Carrier-phase two-way satellite frequency transfer over a very long baseline

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Abstract

In this paper we report that carrier-phase two-way satellite time and frequency transfer (TWSTFT) was successfully demonstrated over a very long baseline of 9000 km, established between the National Institute of Information and Communications Technology (NICT) and the Physikalisch-Technische Bundesanstalt (PTB). We verified that the carrier-phase TWSTFT (TWCP) result agreed with those obtained by conventional TWSTFT and GPS carrier-phase (GPSCP) techniques. Moreover, a much improved short-term instability for frequency transfer of \(2 \times 10^{-13}\) at 1 s was achieved, which is at the same level as previously confirmed over a shorter baseline within Japan. The precision achieved was so high that the effects of ionospheric delay became significant; they are ignored in conventional TWSTFT even over a long link. We compensated for these effects using ionospheric delays computed from regional vertical total electron content maps. The agreement between the TWCP and GPSCP results was improved because of this compensation.

Keywords: time and frequency transfer, frequency standards, carrier phase measurement

(Some figures may appear in colour only in the online journal)

1. Introduction

There is a need for synchronization between remote clocks in radio astronomy, particle accelerators, and metrology [1–3]. With the development of highly accurate optical clocks and an increase in the number of simultaneously controlled instruments, there has been a corresponding increase in the required accuracy for time and frequency transfer. Recently, there have been extensive studies regarding time and frequency transfer over optical fibres [4–6]. Time synchronization based on an Ethernet-based network has been developed to realize sub-nanosecond accuracy [7]. Moreover, optical frequency dissemination through optical fibre links enables the comparison of remote optical clocks and the measurement of the absolute transition frequency with reference to a remote caesium fountain clock without any limitations with respect to its accuracy [8, 9]. The transfer length exceeded 900 km [10].

Optical fibre links may be established for time and frequency transfer among various institutes located within the same continental region. However, it will be challenging to establish intercontinental optical fibre links. To make overseas connections, the utilization of satellite links such as GPS and two-way satellite time and frequency transfer (TWSTFT) will be indispensable, and there is a need to improve their measurement precision and accuracy [11, 12]. These techniques have been adopted since 1999 for the determination of Coordinated Universal Time (UTC) and International Atomic Time (TAI) [13]. Practically all institutes that maintain time and frequency standards adopt GPS time and frequency transfer to become part of the network of institutes collaborating in the realization of TAI with the BIPM. The use of GLONASS and Galileo has become more and more common practice, but in this paper we limit ourselves to use of GPS frequency transfer in parallel to carrier-phase TWSTFT (TWCP). In addition, some institutes also use TWSTFT as a method that is independent of GPS. Unfortunately, the measurement precision has not significantly improved since its implementation many years ago [14]. This is mainly due to the high costs for the lease of large bandwidths of transponder capacity on communication satellites.

Both TWSTFT and GPS utilize phase-modulated signals with pseudo-random noise codes, and the code phase has been
used to measure propagation time. The Coarse/Acquisition (C/A) code rate and carrier frequency of the GPS L1 signal are 1.023 Mega-chips-per-second (cps) and 1.57542 GHz, respectively [15]. The measurement precision realized by the C/A code is about 10 ns with an averaging time of 13 min for time transfer. With the implementation of GPS carrier-phase measurements (GPSCP), the precision was improved to several tens of picoseconds. On the other hand, a code rate of 2.5 Mcps is typically used in TWSTFT. The measurement precision (jitter) for 1 s data points is about 0.5 ns when taken with a carrier-to-noise density ratio of 55 dB Hz [16]. In the case where the carrier-phase measurement is implemented at about 10 GHz, we can expect the measurement precision to be improved by three orders of magnitude. Schäfer et al. demonstrated an intercontinental test result for a few hours [18]. The National Institute of Information and Communications Technology (NICT) confirmed that the result obtained using TWCP agreed with that of GPSCP over a short baseline of 100 km [11]. After this regional exercise, we performed a more ambitious TWCP experiment over one of the longest baselines worldwide with the intention to evaluate the error sources that would be otherwise negligible over a short baseline. Our target is to improve the measurement precision of TWSTFT in intercontinental links. This study covers availability, error sources, and uncertainty over a longer baseline for TWCP. First, we introduce the time difference using carrier-phase information. Next, we discuss the experimental equipment, results, and discussions. Finally, we present our conclusions.

