that atomic clocks can be used in diverse scenarios, and to this end, we are proceeding with the development of CLIFS by proactively using Micro Electro Mechanical Systems (MEMS) technology that fabricates mechanical structures using semiconductor manufacturing technology. The following introduces the development of individual atomic clock components.

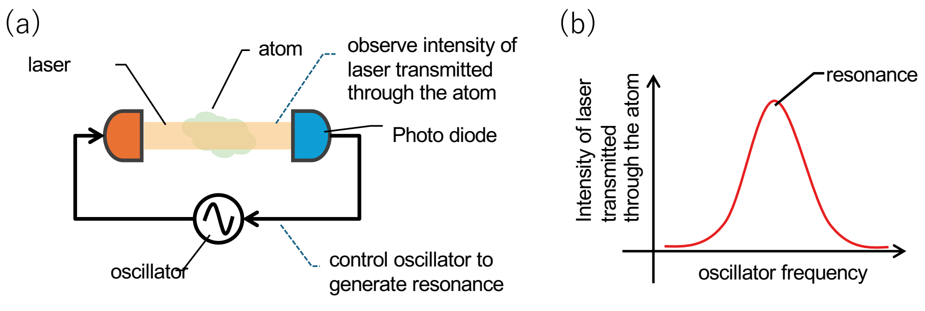


Figure 1 (a) Schematic diagram of atomic clock (b) intensity of laser transmitted through an atom when increasing the oscillator frequency

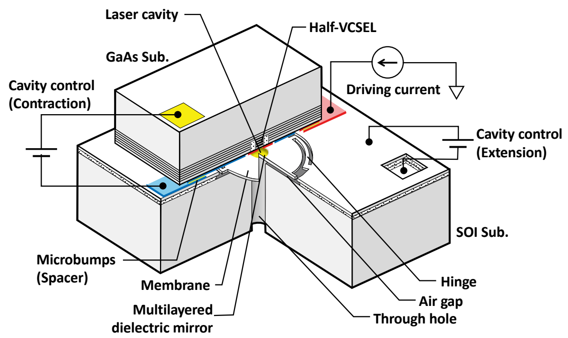


Figure 2 Structure of MEMS tunable semiconductor laser

■MEMS Tunable Semiconductor Laser

We use a Vertical Cavity Surface Emitting Laser (VCSEL, pronounced "vixel") for our chip-scale atomic clock. A VCSEL has a structure in which an emitting active layer is set between semiconductor multilayer films acting as mirrors. This structure is called a cavity within which light is repeatedly reflected, which results in narrow-linewidth laser oscillation. Although a VCSEL forms semiconductor multilayer films on top of the wafer, variation in film thickness within the wafer gives rise to differences in cavity length even for the same wafer and variation in oscillation wavelength as a result. When applying to an atomic clock, variation in oscillation wavelength must be kept within ±1 nm, but this makes it difficult to maintain a good yield rate thereby increasing manufacturing costs. In response to these problems, we placed one side of the multilayer films serving as mirrors on a MEMS movable structure as shown in Figure 2. This scheme makes it possible to vary the cavity length by displacing that MEMS structure and to thereby adjust the wavelength over a wide range. In this way, we could improve the yield rate while reducing the cost of the atomic clock system. At present, we are using a company's prototyping platform and working toward a more sophisticated level of VCSEL manufacturing.

■MEMS Gas Cell

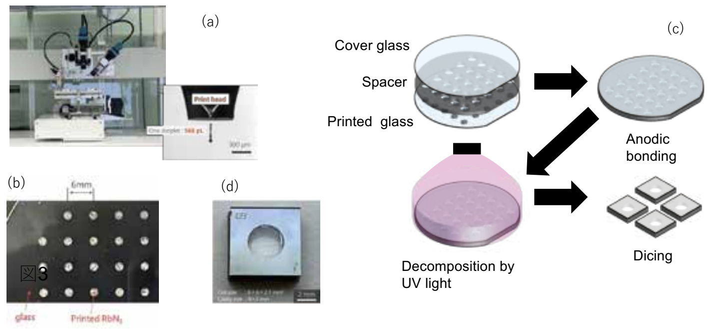


Figure 3 MEMS gas cell and manufacturing procedure: (a) rubidium azide printer, (b) printed glass substrate, (c) manufacturing procedure of MEMS gas cell, and (d) manufactured MEMS gas cell.

In CLIFS, we use a MEMS gas cell enclosing the element rubidium (Rb). Since rubidium immediately reacts in air, it is a material that is difficult to handle. For this reason, we developed rubidium azide jointly with a chemical manufacturer. Rubidium azide is a compound (RbN$_3$) of rubidium (Rb) and an azide consisting of three atoms of nitrogen (–N$_3$). We also developed a method for inkjet printing of rubidium azide onto a glass substrate. Figure 3 (a) and (b) show the inkjet printer and the printed glass substrate, the latter of which can easily be brought into a clean room without creating dust. An inkjet printer, moreover, exhibits very high reproducibility in terms of amount of discharge, etc., so it excels in producing the same thing any number of times.

The MEMS gas cell is manufactured by the procedure shown in Figure 3 (c). First, the glass substrate printed with rubidium azide, a silicon spacer, and a cover glass are overlaid and joined. This achieves a space that confines the rubidium. Next, the above is irradiated with ultraviolet light to decompose rubidium azide into rubidium and nitrogen gas. This nitrogen gas produced by decomposition plays a role in improving resonance characteristics. Finally, the above assembly is diced into individual gas cells. Figure 3 (d) shows a manufactured MEMS gas cell.

