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International Time Comparison by TWSTFT and GPS at KRISS

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ABSTRACT

In this paper, time comparison is performed with standardization institution in Japan using a Two-Way Satellite Time and Frequency Transfer (TWSTFT) technique as one of the methods for high precision time comparison. To analyze the performance of time comparison in the TWSTFT method, time comparison results via the Global Positioning System (GPS) code and carrier wave are analyzed. Through the time comparison performance, frequency stability is analyzed using modified Allan deviation and by this result, characteristics of time comparison of the TWSTFT that is utilized in international time comparison are presented.

Keywords: time comparison, TWSTFT, GPS carrier phase, Allan deviation, UTC

1. INTRODUCTION

Time had no significant impact on industries in the past when one second was calculated to be 1/86,000 of the mean length of a day (solar time). However, as a cesium atom was adopted and definition of second was newly established by the 13th Conference Generale des Poids et Measures in 1967, the importance of time standard has been recognized from industries and scientific fields to practical daily living. Developed nations around the world have developed precise atomic clocks and have performed research on how to utilize them in time scale. Now, a precise and accurate time comparison method is needed more than ever to verify the result of developed atomic clocks and contribute to the generation of the Coordinated Universal Time (UTC), which is the standard time. In addition, precision time synchronization is essential to advance the modern mobile communication field. It can also be utilized in foundational technology that contributes to various areas such as navigation, geodetic surveying, military, astronomy, and science.

The accuracy of the Two-Way Satellite Time and Frequency Transfer (TWSTFT) time comparison method has been verified theoretically through experiments since 1970s in the U.S., Japan, France, and Germany etc. and its precision of time comparison achieved several ns, which was an epoch-making event at that time. However, the needs of time comparison with such high precision were not required at that time and the TWSTFT was not used actively due to the limitation of satellite utilization and enormous expense such as satellite fee and time comparison devices required to operation the TWSTFT system. However, as precise time measurement and synchronization methods are needed more than ever due to the rapid advancement on frequency standards and communication technology, National Measurement Institutes (NMIs) for time and frequency standardization who construct the TWSTFT time comparison system can be found more and more despite high cost investments and measurement technology has also improved steadily up to 1 *ns* currently (Kirchner 1991). Due to this superior precision, time comparison data were first used to create International Atomic Time by employing the TWSTFT between Technical University Graz in Austria and Physikalisch-Technische Bundesanstalt in Germany by the Consultative Committee for Time and Frequency (CCTF)

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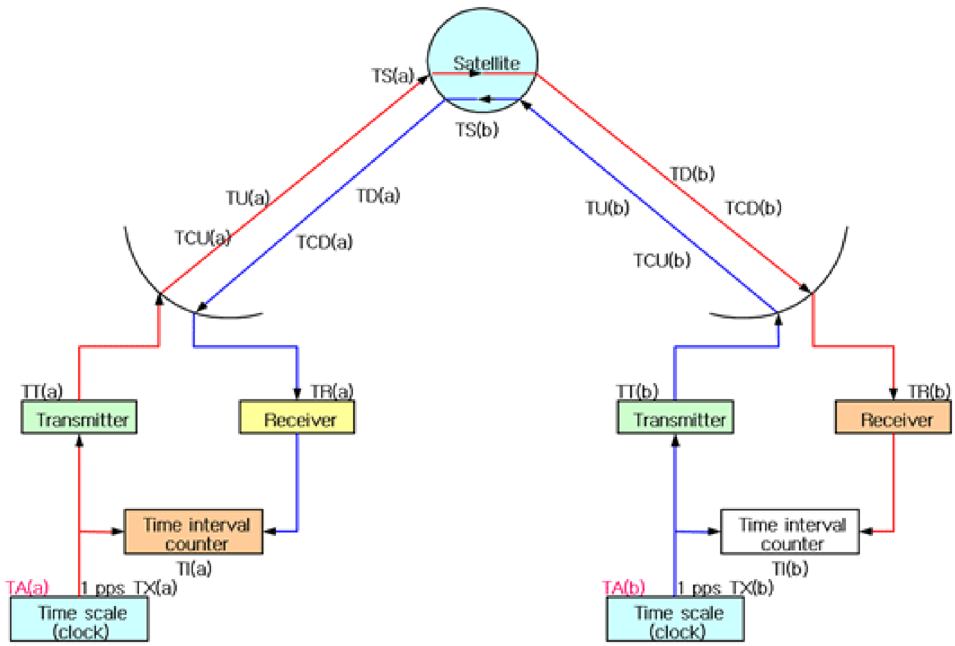