2. Description of carrier-phase two-way satellite frequency transfer

Two Earth stations, A and B, work as a pair. Four sets of phase information are required to describe the time difference by TWCP using a commercial geostationary satellite because we have four unknown values: the time difference between the two stations, the phase fluctuation induced by the translation of the received to the transmitted signal at the satellite, and two geometrical distances between the satellite and the two stations involved. Each station transmits a signal and detects the phases of its own transmitted signal and that of the signal received from the counterpart station.

Uplink and downlink signal angular frequencies are expressed as \( \omega_a \) and \( \omega_d \), respectively; times of the reference clocks at station A and B are expressed as \( \tau_a(t) \) and \( \tau_b(t) \) in seconds, respectively; angular frequency of the translation onboard oscillator is expressed as \( \omega_t = \omega_a - \omega_d \); time of the onboard clock is expressed as \( \tau_d(t) \) in seconds. When a transmitted signal from station A, \( \sin(\omega_d t + \omega_t \tau_a(t)) \), arrives at the satellite, it shifts to \( \sin(\omega_d(t) + \omega_t \tau_d(t)) \) because of the Doppler effect. Here \( \omega_d(t) \) is given with the radial velocity \( v_r(t) \) from station A to the satellite as

\[
\omega_d = \omega_a \left( 1 - \frac{v_r(t)}{c} \right).
\]

Here \( c \) is the speed of light. The signal is down-converted by the onboard signal \( \sin(\omega_c t + \omega_t \tau_a(t)) \) to \( \sin[(\omega_c - \omega_a) t + \omega_a \tau_a(t) - \omega_c \tau_a(t)] \). When this signal arrives at station B, it shifts to \( \sin(\omega_d(t) + \omega_t \tau_d(t) - \omega_c \tau_a(t)) \) because of the Doppler effect. Using a local signal \( \sin(\omega_d + \omega_t \tau_d(t)) \) at station B, the received signal is finally down-converted to \( \sin[(\omega_d \tau_d(t) - \omega_a \tau_a(t) - \omega_c \tau_a(t)) \]. The angular frequency received at station B with the Doppler shift is expressed with the radial velocity \( v_b(t) \) from station B to the satellite as

\[
\omega_b''(t) = (\omega_a - \omega_b) \left( 1 - \frac{v_b(t)}{c} \right)
= \omega_a - \omega_b \frac{v_b(t)}{c} - \omega_a \frac{v_a(t)}{c} + \omega_b \frac{v_a(t)}{c} - \omega_b \frac{v_b(t)}{c}.
\]

In the case of a geostationary satellite, the quantity \( v(t)/c \) is in the range of \( 10^{-8} \) to \( 10^{-9} \). Thus, it is thought that the fourth term on the right hand side is less than \( 10^{-16} \) and negligible. To simplify the description, it is eliminated hereafter. The phase information of the signal includes the ionospheric and tropospheric delays along the signal path multiplied by the signal angular frequency including the Doppler shift. Considering the small magnitude of \( v(t)/c \) we neglect the effects of the Doppler shifts in the ionospheric and tropospheric delays. Accordingly, the phase information \( \phi_{ab}(t) \) in radians of the signal which is transmitted from station A and received at station B is given by

\[
\phi_{ab}(t) = \omega_a \tau_a(t) - \omega_a \tau_b(t) - \omega_a v_b(t)/c - (\omega_a \tau_a(t) + \omega_a \tau_b(t) + \omega_b \tau_b(t) + \omega_b \tau_a(t))/c + \omega_a v_a(t)/c - \omega_b \tau_a(t) - \omega_b \tau_b(t) - (\omega_b \tau_a(t) + \omega_b \tau_b(t) + \omega_b \tau_a(t))/c + \omega_b v_a(t)/c - \omega_b \tau_a(t) - \omega_b \tau_b(t) - \omega_b \tau_a(t)/c + \omega_b \tau_a(t) - \omega_b \tau_b(t) - \omega_b \tau_a(t)/c + \omega_b \tau_a(t) - \omega_b \tau_b(t) - \omega_b \tau_a(t)/c + \omega_b \tau_a(t) - \omega_b \tau_b(t) - \omega_b \tau_a(t)/c + \omega_b \tau_a(t) - \omega_b \tau_b(t) - \omega_b \tau_a(t)/c + \omega_b \tau_a(t) - \omega_b \tau_b(t) - \omega_b \tau_a(t)/c.
\]

Here \( \rho_{as} \) and \( \rho_{bs} \) are the geometrical distances between the satellite and stations A and B, respectively. \( T_a \) and \( T_b \) are tropospheric delays in seconds and are frequency independent over stations A and B, respectively. \( I_{ij} \) is the ionospheric delay correction term in seconds with frequency \( f_i \) \((i = u \text{ or } d)\) at position \( j \), which can be represented as follows:

\[
I_{ij}(t) = \frac{40.3 \cdot \text{TECU}(i)}{c \cdot f_i^2}
\]

The total electron content, the total number of free electrons along the signal path at position \( j \), which is conventionally measured in TEC units, \( 1 \text{ TECU} = 10^{16} \text{ electrons/m}^2 \). \( f_u \) and \( f_d \) are the uplink and downlink frequencies, respectively.

