

Time Transfer Experiments between Two Ground-based Atomic Clocks using Time Comparison Equipment

Fumimaru NAKAGAWA, Yasuhiro TAKAHASHI, Ryo TABUCHI, Jun AMAGAI,
Maho NAKAMURA, Shigeru TSUCHIYA, and Shin'ichi HAMA

Using ETS-VIII satellite and Time Comparison Equipment (TCE) system, we have carried out experiments of carrier-phase Two Way Satellite Time and Frequency Transfer (TWSTFT) between two ground-based clocks. In these experiments, we confirmed that a precision of time transfer using carrier phase is extremely improved. And we have developed a new analysis method for carrier phase TWSTFT which will lead to the next generation technology for the international time transfer.

1 Introduction

The development of time comparison equipment (TCE) systems aims to measure the time difference between an atomic clock mounted on ETS-VIII and one on the earth and to acquire high precision time transfer technology in order to evaluate the on-orbit performance of satellite clocks^[1]. TCE systems use two earth stations to realize Two-Way Time and Frequency Transfer (TWSTFT). This is the same system configuration as that of general TWSTFT using communication satellites used in international time transfer links. (Therefore we call the time and frequency transfer by the TCE system between two ground-based atomic clocks TWSTFT in this paper.)

The most characteristic feature of TCE systems is that they realize carrier phase based measurements. Along with conventional code phase based measurements, TCE systems realize higher precision TWSTFT. Taking advantage of the features of TCE systems, we conducted TWSTFT experiments using the carrier phase, checked the precision, and developed an analysis technique necessary for the carrier phase based TWSTFT.

In this chapter, an overview of two kinds of TWSTFT experiments with TCE systems is given. Then, the results of each experiment are shown and the precision improvement of carrier phase based TWSTFT is discussed.

2 Overview of time and frequency transfer between two ground-based clocks using TCE

2.1 Overview of time transfer experiments using ETS-VIII and TCE

The TCE system consists of a TCE on ETS-VIII and two ground TCEs (a fixed ground TCE and a portable ground TCE). The basic operation of each TCE is to measure both code and carrier phase differences between a reference signal from an atomic clock and the received ranging signal. In the satellite-earth time transfer with ETS-VIII, ranging signals are transmitted and received between ETS-VIII and the TCE earth station, and the time differences (phase differences) in both the code and the carrier phases are measured. Then a time difference between the cesium atomic clock on ETS-VIII and the ground-based atomic clock is calculated with the two-way time transfer method^[2].

At ETS-VIII, ranging signals are generated, transmitted and received by HAC mission^[3] by JAXA. In the earth stations, this is carried out by ground TCEs. To generate ranging signals, ETS-VIII uses the onboard cesium atomic clocks included by HAC and the fixed ground TCE uses the UTC (NICT)^[4], a hydrogen maser, or a cesium atomic clock. A ranging signal of S-band is used in the uplink and those of S- and L-bands are used in the downlink, because the difference between the two frequencies in the downlink can be utilized to correct time delays due to the ionosphere.

A similar technique can be used in the present TWSTFT experiments, and details will be explained in subsequent sections.

The most basic experiment of the TCE system is a satellite-earth time transfer experiment conducted using the onboard TCE and the fixed TCE on the ground. As a result of this experiment, it was verified that the time and frequency transfer using carrier phase was much more precise than conventional time transfer using code phase^[5].

2.2 Two types of earth-earth time and frequency transfer experiments

Here we give an overview of the TWSTFT experiments using the ETS-VIII and TCE systems. In the TWSTFT using the TCE system, not only the code phase but also the carrier phase is used for TWSTFT to improve measurement precision. However time transfer using the carrier phase only cannot determine the absolute value of time and can only compare relative values of time (namely frequencies). For the comparison of absolute values of time, combination with the code phase time transfer is necessary to estimate the absolute values.

There are two types of TWSTFT experiments with TCE: mediated time transfer and relayed time transfer. Their principles and features are introduced below.