Fig. 1. Principle of TWSTFT.
$T_{scale}(k)$: Time scale of the ground station
$T_{diff}(k)$: Time difference
$T_{tx}(k)$: Transmission delay including internal delay in the transmitter
$T_{rx}(k)$: Receive delay including internal delay in the receiver
$T_{up}(k)$: Uplink propagation delay
$T_{down}(k)$: Downlink propagation delay
$T_{sat}(k)$: Satellite delay
$T_{comp.ul}(k)$: Sagnac correction of the uplink
$T_{comp.dl}(k)$: Sagnac correction of the downlink

in the Bureau International des Poids et Mesures (BIPM) and correction campaign was conducted to measure uncertainty as well as adding various contributions (Piester et al. 2008).

The TWSTFT method for the time comparison has been general in these days so it is utilized to contribute to the time scale by the NMIs or designated laboratories. South Korea also participate in the Asia link with Japan and Taiwan thereby performing continuous time comparison and the Asia-Europe link participating with Germany, Russia, and China has been under construction currently. In addition, the time comparison method using carrier phase of the TWSTFT as well as improvements on transmission and receive signals have also been actively underway in order to improve precision of time comparison.

At the early stage of GPS utilization for the time comparison, the time scale was calculated by the C/A code using single channel and single frequency receivers. However, time comparison has now improved results by removing the propagation delay effect due to the ionosphere using P3, that is a combination of P1 and P2 measurement using multi-channel and dual frequency receivers (Zhang 2006). This is the most widely used method to contribute to the time scale calculation for UTC currently. In addition, more precise time comparison can be accomplished than using code if the GPS Carrier Phase (CP) is used. Thus, this paper presented time comparison results utilizing GPS P3 code and CP methods as well as analysis results on performance of the TWSTFT time comparison technique.

2. TWSTFT TIME TRANSFER METHOD

A communication satellite is a geostationary satellite located at an altitude of 36,000 km over the equator. In contrast with the GPS, it does not have an onboard atomic clock for using a reference time. Therefore, since a communication satellite does not have a time information generated from itself, time comparison can be done by transmitting and receiving time information between ground stations interactively using a communication satellite as a transponder in contrast with a method that performs time comparison by receiving only satellite signals as done in the GPS. The effects of the ionosphere and troposphere affect a propagation delay of two-way signals at the uplink and downlink equivalently. But due to the reciprocity of the signal path, the delays and variations can be eliminated, so the time comparison can be measured more accurately (ITU-R TF.1153 2015).

The system for the TWSTFT time comparison method and flow of signals for the time comparison are shown in Fig. 1. The system consists of a reference clock at each ground station, transmitter and receiver to measure a propagation delay time by one pulse per second (PPS) signal of the reference clock, and radio frequency system. The signals in the TWSTFT time comparison method are used for measurement of time of arrival through Time Interval Counter, identification of ground station, and data transfer for time comparison. To do this, a modem in the ground station performs modulation and demodulation of Pseudo-random Number code and message, which are synchronized with 1 PPS time information from the reference clock. An uplink frequency for two-way communication with a communication satellite is 12.040250 GHz, which is transmitted using horizontal polarization and a transponder of the communication satellite receiving the signal converts this to downlink frequency of 10.990250 GHz using vertical polarization.

