4 Precise Time and Frequency Transfer

4-1 Basic Measurement Techniques on Time and Frequency Transfer

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One of the most significant features of time and frequency standards is that it can be compared at remote sites by using the medium waves such as radio signals. Research and development of the time transfer techniques is one of the main research topics in the time and frequency standard field. The performances required for time transfer are gradually increased according to the improvement of the atomic clocks; especially in improvements of TAI (International Atomic Time), more precise time transfer techniques are required. This paper presents a brief introduction about precise time and frequency transfer techniques.

Keywords
Time transfer, International atomic time, GPS, Two way satellite time and frequency transfer

1 Introduction

Time and frequency standards have a number of features that set them apart from other standards. They offer significantly higher accuracy, for example, and allow for comparison among standards at remote sites using electromagnetic waves. Other types of standards can only be compared in one of two ways: by moving one standard to the site of the other, or by comparing the two standards using a transportable intermediary standard. Such comparison requires significant time and labor, particularly when devices must be moved over long distances, as in the case of international comparison.

With time and frequency standards, on the other hand, time and frequency transfer may be performed via a portable standard, in what is referred to as the "portable clock" method. In addition, a ground navigation radio-wave signal may be used as an intermediary between remote sites, in a method that can be traced back to the Omega and Loran C decades ago. Further, beginning in the 1970s, a highly precise time and frequency transfer method using space technology (satellite technology in particular), was proposed and has since been put to practical use[1], with increasing precision and accuracy. Fig.1 shows the relationship between typical time transfer methods and frequency stabilities described in Reference[2], and shows comparison with a frequency stability of the order of 10^{-15} for an averaging time of approximately one day.

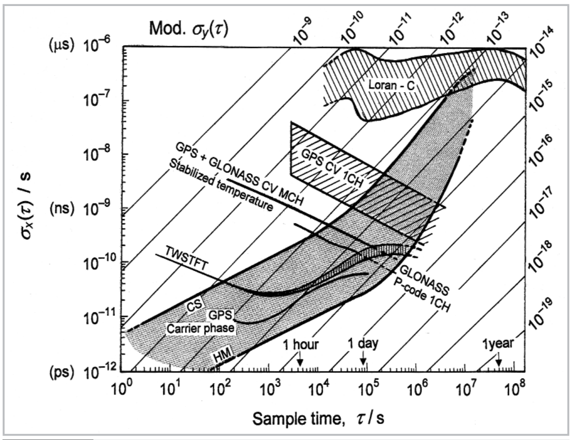

Fig.1 *Relationship between averaging time and stability of typical time transfer methods*[2]

2 History of time/frequency transfer and the need for increased precision

2.1 Need for accurate time/frequency transfer method

As described in other reports in this special issue and in many other papers, time and frequency transfer methods form one of the most important research subjects in time and frequency standards, along with the development of atomic frequency standards and the maintenance and dissemination of time scales.

Since International Atomic Time ("Temps Atomique International," or TAI) and Coordinated Universal Time (UTC) establish reference time scales using atomic clocks from standards organizations around the world, daily time transfer is essential. In determining the TAI and UTC, additional noise resulting from time transfer affects stability and accuracy of TAI and UTC; accordingly, increased precision and accuracy are required in the method of time transfer, along with improvements in the performance of the atomic clocks (frequency standards) themselves.

In addition to TAI and UTC applications, a highly precise method of time and frequency transfer is required in a vast range of fields, from basic science (verifying the effects of the theory of relativity, for example), to engineering, including broadcasting and telecommunications.

2.2 Types of time and frequency transfer methods

Broadly speaking, there are four precise methods of time and frequency transfer for atomic clocks located at remote sites:

(1) Portable clock method
(2) One-way method
(3) Common-view method
(4) Two-way method

In method (1), as described in the previous section, the time difference between reference atomic clocks at two sites is measured by transporting a physical, intermediary atomic clock between the two sites. Methods (2) through (4) consist of systems in which measurement is performed using a medium—radio waves, for example. Conceptual diagrams for the respective methods are shown in Fig.2.