Similarly, the phase information from B to A, from A to B, and from B to A, are respectively represented by

\[
\phi_{ba}(t) = \omega_b \tau_b(t) - \omega_b \tau_a(t) - \omega_d \tau_d(t) - (\omega_b \rho_{ba}(t) + \omega_d \rho_{ba}(t))/c + \omega_b \tau_a(t) + \omega_d \tau_b(t) + \omega_d T_b(t) + \omega_d T_a(t),
\]

\[
\phi_{ab}(t) = \omega_a \tau_a(t) - \omega_a \tau_b(t) - \omega_c \tau_a(t) - (\omega_a \rho_{ba}(t) + \omega_c \rho_{ba}(t))/c + \omega_a \tau_b(t) + \omega_c \tau_b(t) + \omega_c T_b(t) + \omega_c T_a(t),
\]

\[
\phi_{ba}(t) = \omega_b \tau_b(t) - \omega_b \tau_a(t) - \omega_c \tau_b(t) - (\omega_b \rho_{ba}(t) + \omega_c \rho_{ba}(t))/c + \omega_b \tau_a(t) + \omega_c \tau_a(t) + \omega_c T_a(t) + \omega_c T_b(t).
\]
In general, the geometrical distance from station A to the satellite and the corresponding distance from station B to the satellite are not symmetrical. As a result, there is a difference in the arrival times of signals from stations A and B at the satellite. This difference is generally a few milliseconds [19]. We assume that the onboard translation oscillator signal is stable during this time difference, and the induced phase jitter is negligible and thus consider only the one unknown \( \tau_i \) in all equations (3), (5)–(7).

By subtracting equation (3) from equation (5),

\[
\phi_{ab}(t) - \phi_{ba}(t) = \omega_s(\tau_A(t) - \tau_B(t)) + \omega_\rho(\rho_a(t) - \rho_b(t))/c \\
- \omega_u(I_{ab}(t) - I_{ba}(t)),
\]

and (6) and (7),

\[
\phi_{ab}(t) - \phi_{ba}(t) = \omega_\rho(\rho_a(t) - \rho_b(t))/c \\
+ \omega_u(I_{ab}(t) - I_{ba}(t)) + \omega_u(I_{ba}(t) - I_{ab}(t))
\]

the terms related to the onboard signal are cancelled. Here, \( \omega_\rho \equiv \omega_s + \omega_u \) and \( \omega_u \equiv \omega_a - \omega_b \) apply.

In TWCP, the geometrical distances in equations (8) and (9), \( \rho_a \) and \( \rho_b \), are unknown. Therefore, it is necessary to further subtract these intermediate results to cancel them.

\[
\begin{align*}
\omega_s(\phi_{ab}(t) &- \phi_{ba}(t)) - \omega_u(\phi_{ab}(t) - \phi_{bb}(t)) \\
&= (\omega_s^2 - \omega_u^2)(\tau_A(t) - \tau_B(t)) \\
&+ 2\omega_s\omega_u[I_{ab}(t) - I_{ba}(t)] - (I_{ba}(t) - I_{ab}(t)).
\end{align*}
\]

The time difference between stations A and B is finally computed as follows:

\[
\tau_a(t) - \tau_b(t) = \frac{\omega_s\alpha(t) - \omega_u\beta(t)}{\omega_s^2 - \omega_u^2} + \frac{2\omega_s\omega_u}{\omega_s^2 - \omega_u^2}[I_{ab}(t) - I_{ba}(t) - (I_{ba}(t) - I_{ab}(t))].
\]

Here the tropospheric delays are cancelled. On the right hand side of equation (11), the first term is derived from the four observed phases, and the second one is for ionospheric delay correction. Typically, TWSTFT uses uplink and downlink frequencies of 14 GHz and 11 GHz, respectively. In this case, the coefficients of \( \omega_s/(\omega_s^2 - \omega_u^2) \) and \( \omega_u/(\omega_s^2 - \omega_u^2) \) become \( 7 \times 10^{-12} \) and \( 8 \times 10^{-13} \), respectively. Thus, a measurement precision of \( 10^{-13} \) seconds can be expected when the phase detection has a resolution of less than 0.1 rad.