In Fig. 1, $T_{scale}(a)$ refers to a time scale maintained by the ground station a, and $T_{scale}(b)$ is a time scale maintained by the ground station b. The time scale difference in clocks of two ground stations is expressed by $T_{scale}(a)$ - $T_{scale}(b)$, and a time difference $T_{diff}(a)$ measured at the ground station a is a measured value of time difference between time information received from the ground station b and time generated at the ground station a. That is, this is equivalent to Eq. (1) including transmission delay, propagation delay of uplink and downlink, Sagnac correction, and satellite delay between transmitter and receiver occurred over the transmission path from ground station b to ground station a in addition to a time scale $T_{scale}(b)$ of the ground station b.

$$\begin{aligned}T_{diff}(a) = {} & T_{scale}(a) - T_{scale}(b) + T_{tx}(b) + T_{up}(b) + T_{comp.ul}(b) \\ & + T_{sat}(b) + T_{down}(a) + T_{comp.dl}(a) + T_{rx}(a) \end{aligned} \tag{1}$$

A time difference $TI(b)$ measured by the time interval counter in the ground station b is the same as induced by the Eq. (1) in the ground station a, which produces Eq. (2).

$$\begin{aligned}T_{diff}(b) = {} & T_{scale}(b) - T_{scale}(a) + T_{tx}(a) + T_{up}(a) + T_{comp.ul}(a) \\ & + T_{sat}(a) + T_{down}(b) + T_{comp.dl}(b) + T_{rx}(b) \end{aligned} \tag{2}$$

A difference between ground stations a and b is equivalent to Eq. (3) that differentiates Eqs. (1) and Eq. (2).

$$\begin{aligned}T_{diff}(a) - T_{diff}(b) = {} & 2 \cdot T_{scale}(a) - 2 \cdot T_{scale}(b) + T_{tx}(b) - T_{tx}(a) \\ & + T_{up}(b) - T_{up}(a) + T_{sat}(b) - T_{sat}(a) \\ & + T_{down}(a) - T_{down}(b) + T_{rx}(a) - T_{rx}(b) \\ & + T_{comp.dl}(a) - T_{comp.ul}(a) - T_{comp.dl}(b) \\ & + T_{comp.ul}(b) \end{aligned} \tag{3}$$

Thus, a difference in time scale between ground stations calculated via Eq. (3) is equivalent to Eq. (4).

$$\begin{aligned}T_{scale}(a) - T_{scale}(b) = {} & 0.5 \cdot T_{diff}(a) - 0.5 \cdot T_{diff}(b) \\ & + 0.5 \cdot [T_{sat}(a) - T_{sat}(b)] \\ & + 0.5 \cdot [T_{up}(a) - T_{down}(a)] \\ & - 0.5 \cdot [T_{up}(b) - T_{down}(b)] \\ & + 0.5 \cdot [T_{tx}(a) - T_{rx}(a)] \\ & - 0.5 \cdot [T_{tx}(b) - T_{rx}(b)] \\ & + 0.5 \cdot [T_{comp.dl}(a) - T_{comp.ul}(a)] \\ & + 0.5 \cdot [T_{comp.dl}(b) - T_{comp.ul}(b)] \end{aligned} \tag{4}$$

In Eq. (4), a satellite delay time $[T_{sat}(a) - T_{sat}(b)]$ at the right term can be offset if the same frequency, channel, and transponder are used. Otherwise, accurate correction can be done by measuring the satellite delay time and securing the data prior to sending a satellite into orbit. $[T_{up}(a) - T_{down}(a)]$ refers to a delay occurred over the propagation path of uplink and downlink at the ground station a and $[T_{up}(b) - T_{down}(b)]$ refers to a delay occurred over the path of uplink and downlink at the ground station b. Since the two ground stations have the same path, the two delays are offset. $[T_{tx}(a) - T_{rx}(a)]$ and $[T_{tx}(b) - T_{rx}(b)]$ refer to delays occurred at a transmitter-receiver at each of the ground stations. These values are mostly offset in the TWSTFT environment where the same type of modems and transmitter-receiver are used. However, correction campaign is performed in consultation between NMIs according to the plan in order to perform accurate time comparison up to several and these values are measured at each of the ground stations using mobile ground stations and correction cables thereby calculating the correction value.

