

Advanced Satellite-Based Frequency Transfer at the 10^{-16} Level

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Abstract—Advanced satellite-based frequency transfers by two-way carrier-phase (TWCP) and integer precise point positioning have been performed between the National Institute of Information and Communications Technology and Korea Research Institute of Standards and Science. We confirm that the disagreement between them is less than 1×10^{-16} at an averaging time of several days. In addition, an overseas frequency ratio measurement of Sr and Yb optical lattice clocks was directly performed by TWCP. We achieved an uncertainty at the mid- 10^{-16} level after a total measurement time of 12 h. The frequency ratio was consistent with the recently reported values within the uncertainty.

Index Terms—Clocks, frequency measurement, phase measurement.

I. INTRODUCTION

SATELLITE-BASED time and frequency transfers are in demand for long-distance links and typically utilize pseudorange measurements using a code phase of a signal modulated by a pseudorandom noise (PN) sequence. Increasing the chip rate of the PN sequence improves the measurement precision, although it occupies a wider frequency bandwidth at the same time. This has limited the measurement precision of two-way satellite time and frequency transfer (TWSTFT) to an insufficient level for the comparison of advanced optical clocks. To improve the precision, the National Institute of Information and Communications Technology (NICT) has developed a two-way carrier-phase (TWCP) satellite frequency transfer technique [1]. It achieves sub-picosecond-level precision, which is three orders of magnitude better than that of TWSTFT [2]. On the other hand, the precise point positioning (PPP) technique utilizing code and carrier phases has been used by GPS time and frequency transfer (hereafter called GPS transfer) and contributes to the International Atomic Time computation [3], [4]. The measurement precision is improved by two orders of magnitude to a

few tens of picoseconds by the application of the carrier phase in the GPS transfer. However, solving the phase ambiguity may introduce random errors in GPS transfer results. To overcome this limitation, the integer PPP (IPPP) technique has been developed [5]. It has been applied to GPS transfer and recently demonstrated a 1×10^{-16} frequency transfer accuracy [6]. Thus, these advanced satellite-based frequency transfer techniques such as TWCP and IPPP have the potential to enable optical clock comparisons in a long baseline. Aiming at the evaluation and comparison of their techniques, NICT and about 1100 km apart the Korea Research Institute of Standards and Science (KRISS) established the TWCP link in December 2016. In this paper, we describe the frequency transfer techniques in Section II and introduce the comparison between the two techniques in Section III. In Section IV, the frequency ratio measurement of Sr and Yb optical lattice clocks by TWCP is demonstrated.

II. FREQUENCY TRANSFER TECHNIQUES AND SETUPS

NICT and KRISS have performed TWCP and GPS transfer on a regular basis. Here, we introduce the TWCP and IPPP techniques briefly. Then their measurement setups at NICT and KRISS are shown.

A. TWCP

By two-way signal exchange, the delay terms in the propagation path are almost canceled in TWCP. When we determine a pseudorange from the carrier phase of the transmitted signal from an earth station A at an earth station B, however, we have to remove two terms: the Doppler effects caused by the satellite motion and the phase noise introduced by the onboard oscillator in the frequency conversion from uplink to downlink frequencies because most communication satellites do not carry an atomic clock. It was shown in [2] that the mathematical cancelation by using four carrier phases of the four signals from A to A, from A to B, from B to A, and from B to B is effective in removing them. In addition, the ionosphere delay is not canceled either because the uplink and downlink frequencies are different. Therefore, we utilize an ionosphere map and compute the delays using the total electron contents over the earth stations. Since the carrier phase is continuously tracked and accumulated in TWCP measurements without any phase discontinuity, the result basically keeps the continuity as long as the measurement continues.

