4 Measurements of Space-Time Standards

4-1 The Regular Operation of Two-Way Satellite Time and Frequency Transfer

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Two-Way Satellite Time and Frequency Transfer (TWSTFT) is a very precise time transfer method using communication satellite. NICT constructed TWSTFT network as a hub in Asia/Pacific Rim Region, and conducts the regular operation of TWSTFT to keep Japan Standard Time (JST) stable and contributes to International Atomic Time (TAI). In this paper, we introduce the international TWSTFT network and the required calibration for it.

Keywords
Satellite communications, Two-Way Satellite Time and Frequency Transfer (TWSTFT), GPS, International Atomic Time (TAI), Coordinated Universal Time (UTC)

1 Introduction

World standards organizations produce time and frequencies using atomic clocks. As shown in Fig. 1, Bureau International des Poids et Mesures (BIPM) collects comparison information from 300 atomic clocks at over 50 standards organizations in the world in order to construct International Atomic Time (TAI) and Coordinated Universal Time (UTC). It is necessary to carry out time transfer of the atomic clocks in various countries throughout the world for these purposes. For comparison methods between remote locations such as in international comparison, there are several methods: the clock transportation method on which portable standards are transported and compared, the one way method which is mainly focused on dissemination of standard time and standard frequency using standard radio waves, etc., the common-view method which is to compare between clocks placed in remote locations by receiving common signals at multiple locations using GPS, and the two way method with which signals are simultaneously sent between time and frequency comparison participants and comparisons are carried out[1][2]. At present, two methods with the highest transfer precision are adopted as shown in Fig. 2: GPS carrier phase method[3] and Two-Way Satellite Time and Frequency Transfer (TWSTFT) method which uses communication satellites. In this paper we will discuss TWSTFT which is being regularly operated together with time comparisons using GPS for the sake of the stable operation of Japan Standard Time (JST), and then the time transfer network which is being constructed from around 2004 and the calibration.

2 Two-way satellite time and frequency transfer

The equipment for TWSTFT is complex when compared to the equipment for time transfer using GPS, which is composed of just