The Sagnac effect is generated by a rotation around the geocentric axis so that a cylindrical coordinate whose center is z axis can be expected. The correction value $T_{comp.dl}$ at the downlink signal sent to the ground station (k) from the satellite (s) can be calculated via Eq. (5).

$$T_{comp.dl}(k) = \left(\frac{\Omega}{c^2}\right) \times [Y(k) \times X(s) - X(k) \times Y(s)] \tag{5}$$

Here, Ω refers to a speed of Earth's rotation (=7.2921×10^{-5} $[rad/s]$) and refers to the speed of light (=299,792,458 $[m/s]$). A coordinate used in satellites and ground stations

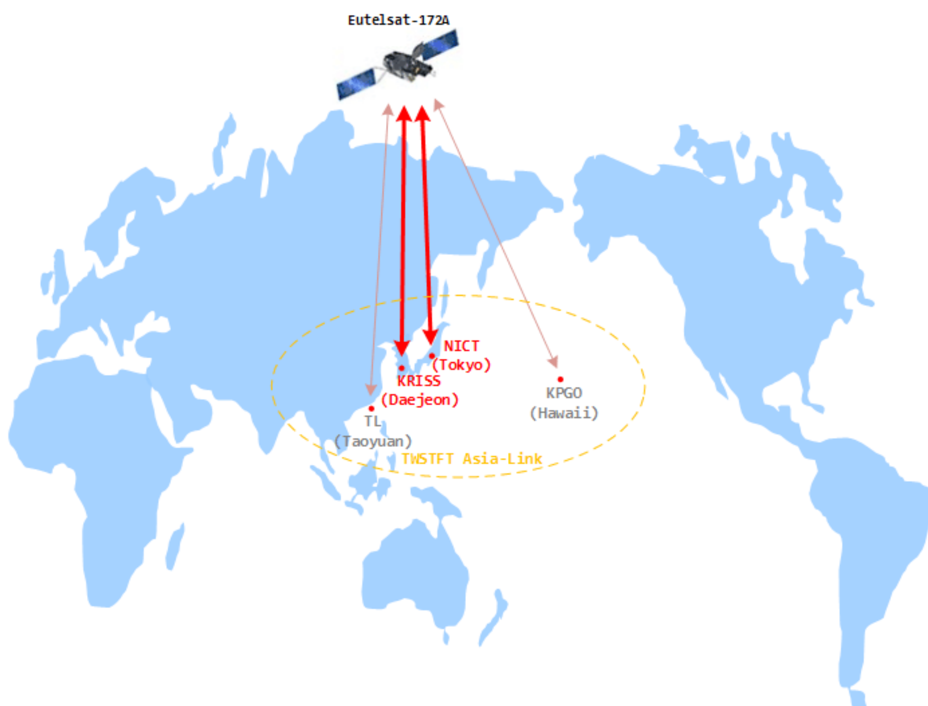

Fig. 2. TWSTFT Asia-link.

is the Earth Centered Earth Fixed coordinate, and $x(=r\cdot\cos[L_{lat}(k)]\times\cos[L_{lon}(k)])$ and $y(=r\cdot\cos[L_{lat}(k)]\times\cos[L_{lon}(k)])$ coordinates of the ground station are $X(k)$ and $Y(k)$. $x(=R\cdot\cos[L_{lat}(s)]\times\cos[L_{lon}(s)])$ and $y(=R\cdot\cos[L_{lat}(s)]\times\cos[L_{lon}(s)])$ coordinates of the satellite are $X(s)$ and $Y(s)$. r refers to the Earth radius (=6,378,140[m]), R refers to satellite orbit radius (=42,164,000[m]), and L_{lat} and L_{lon} refer to latitude and longitude. The geostationary satellite utilized for TWSTFT time comparison is located above the equator. It satisfies $L_{lat}(s)$=0. Thus, Eq. (5) can be arranged into Eq. (6).