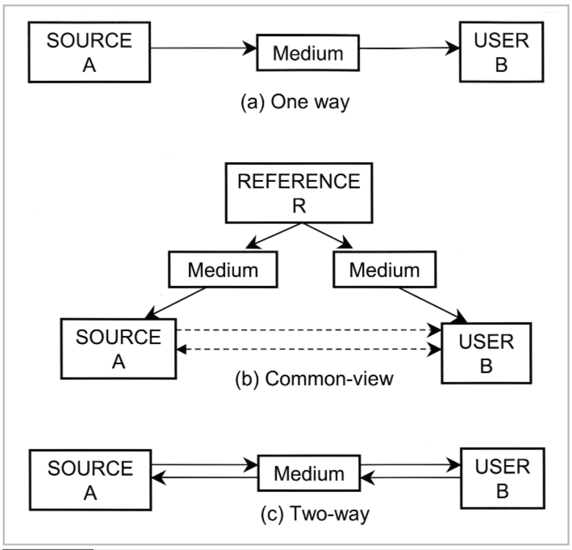

Fig.2 *Conceptual diagrams of remote time transfer*

Method (2) is most applicable to the dissemination of time and frequency—as opposed to comparison among standards—and is characterized by dissemination of standard time and standard frequency using standard radio waves, by independent reception via GPS (Global Positioning System), and similar features.

Method (3) consists of a system of receiving a common signal at multiple sites and performing comparison between clocks located at remote sites using the common signal as an intermediary signal; this approach is typified by the common-view method[3] using GPS satellites, the Loan C[4] method, and the color TV subcarrier method[5], to cite a few.

Method (4) involves a system of performing time transfer through simultaneous transmission of a time/frequency signal between two remote sites (or among multiple remote sites). This method, which includes two-way satellite time and frequency transfer systems (among others) is capable of attaining the highest precision of the available methods.

Table 1 summarizes the typical configurations of each system and typical values of precision in comparison.

Table 1 *Classification of time transfer methods and transfer precision*

Type	Method	Accuracy	Precision	Stability (Averaging over one day)	Coverage area
Portable clock		A few ～ several ten [ns]	< 1 [ns]	10^{-6}～10^{-8}	
One way	HF (High Frequency)	2～200 [ms]	2 [ms]	10^{-6}～10^{-8}	global
	LF (Low Frequency)	0.5～20 [ms]	1 [μs]	10^{-10}～10^{-12}	～2,000 [km]
	GPS	10～40 [ns]	2～7 [ns]	2×10^{-14}	global
Common-view	Loran-C	1 [μs]	100 [ns]	10^{-10}～10^{-12}	～2,000 [km]
	TV color sub-carrier	～10 [ns]	10 [ns]	10^{-13}～10^{-14}	～100 [km]
	GPS C/A code	1～10 [ns]	1～2 [ns]	10^{-13}～10^{-14}	～10,000 [km]
	GPS carrier phase	?	0.1 [ns]	10^{-14}～10^{-15}	global
Two way	TWSTFT	1～5 [ns]	0.1 [ns]	10^{-14}～10^{-15}	global
	LASSO	～ 1 [ns]	0.1 [ns]	10^{-14}～10^{-15}	global

3 Outlines of main time transfer methods and transfer precision

This chapter will provide an outline of typical time transfer systems among the methods introduced in the previous section, as well as a discussion of the time transfer precision of these methods.

3.1 Portable clock method

The portable clock method consists of the following steps: measurement of the time difference between a reference clock at point A at time t_0 and the clock to be transported, transport of the latter to point B, measurement of the time difference between the reference clock at point B and the portable clock at time t_1, and determination of the time difference between the point A reference clock and the point B reference clock based on the difference between the measured values at the two points.

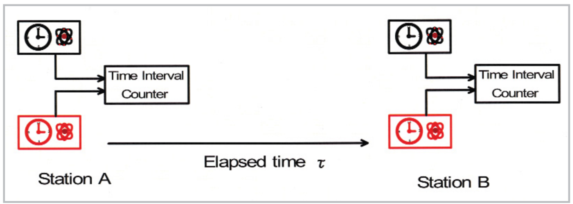

Fig.3 *Portable clock method*

The time differences between the reference clocks at point A or B and the transported clock at time t_0 are expressed by the following formulas.

$$\Delta T_A(t_0)=T_A(t_0)-T_P(t_0) \quad \cdots\cdots(1)$$

$$\Delta T_B(t_1)=T_B(t_1)-T_P(t_1) \quad \cdots\cdots(2)$$

From the difference between formulas (1) and (2), the following formula is obtained.

$$T_A(t_0)-T_B(t_1)=\Delta T_A(t_0)-\Delta T_B(t_1)-\{T_P(t_0)-T_P(t_1)\} \quad \cdots(3)$$

Since a time difference arises from measurement at the different points, this method includes error factors based on the following (among others):

(1) Stability of atomic clocks to be compared
(2) Stability of the portable clock
(3) Environmental dependency of the portable clock

Errors corresponding to (1) and (2) can be estimated using (for example) TIE (Time Interval Error)[6], an index of frequency stability.