When TEC\(_j\)(t) is obtained by other methods such as a theoretical model or actual measurement, the ionospheric correction term can be calculated. The ionospheric delay needs to be considered carefully because of the frequency difference between uplink and downlink and the TEC difference between the ionospheres at stations A and B. The TWCP frequencies are, however, higher than those used in GPS such that the effect due to the ionosphere (prop. \( 1/f^2 \)) is smaller than that encountered in GPS time transfer. The amplitude could be up to a few hundred picoseconds, and is assumed to be negligible in conventional TWSTFT (hereafter TWCode), but it cannot be neglected in TWCP.

### 3. Experimental setup

The TWCP experiment was performed using a link between NICT and Physikalisch-Technische Bundesanstalt (PTB) by employing the geostationary communication satellite AM-2 located at a longitude of 80 degrees east. The actual distance between the two sites is approximately 9000 km, making it one of the longest baselines in the world. In parallel, TWCode measurement was performed once every hour using the same satellite that has been used to link Asian and European laboratories belonging to the TAI networks [13]. The satellite IS-4 was used for this purpose for many years. Due to its malfunction four years ago, however, it was replaced by the satellite AM-2 to continue the link. The TWCP measurement was performed using a narrow frequency band with a bandwidth of 200 kHz, whose centre frequency is 2 MHz higher than the frequency band of 2.5 MHz used for TWCode measurements. Because of limited transponder working time, the measurements were continuously performed only from 12:00 UTC to 22:00 UTC every day. The frequency parameters are listed in table 1.

The experimental setup is shown in figure 1. In each station we employed a narrow-band pseudo-random noise signal to reduce the rental fee for the satellite transponder and to avoid effects due to fading or interference between the signals transmitted simultaneously from the two sites. To generate such a signal, we used an arbitrary waveform generator (AWG) developed for a dual pseudo-random-noise experiment [20, 21]. Pseudo-random noise of 127.75 kcps, which consisted of a maximum-length-sequence code with a length of 511 bits, was generated by the AWG whose output bandwidth was limited by a 200 kHz digital filter. In addition, it had a feature to overlay 50 bps data, allowing it to identify the start of a code pattern which is synchronized with the external 1 pps, and to reduce the interference between codes. A signal with a centre frequency of 70 MHz, which was generated by the AWG, was then up-converted to a higher 14 GHz frequency using a frequency up-converter (U/C). The signal was amplified by a solid-state power amplifier (SSPA) and fed to the antenna. Both stations used a different code in their transmission path.

The signal received by the antenna with a centre frequency of 11 GHz was amplified by a low-noise amplifier (LNA) and down-converted to 70 MHz by a frequency down-converter (D/C). The U/C and D/C were phase locked to external 10 MHz signals. The signal passed through a band-pass filter (BPF) with a frequency bandwidth of 2 MHz, and it was amplified by an additional amplifier. Then, it was sent to an analogue-to-digital (A/D) sampler. The A/D sampler was originally developed for very low-baseline interferometry (VLBI) [22]. Data sampling was performed with a sampling rate of 64 MHz.

### Table 1. Link parameters.

| Parameters          | TWCP | TWCode |
|---------------------|------|--------|
| Uplink centre MHz   | 14260| 14260  |
| Downlink centre MHz | 10960| 10960  |
| Bandwidth MHz       | 0.2  | 2.5    |
Figure 1. Earth station configuration for NICT-PTB TWCP measurement. U/C: frequency up-converter, D/C: frequency down-converter, SSPA: solid-state power amplifier, LNA: low-noise amplifier, BPF: band-pass filter, amp: amplifier, AWG: arbitrary waveform generator, A/D sampler: analogue-to-digital sampler. The instruments in grey colour were not used in the TWCP measurement.

in synchronized timing with the external reference signals of 10 MHz and 1 pps. After splitting the sampled data into in-phase and quadrature components, the cross correlation with a replica code, group delay, and carrier-phase detection were sequentially conducted in the computer. Each antenna received two pseudo-random noise signals, that is, its own and the one transmitted from the counterpart station. Therefore two data-processing sequences ran in parallel. The code and carrier-phase information was then written every 20 ms. Finally, the midpoint of the second-order fit to the 50 data points obtained during each second was defined as the data at that second. With the exception of the AWG and A/D sampler, the instruments were identical to those used for TWCode stations.