2.3 Mediated time transfer

There are two ground TCEs: the fixed TCE and the portable TCE. The TCE on the satellite has the function of simultaneous measurement of multiple codes for the correction of in-device time delays. Between the fixed TCE (on-earth clock 1) and the satellite TCE (on-satellite cesium atomic clock) and between the portable TCE (on-earth clock 2) and the satellite TCE, satellite-earth two-way time and frequency transfer experiments are carried out simultaneously. From these results, the time transfer between two ground TCEs is calculated. This method uses the on-satellite cesium atomic clock as mediation for the time transfer and is hence called mediated time transfer. An advantage of this method is that the principle is simple and established satellite-earth time transfer technology using the carrier phase can be utilized. A disadvantage is that multiple measurements with onboard TCE necessarily have time intervals of 1 to 2 seconds and with the measurement frequency decreased. And mediation by the onboard cesium atomic clock might see lower precision for the resulting earth-earth time transfer.

2.4 Relayed time transfer (carrier phase TWSTFT)

The HAC system on the ETS-VIII has the function of converting the frequencies of received S-band ranging signals and transmitting the converted signals of S- and L-bands. This function is called bent-pipe mode. In this mode, the satellite just relays the ranging signals without using the onboard TCE, and the two ground TCEs can directly transmit, receive and measure the signals. The time transfer of this method is called relayed time transfer and is equivalent to the TWSTFT with communication satellites widely used for international time transfer. It is different from ordinary TWSTFT in that it can make measurements with carrier phase and that the stable cesium atomic clock is used for local signals for the frequency conversion on the satellite. As will be explained below, even if the on-satellite clock is not quite stable, the measurement precision cannot be lowered.

Since the principle of the code phase based time transfer is the same as that of ordinary TWSTFT^[2], we omit the explanation of this type of time transfer. We therefore explain here the carrier phase based TWSTFT (relayed time transfer using carrier phase by TCEs).

TWSTFT using carrier phase cannot utilize the same analysis technique used for code phase based TWSTFT. In the code phase based TWSTFT, since the signal frequency does not change on the way to the station, the subtraction of the measurement data from two stations makes it possible to cancel out the influences from the path of the signals. In the case of carrier phase based TWSTFT, on the other hand, the frequency could change during the down-convert process on a communication satellite (ETS-VIII in the present case) and countermeasures need to be taken.

For two-way satellite time transfer using carrier phase, Fonville et al.^[6] used two round-trip signals with two counterpart signals at two earth stations to solve the above problem. Their method tracks the signal frequency along the signal path to calculate a frequency difference using an approximation, and is therefore complicated.

In the present study we also use round-trip signals as in Fonville's method, and track, not the signal frequency, but the phase change on the signal path, which makes the carrier phase based TWSTFT analysis easier. This analysis method is briefly explained in this paper but the details are given in Nakagawa's paper^[7].

Let us consider time transfer between stations A and B. A signal is transmitted by station A, relayed by satellite S, and received and measured by station B. The measured phase difference ϕ_{ba} (rad) is given by the following equation.

$$\frac{\phi_{ba}(t)}{2\pi} = f_{up}\tau_A(t) - f_d\tau_S(t) - f_d\tau_B(t) - f_{up} \cdot \frac{R_A^S(t)}{c} - f_d \cdot \frac{R_B^S(t)}{c} \quad (1)$$

Here f_{up} and f_d are the uplink and downlink frequencies respectively, f_Δ is their difference ($f_{up}-f_d$), τ_A , τ_B , and τ_S are time of the reference clocks at station A, station B, and satellite S respectively, $R_A^S(t)$ and $R_B^S(t)$ are the distances between A and S and between B and S respectively, and c is the speed of light.