$$T_{comp.dl}(k) = \left(\frac{\Omega}{c^2}\right)\times R\times r\times\cos\left[L_{lat}(k)\right]\times\sin\left[L_{lon}(k)\right]-L_{lon}(s) \quad (6)$$

Eq. (6) is determined by the coordinates of the ground station and satellite. $T_{comp.dl}$ and $T_{comp.ul}$ are functions of locations of the ground station and satellite so that only their signs are opposite. Hence, assuming that the result of the last two terms in the right side of Eq. (4) is a total Sagnac correction value $T_{comp}(ab)$, it produces Eq. (7).

$$\begin{aligned} T_{comp}(ab) &= 0.5\cdot\left[T_{comp.dl}(a)-T_{comp.ul}(a)\right] \\ &\quad +0.5\cdot\left[T_{comp.dl}(b)-T_{comp.ul}(b)\right] \\ &= -T_{comp.dl}(a)+T_{comp.ul}(b) \end{aligned} \quad (7)$$

As a result, a difference $T_{scale}(a)$-$T_{scale}(b)$ in time scale between two ground stations by TWSTFT can be calculated via Eq. (8).

$$\begin{aligned} T_{scale}(a)-T_{scale}(b) &= 0.5\cdot T_{diff}(a)-0.5\cdot T_{diff}(b)-T_{comp.dl}(a) \\ &\quad +T_{comp.ul}(b)+T_{cal} \end{aligned} \quad (8)$$

Here, T_{cal} is a correction value measured using mobile ground stations and time comparison between two ground stations can be achieved up to ns by calibrating the correction value.

Note that correction value T_{cal} of the equipment for the TWSTFT time comparison in KRISS and NICT used in this paper is under planning of correction campaign so that T_{cal} was not reflected in the presented time comparison result. Therefore, since an offset is present in the TWSTFT time comparison result proposed in Chapter 3 as much as T_{cal}, comparison and analysis about clock drift or frequency offset are performed.

3. TIME TRANSFER RESULTS

3.1 Test Environments

The measured values of TWSTFT time comparison presented in this paper are time comparison results between UTC(KRIS) in South Korea and UTC(NICT) in Japan whose distance is approximately 1,093 km by utilizing the TWSTFT Asia Link as shown in Fig. 2. The TWSTFT Asia Link was constructed for the purpose of international

