TIME TRANSFER EXPERIMENT BY TCE ON THE ETS-VIII SATELLITE

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Abstract

ETS-VIII, a Japanese geo-stationary satellite, launched in December 2006, has been developed to obtain the fundamental technologies for satellite positioning systems using two onboard cesium atomic clocks. At NICT, we developed Time Comparison Equipment (TCE) both onboard ETS-VIII and in the Earth station for precise time transfer between the atomic clocks on the satellite and a ground reference clock. Using code and carrier-phase data measured by TCE, the time and frequency difference between the onboard atomic clock and that on the ground is calculated by the Two-Way Satellite Ground Time and Frequency Transfer (TWSGTFT) method. Since February 2007, we have carried out the experiment to confirm the performance of TCE in orbit after the launch. As a result, we confirmed that TCE is able to measure the code phase with subnanosecond precision and measure the carrier phase with a few-picosecond precision.

INTRODUCTION

A satellite navigation system is an important infrastructure for economic and social activities. The Global Positioning System (GPS) was developed by the United States and has become the most popular satellite navigation system in the world, as it can be used for many purposes. The European Union is currently developing a new satellite navigation system named Galileo. In Japan, the Subcommittee for Satellite Navigation Technology of the Committee on Planning under the Space Activities Commission was organized in 1997. The Subcommittee has suggested that Japanese organizations should study the following basic technologies.

1) Development of a space-borne atomic clock;
2) Control and management techniques of atomic clock assembled in space;
3) Precise-orbit determination techniques.

By conducting these studies, we aimed technical improvements in the satellite navigation system to contribute to the next-generation satellite navigation system. This system is related to the control and management techniques of an atomic clock ensemble.

An Engineering Test Satellite (ETS) series has been managed by Japan Aerospace eXploration Agency (JAXA) and aimed at developing satellite common fundamental technologies. ETS-VIII is intended for development of mobile communications using a large deployable antenna (show Figure 1), the world's largest class geostationary satellite bus technology, precise satellite positioning, and other advanced technology required for further space development **[1]**. This is the first plan in Japan to use onboard atomic clocks in space mission for the establishment of the satellite positioning techniques. The National Institute of Information and Communications Technology (NICT) has developed two kinds of Time Comparison Equipment (TCE), onboard ETS-VIII (onboard TCE), and on in an Earth station (ground TCE), for the precise time and frequency transfer between Earth-based atomic clocks and the satellite-borne atomic clocks to verify the performance of the onboard clocks. Once, LASSO experiments verified the performance of space-borne atomic clocks using with satellite laser ranging **[2,3]**. The experiments by TCE are different in that they use two-way time comparison **[4]**.

The onboard TCE receives ranging signals from the ground TCE and vice versa. When receiving the signals, both code and carrier phases are measured. Using measured phase data, the time and frequency differences between the onboard atomic clock and that on the ground are calculated by the Two-Way Satellite Ground Time and Frequency Transfer (TWSGTFT) method. The carrier-phase data are used for the high-precision detection of the variation of time difference. The code data are used for the estimation of the time offset. Using the calibration system and the receiving data for two frequencies at ground TCE, TCE is designed to calibrate the delay caused by terrestrial ionosphere and by internal instruments. Our goal is to perform a precise time and frequency transfer between the onboard atomic clock and the ground reference clock with measurement precisions of subnanoseconds for the code phase and below 10 ps for the carrier phase. This paper presents an outline of TCE, time transfer experiments by TCE, and results of initial experiments.

INSTRUMENTS

ATOMIC CLOCK ONBOARD ETS-VIII AND HAC SYSTEM

ETS-VIII is the first satellite in Japan to equip two highly precise cesium atomic clocks, the same ones as used in a GPS satellite. Its specifications are as follows:

- Output frequency: 10.23 MHz
- Weight: 13.6 kg
- Frequency stability: 1×10^{-11} ($t = 1 - 3.6$ s)
  $1.89\times10^{-11}\,t^{-0.5}$ ($t = 3.6 - 10^5$ s)
  6×10^{-14} ($t = 10^5 - 10^6$ s).