■MEMS RF Oscillator and Atomic Clock IC

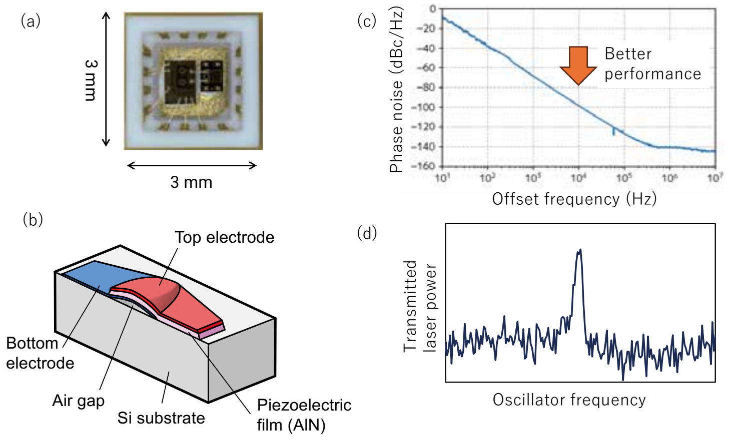


Figure 4 Developed MEMS RF oscillator: (a) MEMS RF oscillator chip, (b) FBAR structure, (c) phase noise of oscillator, and (d) resonance observed by MEMS RF oscillator.

We developed an oscillator using a thin Film Bulk Acoustic Resonator (FBAR, pronounced "eff-bar") as an oscillator for duplicating the transition frequency of an atom (Figure 4 (a)). As shown in Figure 4 (b), FBAR takes on a structure that laminates a piezo electric film on a Si substrate. Since this FBAR is prepared on Si, it can be manufactured simultaneously with an integrated circuit, which is suitable for mass production and lowering costs. The developed oscillator produces a 3.4 GHz wave, and phase noise, which is an indicator of oscillator performance, is of top-class even by international standards (Figure 4 (c)). Rubidium resonance obtained by the developed oscillator is shown in Figure 4 (d). Using this oscillator as an atomic clock requires peripheral functions such as a VCSEL current source, resonance feedback, and temperature stabilization. At present, we are researching and developing an integrated circuit for achieving the circuits needed for CLIFS.

■Future Prospects

CLIFS is a component that lies at the heart of our efforts toward advanced space-time synchronization. By mounting CLIFS on all devices that operate in all sorts of environments and combining it with Wi-Wi for making comparisons and a cluster clock system for distributed time synchronization, we can expect the realization of a new time infrastructure. Going forward, we aim to achieve compact, high-performance, low-power, and low-cost CLIFS that combines the components now under research, and to this end, we will continue with our R&D efforts in collaboration with many parties.

Second Arrow：Wi-Wi

Time Synchronization is the Key for Positioning

How to develop an indoor GPS

SHIGA Nobuyasu

Senior Researcher
Space-Time Standards Laboratory, Electromagnetic Standards Research Center

Dr. SHIGA joined NICT in 2008 after 2 postdoc positions in Alaska and NIST Boulder. He contributed to Strontium optical lattice atomic clock experiment and constructed Ytterbium ion atomic clocks. He then proceeded to develop Wireless two-way Interferometry (Wi-Wi) technology and have been working on the research and development of "Space-Time synchronization."

YASUDA Satoshi

Senior Research Engineer
Beyond 5G Design Initiative, Beyond 5G Research and Development Promotion Unit

Dr. YASUDA has a background in both academia and the tech industry. After completing his doctoral studies in science, he conducted research at Shizuoka University and later worked as a systems engineer in the private sector. Since 2014, he has been deeply involved in developing wireless time synchronization technologies (Wi-Wi) and exploring their applications in spatiotemporal synchronization.

Global Positioning System (GPS) is a convenient way to determine the location of smartphones and other devices, but it cannot be used indoors, underground, or between tall buildings.

At NICT, we are developing technologies that synchronize the clocks of devices via the wireless communication systems we use every day, enabling accurate indoor positioning. We call this combined ability to align both time and position as space-time synchronization technology. In this article, we explain why precise clocks are at the heart of GPS and outline how that principle leads to indoor GPS technologies, giving you a clearer picture of their potential.

Background

GPS technology enables us to navigate to destinations without error and to find the photographs on a smartphone, by searching with location tags (e.g., "Kyoto"). But what is the underlying principle of GPS? By examining its mechanism, we gain insights that point toward new technological developments. We begin with a review of its fundamentals.

The Core of GPS: High-precision Atomic Clocks in Satellites

GPS satellites orbit the Earth at an altitude of approximately 20,000 kilometers, completing two revolutions per day (Figure 1).

Each satellite carries an onboard atomic clock, which provides a highly accurate time reference. These clocks are further synchronized several times daily with terrestrial time standards, allowing them to maintain accuracy in the order of tens of nanoseconds (where 1 nanosecond = 10^{-9} seconds). Why is such precision essential? To answer this, it is necessary to consider how GPS measures position.

How Position is Measured

Suppose we wish to determine the position of a smartphone placed on a table, and our only measuring instrument is a single tape measure. One intuitive approach might be to define orthogonal axes (vertical and horizontal) and measure the phone's X and Y coordinates, as illustrated in Figure 2(a). However, this method requires constructing parallel lines along both axes, which is difficult with a single measuring instrument. An alternative method is more efficient: by designating the four corners of the table as reference points and measuring the distances from each corner to the smartphone, the position can be determined, as shown in Figure 2(b). This method requires only one measuring tool. If we then scale the "table" to the size of the Earth, replace the four corners with satellites, and extend the geometry to three dimensions, we arrive at the operating principle of GPS. The critical question then becomes: by what means does GPS determine these distances?

