A High Accuracy Time Comparison using Time Comparison Equipment (TCE) on the Engineering Test Satellite (ETS –VIII)

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The National Institute of Information and Communications Technology (NICT) developed the Time Comparison Equipment (TCE) on-board the Engineering Test Satellite VIII (ETS-VIII). The ETS-VIII is a Japanese geostationary satellite, which was launched on December 2006. ETS-VIII has missions for mobile communication experiments and for precision timing experiments using Cesium atomic clocks in space. We carried out time transfer of the time difference between on-board standards and the ground reference clocks. This paper describes on the results of the time transfer experiment and the correction of the ionospheric delays using the estimated absolute value of Total Electron Contents (TEC) by the Space Weather and Environment Informatics Laboratory of NICT.

1 Introduction

For the development of satellite positioning technology, the Japan Aerospace Exploration Agency (JAXA) and NICT planned and conducted basic research on the technology and developed for the first time in Japan an on-board atomic clock on the engineering test satellite ETS-VIII, which launched in December 2006[1]. Since NICT has been generating and providing Japan Standard Time, the on-board time comparison equipment (TCE)[2] was developed to compare high-precision time transfers between satellites and the earth for the evaluation of the performance of the clock in satellite orbit.

In the high-precision time transfer between a satellite and the earth, the time delay is almost canceled in the uplink and the downlink due to the troposphere and ionosphere but the delay due to the ionosphere cannot be completely eliminated because of the frequency difference between the uplink and downlink signals. However, the result of high-precision time transfers between satellites and the earth can be corrected by estimating the absolute value of the total electron count (TEC) of the ionosphere using S- and L-bands data received on the earth. In this paper we report on the results of this high-precision time transfer between a satellite and the earth and the correction of the ionosphere-caused time delay. High-precision time transfer is one of the fundamental technologies of satellite positioning and has been applied to technologies for high-precision positioning experiment systems with quasi-zenith satellites[3] in Japan.

2 Two-way high-precision time transfer between satellites and earth

2.1 Two-way time transfer method

Figure 1 shows the configuration of the installed atomic clock and the high-precision time (frequency) transfer between a spaceborne atomic clock and a standard clock on the earth. A time transfer signal is sent from the satellite to the earth and from the earth to the satellite and is received by both. The phase differences between the received signal and the atomic clock are measured. By comparing the phase differences on the satellite and those on the earth, one can find the time difference between the two clocks. This method is called the two-way time transfer method

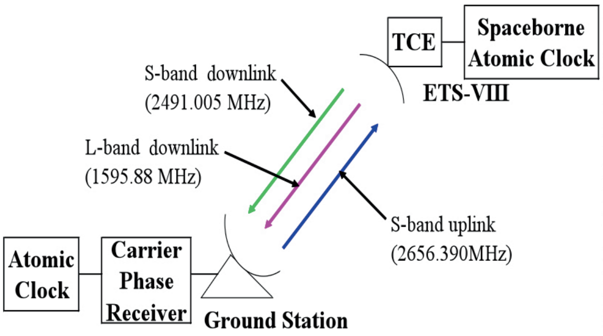

Fig. 1 Configuration diagram of time transfer

and this application for time transfers between a satellite and the earth was the first of its kind in the world. In principle the two-way time transfer method can cancel out the influence of time delays due to the troposphere and ionosphere in the transfer path, the variation of the delay, and the satellite motion, realizing high-precision time transfer. Since highly stable atomic clocks are used on both the satellite and the earth, carrier phase and modulation signals are all generated coherently as is done with GPS, and the phase information of not only the modulation signals, but also the carrier phase, can be utilized to perform phase measurements at a precision of 10^{-12} seconds[4].

2.2 Devices on ETS-VIII and earth station

The positioning-related devices on ETS-VIII consist of a JAXA high accuracy clock (HAC)[5], an atomic clock, an S-band transceiver, an L-band transceiver, 1.0m diameter antenna for both the S-and L-bands, and a satellite laser ranging (SLR) device (LRRA). NICT was in charge of developing a TCE with a measurement function of time delays in S-band signals. The developed TCE is shown in Fig. 2 and the specifications of the HAC and TEC are given in Table 1.

