

HARDWARE EXPERIMENTS OF RESSOX WITH GROUND STATION EQUIPMENT

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Abstract

We have developed ground station equipment and an onboard control program for the remote synchronization system for the onboard crystal oscillator (RESSOX) of the quasi-zenith satellite system (QZSS). First, we introduce the ground station equipment. Second, we explain RESSOX control algorithm using the L1/L2/L5-band navigation signals of the QZSS and related experiments using the ground equipment. We focus on the selection priority of navigation signals for feedback control based on the signal quality estimated from the standard deviation of the pseudorange. If ionospheric delay is not considered, the method that uses only L5Q navigation signal is the best. However, if ionospheric delay is considered, the combination of L1C/A, L2CL, and L5Q navigation signals is the best. Third, we discuss a control method to be implemented during communication interruption that takes place for approximately 32 minutes twice a day. We examined an average of 100 control voltages (150 s) immediately before the communication interruption, and were able to achieve a synchronization error of less than 5 ns.

I. INTRODUCTION

The quasi-zenith satellite system (QZSS) has been under development as a Japanese space project since 2003, and its main mission is navigation [1]. Its constellation consists of three satellites orbiting on inclined orbital planes with a geosynchronous period. The QZSS utilizes a high inclined orbit because of high visibility over high-latitude regions. In the case of the QZSS, at least one satellite is highly visible at the zenith at any time. Therefore, users can always receive navigation signals from at least one of the QZSSs near the zenith.

In general, global navigation satellite systems (GNSSs), such as the GPS of the US, GLONASS of Russia, and GALILEO of Europe, are equipped with onboard atomic clocks that are used as time reference. 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, power-demanding, and sensitive to temperature or magnetic field. Moreover, they are one of the main factors contributing to the reduction of satellite lifetime.

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, the remote synchronization system for the onboard crystal oscillator (RESSOX), which does not require onboard atomic clocks, was developed. 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} for more than 100,000 s. These targets were determined on the basis of the synchronization performance between GPS time 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. Details of primary experimental results have been introduced in our previous papers [5-8]. We have developed a feedback method that uses the L1/L2/L5-band 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. We also found that we can estimate separately the delay of L1/L2/L5/Ku-band signals caused by the ionosphere and other sources, during error adjustment [8]. Strictly speaking, open navigation signals of the QZSS are L1C/A, L1CP, L1CD, L2CM, L2CL, L5I, and L5Q. When RESSOX feedback algorithm is considered, the navigation signal selection method is arguable. We will discuss this later.

The QZSS experiences communication interruption for approximately 32 minutes twice a day as a result of avoiding interference with geostationary satellites (GEO). The control method during interruption communication is also discussed later.

II. RESSOX OVERVIEW

Figure 1 shows the schematic of RESSOX. In order to realize RESSOX, it is indispensable to identify the error factors and the feedback mechanism by measuring the delay at the ground station. The former is related to the estimation of error and delay using models, and is considered to be a feed-forward loop. The latter is an error adjustment system that uses pseudoranges measured with the navigation signals of the QZSS and estimated pseudoranges, and is considered to be a feedback control.

The error and delay models in the feed-forward loop are delays in the ground station and in the satellite, tropospheric delay, ionospheric delay, delay due to distance (orbit estimation), delay due to relativity effects, and errors caused by Earth's motion, such as daily rotation, nutation, and precession. These problems were discussed in our previous paper [5]. However, as is described later, if L1/L2/L5-band navigation signals are used for feedback, use of the delay models becomes unnecessary [7,8].

GPS Block-IIR satellites adopt a timekeeping system (TKS) in which the crystal oscillator is used as the system clock and atomic clocks are used as the reference clock, because the short-term stability of the crystal oscillator is superior to that of the atomic clock [9]. Figure 2 shows a comparison of RESSOX with the TKS of GPS Block-IIR satellites. The GPS Block-IIR TKS utilizes the short-term frequency stability of the crystal oscillator and the long-term stability of the rubidium atomic frequency standard (RAFS); the crystal oscillator contributes to the whole system, whereas the RAFS is considered to be a reference clock. In contrast, in the case of RESSOX, the QZSS is controlled by the crystal oscillator and the crystal oscillator is adjusted based on time information called RESSOX control signal from the ground station where the standard time is kept, similar to the RAFS of the GPS Block-IIR TKS. We assume that the RESSOX control signal is uplinked with a pseudo-noise (PN) code using the Ku-band.

The short-term frequency stability of the QZSS using RESSOX is expected to be at least equivalent to that of the onboard atomic frequency standard system.

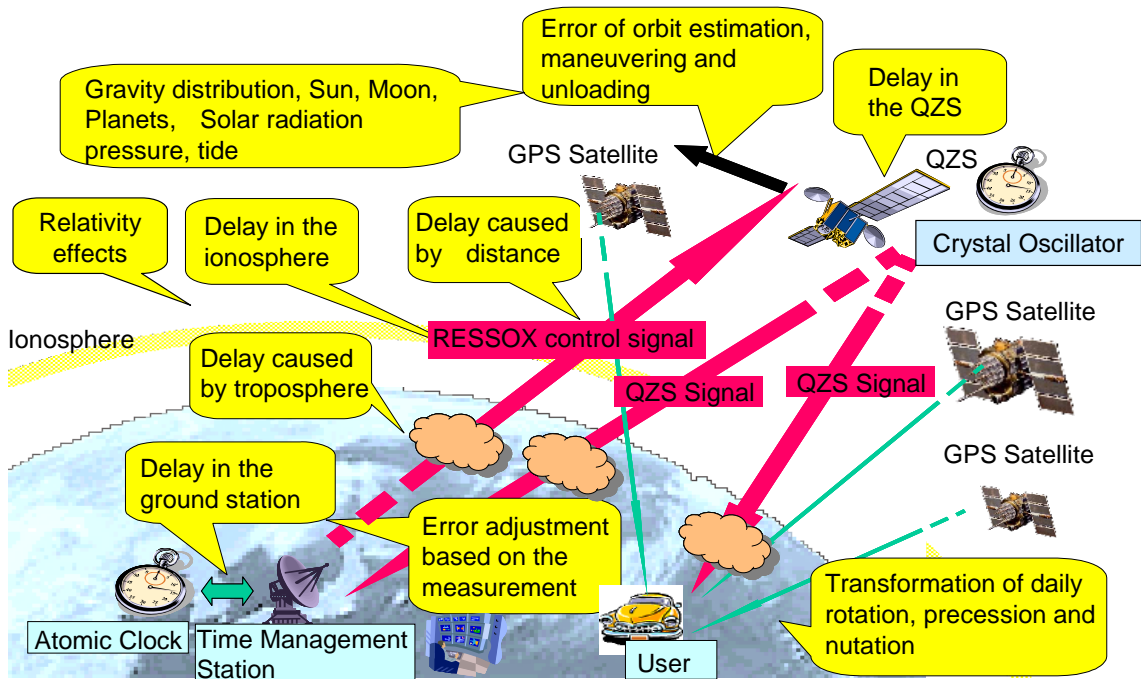


Fig. 1. RESSOX schematic.

