ACTUAL OPERATION SIMULATION OF RESSOX GROUND EXPERIMENTS

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Abstract

The first quasi-zenith satellite (QZS) of Japan, named "Michibiki," was launched on 11 September 2010. After 3 months of initial functional verification tests, the actual operation will start. We have planned three kinds of experiments using Michibiki: (1) experiments without voltage-controlled oven-compensated controlled crystal oscillator (VCOCXO) control of Experiment One, (2) experiments with VCOCXO control of Experiment One, and (3) experiments with VCOCXO control of Experiment Two. In Experiment One, the remote synchronization system of the onboard crystal oscillator (RESSOX) control signal that includes information of the standard time will be sent from ground stations, and the onboard crystal oscillator of Michibiki will be controlled to synchronize the arrival of the RESSOX control signal. The RESSOX control signal is similar to such time calibration signals as WWV or JJY, but the delay is compensated. In Experiment Two, on the basis of the results of a time comparison experiment between the onboard crystal oscillator and the ground standard time conducted by the National Institute of Information and Communications Technology (NICT), the voltage applied to the onboard crystal oscillator will be calculated at the ground station and transmitted to Michibiki to control the crystal oscillator. The effects of some data and command delays on control quality and performance in an actual operation are considered as well. For example, in Experiment One, every 30 s, we expect to receive orbit forecast information in the International Terrestrial Reference Frame (ITRF) for a duration of 3 minutes, which is almost real time, from the Master Control Station. We estimate that the data will take one and a half minutes to reach us as the satellite orbit is measured. In this regard, the available data will be one and a half minutes. We also expect to experience some discontinuities when we use the following data every 30 s. In Experiment Two, approximately 20 s is required from the start of time comparison to the voltage command execution. A large applied voltage change (i.e., sudden frequency change of satellite time standard) may lead to loss of time comparison signal at Michibiki and this may cause loss of time comparison data. We set these conditions in the ground experiments, investigate their effects, and propose countermeasures.

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14. ABSTRACT
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I. INTRODUCTION

The quasi-zenith satellite system (QZSS) has been under development as a Japanese space project since 2003, and its mission is navigation and/or positioning **[1]**. Its constellation consists of three satellites orbiting on inclined orbital planes with a geosynchronous period. The first QZS, named “Michibiki,” was launched on 11 September 2010. The QZSS utilizes a high inclined orbit because of the high visibility over high-latitude regions. In the case of the QZSS, at least one satellite is highly visible near the zenith at any time from Japan. Therefore, users in Japan can always receive navigation signals from at least one of the QZSs near the zenith.

In general, a global navigation satellite system (GNSS), such as the GPS of the USA, GLONASS of Russia, and GALILEO of Europe, is equipped with onboard atomic frequency standards that are used as time references. This is because: (1) atomic clocks have good long-term stability, (2) the orbit of satellites makes monitoring from one ground station impossible, (3) these satellite systems are used for military missions and are, therefore, expected to operate even if ground stations are destroyed, and (4) these systems consist of many satellites, making the control of each satellite with many antennae difficult. However, onboard atomic clocks have the following disadvantages: they are bulky, expensive to manufacture and launch, and power-demanding. Moreover, they are one of the main factors contributing to the reduction of satellite lifetimes.

The following have been taken into consideration in the design of the QZSS as a civilian navigation system: (1) some crystal oscillators have better short-term stability than atomic clocks **[2]**, (2) 24-hour control with one station is possible if the location of the control station is appropriate, for example, Okinawa, Japan, and (3) the number of satellites is assumed to be only three. Given these considerations, it is reasonable to develop the remote synchronization system for the onboard crystal oscillator (RESSOX), which does not require onboard atomic clocks. In the case of RESSOX, modification of the control algorithm after launch is easy because it is basically a ground technology. The target synchronization accuracy of RESSOX is set at 10 ns and the target stability is 1×10^{-13} at 100,000 s. These targets were determined on the basis of the synchronization performance between GPS-Time (GPST) and UTC (USNO) **[3]** and the long-term stability performance of onboard cesium atomic clocks **[4]**.

RESSOX ground experiments and computer simulations have been conducted since 2003. Primary experimental results obtained using navigation signals are detailed in our previous papers **[5-8]**. We have developed a feedback method that uses multiple navigation signals of the QZSS, and found that we do not need precise orbit information or estimation of delays, such as those caused by the ionosphere and troposphere, to realize RESSOX technology.

In the actual QZSS operation, a 35-minute communication interruption (CI) of Ku-band above the equator occurs twice a day because of the need to avoid the interference with other geostationary earth orbit (GEO) satellites. For RESSOX, the control method of the crystal oscillator during CI is the issue to be resolved **[9]**.

Two kinds of experiments are scheduled as RESSOX operations: Experiment One and Experiment Two. In Experiment One, the RESSOX control signal that includes information of the standard time will be sent from ground stations, and the onboard crystal oscillator of Michibiki will be controlled to synchronize the arrival of the RESSOX control signal. The RESSOX control signal is similar to such time calibration signals as WWV or JJY, but the delay is compensated. In Experiment Two, on the basis of the results of a time comparison experiment between the onboard crystal oscillator and the ground standard time conducted by the National Institute of Information and Communications Technology (NICT), the voltage applied to the onboard crystal oscillator will be calculated at the ground station and transmitted to Michibiki to control the crystal oscillator. We have conducted experimental operation in a manner similar to actual operation, and have confirmed that the operation can be performed successfully even with the discontinuity of orbit information data in Experiment One and the time lag of time comparison results in Experiment Two.

In a practical sense, QZSS will load two rubidium atomic standards. RESSOX is used in the experiments to examine their use in future QZSS.

II. RESSOX OVERVIEW

Two kinds of RESSOX experiments, Experiment One and Experiment Two, have been designed.

EXPERIMENT ONE

In order to realize Experiment One, it is indispensable to identify the error and delay of the RESSOX control signal and the feedback mechanism by estimating the delay of the onboard voltage-controlled oven-compensated crystal oscillator (VCOCXO) at the Time Management Stations (TMS), which are ground stations located at NICT sites (Koganei, Tokyo and Onna, Okinawa). The former is related to the estimation of error and delay using models, and is considered to be a feed-forward control. The latter is an error adjustment system that uses the pseudoranges measured with the navigation signals of QZSS and the estimated pseudoranges, and is considered to be a feedback control.

Figure 1 shows the system diagram of Experiment One using QZSS. Experiment One uses JAXA assets, NICT assets, and our own assets. GPST obtained by GPS synchronizer or QZSS-Time 1 (QZSST1) that is based on UTC (NICT) will be used as standard time. RESSOX control signal transmitter (RCST) will advance the time of the RESSOX control signal to compensate the delay during transmission between GPST or QZSST1 and VCOCXO onboard QZSS. Time information of the RESSOX control signal will be modulated with a pseudonoise (PN) code also by RCST at TMS, up-converted to 14.43453 GHz (Ku-band) by the up-converter, and transmitted from the Ku-band antenna of TMS to QZSS ceaselessly, except during the approximately 35-minute CIs twice a day. At QZSS, the RESSOX control signal will be received by the Ku-band antenna, down-converted, and demodulated for comparison with that of the onboard VCOCXO by the time comparison unit (TCU) of NICT. The time-difference information (PN-code phase difference) between the arrived RESSOX control signal and VCOCXO time will be transferred to the navigation onboard computer (NOC) of JAXA. Then, NOC will generate the control command (voltage to be applied) for VCOCXO through an appropriate control algorithm. On QZSS, navigation signals (QZSS signals) of L1-, L2-, and L5-bands will be generated by the L-band signal transmission subsystem (LTS) using VCOCXO as the reference clock. At TMS, QZSS signals will be received by the L-band antenna and transmitted to the QZSS/GPS receiver (QZSSREC) for RESSOX. QZSSREC will compare time information in the QZSS signals with GPST or QZSST1 and output the pseudoranges to the RESSOX controller (RC). The pseudoranges will be used to calculate the time to be adjusted of the RESSOX control signal. RC at TMS will control RCST using both the delay models (feed-forward control) and the time to be adjusted (feedback control). To monitor the performance of RESSOX, the results of the time comparison conducted by NICT will be collected by RC.