Measuring Distance with Radio Waves

GPS measures the distance from a satellite to a device by using radio waves. How is this done? The principle comes from a formula that many people first learned in elementary school:

$$\text{distance} = \text{speed} \times \text{time}$$

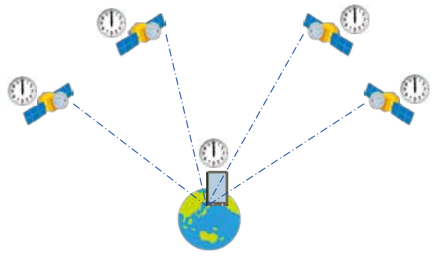


Figure 1 GPS satellites equipped with highly accurate clocks

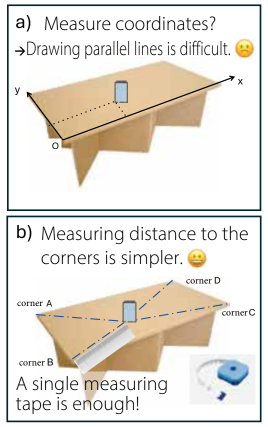
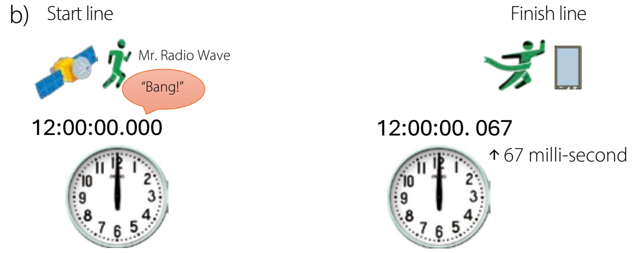


Figure 2 How to measure position

a) Measuring how long it takes an athlete to run: since humans run far slower than light, it's enough to place a single clock at the finish line.



b) Measuring how long it takes a radio wave to travel: since it arrives at the finish at the same instant it leaves the start (speed of light), one clock at the finish cannot capture the travel time. You need synchronized clocks at both the start and finish.

Figure 3 How to measure "time"

Time error	1s 1 second	1/1,000s 1 milli-second	1/1,000,000s 1 micro-second	$1/10^9$s 1 nano-second	$1/10^{12}$s 1 pico-second
Corresponding distance error	7.5 times around the Earth 300,000 km	Tokyo-Nagoya 300km	Eiffel Tower 300m	Scale 30cm	Plankton 0.3mm

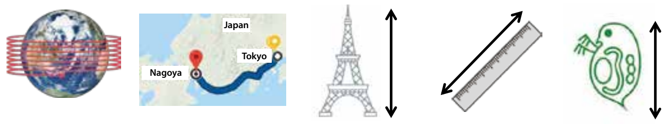


Figure 4 Distance errors caused by time discrepancies in radio signals. Even a 1-nanosecond timing error can result in a 30 cm positional error, so achieving centimeter-level accuracy requires precision on the order of picoseconds.

Many readers will already be familiar with this equation, but let us explain carefully how it applies here. First, we need to know the "speed." Since GPS uses radio waves to measure distance, what matters is the speed of radio waves. This is about 300,000 km per second—fast enough to circle the Earth seven and a half times in one second. Some may wonder, "Isn't that just the speed of light?" In fact, visible light, the 1 GHz radio waves used in GPS, and the signals used in mobile phones or Wi-Fi are all forms of electromagnetic waves. They differ only in frequency, but all travel at the same speed.

Once we know the speed, the next step is to measure the "time" it takes for the signal to travel from the satellite. At first, it might seem like this could be done with a stopwatch: start when the signal leaves, stop when it arrives, like in track and field (Figure 3a). But since radio waves move at the speed of light, the signal arrives essentially at the same instant it is sent, making this method impossible. This is where synchronized clocks become essential.

Suppose a GPS satellite sends a signal at exactly 12:00:00.000. If the device receives it at 12:00:00.067 (67 milliseconds after 12 o'clock), then we know the travel time was 67 milliseconds. From this, the distance can be calculated as:

speed (300,000 km/s) × time (0.067 s) = distance (20,000 km)

(Figure 3b). In this way, GPS uses precise timing to turn time measurements into distance measurements.

Errors in Position Measurement

Now we are ready to consider the question: "Why does GPS require such extremely precise clocks?" Let's take an example. Suppose the clocks at the transmitter (satellite) and receiver (device) are off by just one microsecond (one millionth of a second). How much would that affect the measured distance? The error in distance caused by the clock mismatch can be calculated as:

speed (300,000 km/s) × time error (1 μs) = distance error (300 m).

This means that a seemingly tiny timing error of one microsecond would result in a positional error of as much as 300 meters. In other words, the distance a radio wave travels during the clock's timing error directly translates into the position measurement error. Figure 4 illustrates how clock errors translate into distance errors. From this figure, we can see that a one-nanosecond (one billionth of a second) clock error corresponds to a positional error of about 30 centimeters. As mentioned earlier, the actual clocks on GPS satellites are accurate to within roughly 10 nanoseconds, which keeps the resulting positional error to about 3 meters.

Future Prospects –Toward indoor positioning–

While GPS is extremely convenient, it cannot be used indoors or underground. To address this limitation, NICT has been developing technologies that use radio signals emitted by everyday devices to determine their positions. What becomes crucial here is the technology for synchronizing time and space wirelessly; namely, wireless two-way interferometry (Wi-Wi) (for details, see *NICT NEWS* No. 4, 2022). We have demonstrated that Wi-Wi technology can be implemented on widely used indoor Wi-Fi networks, opening up the possibility of measuring the positions of Wi-Fi devices. In addition, we continue to advance indoor positioning technologies by studying the effects of indoor-specific reflections and creating demos that can monitor positional fluctuations indoors. Beyond this, NICT is also developing other space–time synchronization technologies, such as miniature atomic clocks (CLIFS; see pp. 4–5) and cluster clocks, which combine multiple clocks to generate highly accurate time (see pp. 8–9). These synchronization technologies are attracting attention for their ability to coordinate tens of thousands to millions of servers in data centers with nanosecond-level precision.