These clocks are included in the High Accuracy Clock (HAC) mission by JAXA **[5]**. In this mission, the onboard atomic clocks are monitored and controlled, and some experiments of the positioning and orbit determination with high precision are planned by JAXA. In the HAC system, S-band and L-band ranging signals are generated and transmitted. The ground TCE receives these transmitted signals from HAC system. Moreover, in the HAC system, signals transmitted from the ground TCE or other Earth stations are received and amplified. The amplified signals are sent to the onboard TCE and the phases are measured. The system has an antenna of 1.0 meter in diameter that is used for receiving and transmitting of ranging signals for experiments of satellite navigation.

TCE ONBOARD ETS-VIII (ONBOARD TCE)

Figure 2 shows the flight model of the onboard TCE. The size and weight of the onboard TCE are 32 cm × 32 cm × 32 cm and 12.4 kg, respectively. Figure 3 shows a block diagram of the onboard TCE and the

HAC system. The onboard TCE uses 10.23 MHz and 1 kpps signals fed by the cesium clock in HAC system as the references. At the onboard TCE, phase differences of code and carrier phases between the reference signal and the S-band received (Rx) signal emitted from the ground TCE are measured with high precision **[6]**. The measurement is done every second. Additionally, the onboard TCE has a calibration system and also measures a reception calibration (Rx-Cal) signal and a transmission calibration (Tx-Cal) signal in order to calibrate internal delay at the receiver and the transmitter in the ETS-VIII. A part of the Tx signal generated at HAC is reflected by a directional coupler located near the antenna and the reflected signal is then sent to the onboard TCE as the Tx-Cal signal. The Rx-Cal signal is generated at the onboard TCE and superposed on the Rx signal at the other directional coupler.

TCE IN THE EARTH STATION (GROUND TCE)

We developed two ground TCEs that are for fixed and portable stations. Figure 4 shows an antenna and an outdoor unit for the fixed ground TCE. The diameter of the antenna is 2.4 m. Using this antenna, C/N_0 for ranging signals is planned to be about 60 dBHz. Figure 5 shows a block diagram of the ground TCE. The ground TCE uses 10 MHz and 1pps signals from an atomic clock on the ground as the references. Usually, UTC (NICT) based on a hydrogen maser is employed in the experiments and the frequency stability is higher than that of the onboard cesium atomic clocks. Because of a limit of the onboard processor, onboard TCE cannot compensate for the Doppler effect. Therefore, the ground TCE adjusts the frequency of a reference signal for the transmitter so that the Doppler shift at the onboard TCE is cancelled. The time difference between the reference signals before and after the adjustment is measured with high accuracy by means of a dual-mixer time difference (DMTD) system **[7]**.

These data are used to correct the TCE measurement in TWSGTFT. In addition to an S-band Rx and an L-band Rx, signals at the ground TCE and S-band Rx-Cal, S-band Tx-Cal, and L-band Rx-Cal signals are also measured.

TIME AND FREQUENCY TRANSFER BY TCES

In the time and frequency transfer experiments using TCE, the two-way time transfer uses the S-band signals (uplink: 2,656.390 MHz, downlink: 2,491.005 MHz). In addition, downlink transfer in the L-band signal (1,596.880 MHz) is employed for the correction of ionospheric delay. The ranging signals obtained via spread modulation (Binary Phase Shift Keying, BPSK) of a Pseudo-Random Noise (PRN) code with a chip rate of 1.023 MHz and a code length of 1,023 are used for the time transfer, like the C/A code in GPS. In the experiments of TCE, the time difference is decided by the TWSGTFT method. The advantage of the two-way method is that the various delays in the propagation are cancelled. Such cancellations largely reduce measurement uncertainty and enable us to make a precise time transfer. In the TCE, both the code and the carrier phases of the received signals are measured. Though the measurement precision of the carrier phase is very high, it has an ambiguity in the initial phase. On the other hand, the code-phase measurement has no ambiguity, with not so high a precision. So the variation of time difference is performed using the carrier phase with very high precision, and the uncertainty remaining in the carrier phase is estimated using the code phase, because carrier and code phases are coherent.