In actual operation, three delay estimation methods have been prepared. They are 3-minute orbit estimation/forecast values, 7-day continuous delay estimation using models, and delay estimation using the L1C/A navigation message. To realize continuous RESSOX operation, use of 3-minute orbit estimation/forecast values is indispensable; however, only the 7-day continuous delay estimation using models has been evaluated so far because it is easy to evaluate. In this study, we focus on the processing of 3-minute orbit estimation/forecast values.

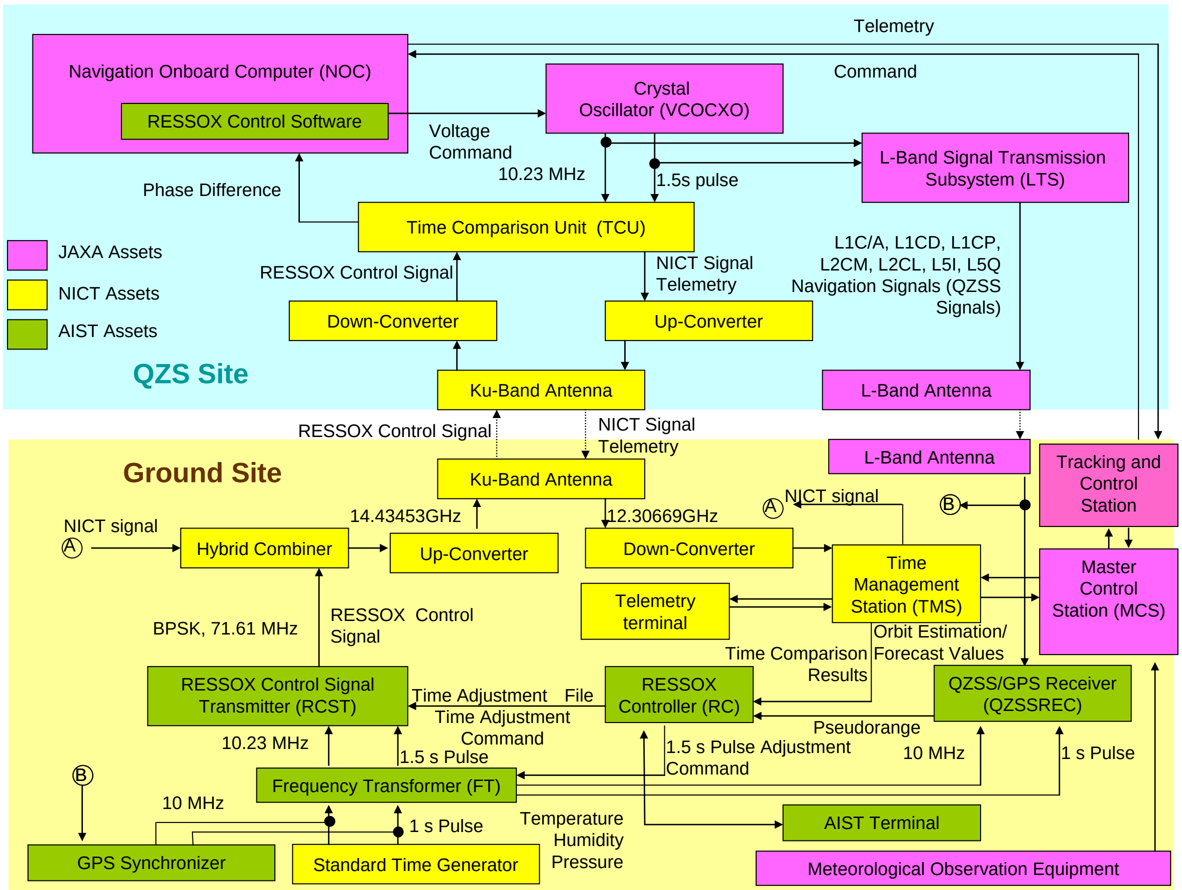


Fig. 1. System diagram of Experiment One using QZSS.

In the case of the 3-minute orbit estimation/forecast values, every 30 s, RC will receive orbit estimation and forecast values in the International Terrestrial Reference Frame (ITRF) for a duration of 3 minutes, as shown in Fig. 2. The data discontinuity that occurs every 30 s would be an issue.

Experiment Two

To realize Experiment Two, the results of the time comparison between the onboard VCOCXO and QZSST1, conducted by NICT, are indispensable. The voltage to be applied to VCOCXO will be calculated on the basis of the results obtained at TMS and up-linked every 1.5 s ceaselessly, except during the 35-minute CIs twice a day.

Figure 3 shows the system diagram of Experiment Two using QZSS. Experiment Two also uses JAXA assets and NICT assets, and the RC at TMS and RESSOX control software in NOC, which are AIST assets.

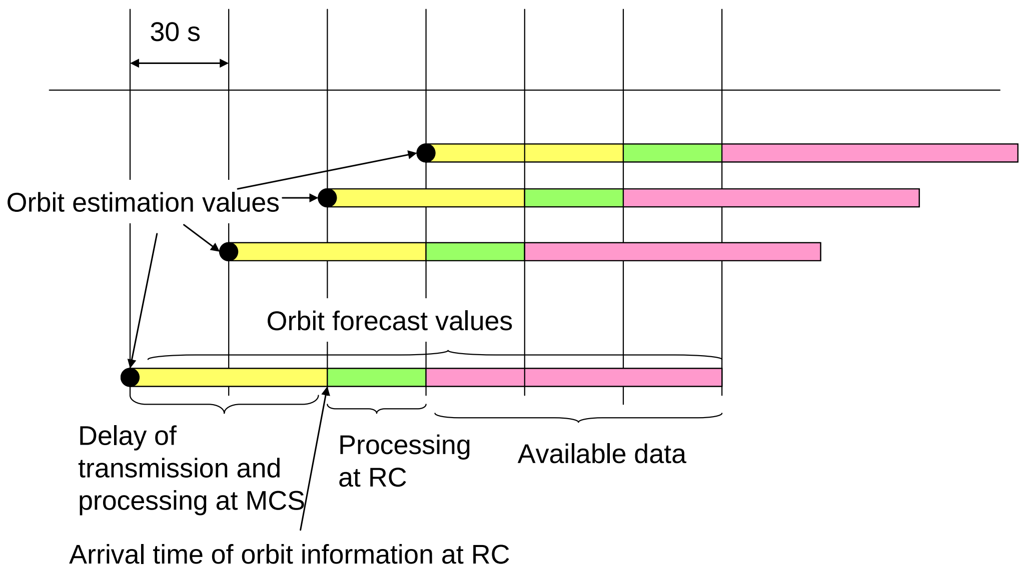


Fig. 2. Processing of 3-minute orbit estimation/forecast values.