Looking ahead, the next decade may bring an era in which space-time synchronization technologies link not only ground-based systems but also satellites, enabling entirely new applications to flourish.

Third Arrow：Cluster Clocks

Synchronizing Time isn't Easy!
A Challenge to Distributed Time Synchronization
Cluster Clocks

YANO Yuichiro

Senior Researcher
Space-Time Standards Laboratory
Electromagnetic Standards Research Center
Radio Research Institute

After completing a doctoral program at graduate school, joined NICT in 2016 following a research fellowship from the Japan Society for the Promotion of Science (JSPS). Engaged in research on compact atomic clocks and their applications. Ph.D. (Engineering).

In today's society, many machines, computers, and other devices operate in a connected manner, so "time synchronization" is extremely important. If clock settings are disorganized, communications and computations and collaborative work too cannot function well. So how can we get the time together for everyone?

In fact, there are surprising innovations and deep mechanisms as well as issues to be solved. This article introduces an approach to a mechanism for "getting the time together" and interesting developments in recent research in a way that even people who are not actively involved in this field can understand.

Getting the time together!? What is distributed time synchronization?

1. What does the word "distributed"—a popular topic today—mean?

Have you heard of the word "distributed"? It may sound a little difficult, but it is a concept that is now drawing attention around the world. The Internet is one example. In the past, one large computer would essentially manage everything, but today, many machines around the world can connect to each other and run in a cooperative manner. "Blockchain" technology is also a distributed mechanism that grows while the information in the blockchain is mutually verified by everyone. In short, "distributed" means that everyone supports each other rather than relying on a single authority. This is a concept that will become increasingly important in society from here on.

2. What happens when clocks deviate from each other?

"Getting the time together" is extremely important in a distributed society. For example, the clock on your smartphone might read "exactly 8:00", but the clock on your microwave oven might display "8:02". This might be a little concerning. If you are a student and your alarm clock is a little slow, you may be late for school. In our daily lives, "time" is involved in all sorts of things, such as train timetables, the broadcast times of television programs, the start times of examinations, and play timing in gaming. It is because such things run according to the correct time that things proceed smoothly. The technology for "getting the time together" in this way is called "time synchronization".

3. What is distributed time synchronization?

The usual way of setting clocks is to "decide on a reference clock and align with that time." However, what would happen if that "reference clock" broke down or was unobservable? As shown in Figure 1, distributed time synchronization means that the peaple involved check each other's time and correct any deviations little by little instead of relying on a specific leader. For example, we can imagine a scenario like "My time is 7:59," "My time is 8:00," and "My time is 8:04" followed by "Alright, 8:01 seems about right on average, so let's set our clocks to that time." In this way, all parties mutually adjust their clocks in a cooperative manner to get them aligned—this is the idea of distributed time synchronization.

4. Advantages of distributed time synchronization

Distributed time synchronization has several key advantages.

(1) No leader is needed!

Even without a central clock, everyone can synchronize the time, so not having to rely on a single source is a major strength. The entire team can continue to operate even if someone's clock stops.

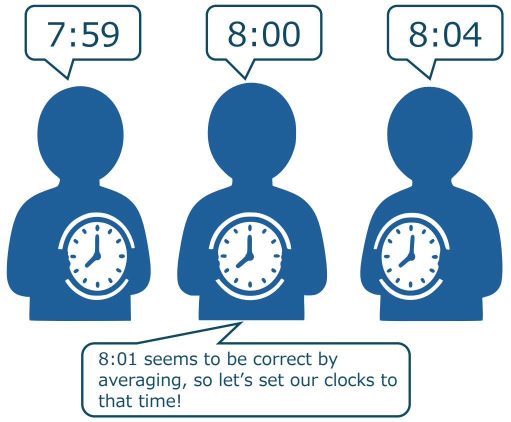


Figure 1 Concept of distributed time synchronization: In actuality, the person on the right does not rewind that clock but adjusts the clock rate to align the time.

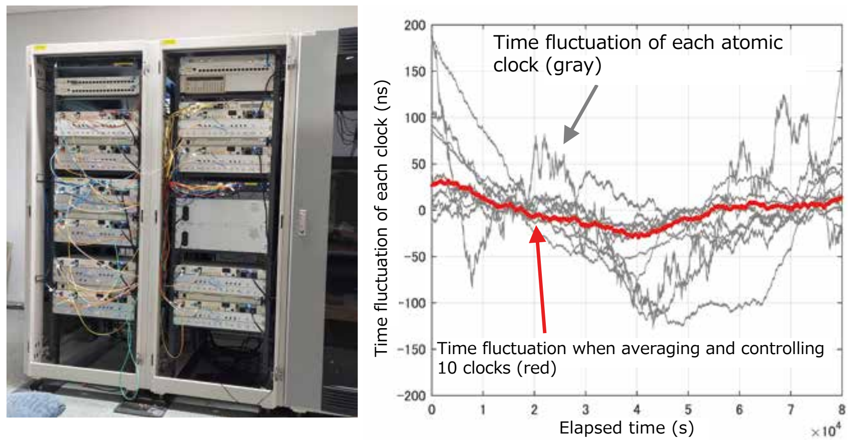


Figure 2 (Left) Experimental setup for distributed time synchronization: Connects 10 atomic clocks by optical fiber and incorporates a control mechanism that measures the time differences between each clock in real time and makes corrections.
(Right) Experiment results by experimental setup (left): Each clock fluctuates greatly, but taking an average greatly reduces noise and obtains a smooth time signal. Each unit can reproduce this smooth time signal from difference information between its own atomic clock and the composite time series.

(2) Robust to problems!

Even if some machines break down or can no longer communicate, remaining machines can support each other by using surrounding information, so there is less worry about everything coming to a halt. This is very important in creating a "resilient society."

(3) Collaboration improves the accuracy of everyone's clocks!