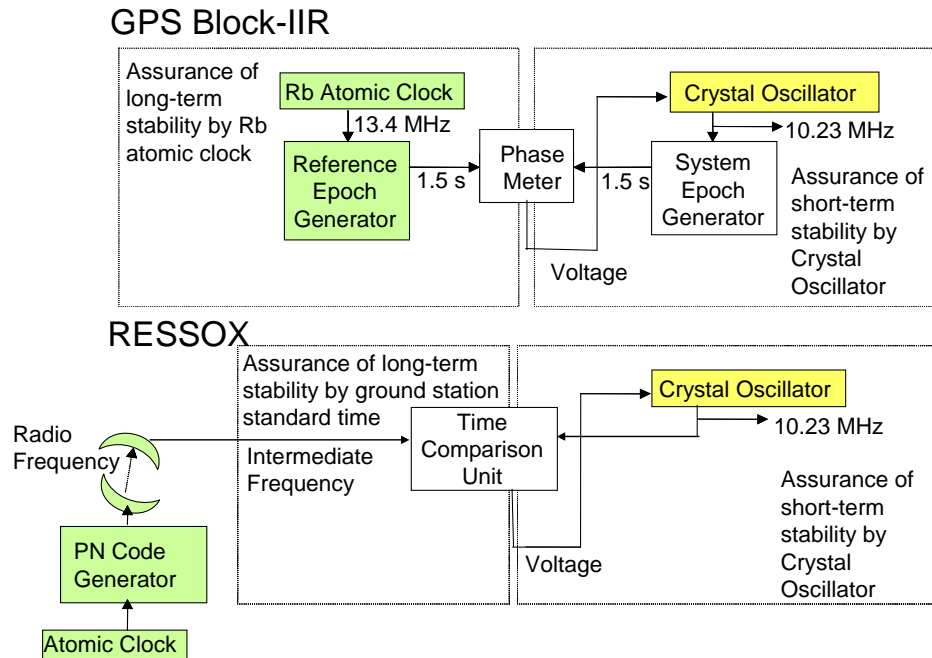


Fig. 2. Comparison between RESSOX and the TKS of GPS Block-IIR.

III. GROUND STATION EQUIPMENT FOR RESSOX

In this section, the hardware for realizing RESSOX technology is described. Figure 3 shows the system diagram of RESSOX. The time of the time management station (TMS) is used as the standard time (called QZSS-Time). The RESSOX control signal transmitter (RCST) advances the time to compensate the delay during transmission between the QZSS-Time and the crystal oscillator onboard the QZS and the time information is modulated using PN codes. The RESSOX control signal is up-converted to 14.43453 GHz (Ku band) by the up-converter and is transmitted from the antenna of the TMS to the QZS.

At the QZS, the RESSOX control signal is received by the antenna, down-converted, demodulated, and compared with that of the onboard oscillator by the time comparison unit (TCU). On the basis of the comparison, the time-difference information (PN-code phase difference) is transferred to the navigation onboard computer (NOC) that then generates the control command (voltage to be applied) for the crystal oscillator inside the timekeeping circuit through some control algorithm. On the QZS, the navigation signals (QZS signals) of L1/L2/L5 bands are generated using the onboard crystal oscillator as reference clock. At the TMS, the QZS signals are received by the antenna and transmitted to the QZSS/GPS receiver for RESSOX. This receiver compares the time information in the QZS signal with the QZSS-Time, and outputs it as the pseudorange. The pseudorange is used as feedback information of RESSOX.

The RESSOX controller at the TMS controls the RCST using the delay models and pseudorange information.

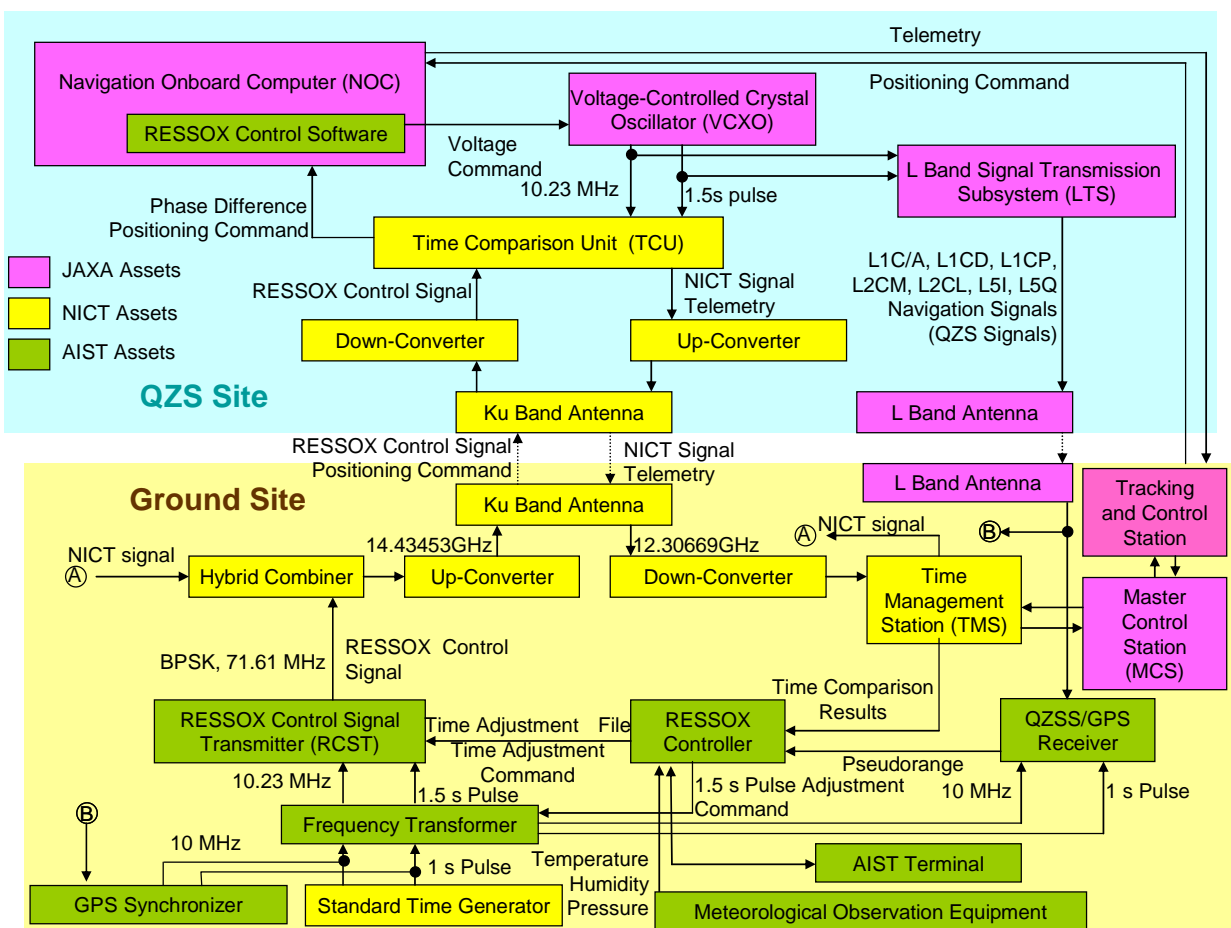


Fig. 3. System diagram of RESSOX.

Other time systems such as GPS-Time can be used instead of QZSS-Time. In such a case, the output of GPS synchronizer or the results of GQTO prepared by the National Institute of Information and Communication Technology (NICT) will be used as standard time.

Figure 4 shows the schematic of the test bed for the preliminary ground experiments using these ground station apparatuses. Most of the components are the same as those illustrated in Fig. 3; however, some special apparatuses and software are required to simulate the delay between the TMS and the QZS. The details of some apparatuses used in the ground experiments are described below.