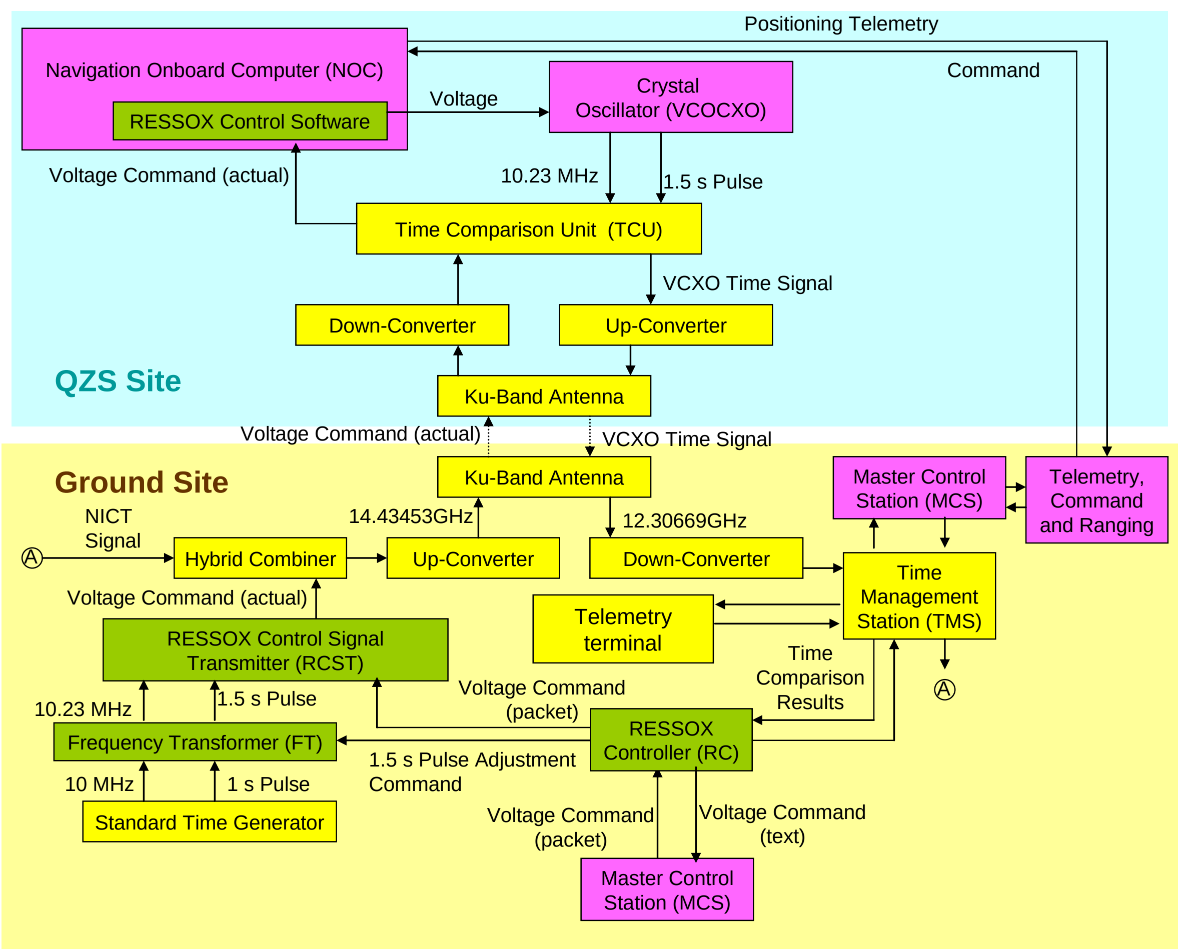


Fig. 3. System diagram of Experiment Two using QZSS.

The time delay of the voltage command from TMS to QZSS is the main issue that must be resolved to realize this architecture. The delay is assumed to be within 20 s. Command processing and delay estimation are shown in Fig. 4. An original voltage command that has one integer digit and eight decimal digits, such as 5.12345678 (V), will be sent to the Master Control Station (MCS) as ASCII characters from the RC. Then, the command data packet that is constructed by a 944-bit binary code will be sent back to the RC. MCS will check the voltage command to determine whether it is acceptable or not, and if it is not acceptable, the packet will not be sent. Using the data packet, RCST will construct the command, combining it with header and dummy packets.

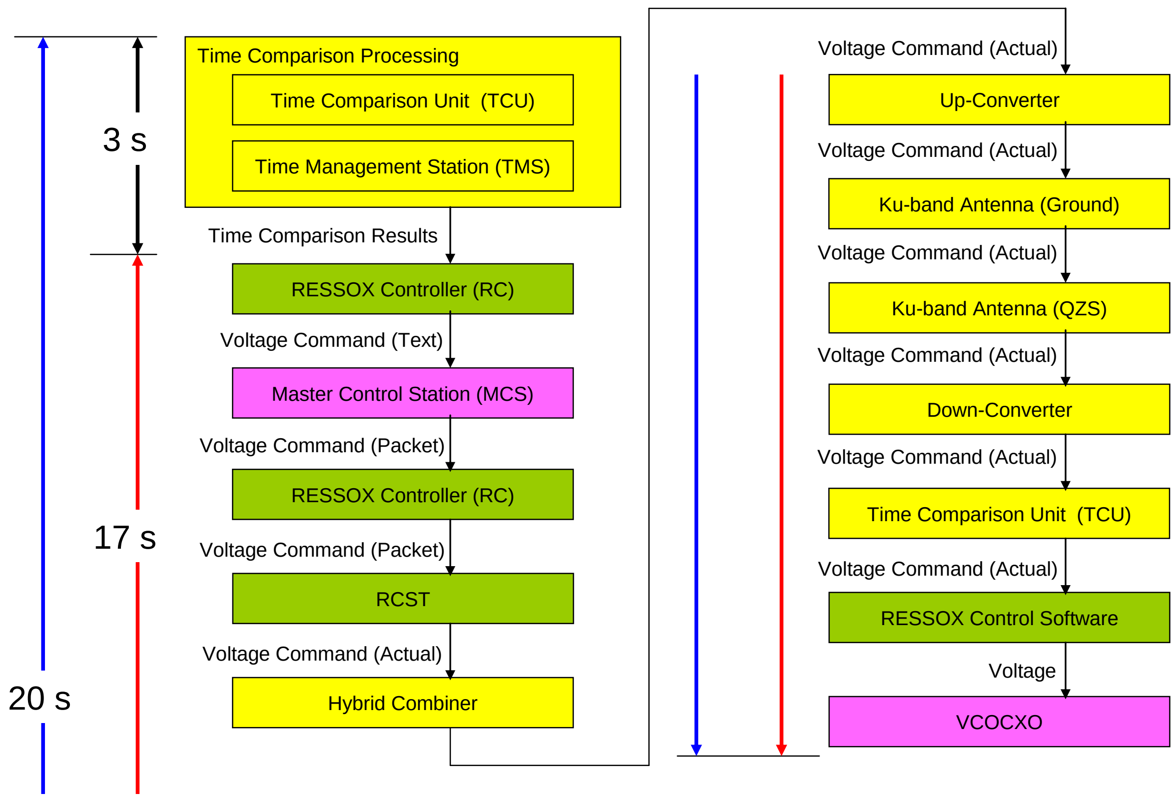


Fig. 4. Command processing of Experiment Two and delay estimation.

VOLTAGE CONTROL METHOD

In the case of Experiment One, RESSOX controls NOC software, and in the case of Experiment Two, RC calculates the voltage based on the following formula:

$$v_k = v_{offset} - \frac{K_1}{l+1} \sum_{i=k-\left[\frac{d}{1.5}\right]-l}^{k-\left[\frac{d}{1.5}\right]} \left(t_{VCOCXO} - t_{RESSOX}\right)_i - K_2 \sum_{i=0}^{k-\left[\frac{d}{1.5}\right]-p} \int_i^{i+p} \left(t_{VCOCXO} - t_{RESSOX}\right) dt$$

where v_k is the k-th applied voltage, v_{offset} = 5.4 (V), K_1 is a proportional gain set at 7.0×10^5, K_2 is an integral gain set at 3.0×10^3, l is the number of past data used for proportional control set at 1, k is the data number from the beginning, p is the integral interval, which means an overlapping integral number, set at 3, t_{VCOCXO} is the time of VCOCXO, t_{RESSOX} is the time of RESSOX control signal, d is the transmission delay (in the case of Experiment One, set at 0 and calculated on NOC; in the case of Experiment Two, set at 20 and calculated on RC), and notation [] is Gauss' symbol ([x] is the largest integer that is less than or equal to x).

III. EXPERIMENTAL RESULTS

RESULTS OF EXPERIMENT ONE

(1) Experimental Method

Figure 5 shows a block diagram of the ground experimental system for Experiment One. To simulate the QZS, TMS, MCS, and transmission delay, software or apparatuses that are shown as green boxes were used.