INITIAL EXPERIMENT

In this section, we present the results of an initial time transfer experiment by TCE. In this experiment, we have not yet carried out the calibrations of internal delay and ionospheric delay. Figure 6 shows an example of the measured data in carrier phase by the onboard (upper) and the ground (bottom) TCE. The same trend in both measured data is seen. This is clearly caused by a variation of range between ETS-VIII satellite and the Earth station. By the TWSGTFT method, a calculated time differences between the onboard cesium atomic clock and UTC (NICT) are shown in Figure 7 (here, linear trends are removed) for the carrier and the code phases. The measurement precision of the carrier phase is far better than that of the code phase, and the variations of code and carrier phases agree very well with each other, showing the coherency of the code and the carrier phases. Figure 8 shows frequency stabilities calculated from the same data in Figure 7 with that of the onboard cesium atomic clock that was measured before the launch. Because the frequency stability measured by the carrier phase is similar to that measured before launch, we confirm that the frequency difference between the onboard clock and UTC (NICT) is correctly measured at a short averaging time. The frequency stability measured by the code phase is not so high, but the precision is subnanosecond and the aim of the code phase precision was achieved.

SUMMARY

At NICT, we have carried out the fundamental experiments for a satellite navigation system, for which we developed two kinds of TCE, onboard TCE and ground TCE. Using the TCE, the time difference between an atomic clock on the satellite and a ground-reference atomic clock is measured by the TWSGTFT method. The TCE have calibration systems to correct the internal delays and to improve the accuracy of the time transfer. For the time transfer, we use S-band ranging signals. In addition, an L-band downlink signal is used for the calibration of ionospheric delay. After the launch of ETS-VIII satellite, we carried out the initial experiments of the time transfer without the calibrations of internal and ionospheric delays. As a result, we showed that the time transfer capability of TCEs is subnanosecond by code phase and a few picoseconds by carrier phase. Such high precision, especially by carrier phases, maybe the best result so far in space-ground time comparison. Next steps are to calibrate various effects such as ionospheric delay and internal delay. Together with the short-term time precision and these calibrations, we will also evaluate the long-term performance of the TWSGTFT by TCE.

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Figure 1. Image of ETS-VIII satellite. The ETS-VIII has two large-scale deployable reflector antennas for development of mobile communications. One reflector size is about the area of two tennis courts.

Figure 2. Flight model of TCE onboard ETS-VIII.

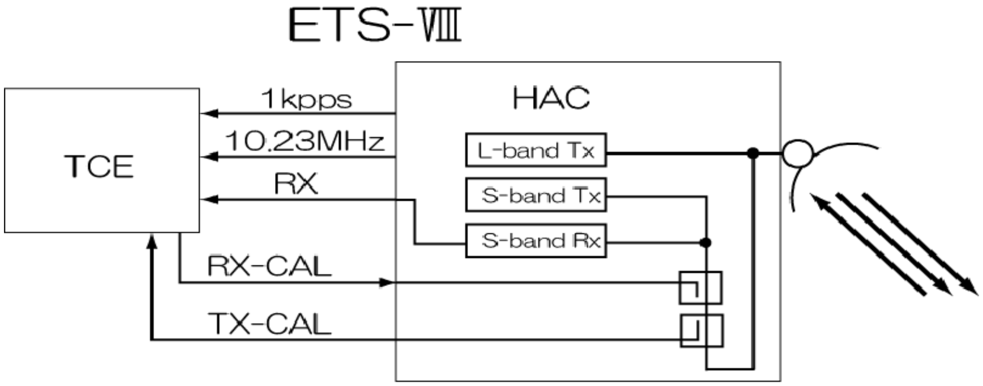

Figure 3. Block Diagram of TCE and HAC onboard ETS-VIII.

Figure 4. The antenna and the outdoor unit of a fixed TCE Earth station.

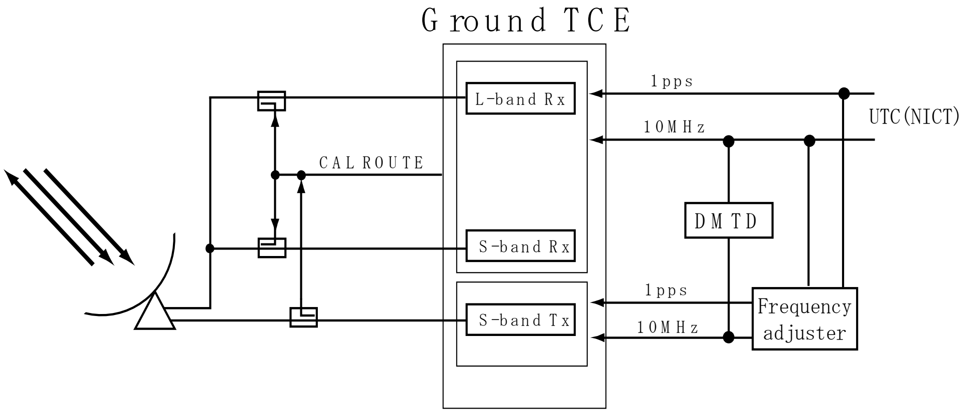

Figure 5. Block diagram of ground TCE.