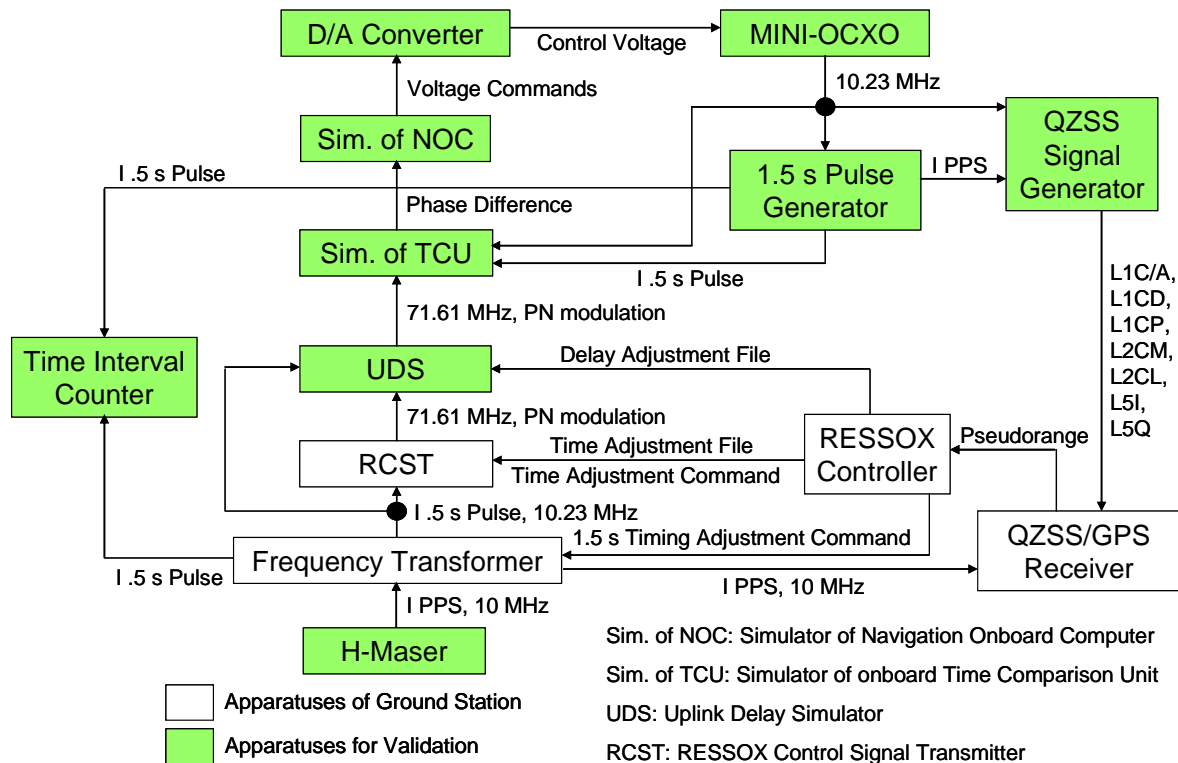


Fig. 4. Schematic of the test bed for preliminary ground experiments.

The equipment for the ground experiments on the rack is shown in Fig. 5.

The apparatuses used in the ground experiments are introduced below.

FREQUENCY TRANSFORMER

Although the TMS uses only the standard time signal of 10 MHz and 1 s pulse, the RESSOX system uses both the time signal of 10.23 MHz and 1.5 s pulse and that of 10 MHz and 1 s pulse. Therefore, a frequency transformer is required. The frequency transformer has one input of each time signal of 10 MHz and 1 s pulse, five outputs of each time signal of 10.23 MHz and 1.5 s pulse, and two outputs of each time signal of 10 MHz and 1 s pulse. Since there are three relationships between the 1 s pulse and the 1.5 s pulse (i.e., shifts of ± 0.5 s and 0 s), the RESSOX controller incorporates a shift of 0.5 s with the RS232C interface.

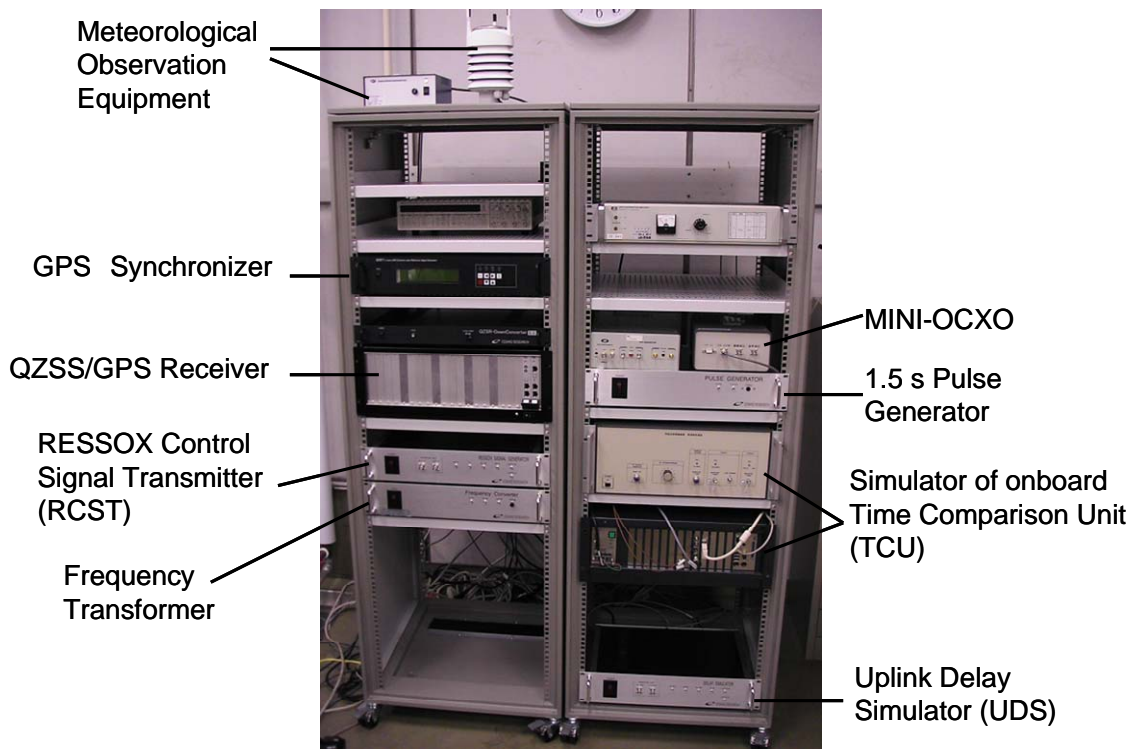


Fig. 5. Equipment for ground experiments.

RESSOX CONTROL SIGNAL TRANSMITTER (RCST)

RCST consists of two parts: transmitting time adjuster (TTA) and PN code generator.

(1) TTA

TTA generates the advanced time used to compensate the delay of the uplink time signal between the TMS and the QZS according to time adjustment files and commands. The time adjustment files and commands for RCST will be generated and transferred by the RESSOX controller at the TMS with TCP/IP connection. TTA changes the frequency using the wavefront clock principle [10].

TTA uses time adjustment files (feed-forward control) and time adjustment commands (feedback control). To realize feed-forward control, the delay estimation will be conducted using delay models or information from MCS. To obtain the time adjustment files, the delay estimation results will be prepared as a delay file, as shown in Fig. 6. This file will include the date and time in UTC and the uplink signal delay in nanoseconds. The time adjustment file shown in Fig. 7 will be generated on the basis of the delay file. This file will include the next file name, data number, modified Julian day (MJD), and UTC of the first data; valid time of each coefficient; and coefficients of the polynomial estimated by Lagrange's interpolation of the 11th order or less.

To realize feedback control, the differences between estimated pseudoranges of navigation signals and measured pseudoranges are used. The differences are extrapolated and expressed in the polynomial.

The coefficients of the polynomial will be used for the feedback control. The mechanism of feed-forward and feedback controls is shown in Fig. 8. Feed-forward polynomial coefficients are adjusted with feedback coefficients.

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2000/1/1 0:00:00,127733388.106641
2000/1/1 0:01:00,127772687.841133
2000/1/1 0:02:00,127812001.174268
...
...
    
```

Fig. 6. Example of delay file.