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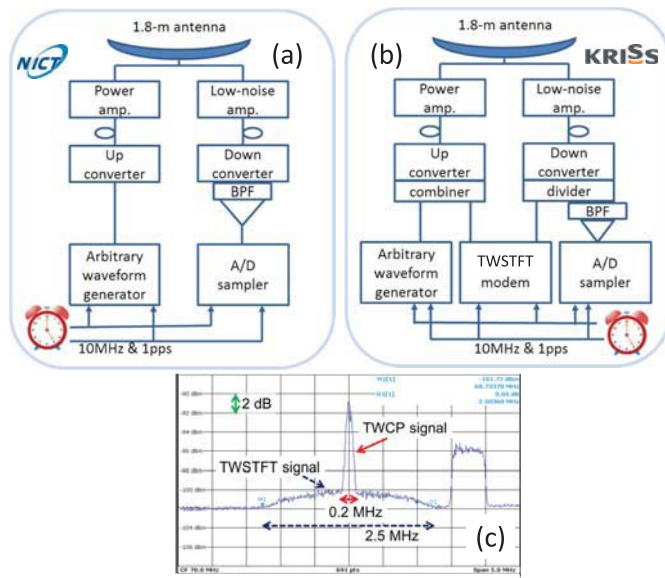


Fig. 1. Schematics of the earth stations at (a) NICT and (b) KRISS. BPF: bandpass filter, amp.: amplifier, and A/D: analog-to-digital converter. (c) Spectrum of the reception signals for TWCP and TWSTFT.

Fig. 1(a) and (b) shows schematics of the earth stations at NICT and KRISS, respectively. We use an arbitrary waveform generator for the signal generation and an analog-to-digital (A/D) sampler for carrier-phase detection. The TWCP signal has a frequency bandwidth of 200 kHz. The code phase of 128 k chips per second is detected, as well as the carrier phase, and it helps the signal tracking. The frequency conversion is carried out by commercial frequency up- and downconverters from 70 MHz to uplink and downlink frequencies of 14 and 11 GHz, respectively. The reference signals of 10 MHz are provided to the frequency converters to maintain the carrier-phase coherence. At NICT, a dedicated earth station is used for the TWCP measurement. On the other hand, at KRISS, the TWCP and conventional TWSTFT measurements share one earth station. The two signals for the TWCP and TWSTFT are combined and divided at 70 MHz by a signal combiner and divider, respectively. Fig. 1(c) shows the reception spectrum where the same center frequency was used by the TWCP signal and the TWSTFT signal with a bandwidth of 2.5 MHz. We did not observe any interference between them caused by sharing the same frequency bandwidth. We started continuous TWCP measurement alongside TWSTFT in December 2016 using a geostationary satellite named Eutelsat 172A. For the ionosphere delay correction between NICT and KRISS, we use a global ionosphere map produced by the Center for Orbit Determination in Europe [7]. The typical amplitude of the ionosphere delay is about 10 ps.

B. IPPP

In IPPP, as in classical PPP, the user's clock is determined from dual frequency GPS phase measurements using satellite clock products generated by analysis of a global network. For IPPP, the satellite products generated by the GRG analysis center [8] are designed so that the user can determine the phase

ambiguities for each satellite pass and the two frequencies as integers $N1/N2$. This is done in a two-step procedure with the CNES GINS software, first determining the widelane ambiguity $Nw = N2 - N1$ and then determining, e.g., $N1$, see details in [6] and [8]. Clock differences are then continuous as long as there is no discontinuity in the set of integer ambiguities for all satellite passes.

As shown in [6], the above treatment is performed on a station by station basis, independently for each day, and the continuity between successive daily batches is then to be established. By design, discontinuities between batches should be an integer number of the so-called narrowlane wavelength λ_N (~ 350 ps) and it is simpler to determine these discontinuities when forming the difference of two station clocks, i.e., a time link. Indeed, when the instability of the two compared clocks is sufficiently low, the extrapolation noise from batch to batch is much lower than λ_N and it is easy to determine the discontinuities as an integer number of λ_N . This extrapolation technique was used for the IPPP solution between UTC(NICT) and UTC(KRIS) which are both based on H-masers. Note that such discontinuities must also be determined when all satellite ambiguities are reset within a daily batch, e.g., by a short data gap.

The GPS receivers used at NICT and KRISS are Septentrio PolaRx 4 and Ashtech Z12T connected to the reference signals from UTC(NICT) and UTC(KRIS), respectively.