In the same manner, the phase difference ϕ_{ab} for the case where station B transmits a signal and station A receives and measures the signal is given as follows.

$$\frac{\phi_{ab}(t)}{2\pi} = f_{up}\tau_B(t) - f_d\tau_S(t) - f_d\tau_A(t) - f_d \cdot \frac{R_A^S(t)}{c} - f_{up} \cdot \frac{R_B^S(t)}{c} \quad (2)$$

The difference between ϕ_{ba} and ϕ_{ab} is then given by the following.

$$\frac{\phi_{ba}(t)-\phi_{ab}(t)}{2\pi} = (f_{up} + f_d)(\tau_A - \tau_B) - (f_{up} - f_d) \left(\frac{R_A^S(t)}{c} - \frac{R_B^S(t)}{c} \right) \quad (3)$$

As seen in this equation, if the uplink frequency and downlink frequency are the same, this is the same as for general code phase based TWSTFT. However, if a carrier phase is used, the frequencies of the uplink and downlink are different from each other and Equation. (3) is not sufficient to calculate the time difference. Therefore round-trip signals are used. The phase differences for a round-trip signal from A to A, ϕ_{aa} , and that from B to B, ϕ_{bb} , can be expressed as:

$$\frac{\phi_{aa}(t)}{2\pi} = f_{up}\tau_A(t) - f_d\tau_S(t) - f_d\tau_A(t) - (f_{up} + f_d) \cdot \frac{R_A^S(t)}{c} \quad (4)$$

$$\frac{\phi_{bb}(t)}{2\pi} = f_{up}\tau_B(t) - f_d\tau_S(t) - f_d\tau_B(t) - (f_{up} + f_d) \cdot \frac{R_B^S(t)}{c} \quad (5)$$

and the difference between ϕ_{aa} and ϕ_{bb} is given by the following equation.

$$\frac{\phi_{aa}(t)-\phi_{bb}(t)}{2\pi} = (f_{up} - f_d)(\tau_A - \tau_B) - (f_{up} + f_d) \left(\frac{R_A^S(t)}{c} - \frac{R_B^S(t)}{c} \right) \quad (6)$$

From Equations (3) and (6), the time difference between the two stations ($\tau_A-\tau_B$), which is the target of our calculation, and the distance difference $R_A^S(t) - R_B^S(t)$ are two unknown variables in the simultaneous equations. One can hence calculate the time difference analytically.

The above is our newly-developed time difference analysis method using carrier phase in relayed TWSTFT. As seen in the equations, the onboard clock time τ , disappeared. This indicates that carrier phase based TWSTFT can be performed with not only the ETS-VIII but also general communication satellites.

3 Results of time transfer experiments

The results of mediated and relayed time transfer experiments are shown below.

3.1 Overview of experiments

Mediated and relayed TWSTFT experiments were conducted using fixed and portable TCEs. In time transfer using TCEs, simultaneous measurements could be made for both code and carrier phases. However since the code phase measurement could not be performed due to a problem during the experiment period, only the results of the carrier phase experiments are shown here. Therefore in the following results of the time transfer experiments, only relative values are effective.

The fixed TCE was placed at Building 2 of the headquarters of the NICT (Koganei, Tokyo) and a UTC (NICT) based on a hydrogen maser was used as a reference signal. The portable TCE was placed at the Optical Center at the headquarters of the NICT or at the NICT Space Technology Center in Kashima, Ibaraki, and a hydrogen maser was used as a reference signal. The baselines of these stations are about 200m and about 110km respectively. The conditions of the experiments are summarized in Table 1.

Figure 1 shows the results of the relayed TWSTFT experiments performed between the headquarters of the NICT and the NICT Space Technology Center in Kashima (No. 4 in Table 1). The figure also shows the time transfer results obtained using GPS carrier phase. For both results, the same primary drift and offset values are removed. From the results, one can see that they have the same slope, i.e. same frequency, and hence that the measurements using the TCE system and the analysis method are appropriate. Also, the measurement using TCE is clearly stable.