```

Next file name
Data number
MJD, UTC
Valid time of each coefficient
C0, C1, ..., C11 ← #1
...
C0, C1, ..., C11 ← #N
    
```

Fig. 7. Example of time adjustment file.

(2) PN Code Generator

The PN code generator generates time information of the RESSOX control signal using the 5115 bit of an L2C code for 0.5 ms. Time information advanced by TTA will be transmitted. The RESSOX control signal has a data overlay of 2000 bit/s to resolve the ambiguity of 0.5 ms. Overlay data will be treated as dummy data.

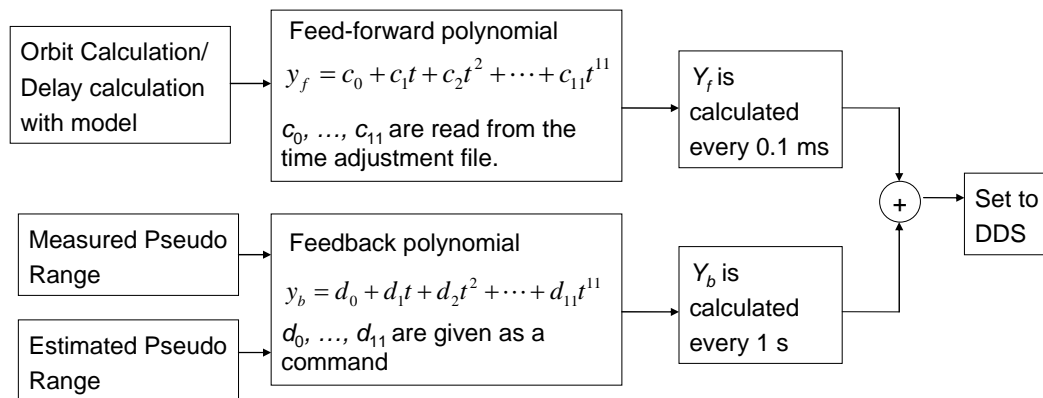


Fig. 8. Mechanism of feed-forward and feedback controls.

QZSS/GPS RECEIVER

The QZSS/GPS receiver has the following capabilities: (1) it measures and outputs raw data of pseudoranges, navigation message, carrier phase, delta range, and signal intensity of tracking satellites; (2) it sends to the RESSOX controller the satellite PRN number and the pseudoranges (three decimal places, in meters) of L1C/A, L1CD, L1CP, L2CM, L2CL, L5I, and L5Q navigation signals every second; and (3) it receives the standard time signal of 10 MHz and 1 s pulse. The L-band antenna (choke coil antenna fabricated by Trimble) is Japan Aerospace Exploration Agency's (JAXA) asset and JAXA has graciously shared the signals with us.

There are two communication channels to the RESSOX controller: serial ports 1 and 2. Serial port 1 is

used for feedback control and serial port 2 is used for maintenance.

The measurement results of constant pseudorange (250.0 km, all signals do not have ambiguity) generated by a simulator of the QZSS signal generator are shown in Fig. 9. Since there are biases among signals, the results are shown for each signal (pseudorange scales are the same to facilitate comparison). The powers of the signals simulate the actual strength, that is, when L1 total signal power is assumed to be

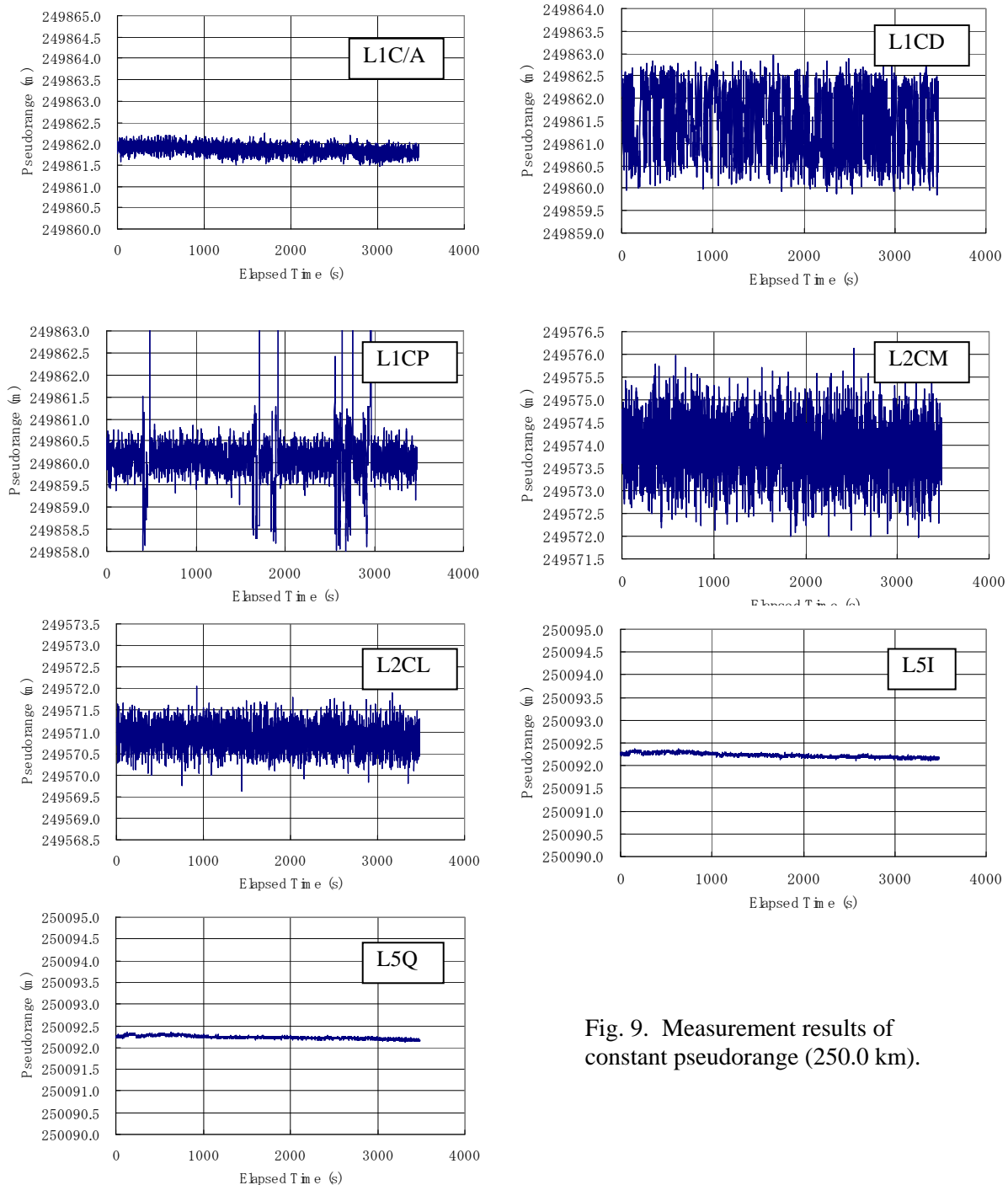


Fig. 9. Measurement results of constant pseudorange (250.0 km).

-110 dBm, the signal power of L1C/A is -113.8 dBm, that of L1CD is -118.3 dBm, that of L1CP is -113.55 dBm, those of L2CM and L2CL are -115.3 dBm, and those of L5I and L5Q are -113.2 dBm, respectively. Pseudorange deviations of the signals are as follows: for L1C/A, it is 0.388588 ns; for L1CD, 2.25394 ns; for L1CP, 0.84281 ns; for L2CM, 2.07249 ns; for L2CL, 1.01295 ns; for L5I, 0.0664703 ns; and for L5Q, 0.0602302 ns. To calculate the deviations, data between 900 and 1100 s were used.

UPLINK DELAY SIMULATOR (UDS)

UDS is a hardware simulator used in the ground test bed to simulate the delay between the ground and the QZS. UDS assigns offset values to first-in first-out (FIFO) memory according to the delay adjustment files for UDS, which have the same format as the time adjustment files for RCST. Then, UDS adjusts the time information of the modified 10.23 MHz generated by RCST. UDS is based on DDS technology of RCST and FIFO memory control techniques. UDS receives an intermediate frequency (IF) signal that includes time information (central frequency of 71.61 MHz, bandwidth of 2.5 MHz), down-converts the frequency, downloads the waveform of time information into FIFO memory in real time, and reads out FIFO memory data using the modified 10.23 MHz generated by TTA inside UDS. Herewith, UDS up-converts the frequency to 71.61 MHz and outputs the modified IF signal using the time adjustment files for UDS.

RESSOX CONTROLLER

The RESSOX controller is a Windows XP PC, as shown in Fig. 10.

The RESSOX controller will conduct orbit calculation of the QZS and delay estimations of Ku/L1/L2/L5-band signals, and output the total delay in nanoseconds with the designated UTC and time interval. The orbit calculation involves the following procedures: 1) The initial values are given as six elements in the International Celestial Reference Frame (ICRF), the International Terrestrial Reference Frame (ITRF), the True of Date (TOD) or Keplerian, and the solution for a predefined period is given by solving the equation of motion. The integral interval can be set by the user. 2) JGM-3 or EGM-96 is selected as the geopotential model, and orders of the model can be set by the user. 3) The effect of the sun, the moon, and other planets can be selected by the user. 4) The effect of solar pressure can be utilized. 5) The solid tide effect can be taken into consideration. 6) The effect of relativity can be included. 7) Impulse acceleration can be set by the user. For the delay estimation, 1) ionospheric delay, tropospheric delay, and geographical delay should be considered, and 2) the delay in the TMS or the QZS should be taken into account.

Every 30 s, the RESSOX controller will also receive from MCS 1-s estimation of orbit information for a duration of 3 minutes, or receive L1C/A navigation message information from MCS every hour. Using this information, the RESSOX controller will calculate the delay files and the time adjustment files every 30 s or every hour and make a chain of files.