The PTB station was dedicated for conducting TWCP measurements; it was equipped with a 1.8 m antenna dish. The elevation angle was 3.7°. The PTB station was connected to UTC(PTB) signals of 1 pps and 10 MHz. UTC(PTB) is derived from a steered active hydrogen maser [23] and the frequency stability is at the 10−15 level for averaging times exceeding 104 s. Because the PTB station was located a few hundred metres away from the building in which hydrogen masers are operated and the UTC(PTB) time scale is realized, the reference signals of 10 MHz and 1 pps were distributed using a 500 m long optical fibre link. It was confirmed that the distribution instability was sufficiently small compared with the stability of the reference signal without any fibre-length stabilization.

On the other hand, the NICT station with a 2.4 m dish was shared by the TWCode and TWCP measurements. The elevation angle was 16.0°, and both measurements were performed simultaneously. The 200 kHz and 2.5 MHz wide signals at sufficiently different carrier frequencies were generated by the AWG and a TWCode modem, respectively, and were combined after the frequency up-conversion from 70 MHz to 14 GHz to avoid the generation of inter-modulation. The received signal was split into two components after amplification by the LNA, and the two components were input into different D/Cs. The 200 kHz signal was separated from the 2.5 MHz TWCode signal by the BPF. We confirmed that there was no degradation in the measurement precision caused by the combined processing of the two signals. The NICT station was connected to UTC(NICT) signals of 1 pps and 10 MHz. UTC(NICT) is generated from a steered active hydrogen maser and the frequency stability is at the 10−15 level for averaging times exceeding 104 s [24].

4. Error sources over a very long baseline
4.1. Compensation for ionospheric delay

Because ionospheric delay is inversely proportional to the square of the signal frequency, it is not cancelled out in TWSTFT because of the frequency difference between the uplink and downlink. In TWCode, it is assumed that the impact of the ionospheric delay is negligible [25]. On the other hand, it should be considerable in the TWCP link taking the high performance into account. Because the TWCP measurement is carried out using a pair of uplink and downlink frequencies, the TEC along the signal path cannot be measured; two downlink frequencies would be needed as is the case when
a dual-frequency GPS receiver is employed. We read out the vertical total electron content (VTEC) over NICT and PTB from some VTEC maps and compensated for the ionospheric delays present in the TWCP result. The Center for Orbit Determination in Europe (CODE) [26] generates the Global Ionosphere Map (GIM) based on observations that are made at about 150 GPS sites around the world. The GIM provides VTEC maps with a time resolution of 2 h and latitude/longitude resolution of $2.5^\circ/5.0^\circ$. It is assumed that the VTEC is present in an infinitely thin layer at a height of 450 km. To compute the VTEC $E$ at latitude $\beta$, longitude $\lambda$, and universal time $t$, we first read out four VTEC values, $E_0,0$, $E_1,0$, $E_0,1$, $E_1,1$, at epoch $T_i$ around the coordinates $(\lambda, \beta)$ and perform grid interpolation:

$$E_i(\beta, \lambda) = E_i(\lambda_0 + p \Delta \lambda, \beta_0 + q \Delta \beta)$$

$$= (1 - p)(1 - q)E_{0,0} + p(1 - q)E_{1,0} + q(1 - p)E_{0,1} + pqE_{1,1},$$

(12)

where $0 \leq p < 1$ and $0 \leq q < 1$. $\Delta \lambda$ and $\Delta \beta$ are the grid resolutions in longitude and latitude, respectively. Then, we perform the interpolation of time using the consecutive VTEC maps:

$$E(\beta, \lambda, t) = \frac{T_{i+1} - t}{T_{i+1} - T_i}E_i(\beta, \lambda) + \frac{t - T_i}{T_{i+1} - T_i}E_{i+1}(\beta, \lambda),$$

(13)

where $T_i \leq t < T_{i+1}$. Next, we compute a slant TEC along the signal path from VTEC $E(\beta, \lambda, t)$ using the elevation angle $z$ of an Earth station to a communication satellite.