III. COMPARISON BETWEEN TWCP AND IPPP

We compared the measurement results obtained by PPP, IPPP, and TWCP for two periods: (1) from MJD 57772 to MJD 57784 and (2) from MJD 57851 to MJD 57883. Here, PPP is computed with NRCan PPP software using 15 day batches and IGS final products. The TWCP measurements were continuously carried out without any downtime. The measurement rates of PPP, IPPP, and TWCP are 300, 30, and 1 s, respectively. Fig. 2(a) shows the time difference between UTC(NICT) and UTC(KRIS) for period (2). The TWCP result has been roughly aligned to the GPS results by inserting an arbitrary offset. Fig. 2(b) shows the differences of IPPP-TWCP, PPP-TWCP, and IPPP-PPP. A time jump can be observed around 6 h on MJD 57861. It is clear that the TWCP result caused it because the signal-to-noise ratio at the KRISS station suddenly decreased by 8 dB due to heavy rain, and a phase excursion of 0.2 ns occurred in the TWCP result. The PPP result also shows a deviation around 8 h on MJD 57861 and this seems independent of that by TWCP. In addition, a small jump can be seen at MJD 57856. It was found that the GPS receiver at NICT caused a reset of all ambiguities at that time. While IPPP found an exact integer number of cycles to go through the reset, PPP could not. Difference between two methods should not have a frequency offset, which can be caused by a disagreement between them. We estimated it by a first-order fitting in Fig. 2(b). In Table I, "disagreement" shows the absolute values of the gradients of IPPP-TWCP and PPP-TWCP. While the difference of PPP-TWCP indicates a clear gradient at the 10^{-16} level, that of IPPP-TWCP is almost flat. IPPP and TWCP show consistency

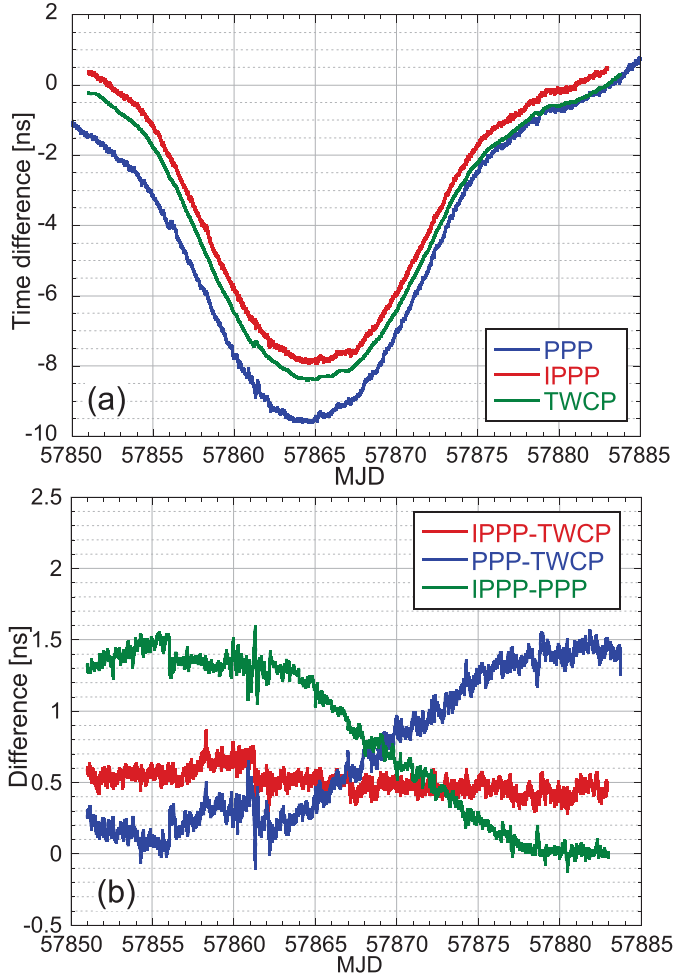


Fig. 2. (a) Time difference between UTC(NICT) and UTC(KRIS). (b) Differences of IPPP-TWCP, PPP-TWCP, and IPPP-PPP.