Figure 2 shows the frequency stability obtained from the experiments. The highest stability was obtained in the relayed experiments, the second highest in the mediated

Table 1 Earth-earth TWSTFT experiment results

No.	Date	TEC portable station location	Experimental method
1	11/5/2008	Optical Center at NICT headquarters	Mediated
2	11/27/2008	NICT Space Technology Center in Kashima	Mediated
3	6/10/2010	NICT Space Technology Center in Kashima	Relayed
4	8/5/2010	NICT Space Technology Center in Kashima	Relayed

experiments and the third highest in the GPS carrier phase experiments. Every result is better than the results obtained in the general code phase based TWSTFT. The result of the mediated TWSTFT is worse than that of the relayed TWSTFT probably because the increased number of steps of the time transfer caused noises. The relayed TWSTFT is particularly stable and has much higher precision than the code phase based TWSTFT. From the specifications of the hydrogen maser used in the measurements, it can be considered that the stability of the hydrogen maser was obtained over 10,000 seconds. For the relayed experiments, the theoretically expected measurement precision is higher than the measured value^[8], although we could not achieve that high precision. However, since the observed stability is close to that of the local signals generated at the earth station, one could consider that the observed stability could be limited by the stability of the local signals.

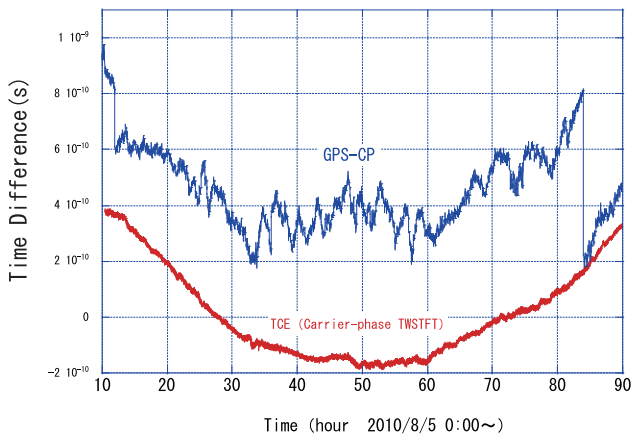


Fig. 1 Results of relayed TWSTFT (carrier phase based TWSTFT) and GPS carrier phase based time transfer (GPS-CP). The same amount of primary drift is extracted from both data.

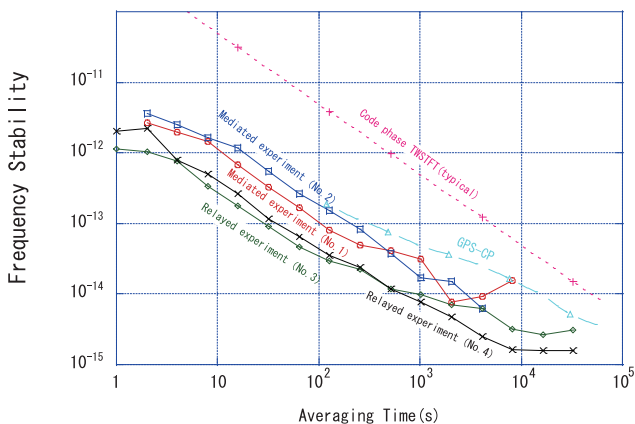


Fig. 2 Measurement accuracy (frequency stability) of the time transfer experiments

4 Discussion

It was found in the relayed TWSTFT experiments that the carrier phase based TWSTFT achieved extremely high precision. Here we discuss possible influences to the precision of the carrier phase based TWSTFT.

4.1 Ionospheric delay

The time delay due to the ionosphere is proportional to the square of the frequency. Since TWSTFT has different frequencies between the uplink and the downlink, the ionospheric delay varies depending on the signal path, which causes an error. On the other hand ground TCEs measure two frequency waves of S- and L-bands in the downlink and these data are used to correct the ionospheric delay. (For details of the mechanism and the analysis method, see Nakagawa's paper^[7].) Here only the results of the experiments before and after the correction of ionospheric delay are shown (for experiment No. 3). Figure 3 shows the frequency stability with and without the correction of the ionospheric delay. The stability is slightly higher with the correction but there is no clear difference. A simple conclusion cannot be reached since the influence of the ionospheric delay always changes depending on the season and/or magnetic storms, but we assume that the correction effect could not be obviously shown in this experiment.