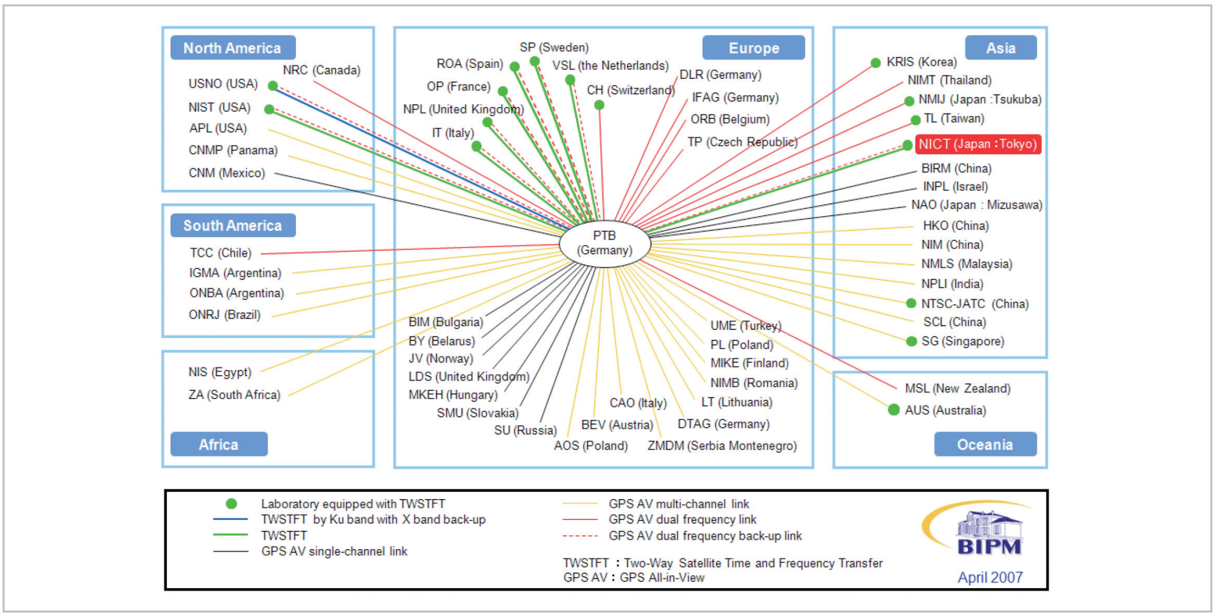

Fig.1 *International time transfer network*

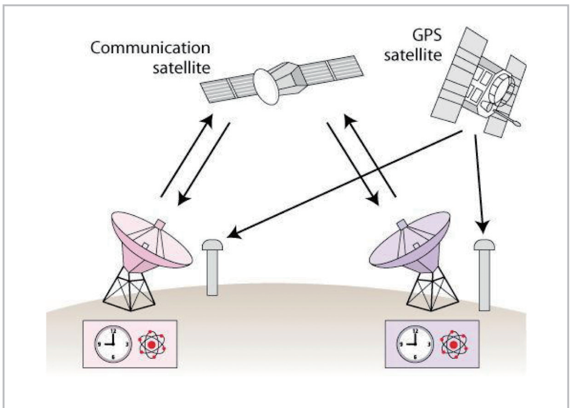

Fig.2 *Schematic of TWSTFT method and time transfer method using GPS*

a receiver and an antenna; however, TWSTFT has good stability over a long term and allows for acquisition of highly precise data in real-time[4]. Due to the high costs, however, it is mainly used in developed nations. In this section we will discuss an overview, the principle, details and operation.

2.1 Overview

As shown in the block diagram in Fig. 3, the system is composed of a specialized modem which modulates and demodulates time information; up- and down- converters which convert modem signals to communication satellite frequency bands; a Solid State Power Amplifier (SSPA) which amplifies transmission output; a Low Noise Amplifier (LNA) which amplifies received signals; control and data collection computer (Fig. 4); and parabolic antennas (Fig. 5). Use of communication satellites which utilize Ku bands is common in order to minimize the effects of the ionosphere and the atmosphere as much as possible.

2.2 Principle

TWSTFT can carry out time transfer within areas visible to the same communication satellite. The principle is shown in Fig. 6 and the factor of errors in Fig. 7. Earth station (ES) A and B send time information t^A and t^B to communication satellite with a modulation method of Pseudo Random Noise (PRN) on which information exchange can be performed at the same time on the same frequency. For this reason, as propagation time from ES A to B is the same as that from ES B to A, it is possible to offset the time required for propagation, and calculate the difference between t^A and t^B to be easily found.

As shown in Fig. 6, the principle of TWSTFT can be shown in Equation (1) with the time difference between ES A and B as Δt^A-Δt^B.

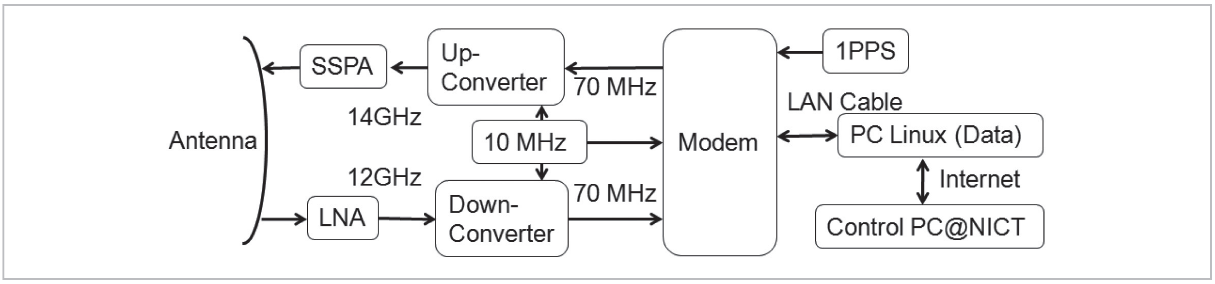

Fig.3 Block diagram

Fig.4 System

Fig.5 Parabolic antennas

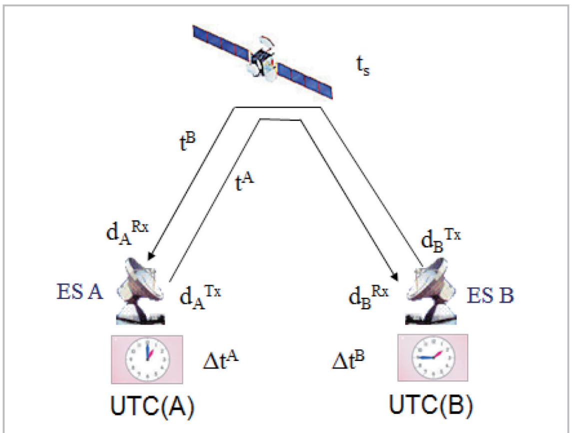

Fig.6 Principle of TWSTFT

$$\Delta t^A - \Delta t^B \fallingdotseq$$
$$1/2[(t^A - t^B) + (d_A^{Tx} - d_A^{Rx}) - (d_B^{Tx} - d_B^{Rx}) + t_s] \quad (1)$$