TABLE I
DISAGREEMENT BETWEEN PPP, IPPP, AND TWCP

Period	Difference	Disagreement (10^{-16})
(1)	IPPP-TWCP	0.43
MJD 57772-57784	PPP-TWCP	3.8
(2)	IPPP-TWCP	0.66
MJD 57851-57883	PPP-TWCP	5.9

at the 10^{-17} level. Fig. 3 shows the modified Allan deviation of UTC(NICT)-UTC(KRIS) for period (2). All techniques are limited by the stability of the time scales at some averaging times: at or below 20000 s and larger for TWCP, around 0.5 day and larger for IPPP, and around 1 day and larger for PPP. On the other hand, the differences of IPPP-TWCP and PPP-TWCP are free from the limitation. While the curve of IPPP-TWCP is decreasing and reaches 10^{-17} level after 500000 s, that of PPP-TWCP becomes flat. For period (1), similar stabilities are achieved of 5.5×10^{-17} at 250000 s for IPPP-TWCP and 1.7×10^{-16} at 250000 s for PPP-TWCP. By the comparisons among PPP, IPPP, and TWCP, it proved that TWCP, as well as IPPP, has superior long-term stability. Until now, unless the signal-to-noise ratio decreases suddenly owing to the weather conditions, the measurement has successfully

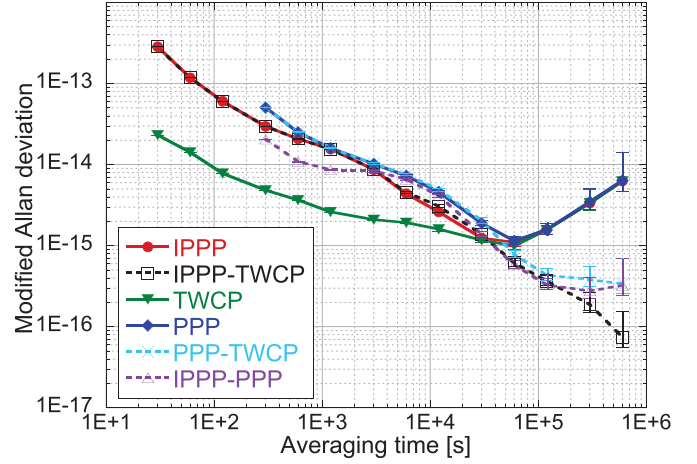


Fig. 3. Modified Allan deviation of UTC(NICT)-UTC(KRIS) from MJD 57851 to 57883.

continued and phase continuity can be preserved in the TWCP results.

IV. YB/SR FREQUENCY RATIO MEASUREMENT BY TWCP

A. Measurement Setup

NICT and KRISS operate a ^{87}Sr optical lattice clock [9], [10] and a ^{171}Yb optical lattice clock [11]. The frequency ratio was measured by TWCP through microwave references. The optical clocks were continuously operated for around 4 h per day over 3 days during February 1, 2017 to February 3, 2017. We performed two local measurements and one TWCP measurement at the same time. The frequencies of the optical clocks were measured with reference to the microwave references by using an optical frequency comb at each site. The systematic frequency shifts of the optical clock were corrected including the gravitational redshift. TWCP evaluates the frequency difference between the microwave references of both sites. At NICT and KRISS, a free-running hydrogen maser, HM(NICT), and UTC(KRIS) with frequency $f_{\text{HM(NICT)}}$ and $f_{\text{UTC(KRIS)}}$, respectively, were used as the microwave references. These signals were provided to the earth stations for TWCP. By obtaining fractional frequencies y_{Yb} and y_{Sr} against each result of previous absolute frequency measurements $\overline{f_{\text{Yb}}}$ and $\overline{f_{\text{Sr}}}$ [11], [10] on the basis of $f_{\text{UTC(KRIS)}}$ and $f_{\text{HM(NICT)}}$, the frequency ratio of the two optical clock transitions $\nu_{\text{Yb}}/\nu_{\text{Sr}}$ is measured as

$$\begin{aligned} \frac{\nu_{\text{Yb}}}{\nu_{\text{Sr}}} &= \frac{y_{\text{Yb}}}{y_{\text{Sr}}} \cdot \frac{\overline{f_{\text{Yb}}}}{\overline{f_{\text{Sr}}}} \\ &= \frac{f_{\text{HM(NICT)}}}{f_{\text{Sr}}/f_{\text{Sr}}} \cdot \frac{f_{\text{UTC(KRIS)}}}{f_{\text{HM(NICT)}}} \cdot \frac{f_{\text{Yb}}/\overline{f_{\text{Yb}}}}{f_{\text{UTC(KRIS)}}} \cdot \frac{\overline{f_{\text{Yb}}}}{\overline{f_{\text{Sr}}}} \quad (1) \end{aligned}$$

