GROUND EXPERIMENTS OF REMOTE SYNCHRONIZATION FOR ONBOARD CRYSTAL OSCILLATOR OF QUASI-ZENITH SATELLITES — USE OF MULTIPLE POSITIONING SIGNALS FOR FEEDBACK CONTROL

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Abstract

We have developed a new control method for the quasi-zenith satellite (QZS) remote synchronization system for the onboard crystal oscillator (RESSOX). The new method utilizes L1 and L2 positioning signals of the QZS system. We have proved that precise orbit prediction or estimation of delays such as those caused by the ionosphere and troposphere is not necessary to realize RESSOX technology. L1/L2/Ku-band signal delay caused by the ionosphere and other sources is calculated separately using RESSOX feedback control. The results of Ku-band delay are used to generate the appropriate control signal. The results show that synchronization within 2 ns between the ground-site atomic clock and the QZS site is achievable. We also confirmed that the crystal oscillator that has the same specifications as the actual onboard crystal oscillator could be controlled by the same method as the prototype in the test bed.

I. INTRODUCTION

The quasi-zenith satellite system (QZSS) has been under development as a Japanese space project since

2003, and its new main mission is navigation **[1]**. Its constellation consists of three satellites orbiting on inclined orbital planes with a geosynchronous period. QZSS utilizes a high inclined orbit because of the high visibility over high latitude regions. In the case of QZSS, at least one satellite is highly visible at the zenith at any time. Therefore, users can always receive positioning signals from at least one of the QZSs near the zenith.

In general, global navigation satellite systems (GNSSs), such as the GPS of US, GLONASS of Russia, and GALILEO of Europe, are equipped with onboard atomic clocks that are used as time reference **[2]**. 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 systems are used for military missions and are therefore expected to operate even if ground stations are destroyed, and (4) these systems include 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 QZSS as a civilian navigation system: (1) some crystal oscillators have better short-term stability than atomic clocks **[3]**, (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, has been developed. In the case of RESSOX, modification of the control algorithm after launch is easy because it is basically a ground technology. The tentative goal of the synchronization accuracy of RESSOX is set at 10 ns, with the target stability of 10^{-13} for more than 100,000 s. These goals are determined on the basis of the synchronization performance between GPS time and UTC (USNO) **[4]** and the long-term stability performance of onboard cesium atomic clocks **[5]**.

RESSOX ground experiments and computer simulations have been conducted since 2003. Details of primary experimental results obtained using only the L1 positioning signal have been introduced in our previous papers **[6-8]**. We have developed a new feedback method that uses L1 and L2 positioning signals of the QZS, 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 the delay of L1/L2/Ku-band signals caused by the ionosphere and other sources separately during error adjustment.

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 using the pseudo-range measured with the positioning signal of the QZSS and the estimated pseudo-range, 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, troposphere delay, ionosphere 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 **[7]**. However, as is described later, if L1 and L2 signals are used for feedback, use of the delay models become unnecessary.

GPS Block-IIR, which is the newest line-up of the US's GPS, adopts 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]**.

