4-8 Time Comparison Experiment

4-8-1 Earth Station of Time Comparison Experiment

FUJIEDA Miho, TAKAHASHI Yasuhiro , GOTOH Tadahiro ,
NAKAGAWA Fumimaru , and IMAE Michito

The Time Comparison Equipment (TCE) for ETS-VIII has been developed to transfer time precisely between the ground reference clock, UTC (CRL) and the on-board atomic clock. We have finished the development of the TCE and been under construction of the earth station as well as a data-analysis program. In order to upgrade the stability of the time transfer, temperature control of the outdoor unit, improvement of the code-phase resolution and so on are planed in the earth station.

Keywords
ETS-VIII, Time transfer, Satellite Navigation

1 Introduction

In satellite navigation using GPS or similar devices, time differences between the onboard atomic clocks used for satellite navigation significantly influence the precision of positional determination. Precise time transfer between the satellites and the ground is essential in determining the time discrepancies among the onboard clocks of multiple satellites. High-precision time transfer thus represents a fundamental technology for satellite navigation.

In this context, the Communications Research Laboratory (CRL) will install Time Comparison Equipment (TCE) [1] on the Engineering Test Satellite VIII (ETS-VIII). This equipment will be used for precise time transfer between the satellite and the ground and to investigate the behavior of atomic clocks in orbit. In time-transfer operations the TCE will transmit and receive signals to and from the ground. As the two-way uplink and downlink transmission pathways are approximately equivalent, the effects of transmission delay in the atmosphere or those due to the motion of the satellite will be cancelled out, enabling highly precise time transfer [2], with anticipated precision on the order of several nanoseconds in code-phase operation and approximately 100 ps in carrier-phase operation.

We have completed development of the TCE and have begun development of the earth station and of the data analysis program. This report presents an outline of the earth station (TCE earth station) under development.

2 Two-way time transfer

The TCE earth station measures the code phase and the carrier phase with reference to the ground clock and calculates the time T_e at which the signal was received from the satellite. The TCE calculates the reception time T^s with reference to the onboard cesium atomic clock. These observed values can be expressed in the following equation.

$$T_e=\tau_g+dt_e-dt^s+d^s_{Tx}+d_{eRx}+I_d+T \quad (1)$$

$$T^s=\tau_g+dt^s-dt_e+d_{eTx}+d^s_{Rx}+I_u+T \quad (2)$$

Here, τ_g is the geometrical delay between the earth station and the satellite, dt_e and dt^s are the time differences between the clocks at the earth station and aboard the satellite, respectively. T is delay due to the troposphere and I_d and I_u are the uplink and downlink delays attributable to the ionosphere, respectively. d_{eTx} and d_{eRx} represent internal delay values in transmission and reception for the TCE earth station, and d^s_{Tx} and d^s_{Rx} represent internal delay in transmission and reception for the TCE. The time difference between the clocks on the satellite and on the ground can be obtained by subtracting the value observed on the ground, T_e, from the value observed on the satellite, T^s.

$$T_e - T^s = 2(dt_e - dt^s) + (d^s_{Tx} - d^s_{Rx}) + (d_{eRx} - d_{eTx}) + (I_d - I_u) \quad (3)$$

Equation 3 shows that the difference between these two observed values is expressed by the sum of several terms: the time difference between the clocks on the ground and on the satellite, delay difference within the transmission and reception units of both systems, and the difference between uplink and downlink ionospheric delay. The TCE and the TCE earth station measure and correct for internal delay in real time. Given the frequency dispersion of ionospheric delay, the TCE earth station is designed to receive radio waves in two frequency bands—the L-band and the S-band. Total Electron Content (TEC) is then estimated and correction is performed [3].

3 Measurement principles

This section outlines the code-phase and carrier-phase measurement principles in place at the TCE earth station. The TCE earth station transmits and receives PSK (Phase Shift Keying) modulation signals diffused by a C/A (Clear and Acquisition) code compatible with GPS. The code clock frequency is 1.023 MHz. The code of the signals transmitted from the satellite is known, allowing the receiver to track the code. The code phase is the amount of phase shift required to synchronize the code generated in the receiver with the reception-signal code. The carrier code is determined in a similar manner. The TCE earth station generates the code and the carrier in coherence with a reference signal, enabling measurement of the time difference between the satellite and ground clocks.

The data-processing unit [4] generates the code (Lead, Typical, Lag) with the shift of the chip phase $(+\frac{1}{2}、0、-\frac{1}{2})$. For each code, the sine and cosine components are obtained for the correlation integral of the measured signal. The carrier phase is obtained from the arctangent calculated from these components. The code phase can be obtained from the shift of the code resister.