In distributed time synchronization, everyone will talk to each other to gradually correct any clock deviations. If many persons should have a very accurate clock, what does that mean for overall accuracy? In actuality, bringing together such high-accuracy clocks and having them consult with each other can skillfully average out deviations and produce even more accurate time. This is exactly similar to averaging out everyone's test scores to get a more stable result overall.

But it's not that easy!

Distributed time synchronization looks to become an important mechanism in society of the future, but no one has yet brought it to completion. Today, research continues, but many difficult issues remain.

(1) Clock deviation characteristics

Each clock has its own deviation characteristics. For example, there are clocks that always run a little faster, clocks that run slower little by little, clocks that change depending on the day, etc. If such characteristics are not well understood, mutual deviations cannot be properly adjusted.

(2) Averaging is actually difficult

Overall unification varies greatly according to which time is used as a reference and how weights are added in averaging. What's more, no one can verify whether "that averaged timed is truly correct". This "unobservable property" is also a problem that's not limited to this field—in control theory too, how to handle such an unobservable property is a deeply interesting theme.

(3) Minimize deviations with others without losing cohesion

When aligning clocks, it is necessary to approach an average time overall while time differences with surrounding clocks are made as small as possible. Yet, if aligning is performed only with neighboring clocks, the whole may end up uneven. The real challenge in distributed time synchronization is how to achieve a balance between "reducing deviation while cooperating with neighbors" and "maintaining cohesion among everyone."

Future Prospects

We are currently taking up the challenge of solving this unexplored technical issue of distributed time synchronization by joining forces with researchers from universities and companies. In this field, there are still many things that have not been sufficiently clarified, so we are earnestly tackling them in advanced studies while combining knowledge from control engineering, communication engineering, measurement technology, and other fields. For example, we have so far designed a new index for evaluating clock characteristics—the way that time fluctuates in each clock—and established technology for quantifying clock reliability. In addition, we have designed and implemented an entirely new control mechanism on our own to approach an average without the overall timing collapsing while keeping deviation with neighboring clocks as small as possible. Furthermore, provided that clock characteristics are understood beforehand, we have developed an algorithm to recalculate the theoretically most stable time from overall network operation. We are verifying the effectiveness of this algorithm through tests using an experimental setup (Figure 2). We plan to move toward real-world implementation of "creating time together" technology through field tests under more complex and realistic environments and comparison tests with other algorithms.

Time Synchronization via Optical Fibers

Aiming for a nationwide rollout

FUJIEDA Miho
Researcher
Space-Time Standards Laboratory
Electromagnetic Standards Research Center
Radio Research Institute

After completing graduate school, Dr. FUJIEDA received a Research Fellowship for Young Scientists of Japan Society for the Promotion of Science and worked at the Communications Research Laboratory (now NICT) and National Astronomical Observatory of Japan before taking up her current position in 2024. She is engaged in accuracy measurement, two-way satellite time and frequency transfer, optical-fiber reference signal transmission, and other studies. Ph.D. (Science).

Time synchronization between remote sites is one technology supporting teleworking, online conferencing, remote robot control, and other commonplace services. In addition to making time and timing the same, matching up content and information can also be called "synchronization." As for the latter, taking constantly changing information as an example, time is an important index of what point in time such information matches up. The key here is the sharing of time between various settings = time synchronization.

■Background

At present, GPS satellites familiar from car navigation systems are widely used for time synchronization between remote sites. However, major errors can sometimes occur in GPS communications due to ionospheric storms as reported in Space Weather Forecast, or reception of signals from satellites can be disrupted by jamming radio signals.

■Time Synchronization Independent of GPS Satellites

In response to those problems, we are researching and developing methods for distributing time synchronization via optical fiber independent of GPS satellites on a project basis. One is the Otemachi Project that aims to achieve high reliability using commercially available products, and another is the High Accuracy Project that pursues time synchronization accuracy using a system researched and developed by NICT.

【Otemachi Project】

This project aims to continuously distribute Japan Standard Time from NICT headquarters to the Otemachi district in central Tokyo, a key connection point to regional areas, with a time synchronization accuracy within a nanosecond (10^{-9} s) using optical fiber over a distance of approximately 45 km. Japan Standard Time is then distributed to surrounding buildings in Otemachi with the aim of achieving synchronization at end users on a level from a nanosecond to a microsecond (10^{-6} s). Preparations are now being made to confirm long-term reliability, establish calibration methods, etc. toward use by data center operators, mobile phone operators, and other enterprises.

【High Accuracy Project】

Quantum key distribution, which is applicable to communications involving highly confidential information and is expected to achieve early social implementation, requires very high time synchronization accuracy on a level of tens of picoseconds (10^{-11} s) between two parties receiving a key. To this end, we are developing a system for improving measurement accuracy and reproducibility (Figure 1). In addition to conducting distribution experiments between Koganei City, Tokyo (NICT headquarters) and Otemachi, we are developing a repeater system to achieve time synchronization over even longer distances. Moreover, we plan to take a flexible approach toward social implementation such as by making equipment more compact and incorporating a frequency synchronization function previously developed as a separate system.

■Future Prospects

In actually deployed optical fiber, noise is greater than that in a quiet laboratory environment by an order of magnitude due to temperature fluctuations, vibrations, and other factors. Its removal holds the key to research and development in this area. It is therefore essential that time synchronization be tested in actual environments. In Europe, the use of optical fiber for scientific research purposes is often free, so distribution experiments in excess of 1,000 km and submarine optical cable experiments too are underway.

In Japan, however, rental fees for optical fiber are currently very high and long-haul-distribution experiments are difficult. Consequently, in parallel with R&D activities, we are focusing on value pursuit in relation to Japan Standard Time distribution together with promotional activities (Figure 2).

Going forward, we aim to broaden the use of time synchronization via optical fiber such as in microseismic detection while aiming for long-haul distribution.

