Advanced two-way satellite frequency transfer by carrier-phase and carrier-frequency measurements

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Abstract. Carrier-phase measurement is one of the ways to improve the measurement resolution of two-way satellite frequency transfer. We introduce two possible methods for carrier-phase measurement: direct carrier-phase detection identified by Two-Way Carrier-Phase (TWCP) and the use of carrier-frequency information identified by Two-Way Carrier Frequency (TWCF). We performed the former using an arbitrary waveform generator and an analog-to-digital sampler and the latter using a conventional modem. The TWCF measurement using the modem had a resolution of $10^{-13}$ and the result agreed with that obtained by GPS carrier-phase frequency transfer in a 1500 km baseline. The measurement accuracy may have been limited by the poor frequency resolution of the modem; however, the TWCF measurement was able to improve the stability of conventional two-way satellite frequency transfer. Additionally, we show that the TWCP measurement system has the potential to achieve a frequency stability of $10^{-17}$.

1. Introduction

Recently developed optical clocks require a highly stable frequency transfer technique [1]. Optical-fiber frequency transfer enables optical-clock comparison without any degradation of the clock accuracy of $10^{-17}$ or better [2]. However, this method is physically dependent on existing optical-fiber networks. The procurement of optical fiber link is sometimes difficult from a viewpoint of the rental cost of optical fibers. Additionally, the use of submarine cables is necessary for intercontinental frequency transfer, whose availability remains unclear. As a result, we occasionally have to depend on satellite-based frequency transfer techniques such as GPS frequency transfer and two-way satellite time and frequency transfer (TWSTFT) [3, 4]. In TWSTFT, paired earth stations transmit and receive modulated signals by code sequences via a geostationary satellite and determine the propagation delay of the signal transmitted from the counterpart station from the code phase. The time difference between the paired stations is calculated from the difference between the two delays. The measurement is typically carried out using a commercially available instrument for signals modulation and demodulation called a modem. The stability, which is at the low $10^{-15}$ level in one day, is insufficient in comparison with that of optical clocks [5]. Since the measurement resolution for a code phase is inversely proportional to the chip rate, a higher chip rate gives a higher measurement resolution. At the same time, the signal bandwidth becomes broader, which means that a higher satellite-link cost is necessary. Thus, it is not easy to obtain better measurement resolution by increasing the chip rate. In a recently reported frequency transfer by GPS precise point positioning (PPP)
with integer ambiguity resolution, an accuracy in fractional frequency uncertainty of $1 \times 10^{-16}$ was obtained in a few days [3]. We also implemented a carrier-phase measurement to improve the stability of TWSTFT and established a carrier-phase two-way satellite frequency transfer technique (TWCP) [6]. So far, we have used an analog-to-digital (A/D) sampler [7] to detect the carrier phase and have succeeded in improving the measurement resolution to the $10^{-15}$ level. Additionally, we performed TWCP measurement with a very long baseline of 9000 km and confirmed that it was operational, and the result agreed well with that obtained by GPS carrier-phase (GPS CP) frequency transfer [8]. To achieve the general versatility of advanced two-way satellite frequency transfer measurement, we perform measurement using TWCF data recorded by a modem (here, the A/D sampler is not used). This may enable the improvement of the measurement resolution since all the participating stations in TWSTFT own the modem. In TWCF, the calculation of frequency difference between paired stations requires the Doppler coefficient in addition to carrier-frequency data of four signals [9]. The Doppler coefficient can be given from the ranging measurement using the code-phase since the code-phase measurement is simultaneously carried out by the modem. The thus obtained results and a comparison between TWCP and TWCF are introduced in this paper.

2. Measurement setup

2.1. TWCP

Figure 1(a) shows a schematic of the earth station used for TWCP measurement. We typically use a 1.8 m parabolic antenna. A signal modulated by a code sequence is generated at a frequency of 70 MHz by an arbitrary waveform generator (AWG). The measurement scale is the carrier phase. However, a chip rate of about 128 kHz is used to assist the signal tracking. The signal bandwidth has previously been limited to 200 kHz when the waveform file is generated. This bandwidth is helpful for reducing the satellite-link cost and is about 10 times narrower than that used in conventional TWSTFT. The phase of the reception signal is sampled by an A/D sampler and the carrier phase is detected. The U/C, D/C, AWG and A/D sampler are phase-locked to the external reference at 10 MHz. Additionally, the head of the code sequence generated by the AWG is synchronized to an external 1 pulse-per-second (pps) signal. The sampling by the A/D sampler is also carried out synchronously to the 1 pps signal.