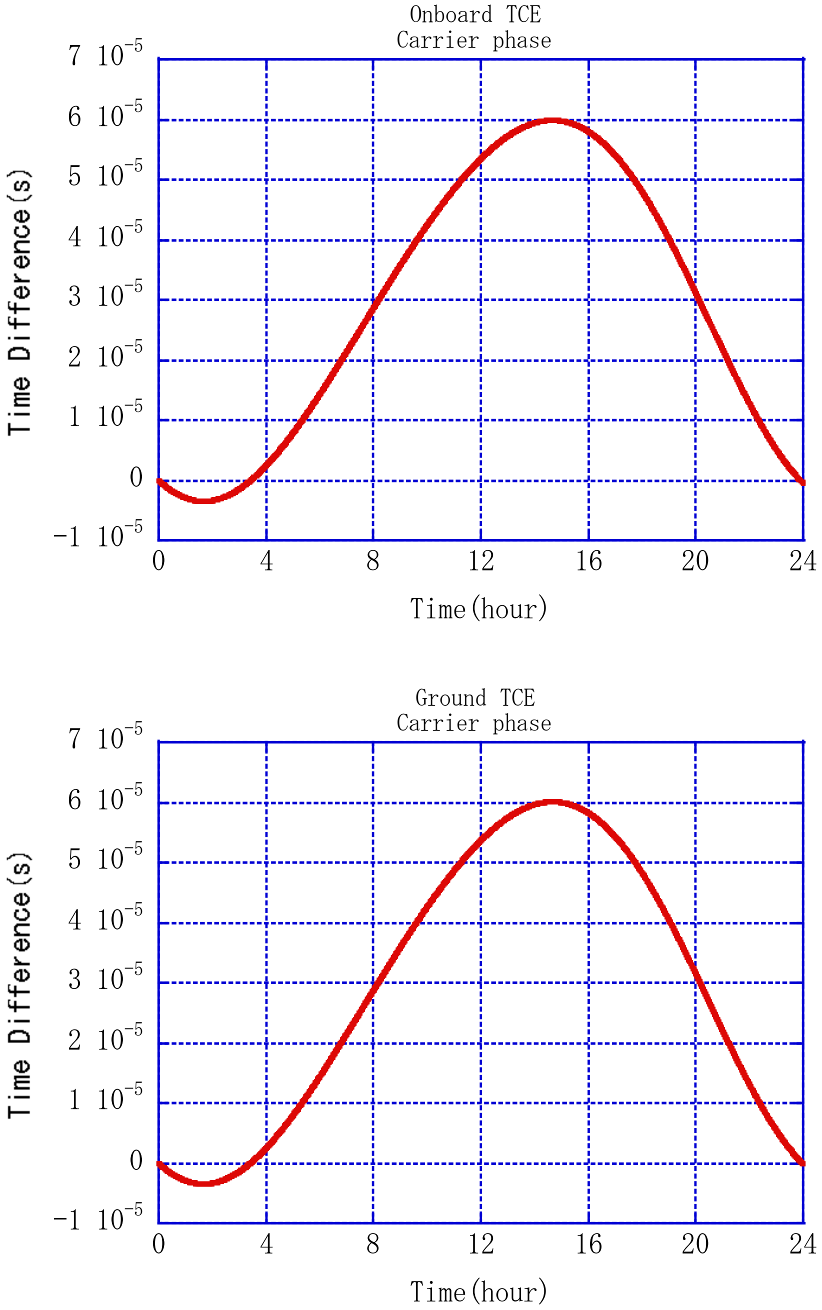

Figure 6. Examples of the measured data in carrier phase by TCE onboard ETS-VIII (top) and in the Earth station (bottom).