B. Data Analysis

The data acquisition rates of the two local measurements and one TWCP measurement were 1 point per every second. First, we extracted the data where both optical clocks were simultaneously operated. Fig. 4(a) depicts their Allan deviations measured on February 1. The HM(NICT) signal

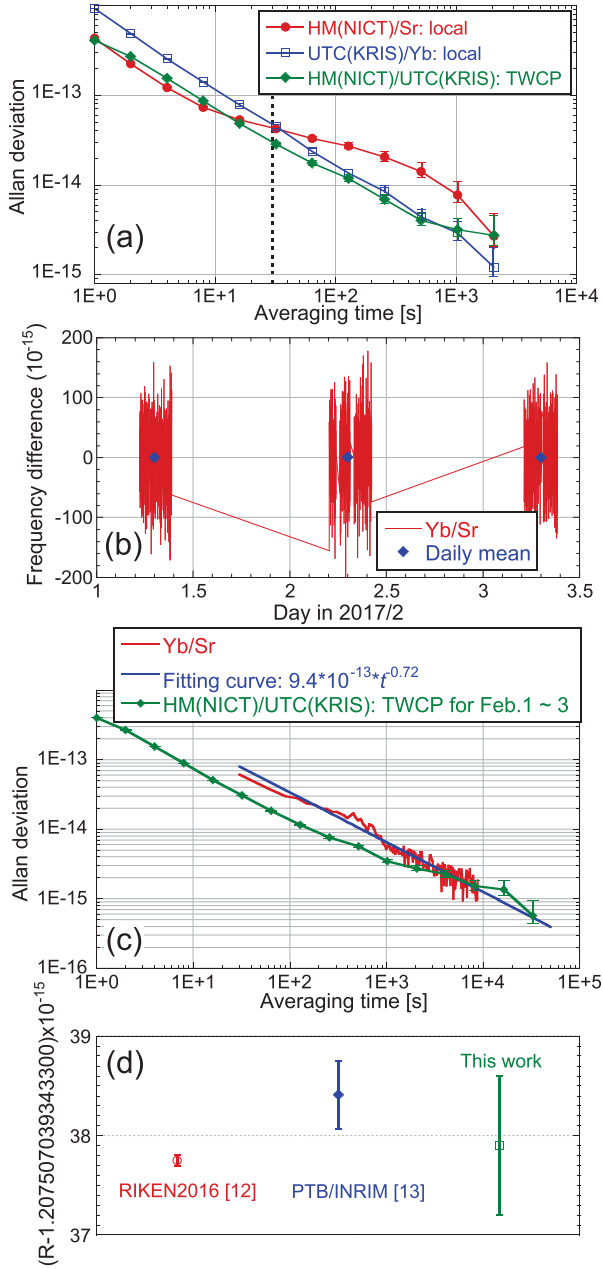


Fig. 4. (a) Allan deviations of two local measurements and one TWCP measurement carried out on February 1. (b) Frequency difference of $y_{Yb}/y_{Sr} - 1$ for 3 days. (c) Allan deviation by treating the whole data of y_{Yb}/y_{Sr} as one continuous measurement, its fitting curve and the Allan deviation of $f_{HM(NICT)}/f_{UTC(KRIS)}$ measured from February 1 to February 3. (d) Frequency ratio R reported so far.

was transferred by an unfixed coaxial cable to the Sr clock at this measurement, which caused an unwanted fluctuation and instability at around 100 s. Since the stabilities shown in Fig. 4(a) display similar values around 30 s, we averaged three frequency ratios over 30 s, aligned the time stamps, and then calculated y_{Yb}/y_{Sr} following (1). The computed difference relative to f_{Yb}/f_{Sr} is depicted in Fig. 4(b). The Allan deviation was calculated from the whole data for 3 days as one continuous measurement, as shown in Fig. 4(c) by a red line, where the fitting curve of $9.4 \times 10^{-13} \times t^{-0.72}$ is also depicted by a blue line. The underlying cause of the