Since the carrier phase based TWSTFT has a higher precision than conventional methods, the correction to the ionospheric delay becomes more important. However since ordinary communication satellites cannot make such corrections as the ETS-VIII does, another correction

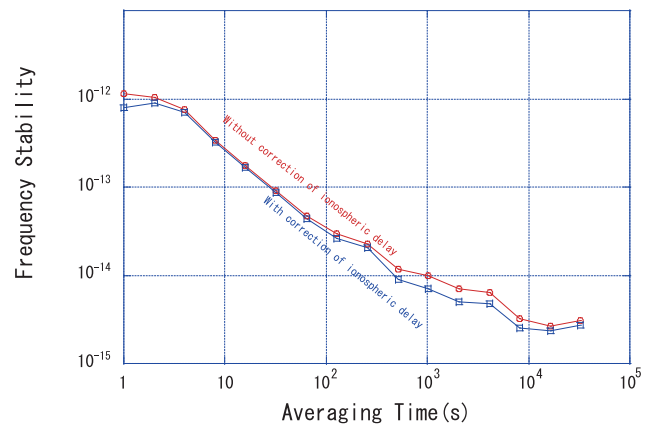


Fig. 3 Frequency stability of carrier phase TWSTFT with and without correction to ionosphere time delay. The relayed experiments between Koganei and Kashima were conducted on 6/10/2010.

method based on an ionosphere model and/or others needs to be examined.

4.2 Doppler shift

A Doppler shift due to satellite movement should be taken into consideration for the carrier phase based TWSTFT. The ETS-VIII is a stationary orbit satellite but still moves slightly. The influence of the motion needs to be taken into account for precise measurements.

Here we consider a frequency change in the case where a signal is transmitted by station A and received by station B through satellite S. If the satellite motion is sufficiently slower than the speed of light, the frequency of the signal received by station B is given by the following equation.

$$f_d - f_{up} \frac{v_a}{c} - f_d \frac{v_b}{c} - f_{up} \frac{v_a v_b}{c^2} \quad (7)$$

Here v_a and v_b are the radial velocities from station A and station B to the satellite, respectively. The second term in the above equation is a Doppler shift due to the change of the range between A and S and the third is a Doppler shift due to the change of the range between B and S. The fourth term presents a Doppler shift of second order. In the above we have focused on phases in the discussion of the carrier phase based TWSTFT. However since the time differential of the phase is frequency and the time differential of the range is speed, $dR_A^S/dt = v_a$ and $dR_B^S/dt = v_b$, and the second and third terms in the above equation are already taken into account in Equation. (1) of the phase ϕ_{bn} . The fourth term is not included in Equation. (1) and additional correction should be made for this term.

The value of this term can be estimated in actual measurements. Since v/c is calculated from the velocity of the ETS-VIII to be about 2×10^{-8} , and its contribution to the frequency is the square of v/c , or about 4×10^{-16} . On the other hand the frequency stability calculated from the experimental results was about 1×10^{-15} , which indicates that the Doppler shift of second order has little influence on the experiments.

In the case of large orbital changes of a communication satellite used for experiments and/or in the case of a request for a higher precision time transfer, it would be necessary to take into account the Doppler shift of second order. Since this shift varies in the revolution period of the satellite, the correction could be calculated by examining the contribution from the satellite orbital changes. The influence of errors in the orbit determination on the correction needs to be studied, which will be one of our

future works.

5 Conclusions

We conducted two kinds of experiments using the ETS-VIII and TCE system to verify the earth-earth time and frequency transfer with a focus on carrier phase. The experiments showed higher precision than obtained with conventional methods. In particular, in relayed experiments, a new analysis method was established and its validity and high precision could be confirmed.

The experiments were therefore successful as verification experiments of carrier phase TWSTFT using communication satellites and could show the way to a next-generation TWSTFT technology. The technology established with the ETS-VIII and TCE system is already being applied to a carrier phase based TWSTFT experiment with an ordinary communication satellite^[9], which is expected to be one of the next-generation distant-place time and frequency transfer experiments.