Table 2 describes examples of the evaluation of measurement intervals and error in the case in which the 5071A Cesium Standard (Agilent Technologies) is used as a typical atomic clock.

Table 2 *Transfer precision corresponding to frequency stability using the portable clock method*

τ (sec)	5071A normal		5071A super	
	$\sigma_y(\tau)$	TIE	$\sigma_y(\tau)$	TIE
1	1.2×10^{-11}	0.017 ns	5×10^{-12}	0.0071 ns
10	8.5×10^{-12}	0.12 ns	3.5×10^{-12}	0.05 ns
100	2.7×10^{-12}	0.38 ns	8.5×10^{-13}	0.12 ns
1,000	8.5×10^{-13}	1.2 ns	2.7×10^{-13}	0.38 ns
10,000	2.7×10^{-13}	3.8 ns	8.5×10^{-14}	1.2 ns
100,000	8.5×10^{-14}	12 ns	2.7×10^{-14}	3.8 ns
5 days	5×10^{-14}	30 ns	1.0×10^{-14}	6 ns

Table 2 indicates that in cases in which approximately one day is required to move the portable clock, it is likely that the movement will result in a time transfer error of approximately 10 ns when a normal cesium beam tube is used, and an error of several ns when a high-performance beam tube is used. Naturally, the shorter the time required for transport and the higher the stability of the atomic clock to be transported, the greater the precision of time transfer.

3.2 GPS common-view method

3.2.1 Outline of GPS

The GPS is a global positioning system that has been under development by the U.S. Department of Defense since the latter half of the 1970s. This system has since become

Table 3 *GPS satellite specifications*

Number of satellite	24 satellites
Altitude	20,200 km
Inclination	55 degree
Orbital planes	24 operational satellites are launched (There are 6 orbital planes equally spaced in 60 degrees, 4 satellites are located in each plane.)
Period	11hour58minutes(0.5 sidereal day)
Carrier frequency of ranging signal	L1:1575.42 MHz、L2:1227.6 MHz
PN Code for ranging	
C/A code(L1-Band)	Generated from Gold-code by using Two 10-bit Tapped Feedback Shift Registers (TFSR). Code length :1023 bits Chipping rate :1.023 MHz Code period :1 ms
P(Y) code (L1/L2-Band, for military use)	Generated in an analogous manner to the C/A code, using two TFSRs but more long sequences. Chipping rate :10.23 MHz Code period :1week (Reset at 1 week)
Atomic clocks	3～4 clocks are being loaded, some are Cs, and others are Rb. (mainly Rb clocks are being loaded in the recent satellites)
Navigation data	Modulates the L1-C/A-code signal in the rate of 50bps. 1sub-frame 300 bits, 1 frame = 5 sub-frame, 1 page = 25 frame (1 page = 12.5 分)

indispensable in a variety of fields requiring positioning technology, including car navigation systems. Application of GPS satellites to time transfer began in the early 1980s, and the common-view method proposed by the U.S. National Bureau of Standards (NBS; presently NIST) is now in use as a leading method of determining standard TAI. Table 3 shows the specifications of the GPS satellite system.

Fig.4 illustrates the principle behind the GPS common-view method. Although this method employs the same concept as that of the general common-view method shown in Fig.2 (b), the GPS common-view method provides various additional items of information, including satellite positional information and GPS time, using navigation data superposed on the ranging signals.

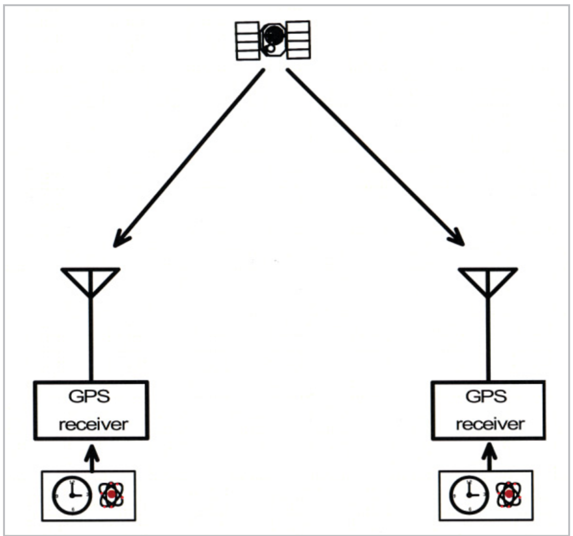

Fig.4 GPS common-view method

Note that reception of the GPS satellite signal at every site must be simultaneous for a given satellite. Under the GPS satellite common-view method for TAI determination, the BIPM establishes a common-view reception schedule approximately once every six months, and each organization conducts reception according to this schedule. The observation time for one satellite is 13 minutes (780 seconds). The measured values obtained for each second are subject to quadratic approximation every 15 seconds, and 52 sets of such 15 second data are averaged and summarized to a single reception result. This final reception data is converted to CGGTTS (Common GPS GLONASS Time Transfer Standard) format designed for international time transfer[6] among the respective organizations, and is reported to the BIPM.