For the results of total delay estimation of the Ku-band RESSOX control signal, the RESSOX controller will output the time adjustment files for feed-forward control using Lagrange's interpolation of the 11th order or less. RCST will refer to these files. The RESSOX controller will also output the delay adjustment files for UDS, which are similar to the time adjustment files for RCST.

The pseudoranges of the L1/L2/L5-band navigation signals will be received from the QZSS/GPS receiver every second. Using the pseudoranges from the QZSS/GPS receiver and the estimation results of the total delays of the L1/L2/L5-band navigation signals, the RESSOX controller will calculate Lagrange's

extrapolating coefficients of the 11th order or less and generate the feedback command for RCST. The time interval of data or output will be chosen between 1 and 900 s.

The RESSOX controller will generate the command for the frequency transformer to adjust the 1.5 s pulse, and for RCST or UDS to start or stop the job or to set parameters. The RESSOX controller will also monitor the status of RCST and UDS.

As reference, the RESSOX controller will accumulate the results of the time difference and orbit estimations of MCS obtained from the TMS.

SIMULATOR OF ONBOARD TIME COMPARISON UNIT (TCU SIMULATOR)

TCU will be prepared by NICT, and to realize experiments on the ground, we prepared the simulator. Since the onboard system clock is 1.5 s epoch, the time difference between RESSOX control signal and MINI-OCXO, which is the engineering model of the onboard crystal oscillator, is expressed between -0.75 s and $+0.75$ s.

SIMULATOR OF NAVIGATION ONBOARD COMPUTER (NOC SIMULATOR)

NOC will be prepared by JAXA, and to realize experiments on the ground, we prepared the simulator. The Windows XP PC shown in Fig. 11 is used for this purpose. This simulator receives the phase difference from the onboard TCU simulator and drives the D/A converter that generates voltage between 0 V and 10 V.



Fig. 10. RESSOX Controller.



Fig. 11. Simulator of NOC.

SIMULATOR OF QZSS SIGNAL GENERATOR

The QZSS signal generator will be prepared by JAXA, and to realize experiments on the ground, we prepared the simulator (special equipment fabricated by Spirent Communications).

The specifications of the simulator are as follows:

(1) The types of signals are L1C/A (PRN: 193-202); L1CP and L1CD (BOC(1,1)); L2CM and L2CL; and L5I and L5Q of each channel with QZSS navigation message.

(2) Operation is accomplished with a modified SimQZ file and SimPlex30 software [11], with 10.23 MHz. At least seven signals described in (1) can be broadcast simultaneously. The modified SimQZ file includes information of time stamp in ms, the satellite identifier as an integer value (193-202), five bits of L1C/A navigation message to be transmitted during the 100 ms time step, power level for L1 navigation signal, L1 navigation signal carrier pseudorange in meters, offset of L1 code pseudorange from L1 navigation signal carrier pseudorange in meters, L1 navigation signal carrier pseudorange rate of change in meters per second, offset of L1 code pseudorange rate from the L1 carrier pseudorange rate in meters per second, power level for L2 navigation signal, L2 navigation signal carrier pseudorange in meters, offset of L2 code pseudorange from L2 navigation signal carrier pseudorange in meters, L2 navigation signal carrier pseudorange rate of change in meters per second, offset of L2 code pseudorange rate from the L2 carrier pseudorange rate in meters per second, ten symbols of navigation message to be transmitted during the 100 ms time step for L1C, five symbols of navigation message to be transmitted during the 100 ms time step for L2C, ten symbols of navigation message to be transmitted during the 100 ms time step for L5, power level for the L5 navigation signal, L5 navigation signal carrier pseudorange in meters, offset of L5 code pseudorange from L5 navigation signal carrier pseudorange in meters, L5 navigation signal carrier pseudorange rate of change in meters per second, and offset of L5 code pseudorange rate from L5 navigation signal carrier pseudorange rate in meters per second.

(3) The simulator is operated in a stand-alone configuration or synchronized with the GPS simulator.

(4) When the simulator is synchronized with the GPS simulator, the synchronization should be within 10 ns.

(5) Software that synchronizes the operations of both GPS and QZS simulator should be prepared.

(6) Clock change rate is 3.3 Hz/1.5 s in maximum.

(7) Specify power range, code, and navigation message by referring to IS-QZSS [12].

1.5 s PULSE GENERATORS

To synchronize MINI-OCXO, the simulator of QZS signal generator, and the TCU simulator in the ground experiment, a 1.5 s pulse generator is used.

MINI-OCXO

To simulate the onboard crystal oscillator, an engineering model of the onboard crystal oscillator, called MINI-OCXO, is used. Specifications for frequency stability are the same as those of the onboard crystal oscillator. The measured Allan deviation of MINI-OCXO is shown in Fig. 12.

IV. CONTROL METHODS