As a reference clock, a hydrogen maser (H-Maser) was used. An uplink delay simulator (UDS2), an engineering model of the onboard crystal oscillator (MINI-OCXO) that has the same specifications as VCOCXO, a simulator of the onboard TCU (TCUSIM), a simulator of the NOC (NOCSIM), a D/A converter, a QZSS simulator (QSIM2) that provides navigation signals with transmission delay using SimQZ software, and a pulse generator (PG) that supplies 1 s and 1.5 s pulses were also provided to confirm the operation of the ground station apparatuses. On the ground site, TMS and MCS were simulated by SimIF software. Orbit estimation/forecast values were generated by SimIF. SimQZ software was used to control the navigation signals of phase and code pseudoranges and the navigation messages generated by QSIM2. A time-interval counter (TIC) was used to measure the time difference between H-Maser and MINI-OCXO.

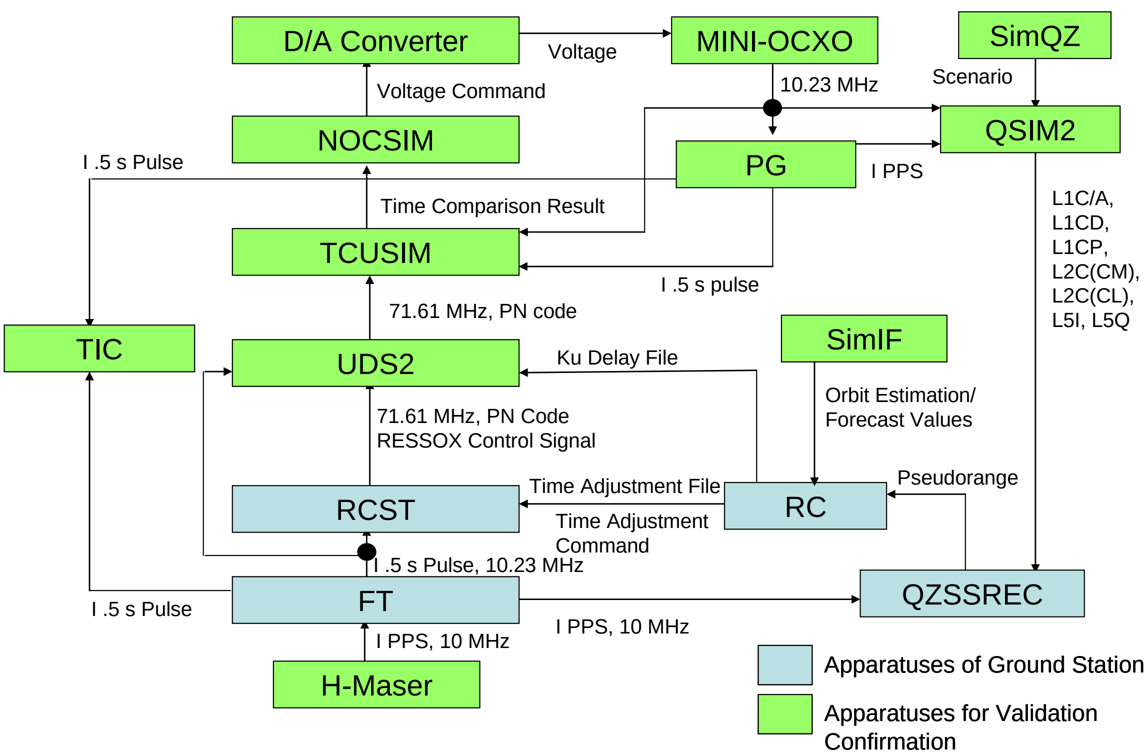


Fig. 5. Block diagram of the ground experimental system for Experiment One.

For feedback, L1CD and L5I, the best combination of the navigation signals, were used in the experiments **[10]**.

We assumed that the time taken for the orbit estimation/forecast values to reach RC is 90 s, after obtaining the initial orbit estimation value. Therefore, we used latter-half data of the orbit estimation/forecast values shown in Fig. 6. In our case, as data discontinuity, uniform random values between 0 and 1 meter were added to the real value of the ITRF satellite position every 30 s. For the orbit calculation, we assumed the conditions shown in Table 1. In the experiments, UDS2 and SimQZ adopted the delay with ionospheric, tropospheric, and relativity effects because these delays were real, and RCST and data for feedback employed the delay without ionospheric, tropospheric, and relativity effects and added random uncertainty of the satellite position with uniform random number between 0 and 1 meter in ITRF every 30 s, because these delays were calculated using the orbit estimation/forecast values at TMS.

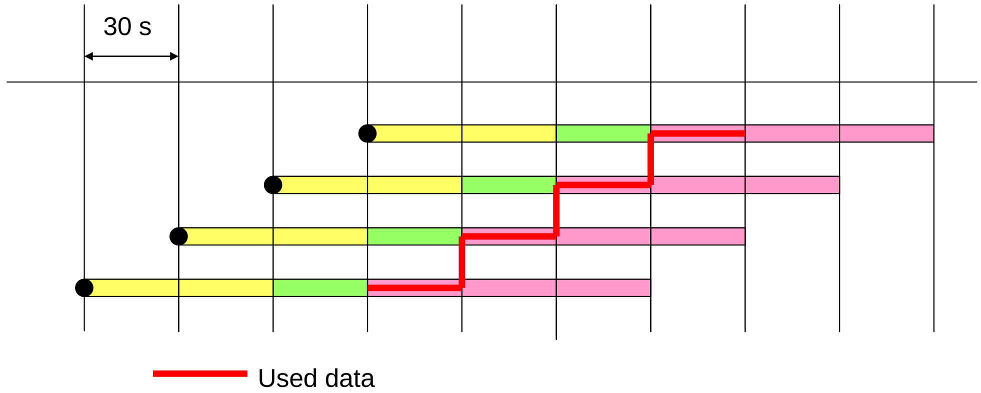


Fig. 6. Used data of orbit estimation/forecast values (refer to Fig. 2).

(2) Experiments Without CI

First, an experiment without CI was conducted. Figure 7 shows the results of a 24-hour experiment. The synchronization error was within 2 ns. The applied voltage had a fluctuation of approximately 4 mV. The rates of change of the synchronization error and the applied voltage were rather low, as shown in Fig. 8. The reason is the filtering effect of the time adjustment command (feedback command); 100 error samples of time to be adjusted were used to calculate the time adjustment command, as shown in Fig. 9.

(3) Experiments With CI

In an actual operation, CI should be considered twice a day. During CI, an average of 100 sample voltages immediately before CI was applied constantly. Figure 10 shows the synchronization error of a 24-hour experiment. The first CI caused an approximately 20-ns synchronization error, and the second CI caused an approximately 15-ns error. Later, we will consider the origin of the error.

Table 1. Experimental conditions.

Condition of orbit and delay calculation	No error (for UDS2 and SimQZ)	Error (for RCST and Feedback)
Initial condition of orbit calculation (ICRF)	x = -23342012.770 m y = -33282936.570 m z = 15995302.769 m vx = 2184.551 m/s vy = -935.546 m/s vz = 1774.093 m/s	ITRF(x)+random(0,1) m ITRF(y)+random(0,1) m ITRF(z)+random(0,1) m (Initial Condition is same as the left column)
Gravity potential model	EGM96, 360 degree, 360 order	
Other bodies	Moon, Sun, Mercury, Venus, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto	
Solar radiation pressure model	Cr model, Cr=1.2, 30 m^2	
Solid tide effect	Considered	
Satellite mass	1816 kg	
Ionospheric effect	CODE data are used	Not considered
Tropospheric effect	Saasamoinen, temperature 15 ºC, pressure 1013.25 hPa, humidity 70%	Not considered
Relativity effect	Considered	Not considered
Simulation period	1999/12/31 23:59:47 - 2000/01/01 23:59:47	
Observed position	Okinawa（26.5 N, 127.9 E, 0.0 m geodetic height ）	