3.2.2 Error factors in GPS time transfer [7]

Mathematical formulation of the principle of time transfer by the GPS satellite common-view method results in the following:

$$\Delta T_A = \rho_A(t)/c - \hat{\rho}_A(t)/c + \Delta T_{ion,A}(t) - \Delta\hat{T}_{ion,A}(t) + \Delta T_{trop,A}(t) - \Delta\hat{T}_{trop,A}(t) + T_A(t) - T_{GPS}(t) + \Delta T_{rec,A}(t) \quad \cdots\cdots(4)$$

$$\Delta T_B = \rho_B(t)/c - \hat{\rho}_B(t)/c + \Delta T_{ion,B}(t) - \Delta\hat{T}_{ion,B}(t) + \Delta T_{trop,B}(t) - \Delta\hat{T}_{trop,B}(t) + T_B(t) - T_{GPS}(t) + \Delta T_{rec,B}(t) \quad \cdots\cdots(5)$$

Here,

ΔT_i: measurement result at point i (i = A or B),

$\Delta\rho_i(t)$: geometric distance between the satellite and point i at time t,

$\Delta\hat{\rho}_i(t)$: calculated value of the geometric distance between the satellite and point i at time t (based on ephemeris data),

$\Delta T_{ion,i}(t)$: ionospheric delay from the satellite to point i at time t,

$\Delta\hat{T}_{ion,i}(t)$: estimate (or measured value) of the above quantity,

$\Delta T_{trop,i}$: atmospheric delay from the satellite to point i at time t,

$\Delta\hat{T}_{trop,i}$: estimate (or measured value) of the above quantity, and

$\Delta T_{rec,i}(t)$: receiver noise.

The time difference between the reference clocks at point A and at point B is derived from formulas (4) and (5) as follows.

$$T_A(t) - T_B(t) = \Delta T_A - \Delta T_B(t) + \delta\rho + \delta T_{ion} + \delta T_{trop} + \Delta T_{rec} \quad \cdots\cdots(6)$$

As expressed in formula (6), error factors for the time difference include the following:

(1) Satellite orbit estimation error
(2) Antenna position error at receiving point
(3) Ionospheric delay error
(4) Atmospheric delay error
(5) Receiver noise (including temperature dependency)

Taking these error factors into consideration, the time transfer method employing the GPS L1 single-frequency C/A code single channel system, the leading method of conventional international time transfer, can attain time transfer precision of a few ns for short distances and approximately 10 ns for long distances (as in cases of intercontinental time transfer).

3.2.3 Attaining higher precision under the GPS common-view method [2]

More than 20 years have passed since the initial introduction of the GPS common-view method. During this time the precision of atomic clocks has increased dramatically; as a result, the conventional L1 C/A code 1 channel method of international time transfer has been revealed as insufficiently precise in comparison. Thus to increase the precision of the GPS common-view method, the three directions listed below have proven effective.

(1) Shift from single-channel to multi-channel method
(2) Measurement of the ionospheric delay by dual-frequencies P1 and P2
(3) Enhanced resolution of pseudo distance measurement via carrier phase

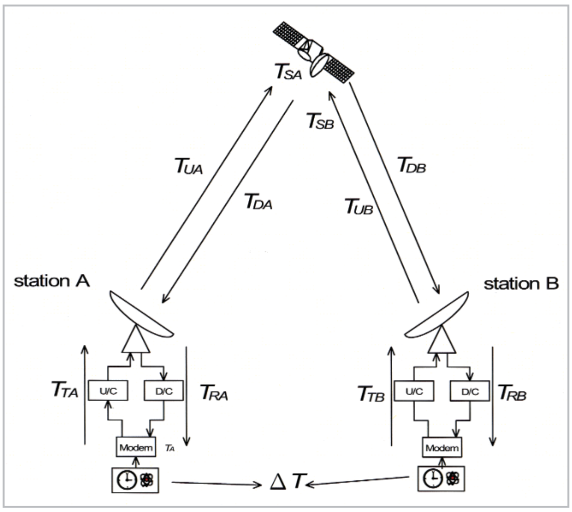

Fig.5 *Principle of two-way satellite time and frequency transfer*

These directions are not implemented independently: direction (2) is employed in conjunction with multi-channel design, and direction (3) is implemented together with dual-frequency reception and multi-channel design, with an aim to achieving measurement resolution of approximately 1 ps.