Figure 1. Configuration of earth stations for TWCP (a) and TWCF (b). SSPA: solid-state power amplifier, LNA: low-noise amplifier, U/C: frequency upconverter, D/C: frequency downconverter, AWG: arbitrary waveform generator, A/D: analogue to digital, BPF: bandpass filter.
2.2. **TWCF**

Figure 1(b) shows a schematic of the earth station for TWCF measurement, which is identical to that for conventional TWSTFT measurement. The modem generates a modulated signal by a code sequence. The chip rate can be chosen from different options. In the TAI time-transfer network, 1 MHz or 2.5 MHz is typically adopted. The BPF is installed in the transmission and reception paths to limit the signal bandwidth.

3. **Measurement results**

3.1. *Common clock measurement*

![Figure 2](image)

**Figure 2.** Results of common clock measurement. (a), (b): Phase and frequency differences obtained by TWCP, (c): frequency difference obtained by TWCF.

We evaluated the systematic instability of TWCP and TWCF by common-clock measurements which are free from the stability of the reference clock, ionosphere delay and the effects of the satellite orbit. Figure 2 depicts the results of the common clock measurements by TWCP and TWCF via a satellite. Two independent earth stations at National Institute of Information and Communications Technology (NICT) and the same uplink and downlink frequencies were used for both measurements, where 1 data point per second was available. For the TWCF measurement, a chip rate of 2.5 MHz was adopted. Figures 2(a) and (b) show the time and frequency differences obtained by TWCP, respectively. Figure 2(c) depicts the frequency difference obtained by TWCF. It can be clearly seen in Figure 2(a) that the daily phase variations were synchronized with those of the outdoor temperature. The mean frequency differences in Figures 2(b) and (c) were $-3.5 \times 10^{-18}$ and $-6.0 \times 10^{-16}$, respectively. Figure 3 shows the modified Allan deviation of the common clock measurements. The TWCF result appears to be slightly noisier than the TWCP result, however, measurement resolution at the $10^{-13}$ level was obtained, which reached the $10^{-16}$ level after an averaging time of a few hours. The resolution of the carrier frequency was limited to the mHz level by the modem, which determined the TWCF resolution at the $10^{-13}$ level. However, the TWCF result obtained is better than those previously reported [9, 10]. The green inverted triangles depict the TWCP result of internal loop measurement configured using the AWG, U/C, D/C and A/D sampler, that is, without the satellite. From the other measurement result carried out using the AWG and A/D sampler, we found that the phase noises due to the U/C and D/C determine the slope of the common-clock instability. The long-term instability of TWCP is clearly limited by the
phase noise. However, the result indicates that TWCP has the potential to reach a frequency stability of $10^{-17}$.

![Figure 3](image)

**Figure 3.** Modified Allan deviation of common clock measurements. Internal-loop measurement refers to the common clock measurement by TWCP without the satellite, that is, configured using the AWG, U/C, D/C and A/D sampler.

### 3.2. TWCF measurement with zero baseline between UTC(NICT) and a H-maser

To evaluate the measurement accuracy, we measured the frequency difference between UTC(NICT) and a hydrogen maser (H-maser) by TWCF and using a phase comparator. Two earth stations were connected to UTC(NICT) and the H-maser signals. The resultant frequency differences almost agreed as shown in Figure 4(a). The frequency stability expressed in terms of modified Allan deviations is depicted in Figure 4(b). Owing to the high stability of the H-maser, we obtained stability at the $10^{-16}$ level. The mean frequency differences obtained by TWCF and using the phase comparator were $-698.0 \times 10^{-15}$ and $-696.1 \times 10^{-15}$, respectively, when the outliers were removed. The difference was $-1.9 \times 10^{-15}$. On the other hand, we performed the similar measurement by TWCP to evaluate its accuracy. We confirm that the frequency difference between the results obtained by TWCP and using the phase comparator is $1 \times 10^{-16}$ [11].