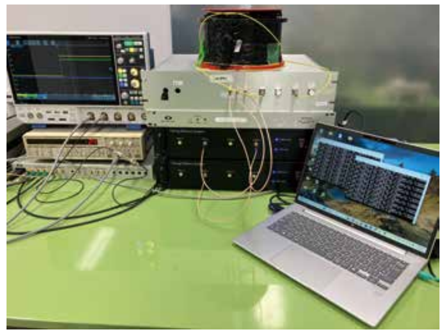
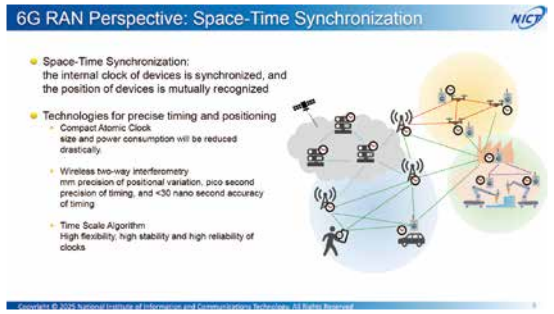


Figure 1 Tens-of-picoseconds time synchronization distribution test setup

Figure 2 Engineer Eiji Nomura and Senior Researcher Yuichiro Yano during promotion activities at JANOG (JApan Network Operators' Group)

On International Standardization Activities of Space-Time Synchronization



6G RAN Perspective: Space-Time Synchronization

- Space-Time Synchronization:
  the internal clock of devices is synchronized, and the position of devices is mutually recognized
- Technologies for precise timing and positioning
  - Compact Atomic Clock
    size and power consumption will be reduced drastically
  - Wireless two-way interferometry
    mm precision of positional variation, pico second precision of timing, and <30 nano second accuracy of timing
  - Time Scale Algorithm
    High flexibility, high stability and high reliability of clocks

Figure 3 Presentation in the 6G workshop regarding three arrows of space-time synchronization

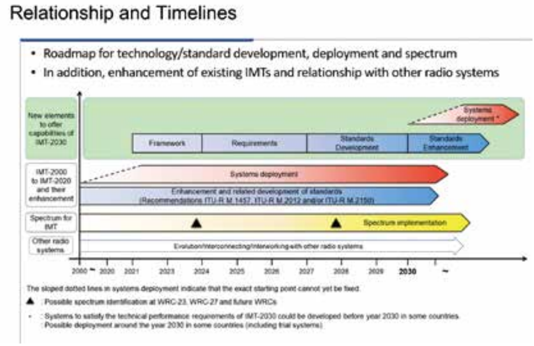
MAZAWA Shiro
Research Engineer
Space-Time Standards Laboratory, Electromagnetic Standards Research Center, Radio Research Institute

After completed his master's degree, he joined a manufacturing company, where worked for development of mobile telecommunication system and international standardization of 3GPP and 3GPP2. He joined NICT in 2024 and has been working for international standardization of 3GPP and IEEE.

To enable communication equipment to connect "anytime", "with anyone", and "anywhere", the same communication system must be used worldwide, and to achieve such a system, standardization organizations of countries and regions around the world come together to formulate international standards. At NICT, we are participating in standardization organizations such as ITU, 3GPP, and IEEE to implement our research achievements in society, and we are taking part in various types of communications-related standardization activities. This article introduces international standardization activities of space-time synchronization technology for the sixth-generation mobile communication system.

■What is the Sixth-generation Mobile Communication System?

As of 2025, the fifth-generation mobile communication system (so called 5G) is in widespread use. In international standardization activities, the development of the sixth-generation mobile communication system as the next-generation system has begun.



Relationship and Timelines

- Roadmap for technology/standard development, deployment and spectrum
- In addition, enhancement of existing IMTs and relationship with other radio systems

The sloped dotted lines in systems deployment indicate that the exact starting point cannot yet be fixed.
▲ : Possible spectrum identification at WRC-23, WRC-27 and future WRCs
* : Systems to satisfy the technical performance requirements of IMT-2030 could be developed before year 2030 in some countries. : Possible deployment around the year 2030 in some countries (including trial systems)

Figure 1 IMT-2030 schedule

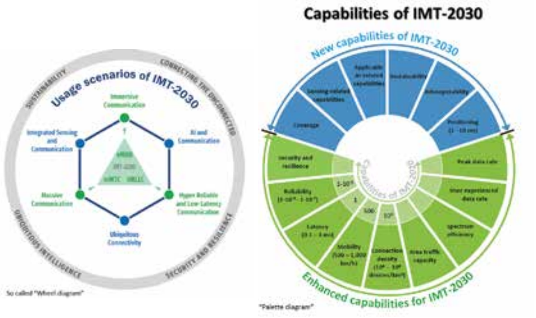


Figure 2 Vision of IMT-2030

Figure 1 shows the IMT-2030 standardization schedule at ITU-R. Here, ITU-R is an organization responsible for radio communications under the International Telecommunication Union (ITU), a specialized agency of the United Nations, and IMT-2030 (International Mobile Telecommunications-2030) is the name given to the sixth-generation mobile communication system at ITU-R. As the name implies, development is progressing with a view to implementation around 2030. Figure 2 illustrates the vision of IMT-2030. In addition to improving communications performance, such as by increasing transmission speeds and shortening delay times, IMT-2030 features expansion to new applications such as AI and sensing.

■International Standardization at 3GPP

International standardization activities of the sixth-generation mobile communication system are underway at the 3rd Generation Partnership Project (3GPP). This project was initially founded during the international standardization of the third-generation mobile communication system, which explains its name. At 3GPP, the sixth-generation mobile communication system is called 6G, and 6G standardization is progressing in accordance with the requirements of IMT-2030 described above. Standardization at 3GPP is divided into three stages, and as of 2025, discussions of use cases and requirements in Stage 1 and discussions of architecture in Stage 2 are being held in parallel. Use cases present 6G usage scenarios and propose functions for achieving them. In March 2025, a 6G workshop was held in Incheon, South Korea where about 240 proposals were received and discussions held.