As the carrier frequency of the signals transmitted from the satellite is in the L-band or S-band, the carrier phase offers resolution on the order of picoseconds. However, since the number of carrier-phase rotations during signal transmission cannot be obtained, this value must be estimated using the results of code-phase measurement.

4 Outline of the TCE earth station

Development of the TCE earth station is based on the TCE engineering test model and has approximately the same configuration and functions as the TCE. The main functions of the TCE earth station are as follows.

- Reception of S-band and L-band signals from the ETS-VIII and measurement of code phase and carrier phase
- Generation of S-band signals to be transmitted to the ETS-VIII
- Generation of the S-band and L-band signals used to measure internal delay in the reception signals; measurement of code phase and carrier phase for the generated signals
- Measurement of the internal delay of the S-band transmission signal (The TCE earth station loops the signal back just before the antenna to measure code phase and carrier phase.)

Table 1 shows the specifications of the TCE earth station, Fig.1 consists of a block diagram of the station, and Fig.2 is an external view.

In Fig.1, the block on the left, enclosed by

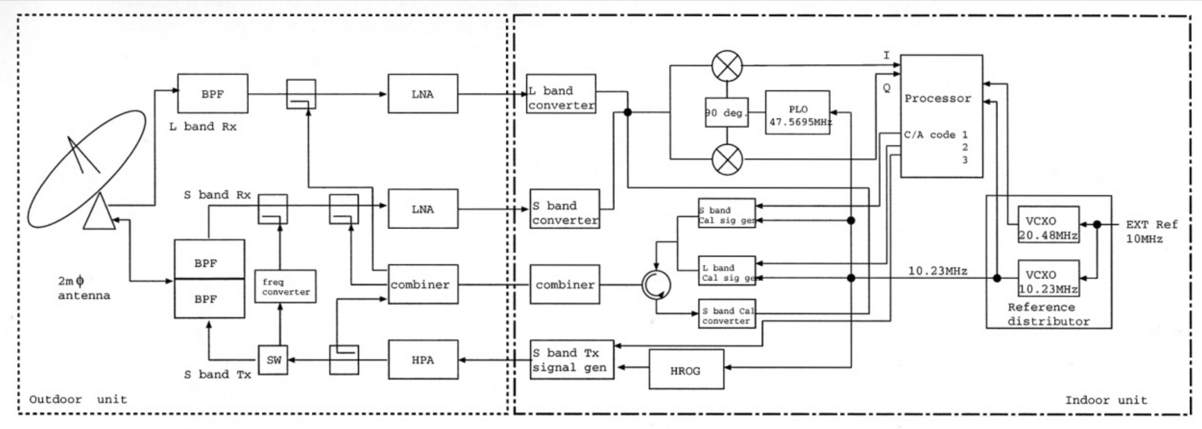


Fig.1 Block diagram of the TCE earth station

Fig.2 External view of the TCE earth station

Table 1 Specifications of the TCE earth station

Antenna	
Diameter[m]	2.4
Polarization	L band : RHCP S band : LHCP
Gain[dBi]	Rx : 34.2 Tx : 34.2
Transmitter	
Tx frequency[MHz]	2656.390
Output power[W]	18.0
EIRP[dBW]	43.8
Receiver	
Rx frequency[MHz]	L band : 1596.880 S band : 2491.005
Rx signal power[dBW]	-134
Gain[dB]	60.0
C/N_0[dBHz]	67.0

a dotted line, is the outdoor unit. The TCE earth station generates 10.23-MHz signals, as does the satellite, based on the UTC (CRL) reference signal, and uses the 10.23-MHz signal as the clock for each module.

The signal path of the reception system is as follows. First, the signal (received by an antenna 2 m in diameter) is amplified with an LNA (Low Noise Amplifier) and input into the converter. The converter down-converts the signal frequency—first to a 50.127-MHz intermediate frequency (IF) and then to 2.5575 MHz. Next, the signal is divided into two components, denoted as I and Q, with a phase difference of 90 degrees. The signal components are then input into the processor, which demodulates the C/A code and measures the code phase and the carrier phase.

For the transmission signal, the signal generator generates the carrier on which the code is superposed. The signal is then amplified with an HPA (High Power Amplifier) and transmitted. To measure the internal delay, the reception calibration signal is input into the reception signal pathway directly before the LNA input from the combiner. The calibration signal then follows the same path as the reception signal. The transmission calibration signal is amplified with the HPA, divided, input into the combiner, and demodulated.

The three calibration signals (for transmission calibration, L-band reception calibration, and S-band reception calibration) follow the paths common to all calibration signals to be inserted into the pathways of the transmission and reception signals. Thus, the difference between the delay values of the transmission and reception calibration signals enables determination of the difference in internal delay between the transmission and reception units. Signal loop-back is also enabled by switching the pathway of the S-band transmission signal after HPA amplification, performing frequency conversion, and inputting the converted signal into the S-band reception signal pathway. This function will be used to test the system.