t_s: Delay time due to Sagnac effect
d^{Tx}: Uplink delay time (up converter, SSPA, cables, etc.) in ES A and B
d^{Rx}: Downlink delay time (LNA, down converter, cables, etc.) in ES A and B
Δt: Time difference in ES A and B
t: Reception time in ES A and B

Both ES A and B simultaneously receive the Ku band radio waves transmitted simultaneously by both stations. Specifically, the effect of the ionosphere and the atmosphere can be nearly completely offset by passing along the same course, which makes it possible to perform extremely high precision time transfer. In this regard, even with the position of the communication satellite and the effects of the ionosphere and atmosphere taken into account, the error is in principal at approximately 100 ps[4]. The error will actually be several hundred ps due to system noise, temperature and other effects. In addition, during calculation, the Sagnac effect caused by the rotation of the earth must also be taken into account[1][2].

2.3 Details

NICT, as a hub organization in Asia's TWSTFT network, has constructed networks in cooperation with Asia/Pacific Rim Region and Asia/Europe standards organizations. In addition, an Asia/the United States (NICT-Hawaii-USNO) network was constructed aimed at monitoring Quasi-Zenith Satellite System (QZSS) time transfer. These have been constructed smoothly and are carrying out stable

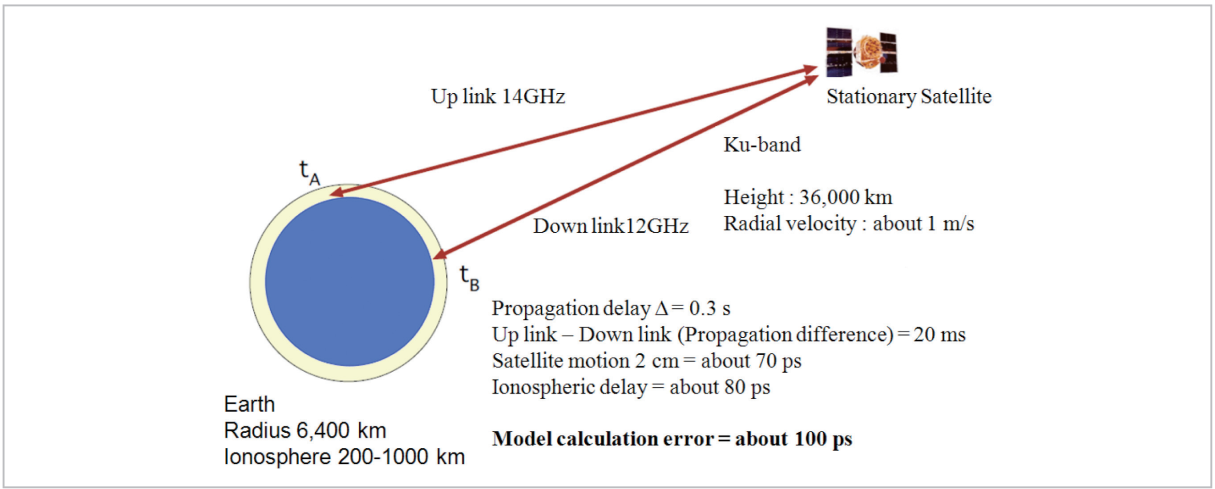

Fig.7 *Factor of errors in TWSTFT*

measurements. Actual time transfer results measured between NICT and Physikalisch-Technische Bundesanstalt (PTB) in Germany are shown in Fig. 8 and transfer precision in Fig. 9. The absolute value of time difference cannot be found unless the delay amount for each system from the modem to the antenna is offset, so the calibration methods for doing so are discussed in Capter **4**.