The earth station was set up at NICT (Koganei, Tokyo, Japan) and measured uplink/downlink signals in S-band and received signals in L-band. Japan standard time UTC (NICT) was used as a reference signal.

2.3 Two-way time comparison principle and major errors

The satellite and earth stations both measure the code phase and carrier phase of time transfer signals, which contain a geometrical delay, atomic clock error, delays due to the ionosphere and troposphere, and internal delays. The code phase C^S on the satellite, code phase C_e on the earth, carrier phase Φ^S on the satellite, and carrier phase Φ_e on the earth can be expressed with the following observation equations[6][7].

$$C^S = \tau + dt^S - dt_e + I_u + T + d_{eTx} + d^S_{Rx} \tag{1}$$

$$C_e = \tau + dt_e - dt^S + I_d + T + d^S_{Tx} + d_{eRx} \tag{2}$$

$$\Phi^S = \tau + dt^S - dt_e - I_u + T + d_{eTx} + d^S_{Rx} + \Phi^S(0) \tag{3}$$

$$\Phi_e = \tau + dt_e - dt^S - I_d + T + d^S_{Tx} + d_{eRx} + \Phi_e(0) \tag{4}$$

where τ is the geometrical time delay between the satellite and earth stations, dt^S and dt_e are the time differences of the atomic clock on the satellite and that of the UTC (NICT) respectively, I_u and I_d are the ionospheric delays in the uplink and downlink respectively, T is the troposphere time delay, d^S_{Rx} and d^S_{Tx} are the internal time delays of the receiver and transmitter on the satellite respectively, and d_{eRx} and d_{eTx} are the internal time delays of the receiver and transmitter on the earth respectively. The carrier phases received by the satellite and the earth station are accompanied by initial phases $\Phi^S(0)$ and $\Phi_e(0)$ respectively.

In the two-way time transfer, time differences can be estimated from either the code phase or the carrier phase by finding the difference between the received signal on the satellite and that on the earth to eliminate the geometrical time delay and the tropospheric time delay. However, despite this calculation, there remains an ionospheric delay due to the frequency difference between the uplink and downlink signals. The difference in the internal delay between the received and transmitted signals cannot be eliminated. These two are reduced considerably by the two-way signal subtraction but cannot be zeroed out and could be a major cause of errors in high precision time transfer. In what follows, the time difference observation equations of the code phase and the carrier phase are shown. The carrier phase contains uncertainty due to the initial phase, which can however be estimated from the code phase if the

Table 1 Specifications of HAC and TCE

TX Power		5.7W
S-band	TX Frequency	2491.005MHz
	RX Frequency	2656.390MHz
L-band TX Frequency		1595.880MHz
PN Code		Same as GPS C/A Code
Size		32cm × 32cm × 32cm
Mass		12.4kg

Fig. 2 Overview of TCE prototype flight model (PFM)

ionospheric delay can be calculated. TCE also has a correction system and can measure the internal delay.

From the observation equations (1) to (4), one can obtain the time difference of the code phase in the form (5),

$$dt^S - dt_e = \frac{1}{2}\left(C^S - C_e\right) - \frac{1}{2}(I_u - I_d) - \frac{1}{2}(d^S_{Rx} - d^S_{Tx}) + \frac{1}{2}(d_{eRx} - d_{eTx}) \qquad (5)$$

and that of the carrier phase in the form (6).

$$dt^S - dt_e + \frac{1}{2}\left(\Phi^S(0) - \Phi_e(0)\right) = \frac{1}{2}\left(\Phi^S - \Phi_e\right) + \frac{1}{2}(I_u - I_d) - \frac{1}{2}(d^S_{Rx} - d^S_{Tx}) + \frac{1}{2}(d_{eRx} - d_{eTx}) \qquad (6)$$

3 Result of satellite-earth time transfer

Experiments on two-way time transfers between the satellite atomic clock and the UTC (NICT) were conducted intermittently. Figure 3 shows the carrier phase results observed by the TCE and the earth station, and Fig. 4 shows the time transfer results of the code and carrier phases. The primary drift component was removed from the data and the time differences of the code phase and that of the carrier phase at t=0 were 0 ns and 5 ns respectively. The time differences of the code phase and that of the carrier phase change in a quite a similar manner. Within the measurement accuracy, the carrier phase seems to be better than the code phase.