$$z' = \sin^{-1}\left[\frac{R \sin(\pi/2 - z)}{R + h}\right],$$

(14)

$$\text{TEC}(\beta, \lambda, t) = \frac{E(\beta, \lambda, t)}{\cos z'}.\text{ (15)}$$

where $R$ is the radius of the Earth and $h$ is the height of the ionosphere [15]. Thus, the ionospheric delay over an Earth station in TWSTFT is derived using equation (4) and TEC$(\beta, \lambda, t)$ computed from a VTEC map [27]. However, the time resolution and grid interval of the GIM are not sufficiently dense considering the TWCP measurement rate of every second. Therefore, we adopted regional VTEC maps provided by the Royal Observatory of Belgium (ROB) [28] and NICT [29] over Europe and Japan, respectively. The ROB VTEC map is based on real-time GPS observations obtained from more than 100 sites belonging to the EUREF Permanent Network [30]. The grid interval is $(0.5^\circ, 0.5^\circ)$, and the time resolution is 15 min. On the other hand, the NICT VTEC map is generated using the GPS Earth Observation Network (GEONET) data from about 200 sites in Japan [31], and its grid interval is $(2.0^\circ, 2.0^\circ)$, while its time resolution is also 15 min.

We first evaluated the disagreement between NICT and ROB VTEC maps and the GIM. In addition, the VTEC values were calculated from CGGTTS data [32] of dual-frequency GPS receivers at NICT and PTB using equations (4), (14) and (15). Since the GPS receivers have multi channels, the mean values of each measurement epoch every 16 min were calculated. Figures 2(a) and (b) show the VTEC values over NICT and PTB, which were derived from NICT and ROB VTEC maps, GIM and GPS data. Time and grid interpolation was performed as previously described. The time resolutions were 15 min, 1 h and 16 min for the results using
Table 2. Delay variation sources over a very long baseline TWCP link.

| Item                              | Amplitude in time(ps) |
|-----------------------------------|-----------------------|
| phase jitter in satellite transponder | unknown              |
| phase jitter in instruments        | 0.2 frequency converter |
| phase variation in instruments     | 100                   |
| ionosphere                         | 100                   |
| troposphere                        | 2.5                   |
| Sagnac effect                      | 10 to 150             |
| second order Doppler shift         | 2                     |

NICT and ROB VTEC maps, GIM, and GPS, respectively. We found that the disagreement between the NICT VTEC map and GIM was always less than 6 TECU, the maximum difference between the NICT VTEC map and the result by GPS was 7 TECU. In particular, the ROB VTEC map shows a good agreement with GIM and the result by GPS. Thus the regional VTEC maps were considered appropriate for our purpose and were employed for compensation because of their high time resolution. Figure 2(c) depicts the calculated ionospheric delays described in equation (11) and figure 2(d) shows the converted frequency variations whose data spacing is 15 min. The result by GPS shows a larger frequency deviation; however, the mean value looks consistent with those by GIM and the regional VTEC maps. Depending on the VTEC maps utilized, no significant differences were observed. The amplitudes exceeding 100 ps are caused by amplification by GIM and the regional VTEC maps. Depending on the deviation; however, the mean value looks consistent with those obtained using the IS-4 satellite varied from several hundred picoseconds to several tens of picoseconds, depending on the satellite’s orbit. On the other hand, amplitudes of only some tens of picoseconds were computed in the case involving the AM-2 satellite. Evidently, the position of the AM-2 satellite is more tightly controlled than that of the IS-4 used to be. Here, we do not take this correction into account.

In equation (3), the term of the second-order Doppler shift $v_a/c - v_b/c$ is negligible. We measured the magnitudes of $v_a/c$ using the IS-4 and AM-2 satellites, which had a maximum value of $10^{-9}$ and less than $10^{-8}$, respectively. Thus, it is thought that the term induces a maximum instability of $10^{-16}$ with a diurnal pattern. Accordingly, we estimated an amplitude of 2 ps, and we do not consider a correction.

4.3. Environmental effect

During TWCP measurements, we observed some phenomena that may have been related to the outdoor instruments and temperature. Transmission power decreased by about 10 dB when the outdoor temperature at PTB increased to more than 30°C. The measurement precision of TWCP degraded by a factor of four during the daytime, as shown in figure 3, when the outdoor temperature was above 30°C at NICT. There were little changes in the transmission power. The former occurred in June 2013 at PTB, while the latter occurred during the common clock measurement using two antenna dishes performed at NICT in August 2013. We checked the output power levels of the indoor instruments and confirmed that they had not changed in both cases.