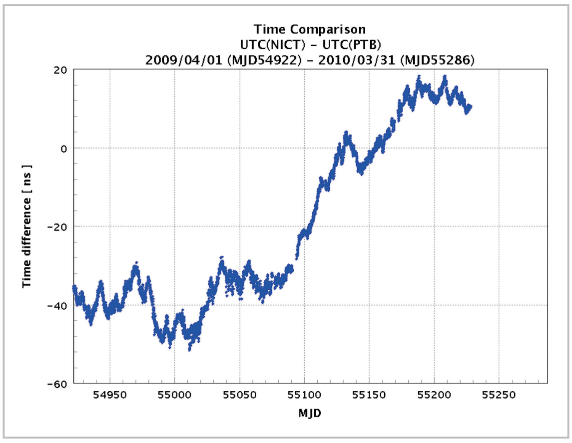

Fig.8 *Time transfer data between NICT-PTB*

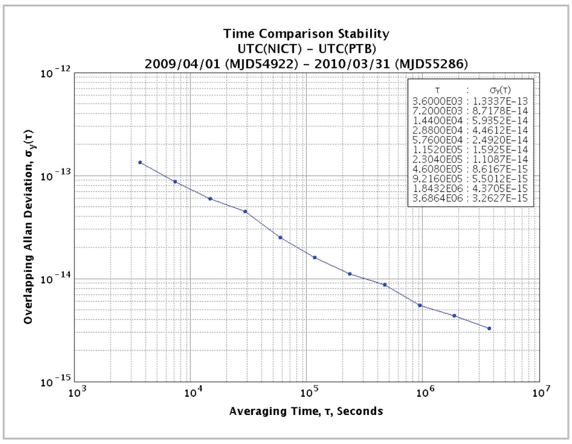

Fig.9 *Time transfer precision between NICT-PTB*

2.4 Operation

TWSTFT operated manually using ATLANTIS modem up until 2004, and time transfer was carried out at a rate of about 1-2 times per week. Thereafter, from 2005, the modem developed by NICT[5][6] was tested and supplied to Asian standards organizations, and an Asia/Pacific Rim Region network was established. The NICT modem has been multichannel and has become possible to carry out time transfer with up to 8 stations at the same time (normally 1 channel is used for calibration), and to perform stable measurement with an automatic operation. From around 2009 German-made SATRE modems have been put into use in the Asia/Europe network. SATRE modem has a maximum of 3 reception channels. Automatic use allowed for setting of the measurement interval on computers for both modems. At first, the operation of NICT modem was carried out as continuous operation. Acquiring the data of equipment calibration each time and the convenience of operation, however, led to the current operation of 5-minute operation for one time per hour. Data is converted to ITU-R format everyday, uploaded to NICT website and reported to the BIPM.

3 Two-way satellite time and frequency transfer networks

NICT, acting as a hub, had been preparing for Asia/Pacific Rim Region TWSTFT networks until October of 2009, at the height of GPS Common View method. Meanwhile, because an Asia/Europe link which can directly carry out time transfer with PTB became considered important, time transfer experimentally started at first between only NICT and PTB. Thereafter, the standards organizations of the major Asian countries participated in it, and Asia/Europe network was established (Fig. 10). After October 2009, Australia and other locations which are distant from PTB and cannot carry out direct time transfer began direct time transfer using GPS carrier phase; however, TWSTFT has better stability over the long term than GPS carrier phase, and so is still in use together with GPS carrier phase in major nations[4]. Hereafter it is likely that both methods will continue to be used for measurement with taking advantage of each strong point. In this section we will discuss TWSTFT networks in the 3 regions.

3.1 Asia/Pacific region network

After 2005, the participating organizations in Asia/Pacific Rim Region Network are NMIA in Australia, NTSC in China, TL in Taiwan, KRISS in South Korea, A*STAR (formerly SPRING) in Singapore, and NMIJ (the National Institute of Advanced Industrial Science and Technology) in Japan and NICT as shown in Table 1. For communication satellites, INTELSAT IS-8 satellite (formerly PanAmSat PAS-8) and JSAT JCSAT-1B satellite are used[7]. In Japan, time transfer is carried out by the Ohtakadoya-yama LF Standard Time and Frequency Transmission Station or the Haganeyama LF Standard Time and Frequency Transmission Station and NICT headquarters as well. An equipment of TWSTFT operates stably, and continuous comparison results among nations are sent to BIPM by each organization.