Figure 5 shows the frequency stability of the same data (of the code and carrier phases) used in Fig. 4 and the specification value of the stability of the atomic clock on the satellite (HAC clock). The frequency stability measured over a second is 0.7 ns for the code phase and 3 ps for the carrier phase. These results indicate that the frequency of the clock on the satellite can be directly measured by time transfer experiments, even averaged over only 1 second, using the carrier phase.

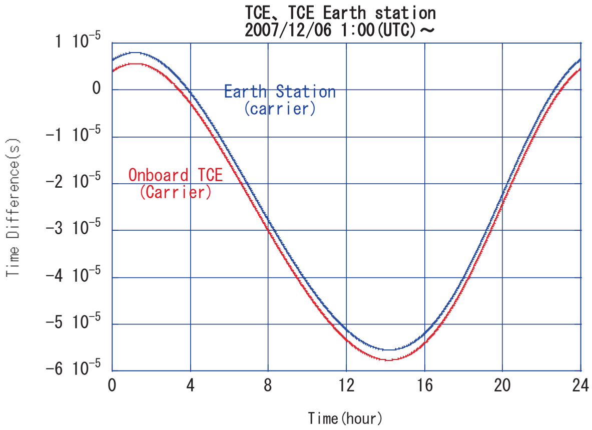

Fig. 3 Results of carrier phase measurement on TCE and earth station

4 Ionospheric delay correction

In satellite-earth high precision time transfers, time delays due to the ionosphere and troposphere are almost cancelled out in principle between the uplink and downlink. However, the time delay due to the ionosphere is not completely cancelled out and slightly remains because of the frequency difference between the uplink and downlink signals. Therefore high precision time transfer experiments need to make corrections for the ionospheric delay through the accurate observation of the total electron count (TEC) in the ionosphere using a carrier phase.

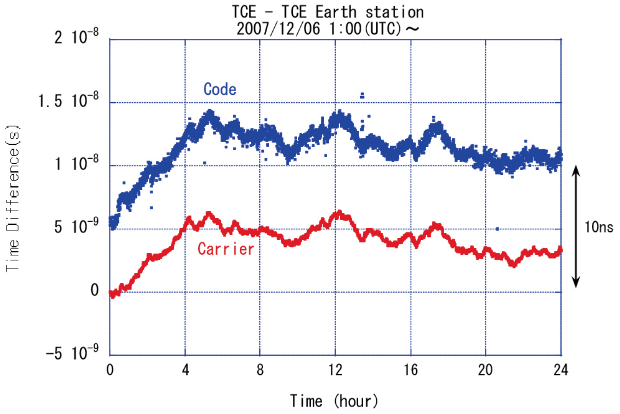

Fig. 4 Results of code phase and carrier phase measurements in time transfer between atomic clock on satellite and UTC (NICT)

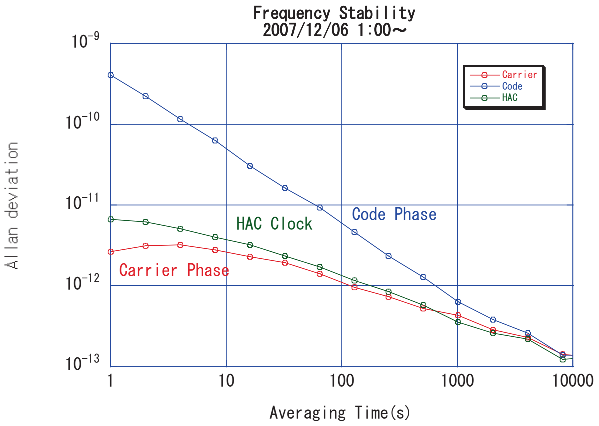

Fig. 5 Frequency stability of code phase and carrier phase measurements in time transfer between atomic clock on satellite and UTC (NICT)

However, with a satellite and a single receiver, the estimation of the absolute value of TEC is difficult due to internal time delays.