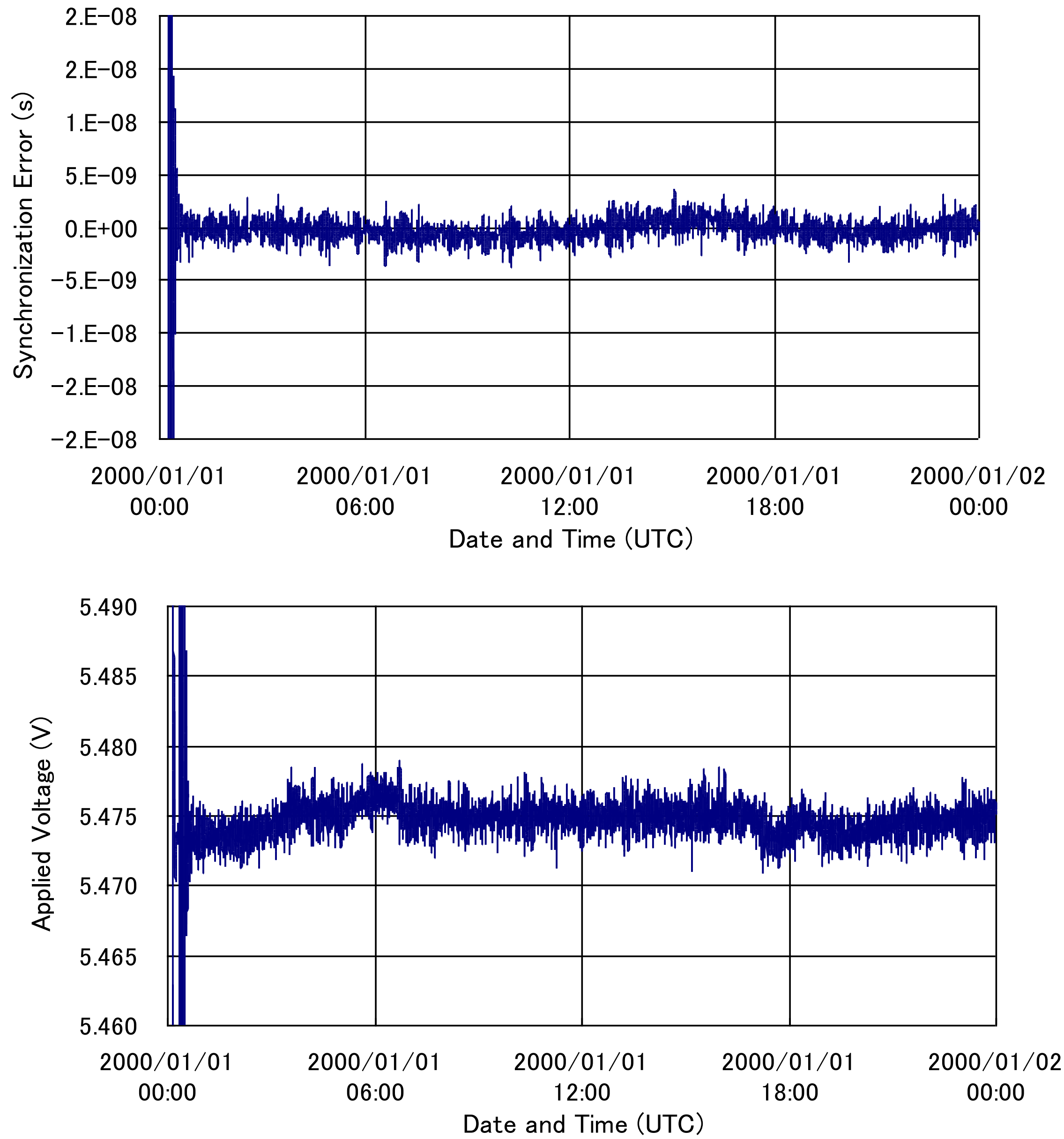


Fig. 7. Experimental result without CI.

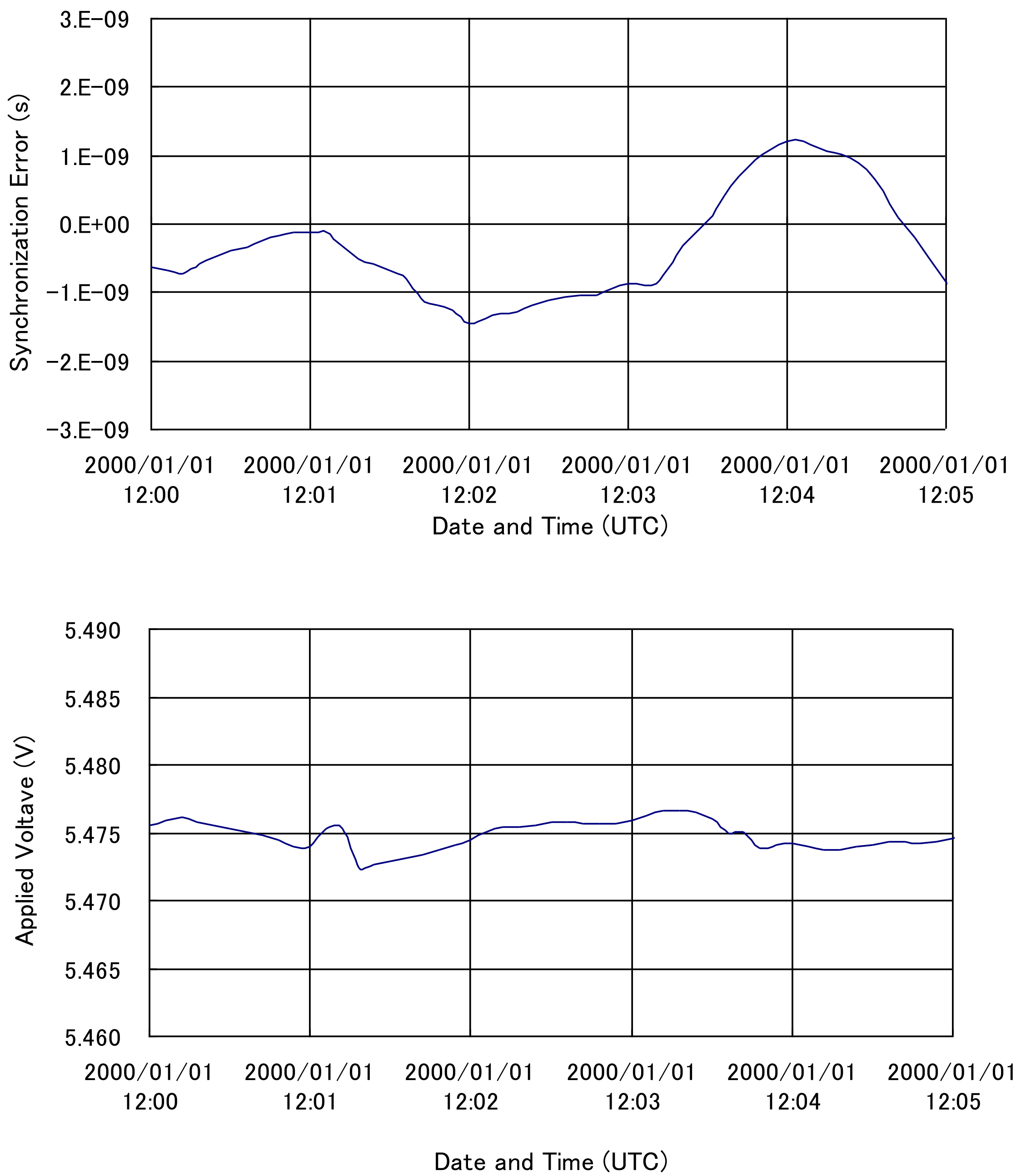


Fig. 8. Change rate of synchronization error.