3.2 Asia/Europe network

The first time transfer between Asia and Europe was experimentally performed between TL and VSL in Holland using PAS-4 satellites from 2002–2003[8]. Thereafter NICT constructed a steady network to contribute to

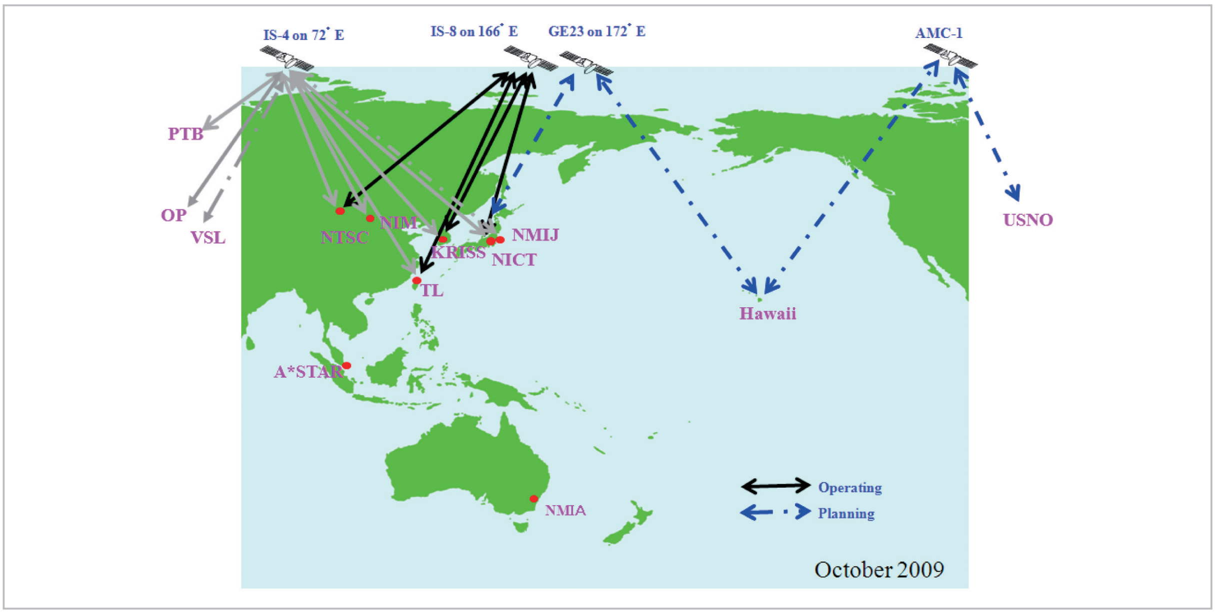

Fig.10 *Asia/Pacific rim region, Asia/Europe, Asia/North America network*

Table 1 *Asia/Pacific rim region participating organizations*

Period	Satellite	Institute
Feb. 2005–Mar. 2006	PAS-8, JCSAT-1B	NMIA, NTSC, TL, KRISS, NMIJ, NICT, SPRING
Apr. 2006–Jun. 2007	PAS-8, JCSAT-1B	NMIA, NTSC, TL, KRISS, NMIJ, NICT, SPRING
Jul. 2007–Mar. 2008	JCSAT-1B	NTSC, TL, KRISS, NMIJ, NICT, SPRING
Apr. 2008–Mar. 2009	JCSAT-1B	NTSC, TL, KRISS, NMIJ, NICT, A*STAR (SPRING)
Apr. 2009–	IS-8 (PAS-8)	NTSC, TL, KRISS, NMIJ, NICT

Table 2 *Asia/Europe participating organizations (IS-4 Satellite)*

Period	Modem	Institute
Apr. 2005–Mar. 2006	NICT	NICT, PTB, KRISS
Apr. 2006–Mar. 2007	NICT	NICT, PTB, KRISS
Apr. 2007–Mar. 2008	NICT, SATRE	NICT, PTB, KRISS, NMIJ, TL
Apr. 2008–Mar. 2009	NICT, SATRE	NICT, PTB, KRISS, NMIJ, TL, NTSC, NIM, OP
Apr. 2009–Jan. 2010	SATRE	NICT, PTB, KRISS, TL, NTSC, NIM, OP

TAI. For Asia/Europe TWSTFT, NICT got fully prepared for earth-based equipment in co-operation with PTB by 2004 and then started measurements[4][9][10]. The PanAmSat PAS-4 (presently INTELSAT IS-4) was used as the communication satellite. At first measurement was begun by NICT and PTB and thereafter the organizations in Table 2 joined successively. Participating organizations were NICT, PTB, KRISS, NMIJ, TL, NTSC, NIM and OP in France. For the modems, the performance of SATRE modem having been mainly used in Europe from 2009 was certified[11] to be the same as that of NICT modem, so operation of this network is operated using SATRE modems. The IS-4 satellite reached its early life span at the end of January 2010, so operation was changed to using Express AM-2 (Long. 80° E.) satellite of INTERSPUTNIK International Organization of Space Communications in Russia. In addition, because this network is a long baseline, the effects of the atmosphere, etc have been researched[12].