On the other hand, the NICT Space Weather and Environment Informatics Laboratory provided a TEC map[8] associated with the ionospheric delay based on the GNSS consecutive observation system (GEONET) provided by the Geospatial Information Authority of Japan. Therefore, for time transfer experiments, the TEC map created at NICT headquarters (Koganei, Tokyo), the same place where the time transfer experiments are conducted, can be utilized. In what follows, we show a method with some experimental results, where the absolute value of TEC is estimated using the code and carrier phases of S-and L-bands and is applied to satellite-earth high precision time transfer experiments.

4.1 Ionospheric delay determined by two-frequency observation

ETS-VIII transmits not only S-band signals for time transfer but also L-band signals for positioning experiments and the TCE at the earth station can receive these two frequency signals. The TEC can be estimated from the observation of the two signals by utilizing the dispersion of the signal waves as shown in Equation. (7), where $C'_{S\text{-}L}$ presents the difference in the code phases between the S-and L-bands and f_S and f_L show the frequencies of the S-and L-bands respectively. The carrier phase can also be described in a similar manner, although it contains uncertainty due to the initial phase. From the estimated TEC [1TECU=10^{16} el/m^2], one can calculate the time delay I [s] at each frequency based on Equation (8) [9][10].

$$TEC = \frac{C'_{S-L}}{1.345\times10^{-7}} \times \frac{f_S^2 f_L^2}{f_S^2 - f_L^2} \tag{7}$$

$$I = \frac{1.345\times10^{-7}}{f^2} TEC \tag{8}$$

The code and carrier phases are both used also to estimate the ionospheric delay. The delay observation using the carrier phase has a higher accuracy but has uncertainty due to the initial phase. Relative variation is measured by carrier wave observation and the initial phase is estimated using the code phase.

First, the data taken at the beginning of the code phase observation is used to make a frequency distribution with about 2,500 data points. The peak value is used as the initial TEC for the experiment to estimate its difference from the carrier phase as the initial carrier phase value (on the assumption that cycle slip etc. are already corrected). An example is shown in Fig. 6, where the horizontal axis is time delay in seconds [s] and the vertical axis is the count. However the estimated TEC, even if calculated from the code phase, contains biases such as internal delay and these biases could be about three times as large as the daily variation of the TEC caused delay. Therefore it is necessary to determine the bias in some way. Since the equipment is mounted in a constant-temperature chamber, the bias due to internal time delay does not change temporally but rather is stationary.

4.2 Absolute value estimation of ionospheric delay

The ionospheric delay observation using the carrier phase is highly accurate but only provides relative variation data. The time delay calculation using the code phase contains a bias due to internal delay and its accuracy is lower than the calculation using the carrier phase[10]. Although GPS observation can make a least-squares estimation to estimate the bias from many satellites and receivers[9], the bias estimation with ETS-VIII is difficult since the entire system consists of only one satellite and one earth device.

Fortunately, NICT has provided the absolute values of TEC that were obtained with least-squares estimation based on data from the GPS observation network, GEONET, provided by the Geospatial Information Authority of Japan[8][9] (Fig. 7). The TEC data obtained at the same place where the ETS-VIII's observation is made and the ionospheric time delay data that NICT releases are compared to estimate the TCE bias and to determine the ionospheric delay. Figure 8 shows an example of the absolute value of the ionospheric delay obtained from the carrier phase, where the bias is determined and the initial phase is estimated using the GPS-TEC absolute value estimate. The horizontal axis of Fig. 7 shows the time in seconds elapsed from the beginning of the observation.

4.3 Results of ionosphere correction in time transfer experiments

Figure 9 shows the time transfer results with the ionospheric delay corrected by the above mentioned method. The horizontal axis is UTC time and the vertical axis is the phase difference between the satellite and the earth station. In the figure, the primary drift component is removed. The red line is the results without the

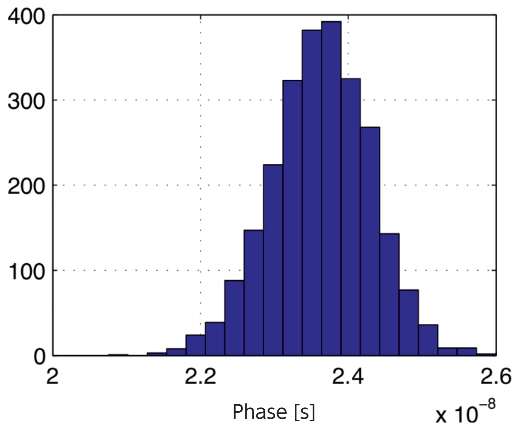

Fig. 6 Example of initial phase estimation for carrier phase. The vertical axis presents the count number.