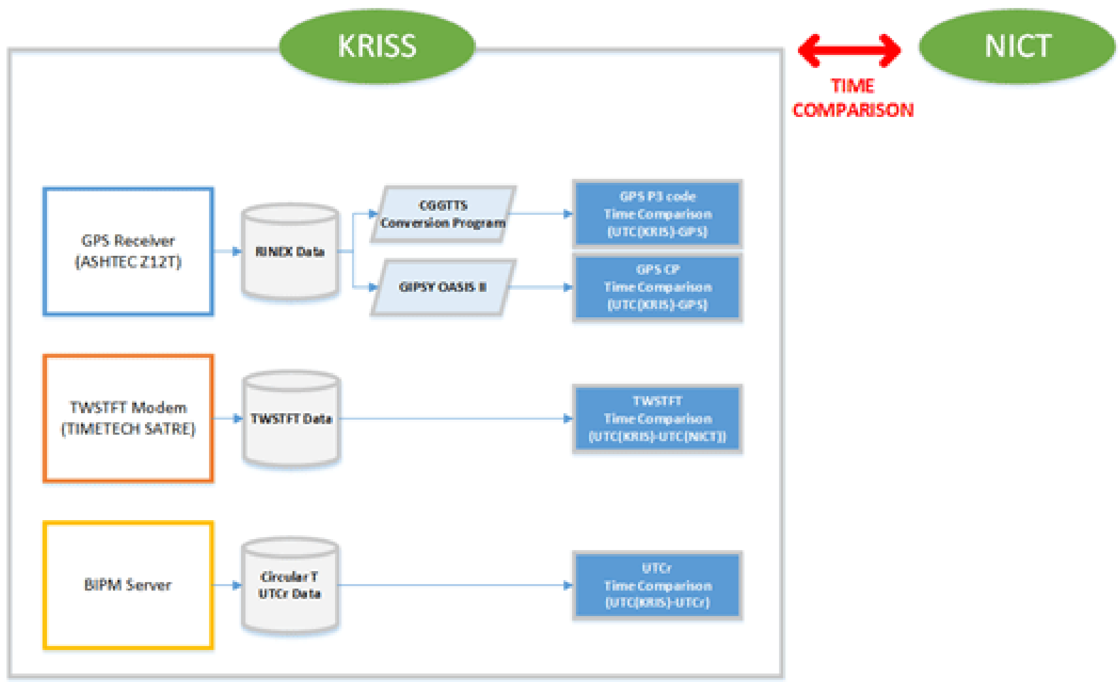

Fig. 3. Methods for time comparison.

time comparison among UTC(KRIS), UTC(NICT) and UTC(TL) for Asia region and UTC(USNO) in the USA via a relay station in Hawaii by utilizing Eutelsat-172A geostationary satellite located over the equator at 127 degrees east longitude. Time comparison is performed by each organization sequentially for five min in every hour according to the agreed schedule. The measurement equipment for time comparison is a SATRE model from TimeTech, which is utilized in the NMIs as standard equipment since high compatibility between modems is required in order to ensure high quality of accuracy due to the characteristic of the TWSTFT time comparison system.

For performing the time comparison between UTC(KRIS) and UTC(NICT), TWSTFT code measurement using a SATRE modem and GPS-based code and CP measurement using ASHTEC Z12T receiver for time comparison are performed as shown in Fig. 3. GPS-based code and CP time comparison are measured by performing post-processing operation using Receiver INdependent Exchange (RINEX) data acquired from KRISS and NICT. The time comparison result using GPS P3 code calculates data that comply with a format of the Common GPS GLONASS Time Transfer Standard in accordance with the method recommended by the CCTF Working Group on GNSS Time Transfer thereby differentiating measured values of UTC(KRIS)-GPS and UTC(NICT)-GPS acquired through the aforementioned calculation (Defraigne & Petit 2015). The time comparison result using the GPS CP is calculated via GIPSY OASIS-II software from the Jet Propulsion Laboratory (JPL 2009). The verification of the time comparison result presented in this paper is conducted with UTC(KRIS)-UTC(NICT) calculated through the rapid UTCr provided by the BIPM.

Table 1. Properties of measurements for time comparison methods.

	TWSTFT	GPS CP	GPS P3 code
Track period (min)	5 (hourly)	5	16
Sample interval (s)	1	30	30
Averaging no.	300	10	26
Comparison method	Two-way	Common-view	All-in-view
Period of data	MJD 57268 ~ MJD 57321 (Sep. 03, 2015 – Oct. 26, 2015)		

The time comparison techniques and specifications of the measured results represented through the measurements for 53 days are summarized in Table 1. The TWSTFT time comparison is performed that UTC(KRIS) and UTC(NICT) are calculated in accordance with the measurement schedule of the TWSTFT Asia Link determined at every second and a measurement track of KRISS and NICT is assigned for five min in every hour. The GPS-based time comparison employs RINEX observation files measured in every 30 sec. During the GPS CP time comparison, a measurement track is set at five min thereby acquiring continuous measurement value in every five min. In the GPS P3 code time comparison, 16-min is defined as a single track according to the definition of the CGGTTS and initial 3-min measurement data are removed and the rest of 13-min measured data are used to perform time comparison measurements.

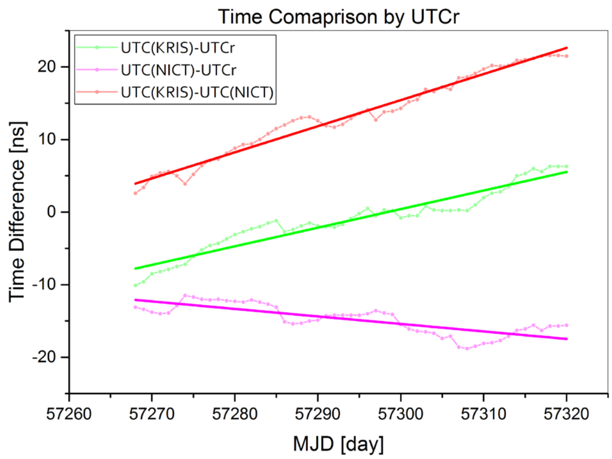

Fig. 4. Time comparison between UTC(KRIS) - UTC(NICT) by UTCr.