A portable TCE earth station is scheduled for development. The antenna for this portable station will have the same diameter as that for the fixed station: 2.4 m. However, the portable antenna features a segmented structure for easier storage and transport. The remaining functions of the portable station will be equivalent to those of the fixed station. The fixed station will be installed at the CRL Headquarters (Koganei, Tokyo) and the portable stations will be transported to various atomic clock facilities for experiments. In addition to experiments on time transfer between the ground clock, UTC (CRL), and the ETS-VIII onboard clock, two-way time transfer experiments are also planned between the UTC (CRL) and other earth-based clocks via the satellite [5].

The data processing unit features a shared structure to enable the simultaneous processing of multiple signal sequences following conversion of these signals into the intermediate frequency. Attributing different C/A codes to different channels will allow simultaneous processing for up to 8 signal sequences. In most experiments between the TCE earth station and the ETS-VIII, five channels will be used: two for reception, one for transmission, and two for calibration. The three remaining channels will be used for experiments, including those between the portable earth stations.

5 Improvements in the TCE

Two-way time transfer will be conducted by calculating the difference between the time at which a signal is received at the TCE earth station (measured at the station) and the corresponding time measured by the onboard TCE. Thus, the precision of time transfer depends on the accuracy of measurement both of the onboard TCE and the TCE earth station. TCE components are limited due to onboard restrictions; for example, the CPU features slow clock speed and limited signal-processing capabilities. As the TCE earth station is free from these restrictions, several improvements have been devised to enhance the measurement accuracy of both the TCE and the TCE earth station. The following describes these improvements in more detail.

5.1 Temperature control of the outdoor unit

Equation 3 for two-way time transfer indicates that the error in the measurement of internal delay reduces the precision of time transfer. The TCE earth station measures the internal delay in real time; accordingly, fluctuation in measurement must be minimized to the fullest extent possible.

The characteristics of equipment such as the HPA, the LNA, and cables are known to change with changes in the surrounding temperature. In time transfer on the order of picoseconds, fluctuation in delay due to temperature change results in significant system error [6]. Thus, all outdoor equipment at the TCE earth station (with the exception of the antenna) is housed in a series of enclosures; temperature inside these enclosures is controlled to suppress fluctuations in delay. All indoor equipment is installed in a thermostatic chamber. Sensors are attached to all items of equipment to monitor temperature, including the cables connecting the indoor and outdoor units.

5.2 Adjustment of transmission power

The carrier phase can be obtained from the sine and cosine components of the C/A code correlation integral. When the C/N (Carrier to Noise ratio) is high, the carrier-phase is quantized in accordance with the bit number associated with the quantization of the correlation integral. The TCE samples the correlation integral with a signed single bit [4]. The resolution of the carrier phase is thus limited to 45°. However, the decrease in the C/N is equivalent to the phase modulation in the receiving signal, thus maintaining linearity in the carrier phase obtained from the integral.

The TCE earth station adjusts the power of the transmission signal with a variable attenuator to optimize the C/N of the reception signal.

5.3 Measurement of code phase

The code tracking of the TCE is performed based on the delay-control method, in which the shift resister values are shifted with reference to 20.46 MHz, which is 20 times greater than the code-clock frequency. The shift resister values are added every 20 ms and collected by telemetry every 1 s. Thus, the code phase is obtained as an average over 1 s.

On the other hand, the TCE earth station executes tracking control using an NCO (Numerically Controlled Oscillator). Thus it is expected that an integrated NCO phase can be obtained with improved code-phase measurement accuracy. The tracking rate of the NCO will also increase to 40.96 MHz, which is expected to lead to an approximately twofold increase in resolution.

5.4 Adjustment of the code phase and the carrier phase of the transmission signals

The carrier phase is calculated from the correlation integral of the code. The correlation integral is obtained as an average over 1 s, as with the code-phase. Thus, if the carrier phase were to fluctuate by ±180°, the average of the transmitted phase would be 0°; this amount of fluctuation corresponds to very low accuracy. To prevent this and similar effects, the earth station will adjust the carrier phase and code phase of the transmission signals sent from the station. Carrier phase will be varied by adjusting the frequency of the 10.23-MHz reference signal input to the transmission signal generator. The code phase will be adjusted by shifting the phase of the NCO.