For a detailed explanation of each system, please see Reference[8] provided at the end of this report.

3.3 Two-way satellite time and frequency transfer

3.3.1 Basic principle

The principle of the two-way satellite time and frequency transfer method is illustrated in Fig.5. Each of the two time-transfer stations transmits a signal to the other via satellite, and each station measures the arrival time of the signal from the other station with reference to the local station clock. The time difference between the reference clocks of the two stations can be determined based on the difference between the measurement results of the two stations.

The measured values at the two stations can be expressed by the following formulas.

$$T_A = \Delta T + T_{TA} + T_{UA} + T_{SA} + T_{DB} + T_{RB} + 2\omega A / c^2 \quad \cdots(7)$$

$$T_B = -\Delta T + T_{TB} + T_{UB} + T_{BA} + T_{DA} + T_{RA} - 2\omega A / c^2 \quad \cdots(8)$$

Here, the last terms of the two formulas represent the effect of the Earth's rotation as predicted under the theory of relativity (the Sagnac effect), with A denoting the area between the projection of the satellite/Earth stations on the equatorial plane and the center of the Earth and ω denoting the angular rotational speed of the Earth. From the difference between formulas (7) and (8), the time difference of the reference clocks of the two stations can be estimated, using the following formula.

$$\Delta T = (T_A - T_B)/2$$
$$- T_{TA} + T_{TB}$$
$$- T_{UA} + T_{DA}$$
$$- T_{SA} + T_{SB}$$
$$- T_{DB} + T_{UB}$$
$$- T_{RB} + T_{RA}$$
$$- 4\omega A / c^2 \quad \cdots\cdots(9)$$

The second term and the sixth term on the right side of formula (9) represent a delay time difference in internal uplink and downlink at stations A and B, respectively, which cannot be canceled out but normally represent fixed biases. The third term and the fifth terms represent propagation delay time in satellite uplink/downlink for station A and station B, respectively; these terms are nearly canceled out in light of the assumption that the signals follow the same path. The fourth term represents internal satellite delay time, and can be canceled out based on the traditional use of frequency spread modulation for time transfer, and also based on the use of a single frequency band for the signals of the two stations.

Through the above-described relationships, almost all signal delay can be canceled out for the two stations under the two-way satellite system. This system thus enables highly precise time transfer in a number of ways, specifically including the following.

(1) The system does not depend on satellite positional error and movement.

(2) The system does not depend on positional error relative to the Earth.

(3) The system allows for measurement featuring relatively high circuit quality.

Although the precision of time transfer depends on the width of the frequency band used for the time transfer equipment and on overall circuit quality, precision on the subnanosecond level was obtained for the Earth stations (in the Ku band, with an effective diameter of about 1.8 m and a transmitting power of several W) now employed in two-way satellite time and frequency transfer aiming at the establishment of international atomic time.

Further details are provided in "Two-way Satellite Time and Frequency Transfer" also included in this special issue.

3.4 Other methods of time transfer

Other highly precise time transfer methods are available in addition to the foregoing, including the LASSO[9] (Laser Synchronization from Stationary Orbit) system (in which a laser pulse and a radio wave are shared) and the ground-based optical fiber system. The former method aims at time transfer with subnanosecond precision by measuring the intervals between arrival times of laser pulses synchronized with atomic time issued from multiple points on a single satellite. However, since the required ground facilities are very costly and the lasers are susceptible to weather variations, this system has not been put to practical use.

As telecommunication speeds increase, time transfer and time synchronization using ground-based optical fibers is becoming subject to greater development and broader implementation[10]. Further, a new method of providing reference signals over relatively short distances (from a few to several dozens of km), has been advanced; under the proposed plan a stabilized reference signal is transmitted in the optical range and applied as a local signal in astronomic observations [11][12].

As described above, demands for time and frequency transfer and the provision of time/frequency values are growing in a variety of fields; we believe that in the future these demands will only continue to increase.

4 Conclusions

The method of time transfer represents one of the most essential technical subjects in the field of time and frequency standards, and stands as a focus of research that will prove indispensable in the development of atomic time, as well as in a variety of additional fields in which the demand for highly precise time transfer and synchronization is growing at a rapid pace.

In this paper we presented outlines of time transfer methods, focusing on the portable clock method, the GPS common-view method, and the two-way satellite time and frequency transfer method.

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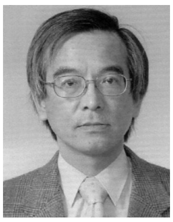

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