RESSOX ALGORITHM

RESSOX control algorithm for ground hardware experiments or computer simulation is outlined as follows.

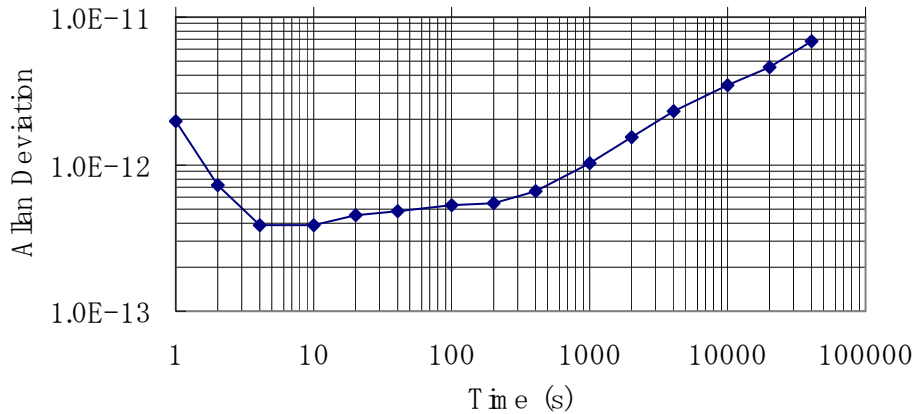


Fig. 12. Allan deviation of MINI-OCXO.

Step 1. Four (L1/L2/L5/Ku-band signals) estimated delay files are prepared, which include model errors such as those due to the orbit, ionosphere, or troposphere, and we assume that they are used at the TMS as measurement results. Three (L1/L2/L5-band navigation signals) delay files include the times (date and UTC) that the L1/L2/L5-band navigation signals are received and the estimated delays of the L1/L2/L5-band navigation signals. Another delay that is contained in the Ku-band estimated time adjustment file includes the time (date and UTC) that the Ku-band signal is transmitted from the TMS and the estimated delay of the Ku-band signal. These estimated delays are converted into database of L1/L2/L5-band delays and the time adjustment file for TTA, respectively.

Step 2. Four (L1/L2/L5/Ku-band signals) authentic delays that do not contain any errors are prepared. Three (L1/L2/L5-band navigation signals) delay files include the times (date and UTC) that the L1/L2/L5-band navigation signals are received at the TMS and the authentic delays of the L1/L2/L5-band navigation signals. Based on the authentic delays, a simulation data file in the CSV format for SimQZ is generated. Another delay file that is used as the delay adjustment file for UDS includes the time (date and UTC) that the Ku-band signal is transmitted from the TMS.

Step 3. The time adjustment file for RCST is fed into the RCST as feed-forward control.

Step 4. UDS delays the RESSOX control signal according to the delay adjustment file for UDS.

Step 5. The onboard crystal oscillator is controlled using the time difference between the RESSOX control signal and the time of the crystal oscillator itself.

Step 6. The QZS signal generator generates L1/L2/L5-band navigation signals according to the simulation data file in the CSV format for SimQZ.

Step 7. Pseudoranges of L1/L2/L5-band navigation signals obtained by the QZSS/GPS receiver are compared with the database of L1/L2/L5-band delays and the differences between the pseudoranges and the database are designated as E_1 for L1 (frequency $f_{L1}=1.57542\times 10^9$ Hz), E_2 for L2 ($f_{L2}=1.2276\times 10^9$ Hz), and E_3 for L5 ($f_{L5}=1.17645\times 10^9$ Hz).

Step 8. The system of equations (1), (2), and (3), which includes E_1 , E_2 , and E_3 and delays due to the non-frequency-dependent term e and the coefficient of delay k due to the frequency-dependent term (i.e., ionospheric delay) as unknowns, is prepared.

$$e + \frac{k}{f_{L1}^2} = E_1, f_{L1} = 1.57542 \times 10^9 \text{ [Hz]} \quad (1)$$

$$e + \frac{k}{f_{L2}^2} = E_2, f_{L2} = 1.2276 \times 10^9 \text{ [Hz]} \quad (2)$$

$$e + \frac{k}{f_{L5}^2} = E_3, f_{L5} = 1.17645 \times 10^9 \text{ [Hz]} \quad (3)$$

Step 9. If the navigation signals of all the three frequencies are available, the system of equations (1), (2), and (3) is expressed as follows:

$$\begin{bmatrix} 1 & 1/f_{L1} \\ 1 & 1/f_{L2} \\ 1 & 1/f_{L5} \end{bmatrix} \begin{bmatrix} e \\ k \end{bmatrix} = \mathbf{A}\mathbf{x} = \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \mathbf{E} \quad (4)$$

This means that three equations exist for two unknown parameters (e and k). Therefore, the solution of simultaneous equations (1), (2), and (3) is given as follows:

$$\mathbf{x} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{E} \quad (5)$$

If the navigation signals of two frequencies are available, then two equations exist with two unknown parameters. Using the solutions of the system of equations, we obtain the time to be adjusted of the RESSOX control signal using the Ku band ($f_{Ku}=1.43453 \times 10^{10}$ Hz) for the TTA.

$$e + \frac{k}{f_{Ku}^2}, f_{Ku} = 1.43453 \times 10^{10} \text{ [Hz]} \quad (6)$$

If the navigation signals of only one frequency are available, the time to be adjusted is given by E_i ($i=1$ or 2 or 3).

Step 10. By combining the time adjustment file in Step 3 and the time adjustment command based on the time to be adjusted, TTA is controlled. We consider some filters in this step, as described later. Then, we go back to Step 4. The calculation of the time to be adjusted and the time adjustment command is conducted every second.

Figure 13 shows the block diagram of the RESSOX algorithm using the three-frequency navigation signals in Step 8.

CRYSTAL OSCILLATOR CONTROL METHOD

To control MINI-OCXO using the difference between uplinked time information and MINI-OCXO time, a kind of PI control for applied voltage was utilized. The following formula describing PI control was used:

$$v_k = \text{offset} - \frac{k_1}{l+1} \sum_{i=k-l}^k (t_{OCXO} - t_{RESSOX})_i - k_2 \sum_{i=0}^{k-1} \left(\int_i^{i+p} (t_{OCXO} - t_{RESSOX}) dt \right), \quad (4)$$