■International Standardization of Space-time Synchronization Technology

At NICT's Space-Time Standards Laboratory, the three technologies of CLIFS (Chip Level Integrated Frequency Standard), Wi-Wi (wireless two-way interferometry), and cluster clocks are called "the three arrows of space-time synchronization," and international standardization in relation to these technologies is underway. At the 6G workshop mentioned above, these technologies were proposed as shown in Figure 3. In Stage 1 discussions, automatic construction, critical infrastructure monitoring, and pedestrian crossing support were proposed as three use cases applying Wi-Wi's high-accuracy time synchronization and position measurement. All were approved for reflection in international standards. Going forward, we aim to reflect these technologies in Stage 2 and Stage 3 based on these use cases.

■Toward Social Implementation

The sixth-generation mobile communication system is an important technology destined to become a social infrastructure of the 2030s. At NICT, we are committed to participating actively in the formulation of its specifications and to contributing to its social implementation.

Forums and Tech Meetups on Space-Time Synchronization Technology

HARA Motoaki

Senior Researcher
Space-Time Standards Laboratory, Electromagnetic Standards Research Center, Radio Research Institute

After receiving Ph.D. in engineering, Dr. HARA Joined Fujitsu Laboratories Ltd. He became an associate professor at the Graduate School of Tohoku University in 2013. Then he joined NICT in 2016. He has been engineering in devise development by applying semiconductor microfabrication. Ph.D. (Engineering).

At the Space-Time Standards Laboratory, we have been developing technologies that compactly implement the time synchronization and positioning techniques that we have refined over many years into consumer communication devices. Since 2022, in particular, we have been conducting research commissioned by the Ministry of Internal Affairs and Communications (MIC), focusing on two key areas: miniaturization of atomic clocks (CLIFS: Chip-Level Integrated Frequency Standard) and distributed timekeeping systems (cluster clocks). To efficiently bring the outcomes of these activities into practical use in society, three points are especially important:

(1) Timely transfer of manufacturing technologies to private companies, along with ongoing support for productization.
(2) Identifying areas where further research is needed, and sustaining technological advancement through collaboration with universities and other institutions
(3) Strengthening intellectual property and standardization efforts in parallel with research and development, as a foundation for social implementation.

Since these objectives require multiple players to connect organically across organizational boundaries in alignment with each technological phase, it is essential to foster open and constructive discussion forums. While point (3) will be addressed in a separate article within this issue, here we will focus on activities particularly related to points (1) and (2).

About the Space-Time Synchronization Symposium

Alongside the commissioned research project by MIC on "Research and Development of a High-Precision Time Synchronization Infrastructure for Effective Utilization of Frequency Resources" (launched in FY2022), we initiated the Space-Time Synchronization Symposium as a forum for sharing progress and engaging in forward-looking discussions. The first symposium was held on May 23, 2023. This fiscal year, the 5th and 6th symposia are scheduled for October 3 and March 24, respectively (those interested are encouraged to contact the author). Table 1 shows the history and participant trends. As seen in the table, participation from both industry and academia has steadily increased, demonstrating that the symposium meets the demand for forums to discuss items (1) and (2) mentioned earlier. Furthermore, starting this year, we plan to strengthen collaboration with external organizations, such as the XG Mobile Promotion Forum (XGMF) and academic societies (as described in the next section), thereby offering an even broader range of opportunities for diverse discussion.

Establishing Other Forums for Technology Exchange

Aiming for further expansion of 5G and growth toward 6G, the XG Mobile Promotion Forum (commonly called XGMF) was established and currently includes approximately 120 corporate and organizational members, along with 76 individual members. Under XGMF, 22 subgroups called projects have been created to foster the development of new industries related to wireless communications. The Space-Time Synchronization Project, proposed by our team, is one of these initiatives (1). This project currently involves 24 participants, mainly from industry (9 companies), along with 2 public research institutions and 2 universities. They engage in regular discussions aimed at realizing infrastructure and applications based on space-time synchronization technologies. A "Special Investigation Committee on Device Technologies and Their Applications for Building Smart Networks of Mobility Devices Using Space-Time Information" was established under the IIEJ Sensors and Micromachines Society (Code E) Technical Committee on Micromachine Sensor Systems on July 1, 2024 (2). Currently, 20 participants, primarily from universities (11 institutions), along with 6 companies and 3 public research institutions, are involved, and the committee holds roughly four research meetings per year.

Table 1 Development of the Space-Time Synchronization Symposium

No.	Date	Venue		Number of attendees			Note
				Academia	Industry	Total	
1st	May 23, 2023	NICT Innovation Center	Collaboration Space	43	47	90	*
2nd	Oct. 11, 2023	NICT HQ (Koganei)	Seminar Room, Building 3	14	56	75	
3rd	Aug. 2, 2024	NICT HQ (Koganei)	Seminar Room, Building 3	33	65	98	
4th	Nov. 1, 2024	NICT HQ (Koganei)	Seminar Room, Building 3	50	58	108	
5th	Oct. 3, 2025 (planned)	NICT Innovation Center	Training & Collaboration Room A (TCR A), Collaboration Space	-			**
6th	Mar. 24, 2026 (planned)	NICT Innovation Center	Training & Collaboration Room A (TCR A), Collaboration Space	-			

* First Symposium, invited talk by Dr. Ahmad Byagowi (Meta Platforms Inc., at that time)
** To be held jointly with XGMF and the IEEJ Special Investigation Committee

References

(1) XGMF Space-Time Synchronization Project: [https://xgmf.jp/project/pj-2422/] (in Japanese)
Membership information and regulations: [https://xgmf.jp/join-xgmf/] (in Japanese)
(2) IEEJ (Institute of Electrical Engineers of Japan) Special Investigation Committee: [https://www.iee.jp/smas/mss/emss1043/] (in Japanese)
Membership: Please contact the committee chair or secretariat.