3.3 Asia/North america network

TWSTFT between Asia and the United States uses the GE-23 satellite and AMC-1 satellite and began time transfer between NICT and USNO through Kokee Park Geophysical Observatory (KPGO) as the relay station on Kauai of the Hawaiian Islands in July 2010. This link is a monitoring station of QZSS plan; however, it also has a potentiality to be used as the eastbound line (NICT-KPGO-USNO-PTB) for regular time transfer.

4 Calibration

One way to calibrate the amount of TWSTFT equipment delay is performed by using GPS data. This section, however, provides an overview, principles, and an implementation history of calibration done by using a portable station for calibration with only two-way satellite.

4.1 Overview

Calibration requires a portable antenna and a system (Fig. 11). The antenna is a 1.2m high with an easily assembled structure, the equipment is stored in a small container, and the system and the antenna are connected by a 100 m optical fiber cable with the high frequency signal routed through an E/O-O/E converter. In Europe, etc. it is easy to transport the portable station overland and calibration is carried out periodically[13]. On the other hand, in the various countries of Asia, the portable station must be transported by aircraft, with time-consuming tasks such as procedures of transportation and customs clearance making it difficult. NICT has positively carried out the calibration.

4.2 Principle

The measurement of delay amount from the modem to the antenna of ES A and B is difficult. The time transfer delay amount between atomic clock A and B is measured as follows: simultaneous measurement of ES A and B using a Portable Station (PS) at ES A is performed, then the PS is moved to ES B and simultaneous measurement of ES B and A using PS at ES B is carried out (Fig. 12). Calibration is made possible by finding delay amount be-

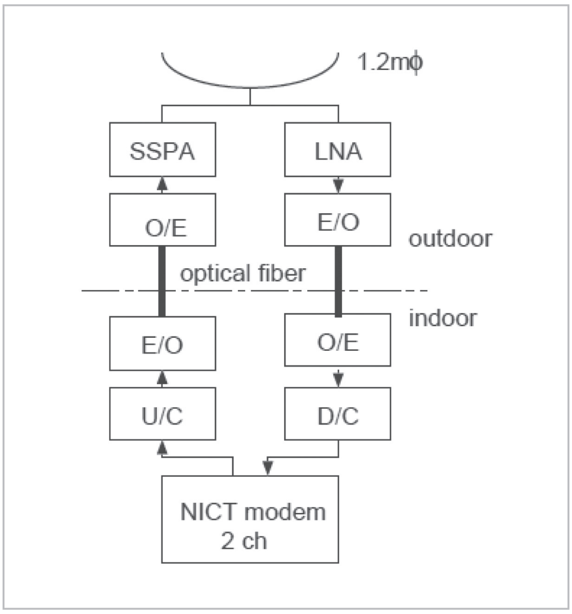

Fig.11 *Portable station antenna and system*

tween the PS and ES A, the PS and ES B respectively. The delay difference can be found as follows.

The time transfer for ES A and PS is shown in Equation (2) and for ES B and PS in Equation (3).

$$(d_A^{Tx} - d_A^{Rx}) - (d_p^{Tx} - d_p^{Rx})_A = -(t^A - t^P) \qquad (2)$$

$$(d_B^{Tx} - d_B^{Rx}) - (d_p^{Tx} - d_p^{Rx})_B = -(t^B - t^P) \qquad (3)$$

d^{Tx}: Uplink delay time (up converter, SSPA, cables, etc.) in ES A, B and PS

d^{Rx}: Downlink delay time (LNA, down converter, cables, etc.) in ES A, B and PS

t: Reception time in ES A, B and PS

Delay difference (2)–(3) is given by

$$(d_A^{Tx} - d_A^{Rx}) - (d_B^{Tx} - d_B^{Rx}) = -(t^A - t^P) + (t^B - t^P), \qquad (4)$$