5.5 Removal of Doppler frequency shift and correction of transmission frequency

The TCE does not automatically track the Doppler frequency. Thus, it cannot obtain the code correlation when the Doppler frequency shift is large, failing to perform the measurement of transmission frequency. On the other hand, the TCE earth station automatically tracks the carrier frequency using the NCO; thus, frequency shift can be obtained from the integrated NCO phase. Using this frequency shift value, the reference frequency of the TCE earth station is adjusted to shift the reception frequency to cancel the TCE Doppler shift. This frequency enables determination of the code correlation and allows measurement to be performed.

Fig.3 shows the concept behind this correction. SG in the figure stands for Signal Generator, TIC represents the Time Interval Counter, and DMTD refers to the Dual Mixer Time Difference. This system reads the frequency shift of the NCO and converts it to a shift with reference to the 10.23 MHz reference signal frequency. To cancel the shift at the satellite, the direction of the shift away from the central frequency of the transmission

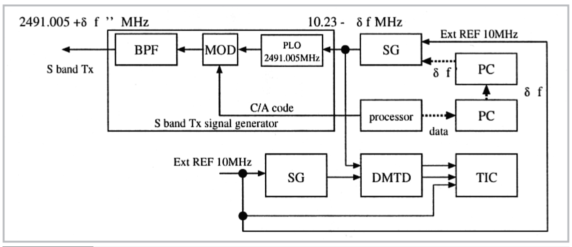


Fig.3 S-band signal generator of the TCE earth station

signal is reversed. A frequency signal slightly away from 10.23 MHz is output from the SG and is used as the reference frequency for the S-band transmission signal generator. This will shift the S-band transmission frequency away from 2491.005 MHz. In two-way time transfer, the subtraction cancels Doppler shift without requiring correction. However, because the frequency is shifted to enable measurement with the TCE, correction is required in time-difference calculations.

In general, the phase is the time integral of the frequency. Thus, precise determination of the frequency change over time is necessary. To achieve this, time variation in the reference frequency is monitored in picoseconds using the DMTD equipment for use in time-transfer frequency correction.

6 Summary

The TCE is designed for time transfer featuring precision on the order of several nanoseconds using the code phase, and with 100-ps precision using the carrier phase. Time transfer with precision on the order of picoseconds is now the goal, as clock stability has surely advanced. This is also an important issue in terms of the establishment of satellite navigation technologies.

To increase measurement resolution, the TCE earth station implements temperature control for the outdoor unit and improves code tracking frequency in the data-processing unit. It will also feature functions to adjust the code phase and transmission power and to correct the Doppler frequency. Next we will test the performance of the earth station and complete the data-analysis program to prepare for satellite launch.

References

1 Y. Takahashi et al., "Experimental Plan for Time Comparison Equipment for ETS-VIII Satellite", the Transactions of the Institvte of Electronics, Information and Communication Engineers B, Vol. J84-B, No. 12, pp. 2101-2107, 2001. (in Japanese)

2 H. Sun et al., "Performance of Two-way Satellite Time and Frequency Transfer in Asia-Pacific Region", Journal of the Geodetic Society of Japan, Vol. 49, No. 2, pp. 135-142, 2003.

3 F. Nakagawa et al., "4-8-2 Time Comparison Equipment for ETS-VIII — Data Processing, Analysis and Capability of Time Comparison — , This Special Issue of NICT Journal.

4 H. Kiuchi et al., "3-10-2 On-board Data Processing Part Time-comparison-equipment Processing Unit (TCE-PRO), This Special Issue of NICT Journal.

5 Y. Takahashi et al., "5-2 Experimental Plans using Time Comparison Equipment", This Special Issue of NICT Journal.

6 E. Powers et al., "Hardware Delay Measurements and Sensitivities in Carrier Phase Time Transfer", Proc. of the 30th PTTI, pp. 293-306, 1998.

***FUJIEDA Miho**, Ph. D.*

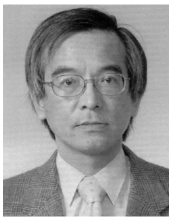
Research Fellow, Time and Frequency Measurements Group, Applied Research and Standards Division

Time Transfer, Satellite Navigation

GOTOH Tadahiro

Researcher, Time and Frequency Measurements Group, Applied Research and Standards Division

GPS Time Transfer



IMAE Michito

Leader, Time and Frequency Measurements Group, Applied Research and Standards Division (present National Institute of Advanced Industrial Science and Technology)

Frequency Standard, especially on Precise Time Transfer

TAKAHASHI Yasuhiro

Senior Researcher, Time and Frequency Measurements Group, Applied Research and Standards Division

Satellite Communication, Satellite Positioning System

***NAKAGAWA Fumimaru**, Ph. D.*

Research Fellow, Time and Frequency Measurements Group, Applied Research and Standards Division

Satellite Navigation, Satellite Time Transfer