where v_k is the k -th output voltage, $\text{offset} = 5.4$ (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 data number from the beginning, p is the integral interval, which means an overlapping integral number, set at 2, and t_{RESSOX} is time information of the received RESSOX control signal.

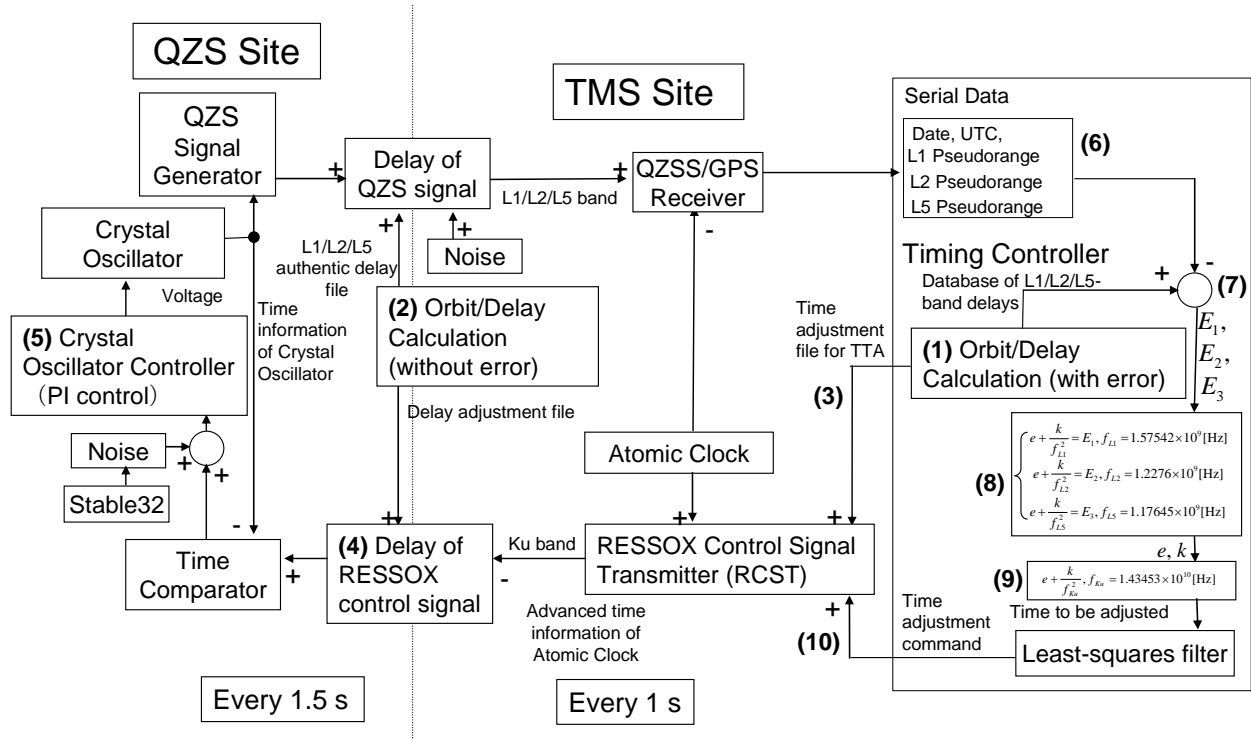


Fig. 13. Block diagram of the RESSOX algorithm.

GROUND STATION CONTROL METHOD

At the ground station, the control method was dependent on how the feedback was conducted, i.e., the filtering method in Fig. 13. The filter was constructed with 100 data of time to be adjusted using the difference between measured pseudoranges of L1/L2/L5-band navigation signals and estimated pseudoranges of the same signals prepared as the database of L1/L2/L5-band navigation signal-delays every second from 6 s before to 105 s before the time to transmit the time adjustment command to RCST.

The 100 data of time to be adjusted were used for the first-order least-squares filtering, and the time to be adjusted was extrapolated to the current time, as shown in Fig. 14. To calculate the filtering result and send it to the TTA as the time adjustment command, 6 s is required.

V. HARDWARE EXPERIMENTS

EXPERIMENTAL CONDITIONS

The experimental conditions are shown in Table 1, Fig. 14, and Fig. 15. The simulated date was 1 January 2000, and ionospheric conditions and conditions of other celestial bodies for that day were used as data. In Table 1, typical Keplerian elements of the QZSS are shown as the initial conditions (i.e., on 1 January 2000, 00:00:00 in UTC). These conditions can be expressed as $x = -23368756.806$ m, $y = -33272667.250$ m, $z = 15970670.048$ m, $v_x = 2138.110$ m/s, $v_y = -937.528$ m/s, $v_z = 1775.120$ m/s in the ICRF. The TMS was assumed to be located in Okinawa, and meteorological conditions used to calculate tropospheric delay were assumed to be constant. Based on the calculations of orbit and delay, the delay adjustment file for UDS and the CSV file for SimQZ were prepared.

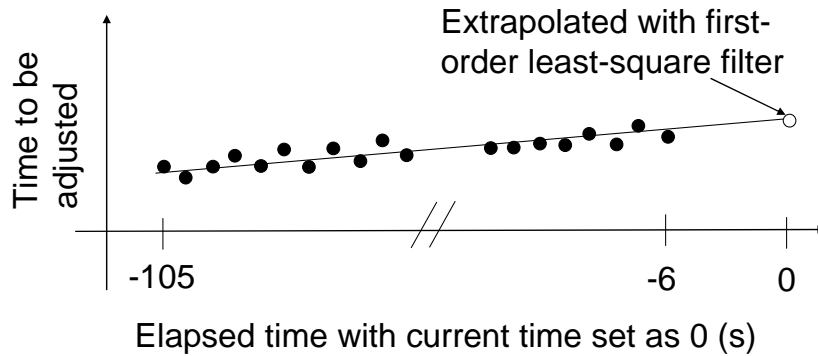


Fig. 14. Control method at TMS.

Table 1. Experimental conditions.

Items	Values	Items	Values
Simulation period	2000.1.1 00:00:00 UTC	Satellite cross section, m ²	37.0
	- 2000.1.2 00:00:00 UTC	CODE data of ionosphere	COD10426.ION
Semimajor axis, m	42164000.0	Meteorological condition	15°C, 1013.25hPa, 70% (relative humidity)
Eccentricity	0.075		
Inclination, deg	43.0	Radiation pressure coefficient (Cr)	4.56×10^{-6} N/m ² (McCarthy 1996), Cr = 1.2
Right ascension of the ascending node, deg	210.0		
Argument of perigee, deg	270.0	Position of ground station	26.5N, 127.9E, Height = 0.0m (Okinawa)
Mean anomaly, deg	115.0	Solid Earth tide	Moon and Sun are considered, k ₂ = 0.3 (IAG 1999)
Geopotential model	EGM96	Other celestial bodies	Moon, Sun, Mercury, Venus, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto (JPL-DE405)
Potential deg	n, m=360		
Satellite mass, kg	4100.0		

FEED-FORWARD CONTROL EXPERIMENTAL RESULTS

Uplink experiments (feed-forward control) were conducted. In the experiments, the delay compensation was applied to the TTA, the delay due to transmission was applied to the UDS, and MINI-OCXO was controlled by PI control. As the estimated delays, three cases were prepared. The initial satellite positions have no error, +5 m error in each ICRF axis, and -5 m error in each ICRF axis. The synchronization results of the experiments and the expected synchronization errors are shown in Figs. 17 and 18, respectively. They are consistent with each other.

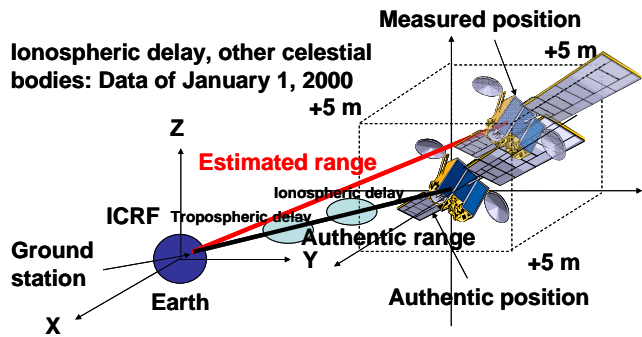


Fig. 15. Experimental conditions (+5 m ICRF error).

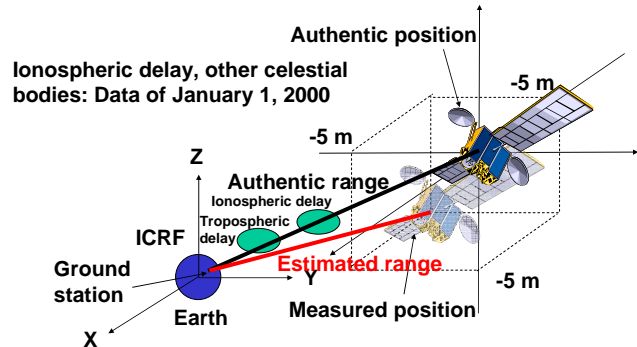


Fig. 16. Experimental conditions (-5 m ICRF error).

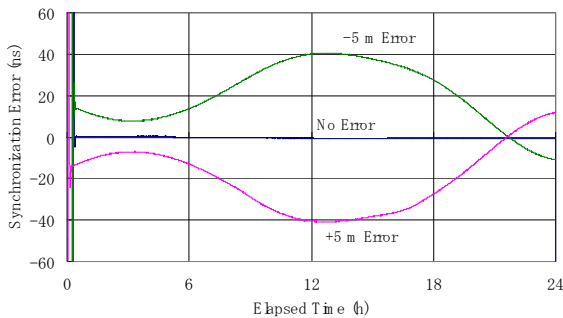


Fig. 17. Feed-forward control results.

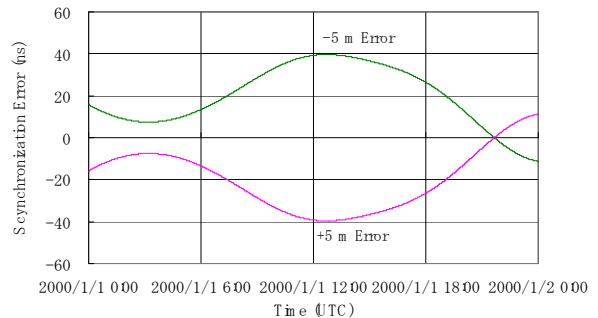


Fig. 18. Expected synchronization error.

CONTROL DURING COMMUNICATION INTERRUPTION

Figure 19 shows the control results during communication interruption (approximately 1920 s) when interference with GEO satellites is avoided. To simulate the communication interruption, experiments were conducted once every hour. The average of the voltages in the last 150 s (100 samples) before communication interruption was supplied to MINI-OCXO. In the experiments, the time difference of 3.370 μ s corresponds to complete synchronization between the QZSS and the ground station (3.370 μ s is the internal delay of RCST and UDS). The maximum error was approximately 5 ns in the experiments. However, since the errors are statistical, the probability of error exceeding 10 ns is possible.

VI. SIGNAL PRIORITY

Based on the distribution of pseudoranges shown in Fig. 6, the combination of navigation signals for RESSOX was evaluated using RESSOX algorithm. In this evaluation, only transmission delay error was considered (the initial position of the QZS has +5 m error for each ICRF axis, and the error does not contain ionospheric or tropospheric error). The distribution of synchronization error of RESSOX was evaluated. The results are shown in Table 2.