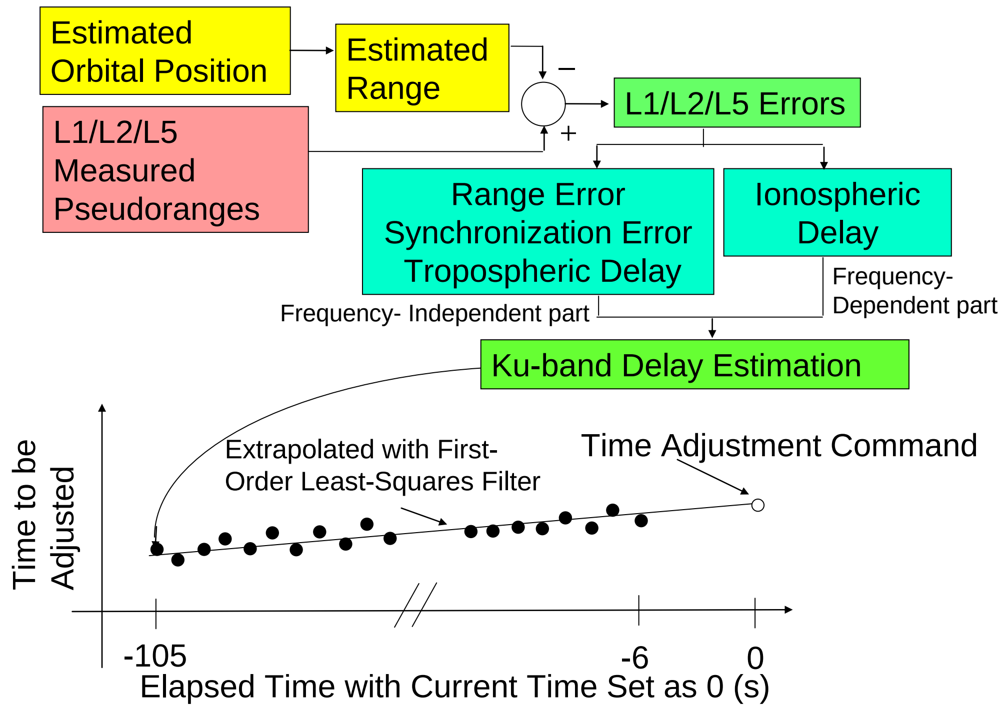
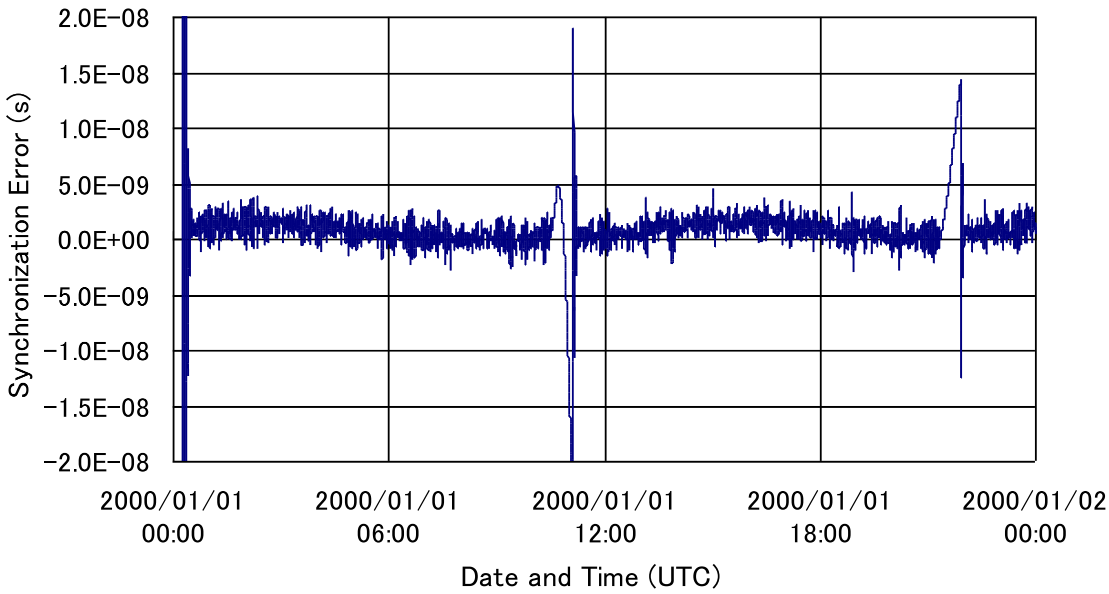


Fig. 9. Feedback method.



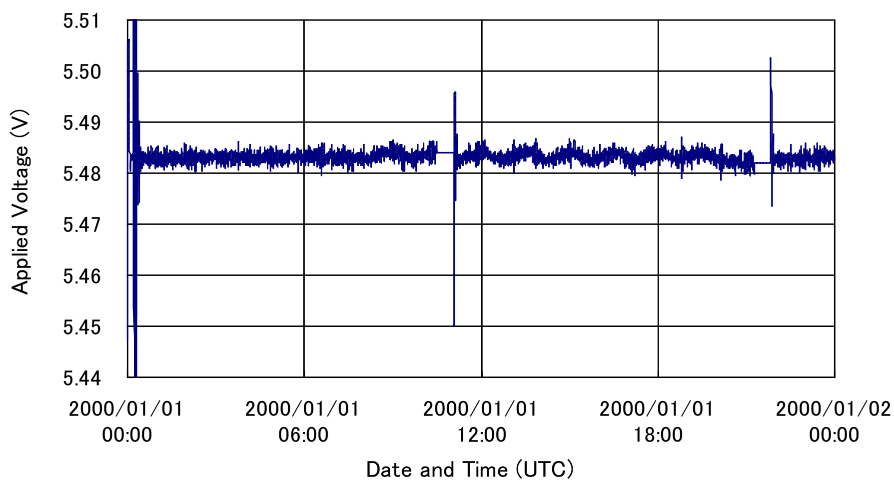


Fig. 10. Experimental result with CI.

RESULTS OF EXPERIMENT TWO

In Experiment Two, the 20-s transmission command delay restricted the initial synchronization error and the time to converge. Figure 11 shows a block diagram of the ground experimental system for Experiment Two. TIC compares the time difference between MINI-OCXO and H-Maser and outputs the time difference to SimIF. SimIF sends the time difference to RC with a delay of 20 s first, and then RC calculates the control voltage and sends it back to SimIF as the voltage command (text). SimIF constructs the voltage command (packet) and sends it again to RC. RCST constructs the voltage command (actual) and sends it to TCUSIM. Finally, NOCSIM and D/A converter generate the control voltage for MINI-

OCXO.

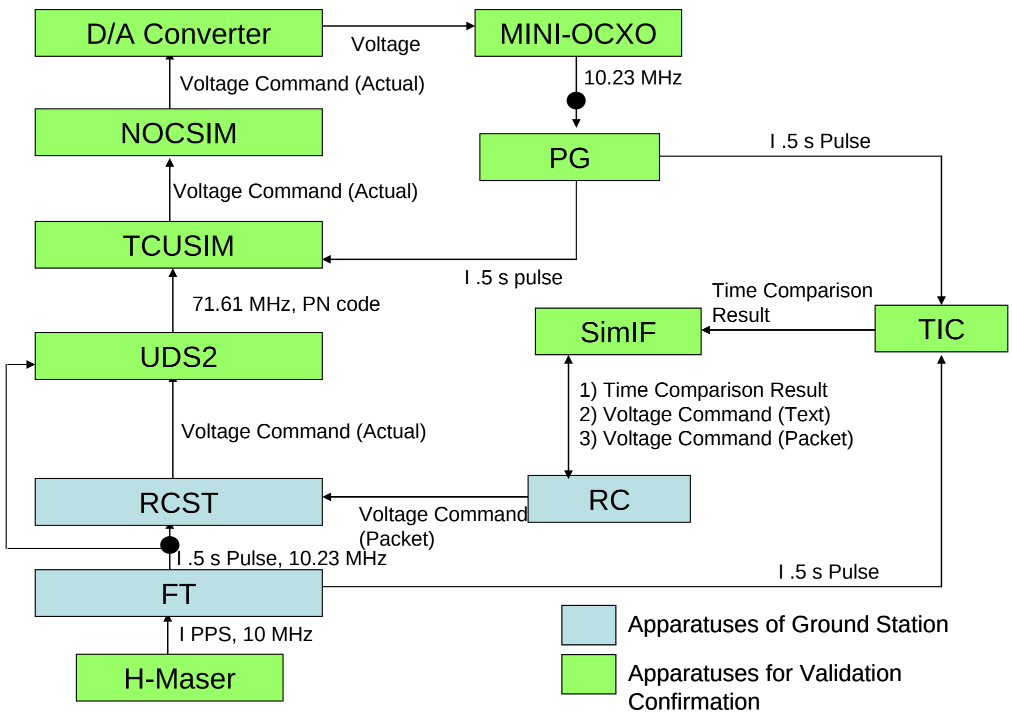


Fig. 11. Block diagram of the ground experimental system for Experiment Two.