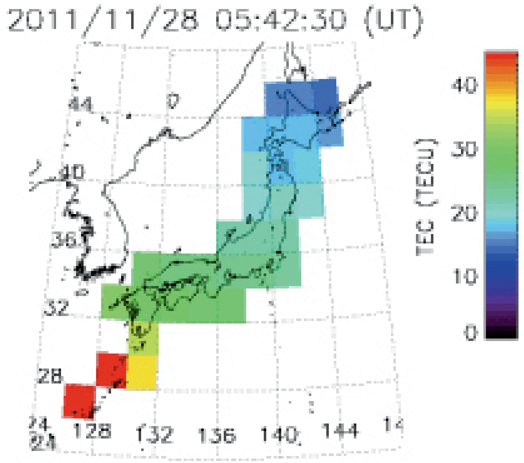

Fig. 7 Total electron count map provided by NICT

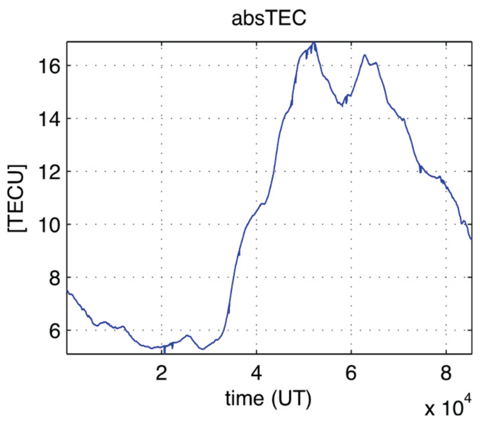

Fig. 8 Total electron content as of December 6, 2007 from bias estimation. The horizontal axis is elapsed time of the observation [sec] and the vertical axis the total electron content unit [TECU].

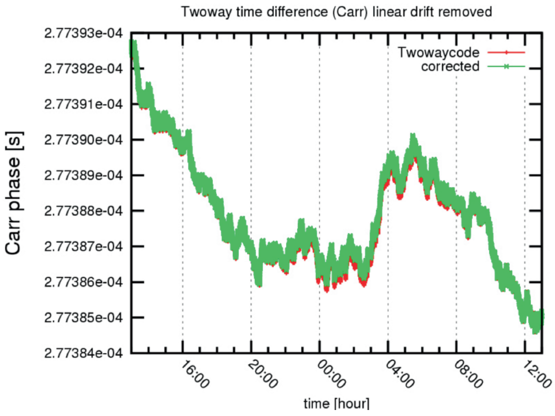

Fig. 9 Example of two-way time transfer result with carrier phase to which the ionospheric delay correction is applied. The horizontal axis presents the time (UTC) and the vertical axis shows the carrier phase [s].

ionospheric delay correction and the green is the data with the correction. Although the phase difference is up to about 1 ns, the correction is effective in the day time when the TEC increases. The above experiment period (2008) was a solar minimum and effects of the ionosphere were small. Since the ionosphere electron density in a solar maximum is about ten times higher than that of in the solar minimum and the time delay of S-band signals by the ionosphere may reach several tens of nanoseconds in some areas in Japan, ionospheric delay corrections will be required in a high precision time transfer experiment.

5 Summary

High precision measurements of the stability of the atomic clock on the satellite by the two-way time transfer method using carrier phases with TCE on ETS-VIII have been shown.

An ionosphere correction method for higher precision time transfer was also studied. The absolute value of the TEC was estimated using the ionosphere TEC map from the NICT Space Weather and Environment Informatics Laboratory and the corrections for the time transfer experiments were shown.

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