### 3.3. TWCF measurement with 1500 km baseline between UTC(NICT) and a H-maser

As the next step, we performed TWCF measurement between the NICT Koganei headquarters and our Okinawa site. Okinawa is in the southwest of Japan and about 1500 km away from Koganei. There is an earth station with a 1.8 m dish and a H-maser at the Okinawa site. We measured the frequency difference with respect to UTC(NICT) by TWCF and the GPS carrier phase (GPS CP) [12] and compared the results. Unfortunately the measurement period was limited to two days because a typhoon hit Okinawa and during which the SSPA in the station broke. Figure 5(a) shows the frequency difference between UTC(NICT) and the H-maser obtained by TWCF and the GPS CP. The ionosphere delay was not compensated in the TWCF result. The data rate of GPS CP was every 120 s. There was a frequency jump at MJD 57212 because we manually changed the frequency of the H-maser at the Okinawa site. Both results show good agreement before and after the frequency change. The mean values are summarized in Table 1 and agree within $3 \times 10^{-15}$. The frequency stability, before the frequency change, is depicted in Figure 5(b). The short-term stability was limited by the poor stability of the H-maser. The bump at approximately 1000 s is attributed to the phase variations in
Figure 4. Results of the frequency-difference measurement with zero baseline by TWCF and using the phase comparator. Frequency difference of UTC(NICT)-H-maser (a) and modified Allan deviations (b).

the U/C and D/C, which are caused by the variation of the indoor temperature of 2 °C at the Okinawa site. As shown by this result, we confirm that the TWCF measurement was consistent with the result obtained by GPS CP and that the stability was higher.

Table 1. Means of frequency difference before and after the frequency change of the H-maser.

| Frequency difference (10^{-15}) | GPS CP | TWCF | Δ   |
|---------------------------------|-------|------|-----|
| Before                          | 456.6 | 457.3| -0.7|
| After                           | -177.8| -180.8| 3.0 |

Figure 5. Results of the frequency-difference measurement by TWCF and the GPS CP with the 1500 km baseline. Frequency difference of UTC(NICT)-a H-maser (a) and the modified Allan deviation before the frequency change of the H-maser (b). The data rate in the GPS CP is every 120 s. The 1 s data of TWCF are averaged over 100 s in (a).
3.4. Discussion
We demonstrated that TWCF enables higher frequency-transfer stability than conventional TWSTFT. However, the measurement accuracy is also an important factor in clock comparison. We compared our measurement results with others obtained by a phase comparator and a GPS CP. As a result, it is considered likely that the TWCF accuracy in fractional frequency uncertainty will remain at the low $10^{-15}$ level. To obtain the results shown in this paper, instruments other than the modem were commonly used in both TWCF and TWCP measurements. Therefore, the modem appears to have a limitation. For confirmation, we measured the frequency difference between two continuous-wave (cw) signals at 70 MHz generated by the modems. The resultant frequency difference was $1 \times 10^{-12}$, which can cause a frequency error of $10^{-5}$ Hz in the uplink frequency, which corresponds to measurement inaccuracy at the $10^{-15}$ level. This may be attributed to the poor frequency resolution of the modem. We will investigate this by carrying out further measurements.

4. Conclusions
Conventional TWSTFT has been carried out by code phase measurement. Carrier-phase measurement is one of the ways to improve the measurement resolution without increasing the satellite-link cost. We introduced two possible methods for carrier-phase measurement: direct carrier-phase detection (TWCP) and the use of carrier-frequency information (TWCF). The former was enabled using an AWG and an A/D sampler and the latter was performed by employing a modem used in conventional TWSTFT. We confirmed that both TWCP and TWCF gave us higher stability than that obtained by conventional TWSTFT. However, the measurement accuracy of TWCF using the modem appears to remain at the $10^{-15}$ level owing to the lack of the frequency resolution, and improvement of the hardware may be necessary to reach a frequency stability of $10^{-16}$. On the other hand, we showed the high potential to achieve a frequency stability of $10^{-17}$ by TWCP. To eliminate as much of the error source as possible such as that in common-clock measurement, careful attention should be paid to the environment of the outdoor and indoor instruments.

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