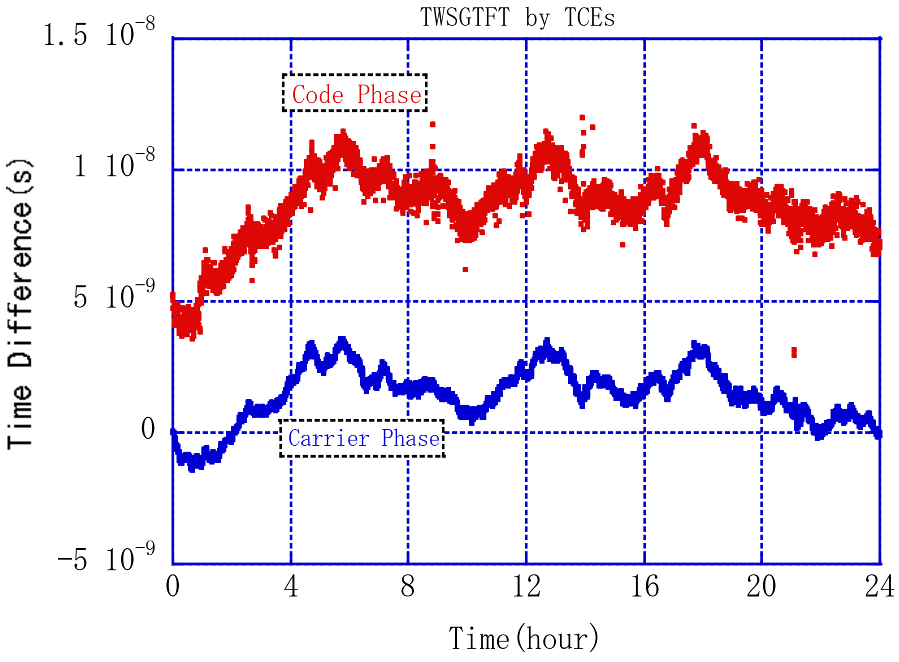

Figure 7. Time differences between the onboard cesium atomic clock and UTC (NICT) calculated by the two-way time and frequency method for code and carrier phase. First-order trends are removed and the value of time difference for code and carrier phase at t = 0 are 5 ns and 0 ns respectively.

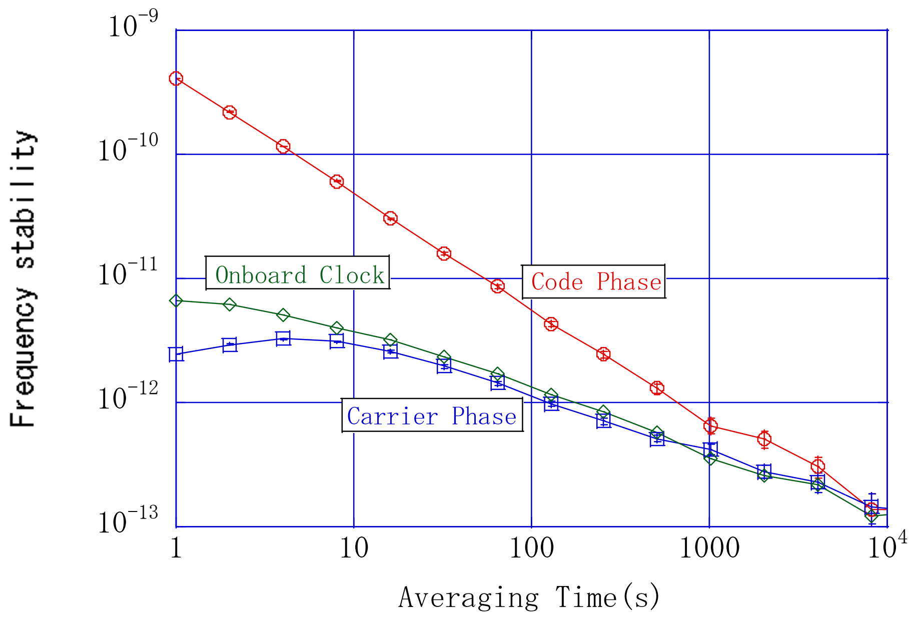

Figure 8. Frequency stabilities of an onboard Cs clock measured by code and carrier and in the experimental room before launch.