Figure 12 shows the results of Experiment Two. On the left is the synchronization error after 10-minute control. The thick black line indicates a synchronization error of 10 ns. On the right is the elapsed time for the error to become less than 5 ns. In the case that the initial error is less than 1.5 μs, VCOCXO will be controlled successfully if the transmission delay is less than 20 s. However, if the transmission delay is more than 25 s, controllability of the VCOCXO will depend on the magnitude of the initial synchronization error.

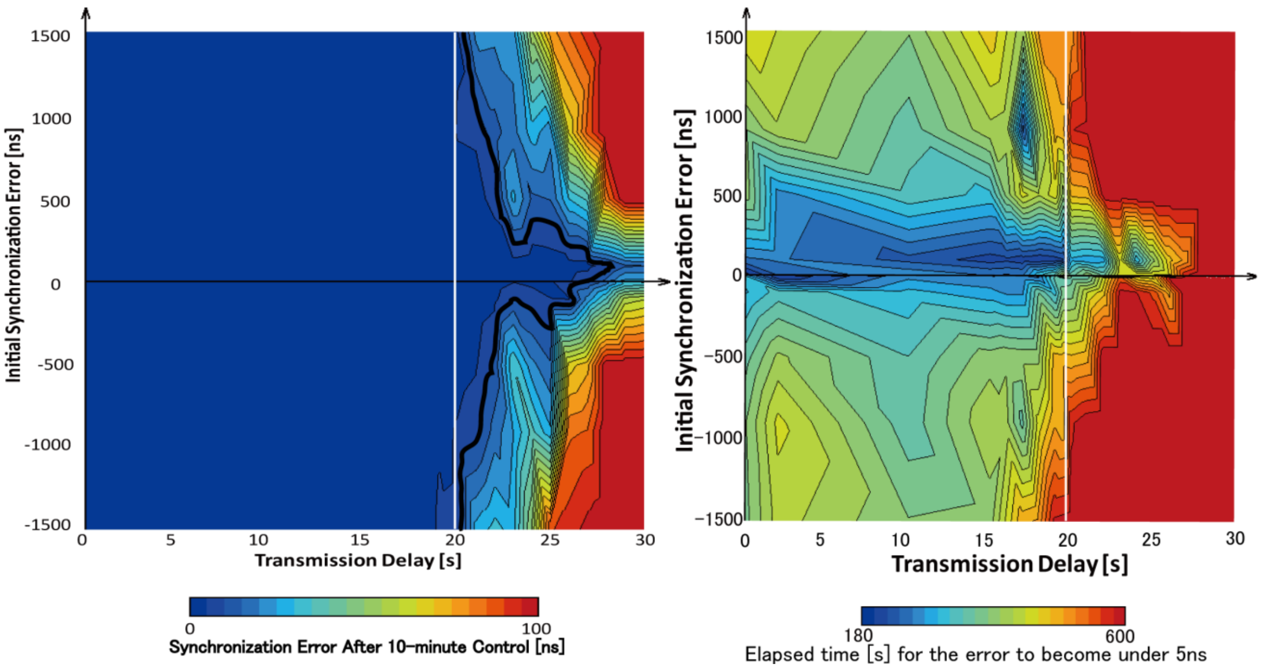


Fig. 12. Results of Experiment Two.

IV. DISCUSSION

QZSSREC UNLOCK IN EXPERIMENT ONE

In Experiment One, sometimes, the navigation signals of L1CD and L5I could not be received successfully. In that case, the feedback mechanism did not work well at that moment. If only one signal were missed, the ionospheric delay would not be calculated correctly and some offset would occur. When both signals were missed, feedback would not work perfectly. Figure 11 shows such cases. In Fig. 13, only the L5I signal was lost approximately 20 minutes around 3:30 UTC and approximately a 20-ns offset was observed. This corresponds with the ionospheric effect of L1 frequency, which is not compensated.

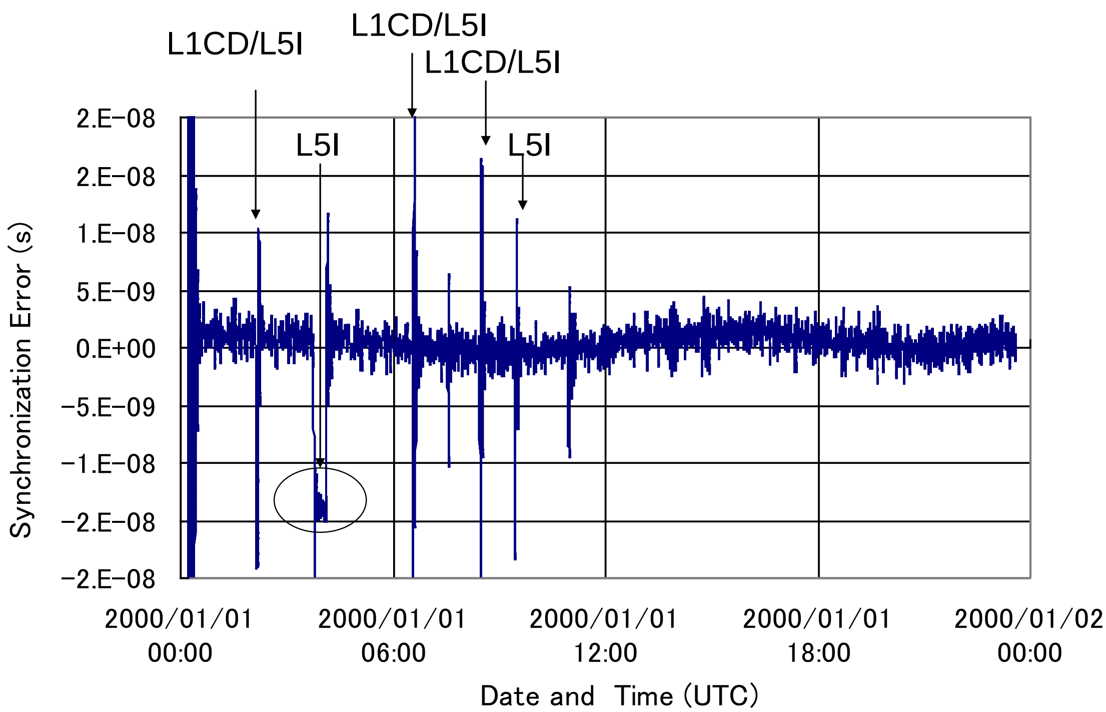


Fig. 13. Unlock case of navigation signals with QZSSREC.

To improve performance during unlocking of navigation signals, the following countermeasures should be taken:

(1) Prioritization of navigation signal combinations for feedback should be done. **[10]**.
(2) The same feedback value as that immediately before unlocking should be utilized.
(3) The Klobuchar model for ionospheric effect should be used.

COMPARISON WITH 7-DAY CONTINUOUS DELAY DATA

So far, we have conducted Experiment One using 7-day continuous delay data, not 3-minute orbit estimation/forecast values. The results of the experiment with CI are shown in Fig. 14. The difference from the case using 3-minute orbit estimation/forecast values is the magnitude of the fluctuation. In the case of using 3-minute orbit estimation/forecast values, the fluctuation of synchronization error is between -2 and 2 ns, and peak-to-peak fluctuation of applied voltage is 4 mV. In contrast, in the case of using 7-day continuous delay data, the fluctuation of synchronization error is between -0.5 and 0.5 ns, and peak-to-peak fluctuation of applied voltage is 1 mV.

These differences affect the control performance during CI. The synchronization error using the 7-day continuous delay data during CI is smaller than that using the 3-minute orbit estimation/forecast values, at less than 10 ns. This is caused by the smaller fluctuation of the applied voltage before CI. As the countermeasure, more samples of applied voltages should be used before CI, for example, 200.