The results show that using L5Q navigation signal alone is the best for RESSOX. However, in the actual case, ionospheric and tropospheric delays exist. In particular, ionospheric delay can be estimated exactly by using two or more frequency navigation signals. This means that if only one frequency navigation signal is used for RESSOX, especially L5 that will cause the largest ionospheric delay due to the lowest frequency, the ionospheric delay will not be cancelled. Therefore, the synchronization errors were investigated again in the case of ionospheric and tropospheric delays. The results are shown in Table 3. In such a condition, the combination of L1C/A, L2CL, and L5Q navigation signals is the best synchronization result.

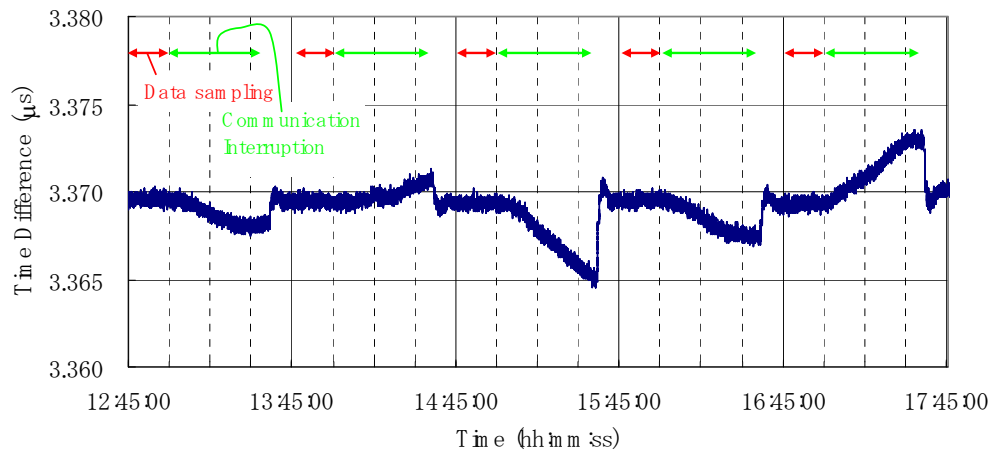


Fig. 19. Control results during communication interruption.

VII. CONCLUSIONS

This study is summarized as follows.

- (1) The RESSOX concept and the apparatuses used in this research were introduced.
- (2) The RESSOX algorithm using any combinations of L1/L2/L5-band navigation signals was introduced.
- (3) Feed-forward control experiment was explained. When orbit calculation was correct, synchronization error fluctuation was within 2 ns. When errors of +5 m and -5 m in the x direction, y direction, and z direction in the ITRF coordinate were added to the epoch satellite position, the fluctuation of synchronization error was 40 ns. The difference of synchronization errors was almost as much as the difference of expected delays.

(4) Drift behaviors of MINI-OCXO during communication interruption were measured. In this experiment, the average voltage of the last 100 voltage commands immediately before communication interruption was used as fixed control voltage. The maximum synchronization error in the experiments was 5 ns; however, since the errors are statistical, the probability of error exceeding 10 ns is possible.

(5) For the combination of navigation signals, priority signals are investigated. If ionospheric and tropospheric delays are not considered, the method using only L5Q is the best. However, if the ionospheric and tropospheric delays are considered, the method that combines L1C/A, L2CL, and L5Q is the best.

Table 2. Signal combination priority in case that ionospheric and tropospheric delays are not considered.

Signal Combination	Standard deviation	Average	Range	Minimum	Maximum
L5Q	1.53331E-10	4.89175E-13	1.223E-09	-5.94E-10	6.29E-10
L5I	1.53403E-10	5.01251E-13	1.223E-09	-5.94E-10	6.29E-10
L1CA	1.66586E-10	-5.2254E-13	1.332E-09	-6.26E-10	7.06E-10
L1CP	2.08868E-10	-1.5412E-12	1.581E-09	-7.89E-10	7.92E-10
L1CA/L5Q	2.12647E-10	-1.7868E-12	1.617E-09	-8.12E-10	8.05E-10
L1CA/L5I	2.12725E-10	-1.8006E-12	1.622E-09	-8.14E-10	8.08E-10
L1CA/L2CL/L5Q	2.22825E-10	-1.8874E-12	1.707E-09	-8.3E-10	8.77E-10
L1CA/L2CL/L5I	2.22877E-10	-1.8976E-12	1.711E-09	-8.32E-10	8.79E-10
L2CL	2.24014E-10	5.86836E-13	1.752E-09	-9.19E-10	8.33E-10
L1CA/L2CM/L5Q	2.45457E-10	-1.9756E-12	1.911E-09	-9.32E-10	9.79E-10
L1CA/L2CM/L5I	2.45513E-10	-1.9865E-12	1.911E-09	-9.31E-10	9.8E-10
L1CA/L2CL	3.3578E-10	-2.2234E-12	2.641E-09	-1.308E-09	1.333E-09
L1CP/L5Q	3.53505E-10	-4.0703E-12	2.618E-09	-1.286E-09	1.332E-09
L1CP/L5I	3.5355E-10	-4.0869E-12	2.618E-09	-1.287E-09	1.331E-09
L1CP/L2CL/L5Q	3.65807E-10	-4.2405E-12	2.73E-09	-1.32E-09	1.41E-09
L1CP/L2CL/L5I	3.65834E-10	-4.2515E-12	2.731E-09	-1.321E-09	1.41E-09
L2CM	3.68563E-10	8.41306E-13	2.834E-09	-1.51E-09	1.324E-09
L1CP/L2CM/L5Q	3.79621E-10	-4.3266E-12	2.964E-09	-1.436E-09	1.528E-09
L1CP/L2CM/L5I	3.7965E-10	-4.344E-12	2.964E-09	-1.435E-09	1.529E-09
L1CD	4.0886E-10	-4.7053E-12	3.055E-09	-1.478E-09	1.577E-09
L1CP/L2CL	4.60857E-10	-4.796E-12	3.745E-09	-1.859E-09	1.886E-09
L1CA/L2CM	5.58574E-10	-2.6077E-12	4.497E-09	-2.329E-09	2.168E-09
L1CP/L2CM	6.40491E-10	-5.1842E-12	5.056E-09	-2.509E-09	2.547E-09
L1CD/L5Q	8.64294E-10	-1.1171E-11	6.578E-09	-3.171E-09	3.407E-09
L1CD/L5I	8.64305E-10	-1.1192E-11	6.578E-09	-3.172E-09	3.406E-09
L5CD/L2CL/L5Q	8.89754E-10	-1.155E-11	6.823E-09	-3.277E-09	3.546E-09
L1CD/L2CL/L5I	8.89762E-10	-1.1562E-11	6.823E-09	-3.278E-09	3.545E-09
L1CD/L2CM/L5Q	8.95E-10	-1.1639E-11	6.886E-09	-3.298E-09	3.588E-09
L1CD/L2CM/L5I	8.95011E-10	-1.1655E-11	6.887E-09	-3.299E-09	3.588E-09
L1CD/L2CL	9.9803E-10	-1.2793E-11	7.636E-09	-3.63E-09	4.006E-09
L1CD/L2CM	1.09063E-09	-1.3181E-11	8.512E-09	-4.222E-09	4.29E-09
L2CL/L5Q	2.00322E-09	1.73599E-12	1.574E-08	-7.541E-09	8.197E-09
L2CL/L5I	2.00358E-09	1.57686E-12	1.574E-08	-7.549E-09	8.191E-09
L2CM/L5I	4.08855E-09	4.63819E-12	3.249E-08	-1.558E-08	1.6916E-08
L2CM/L5Q	4.08856E-09	4.79587E-12	3.249E-08	-1.557E-08	1.6921E-08

Table 3. Signal combination priority in case that ionospheric and tropospheric delays are considered.

Signal Combination	Standard deviation	Average	Range	Minimum	Maximum
L5Q	7.52894E-09	1.73647E-08	2.848E-08	2.191E-09	3.0666E-08
L1CA	4.17895E-09	9.63151E-09	1.614E-08	1.143E-09	1.7287E-08
L1CA/L2CL/L5Q	2.22787E-10	-1.459E-12	1.707E-09	-8.3E-10	8.77E-10
L1CA/L2CM/L5I	2.45471E-10	-1.5609E-12	1.911E-09	-9.31E-10	-9.31E-10

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