TABLE II
DAILY MEAN VALUES

	Feb. 1	Feb. 2	Feb. 3
$y_{Yb}/y_{Sr} - 1$ (10^{-15})	0.33	1.00	0.17
Daily statistical uncertainty (10^{-15})	0.97	0.91	0.96
Measurement period (s)	14370	15510	14310
Weighted mean (10^{-15})	0.52		

TABLE III
UNCERTAINTY BUDGET

	(10^{-16})
Statistical	5.5
Sr systematic	0.5
Yb systematic	1.2
Gravitational redshifts	0.4
Link systematic	1.0
Total	5.8

$t^{-0.72}$ slope is not known; however, there are some evidences in our analysis that show its presence throughout the dead-times of Fig. 4(b). Table II summarizes the daily mean values. As for the daily statistical uncertainty, it was computed using the fitting curve of the Allan deviation for the measurement period. Weighting the daily mean values by the reciprocals of the square of daily statistical uncertainty, we concluded the weighted frequency difference of 5.2×10^{-16} for the 3-day measurement. Table III shows the uncertainty budget. The total statistical uncertainty was determined from the weighted uncertainty: $((1/9.7^2) + (1/9.1^2) + (1/9.6^2))^{-0.5} \times 10^{-16}$. In Fig. 4(c), the Allan deviation of $f_{HM(NICT)}/f_{UTC(KRIS)}$ measured by TWCP for 3 days is depicted by the green line, which meets the fitting curve at 5×10^{-16} around 40000 s. This implies that the total statistical uncertainty was estimated appropriately. It is also noted that when we use total Allan deviation, we get the similar result of the daily statistical uncertainty (1.01×10^{-15} , 0.95×10^{-15} , and 1.01×10^{-15}), which confirms the appropriateness of the uncertainty estimation. The systematic uncertainty for TWCP was 1×10^{-16} from the disagreement with IPPP. On the other hand, the Sr and Yb lattice clocks have systematic uncertainties of 0.5×10^{-16} and 1.2×10^{-16} , respectively. The uncertainties of the differential gravitational redshift between both clocks is 0.4×10^{-16} . We achieved a total uncertainty of 5.8×10^{-16} . Thus, the consistency of the previous absolute frequencies reported by NICT and KRIS [10], [11] was confirmed by $y_{Yb}/y_{Sr} - 1 = (5.2 \pm 5.8) \times 10^{-16}$. We concluded the frequency ratio, R , as

$$R = \nu_{Yb}/\nu_{Sr} = 1.207, 507, 039, 343, 337, 90(70).$$

The recently reported values are shown in Fig. 4(d) [12], [13]. We confirm that our result is consistent with them within the uncertainty.

V. CONCLUSION

We evaluated measurement results achieved by the advanced satellite-based frequency techniques of PPP, IPPP, and TWCP in the NICT-KRIS link. While the disagreement of PPP-TWCP remains at the 10^{-16} level, that of IPPP-TWCP reaches the 10^{-17} level at over 5×10^5 s average time.

The overseas frequency ratio measurement of Sr and Yb optical lattice clocks was directly performed by TWCP. We performed a dead-time-free and simultaneous measurement for about 12 h and confirmed that the achieved frequency ratio is consistent with those shown in other reports within a total uncertainty at the mid- 10^{-16} level. In conclusion, not only optical fiber links but also advanced satellite-based frequency links are applicable to optical clock comparisons. The satellite-based techniques have the potential to realize uncertainty at the 10^{-17} level when optical clocks are continuously operated for a week or more.

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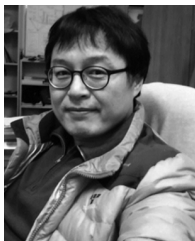


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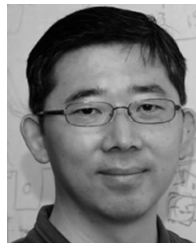
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