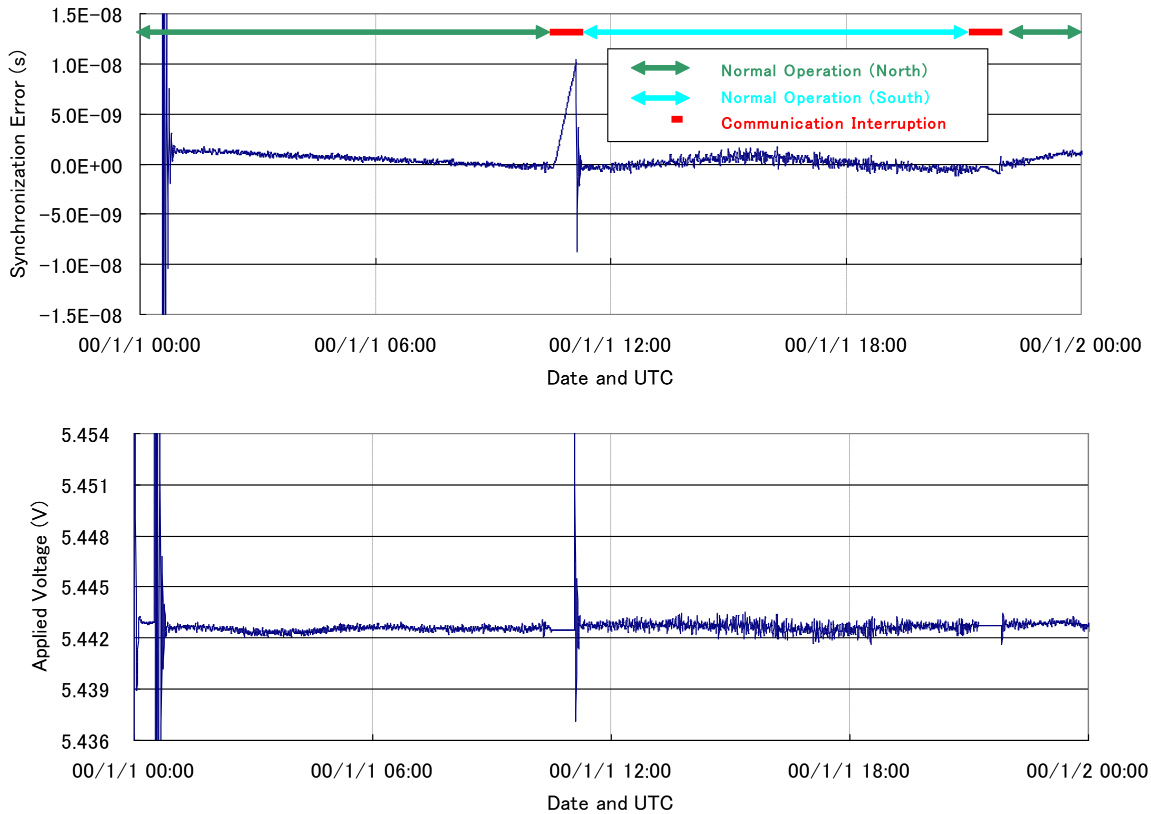


Fig. 14. Results of Experiment One with one-week delay data.

STABILITY COMPARISON

Figure 15 shows the overlapping Allan deviation of the synchronization errors using the 7-day continuous delay data with and without CI, and those using the 3-minute orbit estimation/forecast values with and without CI. The best case is the one that used the 7-day continuous delay data without CI. The cases using the 3-minute orbit estimation/forecast values are approximately one order of magnitude worse, particularly in the case with CI. The peaks around 100 s are due to the first-order extrapolation of 100-s feedback shown in Fig. 9. In the cases using the 3-minute orbit estimation/forecast values, those peaks are larger than the peaks obtained using the 7-day continuous delay data. This would be caused by the change of feedback every 30 s.

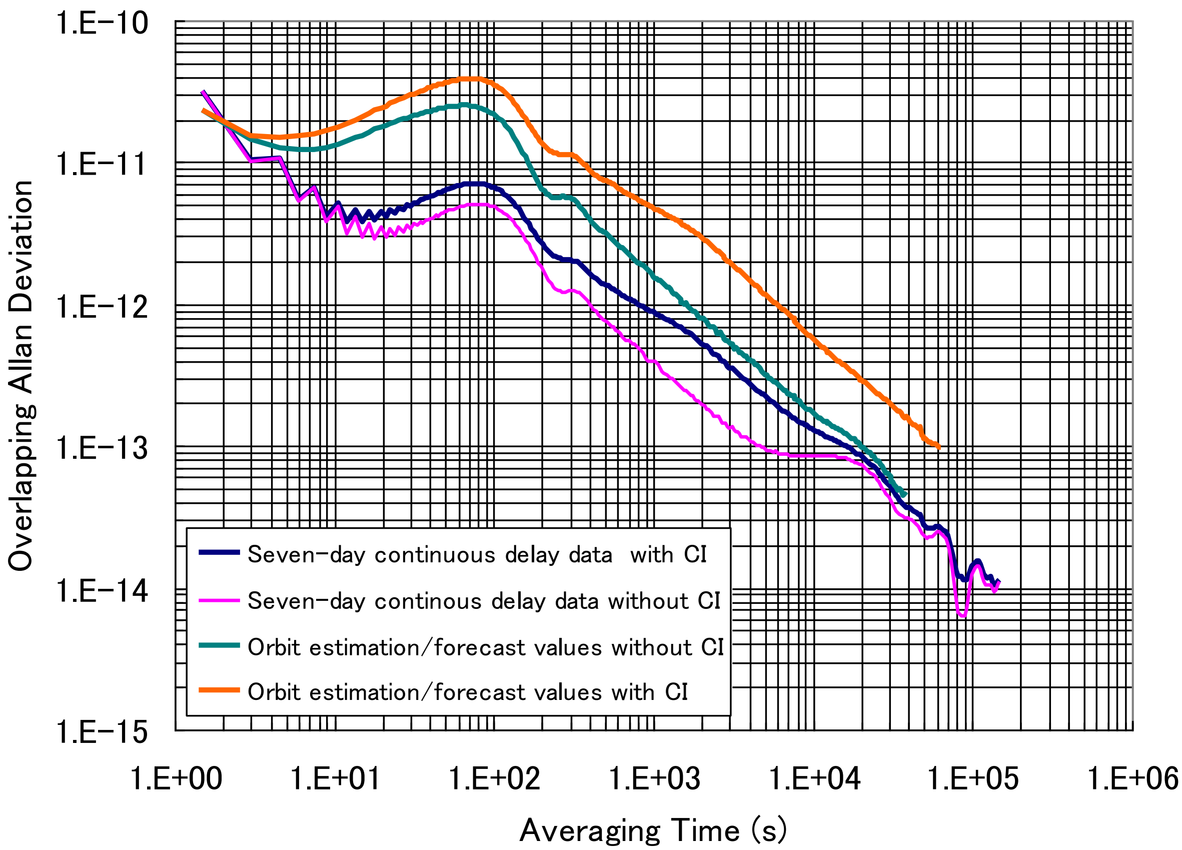


Fig. 15. Overlapping Allan deviation of synchronization errors.

V. CONCLUSIONS

This study is summarized as follows.

(1) As the actual operation of RESSOX, Experiments One and Two were introduced. In Experiment One, discontinuities of 3-minute orbit estimation/forecast values occurred every 30 s. In Experiment Two, approximately 20 s was required from the start of time comparison to the voltage command execution.

(2) In Experiment One using the 3-minute orbit estimation/forecast values, the synchronization error was within 2 ns. During CI, an average of 100 sample voltages immediately before CI was applied constantly. The first CI caused an approximately 20 ns synchronization error and the second CI caused an approximately 15 ns error in a 24-hour experiment.

(3) In Experiment Two, the 20-s transmission command delay restricted the initial synchronization error and time to converge. If the initial error were less than 1.5 μs, VCOCXO would be controlled successfully.

VI. ACKNOWLEDGMENT

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