where

$$(d_p^{Tx} - d_p^{Rx})_A = (d_p^{Tx} - d_p^{Rx})_B. \qquad (5)$$

4.3 Implementation History

NICT has carried out calibration experiments in Japan and neighboring Asian Countries since 2005. The first calibration experiment was carried out between NICT headquarters and VLBI station of the Geographical Survey Institute located in Aira, Kagoshima Prefecture, and the result of the calibration showed a match with the calibration value transferred using GPS data. For the first overseas calibration experiment in Taiwan, measurement was carried out by transporting the portable station by aircraft, and the calibration data was smoothly acquired. After measurement, the calibration

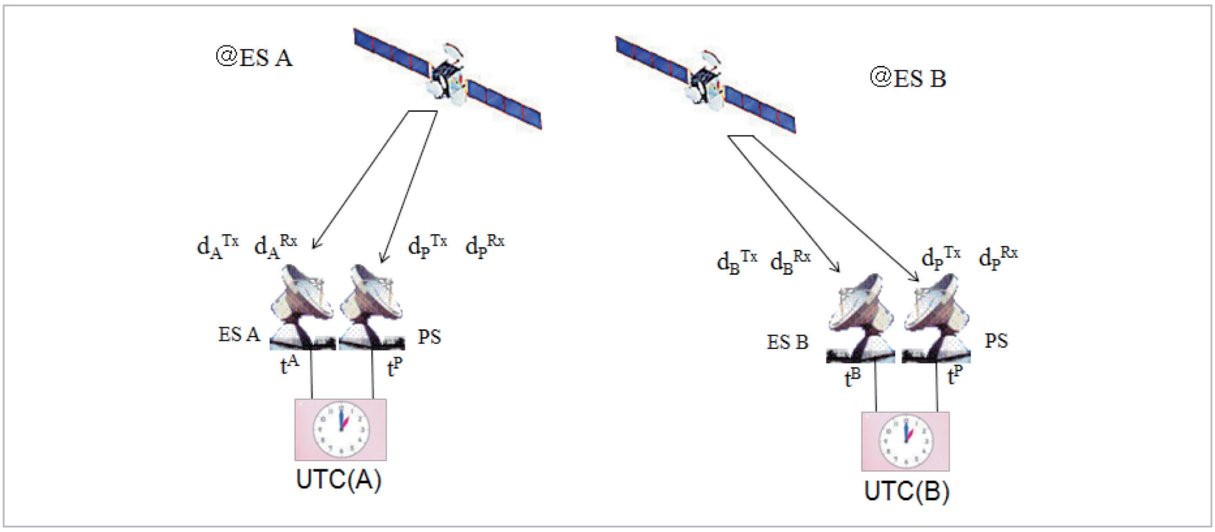

Fig.12 *Portable station calibration method*

data from TL, KRISS and NMIJ was reported to BIPM[14]-[16], and was used as calibration values to be posted to ITU-R data and also the acquired calibration ID (CAL ID) as well. The overall calibration found calibration values with a match of 1–2 nsec or less compared to GPS transfer results, and the values were able to contribute to TAI. Hereafter we hope to implement calibration between Asia - the United States and Asia - Europe.

5 Conclusions

This paper introduced TWSTFT networks which have been developed in recent years. NICT has taken on the leadership role as the hub standards organization for Asia, and has constructed the wide Asia/Pacific Rim Region, Asia/Europe and Asia/the United States networks and carried out stable and continuous high precision time transfer. The operation of INTELSAT IS-4 satellite, however, which was important for TAI as an Asia/Europe satellite, was suddenly stopped at the end of January 2010. At present NICT is constructing a network using Express AM-2 satellite by INTERSPUTNIK. In addition high precision and narrow band methods by Dual Pseudo Random Noise (DPRN) of TWSTFT[17] are being developed, and more continuous operation will likely be possible if the use of available frequencies of satellite transponder becomes easier; moreover, if time transfer methods[19] using optical fiber[18] and VLBI are adopted, more precise and stable continuous time transfer will also be possible.

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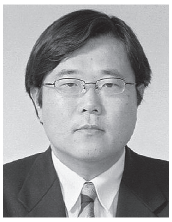

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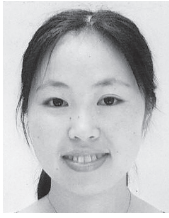

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