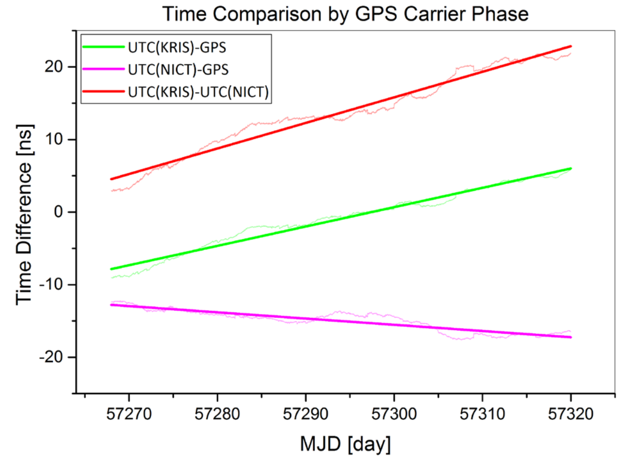

Fig. 6. Time comparison between UTC(KRIS) - UTC(NICT) by GPS CP.

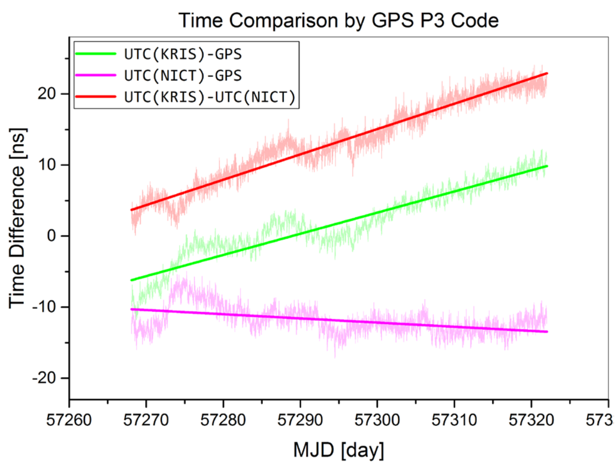

Fig. 5. Time comparison between UTC(KRIS) - UTC(NICT) by GPS P3 code.