For the former case, one possible explanation is that the SSPA (see figure 1) was affected by the heat, and the gain...
gaps in the TWCP and TWCode results because of the limited recorded in RINEX 2.1 format. There were measurement they performed dual-frequency code and phase measurements the outdoor temperature in the common clock measurement at NICT. installed equipment to fully utilize the performance of TWCP. be required to avoid heating and temperature variations on the variation may be enlarged by the local time difference. It would long baseline, the phase variation attributed to the temperature of the outdoor instruments. In particular, in the case of a very concluded that more attention should be paid to the condition outdoor temperature rise caused the phase jitter to increase. We did not vary much at the NICT station, it is thought that the LNA was temperature-stabilized and the indoor temperature with that in the night-time, as shown in figure 3. For the common clock measurement in the latter case, in particular, there was a daily variation with an amplitude of about 20 ps, and it had a correlation with the variation of the outdoor temperature. In addition, the short-term instability observed during the daytime was clearly degraded compared with that in the night-time, as shown in figure 3(a). Because the LNA was temperature-stabilized and the indoor temperature did not vary much at the NICT station, it is thought that the outdoor temperature rise caused the phase jitter to increase. We concluded that more attention should be paid to the condition of the outdoor instruments. In particular, in the case of a very long baseline, the phase variation attributed to the temperature variation may be enlarged by the local time difference. It would be required to avoid heating and temperature variations on the installed equipment to fully utilize the performance of TWCP.

5. Link performance

5.1. Time and frequency transfer

The TWCP experiment was performed from March to June 2013 and the time difference between UTC/NICT and UTC/PTB was measured. The result was compared with those achieved by TWCode and GPSCP for the evaluation. The GPS receivers that were used are listed in table 3, and they performed dual-frequency code and phase measurements recorded in RINEX 2.1 format. There were measurement gaps in the TWCP and TWCode results because of the limited working time of the satellite transponder between 12:00 UTC and 22:00 UTC. The phase discontinuity in the TWCP was filled by an integral multiple of a number to fit the result of GPSCP2. The numbers of the cycle slips in the phases $\phi_{ab}, \phi_{ba}, \phi_{bb}, \phi_{bb}$ are assumed as $n_{ab}, n_{ba}, n_{aa}, n_{bb}$, which are not necessarily the same because the phase information is detected by two independent data-processing sequences at two stations. With the amplitude $A = 1/(\omega_{aa}^2 - \omega_{bb}^2)$, the offset $t_N$ in time due to the cycle slips is written as $t_N = A[(n_{ab} - n_{ba})\omega_{ba} - (n_{aa} - n_{bb})\omega_{bb}] = A(t_{aa} - t_{bb})$. Here $n$ and $m$ are arbitrary integers. Since the minimum resolution of $t_N$ is $A\omega_{bb}$, an integral multiple of $A\omega_{bb}$ is used to fill a gap in a TWCP result. In the subsequent case, it was about 0.8 ps.

Figure 4(a) shows the measurement results obtained using TWCode, GPSCP1, GPSCP2, and TWCP. Offset values are applied to the plot for better visibility. The TWCode measurement was performed once every hour. In each measurement, the midpoint of the second-order fit for 5 min (300 data points) was calculated. The TWCP measurement was continuously performed while the transponder was available, where data were taken every second. The mean values over 5 min are depicted in figure 4. The GPSCP results were computed every 5 min as well [35]. The white squares indicate the time difference published in the Circular T 304 [36]. The time link between PTB and NICT adopted for TAI is built on GPSPPP, and the same receiver data are used by BIPM as in this study. It is clear that the TWCP results agree with that of TWCode within the large dispersion of the TWCode data. On the other hand, TWCP and GPSCP2 show a good agreement because the phase ambiguity in the TWCP result was compensated to fit to GPSCP2. Further, it appears that it is also almost consistent with GPSCP1. A detailed comparison between GPSCP and TWCP is discussed in the next subsection.

Figure 4(b) shows their frequency instabilities presented in the modified Allan deviation, which were from 1 April to 30 April 2013. The TWCP instabilities that were both measured on 1 April 2013 and 300 s averaged from 1 April to 30 April were depicted. We confirmed that an instability of $2 \times 10^{-13}$ at 1 s was possible by TWCP over such a very long baseline. The instability obtained by TWCP reaches a level below $10^{-14}$ after an average time of 200 s. On the other hand, those obtained by GPSCP2 and TWCode reached the same level only after 3600 s and 46 800 s, respectively. At observation times exceeding one day, the comparisons are limited by the combined frequency instability of the two time scales/clocks involved at NICT and PTB. Therefore a detailed analysis using double differences is given in the following section.

| Table 3. GPS receivers used for the NICT–PTB link. |
|-----------------------------------------------|
| Caption | Receiver at PTB | Receiver at NICT |
| GPSCP1 | ASHTECH Z-XIIIT | Septentrio PolaRx2 TR |
| GPSCP2 | ASHTECH Z-XIIIT | ASHTECH Z-XIIIT |