References

1. Y. Takahashi, F. Nakagawa, R. Tabuchi, M. Nakamura, H. Kumimori, J. Amagai, S. Tsuchiya, S. Hama, and H. Noda, "Experimental Results of Time Comparison Using the Time Comparison Equipment on Board ETS-VIII," *Journal of the NICT*, Vol. 57, Nos. 3/4, pp. 279–288, 2010.
2. M. Imae, T. Suzuyama, T. Gotoh, Y. Shibuya, F. Nakagawa, Y. Shimizu, and N. Kurihara, "Two Way Satellite Time and Frequency Transfer," *Journal of the NICT*, Vol. 49, Nos. 1/2, pp. 125–133, 2003.
3. H. Noda, K. Sano, and S. Hama, "High Accuracy Clock (HAC)," *Journal of the NICT*, Vol. 49, Nos. 3/4, pp. 101–107, 2003.
4. F. Nakagawa, Y. Hanado, H. Itoh, N. Kotake, M. Kumagai, K. Imamura, and Y. Koyama, "Summary and Improvement of Japan Standard Time Generation System," *Journal of the NICT*, Vol. 56, Nos. 3/4, pp. 17–27, 2003.
5. M. Nakamura, Y. Takahashi, F. Nakagawa, R. Tabuchi, J. Amagai, S. Tsuchiya, and S. Hama, "A High Accuracy Time Comparison using Time Comparison Equipment (TCE) on the Engineering Test Satellite (ETS-VIII)," *Special issue of this NICT Journal*.
6. B. Fonville, D. Matsakis, A. Pawlitzki, and W. Schaefer, "Development of carrier-phase-based two-way satellite time and frequency transfer (TWSTFT)," *Proceedings of the 36th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting (Washington)*, 149, 2005.
7. F. Nakagawa, J. Amagai, R. Tabuchi, Y. Takahashi, M. Nakamura, S. Tsuchiya, and S. Hama, "Carrier-phase TWSTFT experiments using the ETS-VIII satellite," *Metrologia*, Vol. 50, pp. 200–207, 2013.
8. F. Nakagawa, Y. Takahashi, T. Gotoh, F. Miho, M. Hosokawa, H. Kikuchi, and M. Imae, "Development of Time Comparison Equipment for ETS-VIII Satellite," *Electrical Engineering in Japan*, Vol. 158, No. 3, 2005.
9. M. Fujieda, T. Gotoh, F. Nakagawa, R. Tabuchi, M. Aida, and J. Amagai, "Carrier-Phase-Based Two-Way Satellite Time and Frequency Transfer," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Vol. 59, No. 12, pp. 2625–2630, 2012.

Fumimaru NAKAGAWA, Ph.D.

Senior Researcher, Space-Time Standards
Laboratory, Applied Electromagnetic
Research Institute
Time and Frequency Standards

Yasuhiro TAKAHASHI

Director, Planning Office, Wireless Network
Research Institute
Satellite Positioning System, Time Transfer,
Satellite Communication

Ryo TABUCHI

Technical Expert, Space-Time Standards
Laboratory, Applied Electromagnetic
Research Institute



Jun AMAGAI

Associate Director of Radiowave Remote
Sensing Laboratory/ Director of Okinawa
Electromagnetic Technology Center
Time and Frequency, Radio Interferometer

Maho NAKAMURA, Dr. Eng.

Researcher, Tokyo Gakugei University/
Former: Expert Researcher, Space-Time
Standards Laboratory, Applied
Electromagnetic Research Institute
Time Transfer, Ionosphere, Neural Networks



Shigeru TSUCHIYA

Senior Researcher, Space-Time Standards
Laboratory, Applied Electromagnetic
Research Institute
Time and Frequency Standard, Radio Wave
Propagation



Shin'ichi HAMA

General Manager, Technical Department,
Local Authorities Satellite Communications
Organization/Former: Manager,
Space-Time Standards Laboratory, Applied
Electromagnetic Research Institute
Satellite Communication