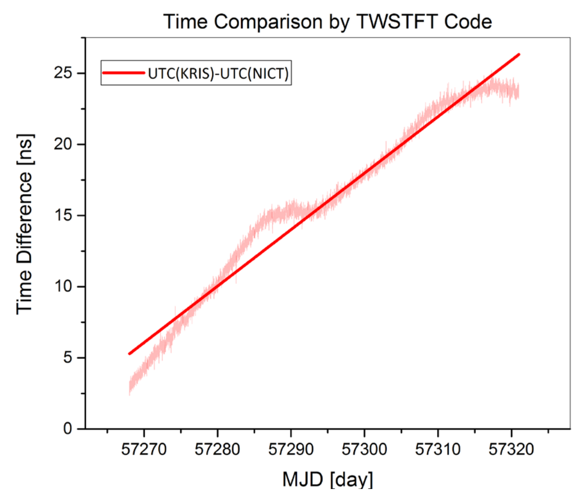

Fig. 7. Time comparison between UTC(KRIS) – UTC(NICT) by TWSTFT code

3.2 Comparison Between UTC(KRIS) and UTC(NICT)

In this section, time comparison results using TWSTFT, GPS P3 code, and GPS CP, which are described in the previous sections, are presented. Fig. 4 shows the result of time comparison of UTC(KRIS) and UTC(NICT) using the UTC(k) - UTCr data announced in every five days from the BIPM. As shown in the fig, UTC(KRIS) has a positive slope whereas UTC(NICT) has a negative slope. Figs. 5 and 6 show the time comparison results of GPS P3 code and GPS CP using measurement values of 16 min and 5 min intervals. The figs verified that a trend of slope is the same as the one using UTCr. The time comparison result by GPS CP revealed high precision of time comparison result but it had an initial phase offset due to the characteristic of carrier wave processing so the offset was estimated based on the time comparison result by GPS P3 code and corrected (Lee et al. 2015). Fig. 7 shows the result of time comparison by the TWSTFT code obtained using one-sec interval measurement values. Time comparison by TWSTFT does not use the GPS system in contrast with the time comparison methods by GPS P3 code and GPS CP. Instead, it uses two-way communication, which is the same as communication satellites. Fig. 8 shows frequency stability calculated to analyze performance of each time comparison method suggested in this paper. As shown in the fig, short-term stability within five min can be obtained by using TWSTFT, which cannot be measured using GPS P3 code or CP. This means that TWSTFT has an advantage of obtaining results about short-term stability within 5 min. The following results can be observed through Fig. 8. First, stability about time comparison results by GPS P3 code shall be over 5×10^5 s. approximately to have similar results by the GPS CP. This means that approximately six days or longer measurement data shall be used and averaged to get the similar time comparison performance with that using CP method. Second, the results using the GPS CP were the best

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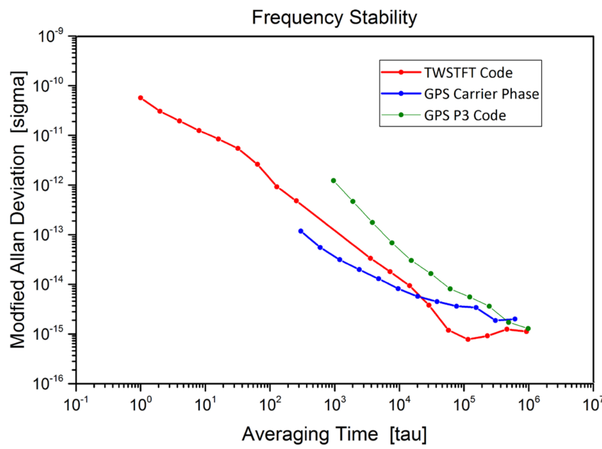

Fig. 8. Stabilities (τ = 1 s) between UTC(KRIS) - UTC(NICT) by TWSTFT code, GPS P3 code and GPS carrier phase.

until 2×10^4 s. approximately. This means that the best time comparison result when using the GPS CP can be obtained by using approximately six hours or less measurement data. Finally, the best time comparison performance can be observed by using the TSWTFT method after 2×10^4 s.

4. CONCLUSIONS

In this paper, time comparison results by GPS P3 code and GPS CP were compared in order to verify the performance of time comparison by TWSTFT. To do this, frequency stability of each time comparison method was verified via time comparison results by UTCr and modified Allan deviation. In the frequency stability results, since the measurement values using GPS CP and GPS P3 code had 5-min and 16-min intervals respectively, short-term frequency stability on shorter averaging time, τ,than the measurement interval cannot be verified. However, the best stability was revealed at the τ section within six hours duration approximately in the case of GPS CP and the best stability was revealed in a section longer than six hours duration in the TWSTFT time comparison method. The TWSTFT time comparison method requires higher construction and operation cost than other GPS-based time comparison methods and a number of limitations in the operation environment. However, it has the highest accuracy that can perform absolute time comparison in real time through correction campaign and precise delay measurement with transmitter and receiver on the basis of ground stations.

In the future, a study on time comparison method by TWSTFT will be focused on the direction of how to apply the TWSTFT carrier phase continuously. We expect the TWSTFT time comparison method to produce up to 10 times precision improvement compared to time comparison using the GPS CP. Through this study result, we concluded that time comparison technology can compare two remotely located clocks highly accurately so that it can be utilized not only time scale but also comparison and evaluation of next-generation frequency standards that are developed currently by the KRISS and oversea NMIs.

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