Supporting Stable Operation of Japan Standard Time with Technology

MORIKAWA Masaki

Research Engineer
Japan Standard Time Group, Space-Time Standards Laboratory, Electromagnetic Standards Research Center, Radio Research Institute

Biography

1994	Born in Tokyo, Japan
2015	Graduated from Numazu National College of Technology, Electrical & Electronics Engineering
2017	Graduated from Chiba University, Faculty of Engineering
2019	Completed Master's Course at Chiba University, Graduate School
2021	Completed doctoral program units without degree at Waseda University, Graduate School
2021	Joined NICT and took up current position

AWARDS

2018	Excellent Paper Award, Industrial Applications Society, IEEJ

Q&As

Q What is the biggest failure in your life so far?

A The first time I wrote a preprint for a research society, I made a mistake in entering the name of an author in a reference paper. This individual was known to be an expert in his research field at the time, so I couldn't stop sweating when I noticed my error.

Q What are you interested in other than research?

A Well, I love reading science books. In "Project Hail Mary" by Andy Weier, a science fiction novel that I recently read, there is a scene in which research engineers in a cross-cultural environment are desperately trying to coordinate their units of measurement. This reminded me of my timekeeping work, and it gave me a sense of determination.

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

A At NICT, the role of a "research engineer" is to collaborate with researchers to realize a project. Being able to directly use one's technical abilities for the benefit of society is truly exciting work.

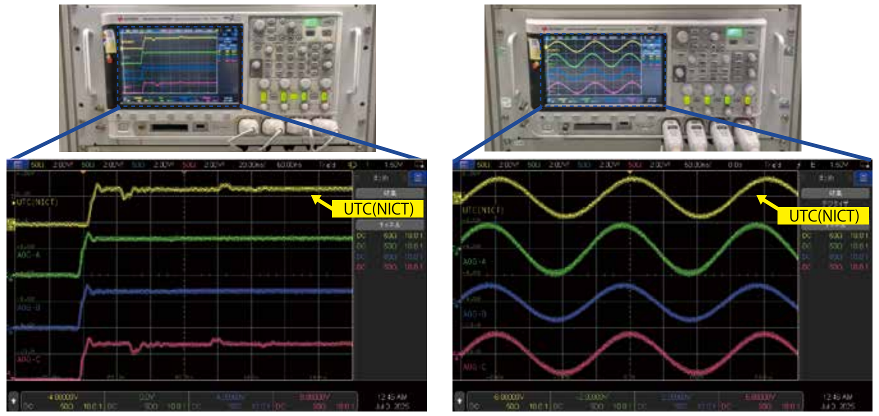
NICT plays an important role in society in generating, maintaining, and supplying Japan Standard Time. In the Japan Standard Time Group, personnel having diverse areas of expertise collaborate to carry out this mission.

Within this effort, I am mainly responsible for providing technical support and improving the infrastructure for maintaining Japan Standard Time. Specifically, this means managing a wide range of facilities, including equipment for continuously measuring and monitoring the time signals of atomic clocks, equipment for comparing those measurement results with domestic and overseas institutions via satellite, complex wiring for connecting that equipment, servers for overall control, and power supply equipment for supplying stable power in case of a power outage.

The mission of this work is to provide accurate time information at all times to support a society in which everyone can lead a life without worry. This is a huge responsibility, but supporting a foundation of society through down-to-earth engineering work can be very fulfilling.

The work of providing standard time includes many innovative technologies and much knowledge seldom seen in other fields, and inheriting all that is extremely important. In particular, I believe that knowledge cultivated over many years is an important and hidden element that supports stable operations. Fortunately, at NICT, there are collaborative relationships with domestic and overseas institutions that my senior colleagues have built up over the years. A culture of exchanging knowledge and collaborating with each other has taken root reflected by technical workshops held by International Bureau of Weights and Measures (BIPM), a standards organization that maintains the metric system, Asia Pacific Metrology Programme (APMP), and other organizations.

Taking advantage of this fortunate environment, I work hard every day to acquire skills and knowledge through exchanges with both Japanese and overseas experts, pass on what I have learned to the next-generation, and support stable operation.



Time-standard signal output once per second

Frequency-standard signal oscillating at 5 MHz

Figure Oscilloscope equipment measuring Japan Standard Time; the yellow lines indicate Japan Standard Time (UTC (NICT)) signals.

The SANKEI Shimbun Award at the 38th "The Advanced Technology Award"

KAJI Takahiro
Research Manager,
Nano-scale Functional Assembly ICT Laboratory,
Kobe Frontier Research Center, Advanced ICT Research Institute

YAMADA Toshiki
Research Manager,
Nano-scale Functional Assembly ICT Laboratory,
Kobe Frontier Research Center, Advanced ICT Research Institute

OTOMO Akira
Senior Expert, Advanced ICT Research Institute /
Director of Nano-scale Functional Assembly ICT Laboratory,
Kobe Frontier Research Center, Advanced ICT Research Institute

From left, Dr. YAMADA, Dr. KAJI and Dr. OTOMO

● Date: July 14, 2025

● Description: Research and development of antenna-coupled terahertz optical modulators using electro-optic polymers and their processing techniques

● Recipients' Comment: We are deeply honored to receive the 38th Advanced Technology Award – Sankei Shimbun Award. We are very pleased that our work, from the development of process technology using electro-optic polymers to the successful demonstration of terahertz optical modulation devices, has been highly recognized. We would like to express our heartfelt gratitude to all those who have supported this research. Moving forward, we will further strengthen collaborations with industry and academia and continue to advance efforts toward practical implementation of these research outcomes in society.

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