![Figure 3.](image-url)
formed which should be free of clock noise. Figure 5(a) shows the double differences in delay between GPSCP2 and TWCP with and without ionospheric compensation. The data were averaged for 1 h and then subtracted. Here GPSCP1 and GPSCP2 are ionosphere free. The data of GPSCP1 were not adopted in the plot because there were some discontinuities. As shown in figure 2(c), the ionospheric delay has its maximum close to 0:00 UTC. Therefore, the disagreement between GPSCP2 and TWCP follows a similar signature. However, it was improved by compensating for the ionospheric delay. The achieved frequency instabilities expressed by the modified Allan deviation are depicted in figure 5(b), and the $10^{-16}$ level is reached after 40000 s. Those having the ionospheric compensation show slightly better values. The dashed line shows the impact due to the ionospheric delay in the NICT–PTB TWCP link, which is at the low $10^{-16}$ level for an averaging time of one day. From this result, we deduce that averaging for longer than one day will be effective in reducing the influence in the case that 24 h continuous measurements will be possible.

The frequency differences for GPSCP1–TWCP, GPSCP2–TWCP, and GPSCP1–GPSCP2 are shown in figure 6 (1 day from 12:00 to 22:00 average values). Outliers exceeding three times the standard deviation were previously removed. In the TWCP results, we compensated for the ionospheric delay. Their differences in March and April 2013 are listed in table 4. Without the ionospheric compensation, the values of GPSCP1–TWCP and GPSCP2–TWCP are $1.24 \times 10^{-15}$ and $1.44 \times 10^{-15}$, respectively. From these results, it is clear that compensation leads to improved consistency. The difference between GPSCP1 and GPSCP2 was caused
by the GPS receiver used at NICT. When we limited the data’s available time from 12:00 to 22:00 in UTC, that is, the satellite transponder working time, the frequency difference between GPSCP1 and GPSCP2 became larger. From this result, the limited measurement period may have contributed to the difference in frequency. In other words, any error source that exists with daily variations may remain in both TWCP and GPSCP. As a result, a frequency offset may be induced by limiting the measurement time. We used the regional VTEC maps to compensate for the ionospheric delay; we have to limit the measurement period. We used the regional VTEC maps to compensate for the ionospheric delay; we have to limit the measurement period. We used the regional VTEC maps to compensate for the ionospheric delay; we have to limit the measurement period. We used the regional VTEC maps to compensate for the ionospheric delay; we have to limit the measurement period. We used the regional VTEC maps to compensate for the ionospheric delay; we have to limit the measurement period. We used the regional VTEC maps to compensate for the ionospheric delay; we have to limit the measurement period. We used the regional VTEC maps to compensate for the ionospheric delay; we have to limit the measurement period. We used the regional VTEC maps to compensate for the ionospheric delay; we have to limit the measurement period.

Table 4. Frequency differences in March and April 2013 (× 10−15).

| Caption | Frequency difference | Standard uncertainty | No of points |
|---------|----------------------|----------------------|--------------|
| GPSCP1−TWCP (12−22 h) | −0.56 | 0.33 | 446 |
| GPSCP2−TWCP (12−22 h) | −0.95 | 0.32 | 453 |
| GPSCP1−GPSCP2 (full day) | 0.47 | 0.19 | 1257 |
| GPSCP1−GPSCP2 (12−22 h) | 0.79 | 0.28 | 442 |

6. Conclusion

We performed a TWCP experiment between NICT and PTB, and we confirmed that TWCP is possible over very long baselines, ranging up to about 9000 km. The result showed good agreement with those measured by TWCode and GPSCP, and a short-term instability of 2 × 10−15 at 1 s was achieved. It is clear that the measurement precision is superior to that of TWCode and GPSCP, and it is independent of the baseline length. On the other hand, the effect of the ionospheric delay is more noticeable over a long baseline. We computed the ionospheric delays using the local VTEC maps provided by ROB and NICT and found that the amplitude reached about 100 ps. The disagreement between TWCP and GPSCP was decreased by the compensation. The modified Allan deviation of GPSCP−TWCP was improved and reached the 10−16 level. Meanwhile, there remains a frequency disagreement between them at the 10−16 level. One possible explanation is that there is an instability due to a daily variation, which induced the frequency offset caused by the limited measurement time. The long-term instability should be further evaluated by performing a 24 h operation. In addition, it may be necessary to improve the environment in which the instruments are installed, when the high performance of TWCP shall be utilized.

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