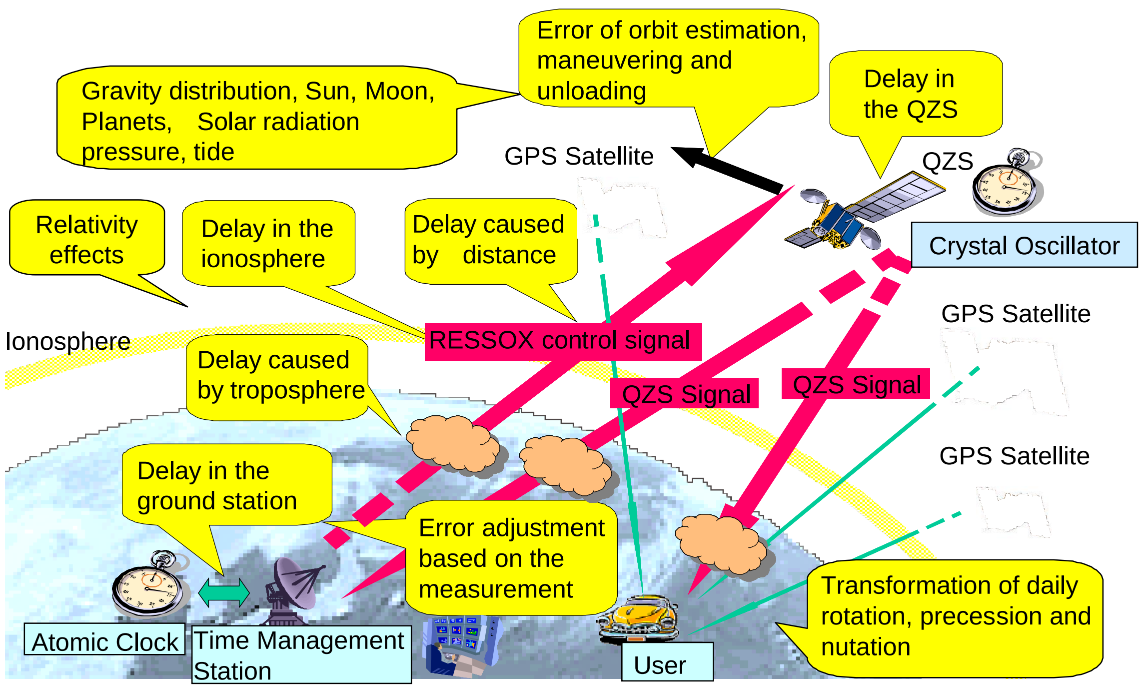

Fig. 1. RESSOX schematic.

Figure 2 shows a comparison of RESSOX with the TKS of GPS Block-IIR. The GPS Block-IIR TKS utilizes the short-term frequency stability of the crystal oscillator and the long-term stability of the rubidium (Rb) atomic clock; the crystal oscillator contributes to the whole system, whereas the atomic clock 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 the RESSOX control signal, from the ground station where the standard time is kept, similar to the Rb atomic clock of the GPS Block-IIR TKS. We assume that the RESSOX control signal is up-linked 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 clock system.

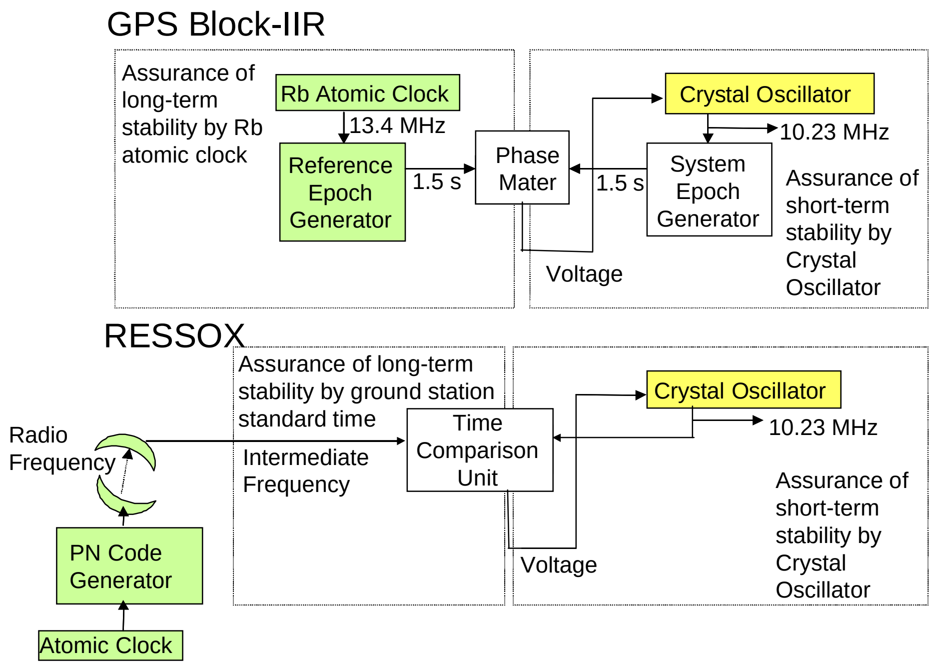

Fig. 2. Comparison between RESSOX and the TKS of GPS Block-IIR.

III. APPARATUSES FOR REALIZING RESSOX

In this section, the hardware tools for realizing RESSOX technology are 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 transmitting time adjuster (TTA) advances the time to compensate the delay during transmission between the QZSS-Time and the crystal oscillator onboard the QZS. The time information is modulated by the PN signal generator at the TMS, up-converted to 14.43453 GHz (Ku band) by the up-converter, and 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 positioning signals (QZS signals) of L1, L2, and L5 bands are generated using the onboard crystal oscillator as the reference clock. At the TMS, the QZS signals are received by the antenna and transmitted to the QZS/GPS receiver for RESSOX. This receiver compares the time information in the QZS signal with the QZSS time, and outputs it as the pseudo-range. The pseudo-range is used as feedback information of RESSOX. The timing controller at the TMS controls the TTA using the delay models and pseudo-range information.

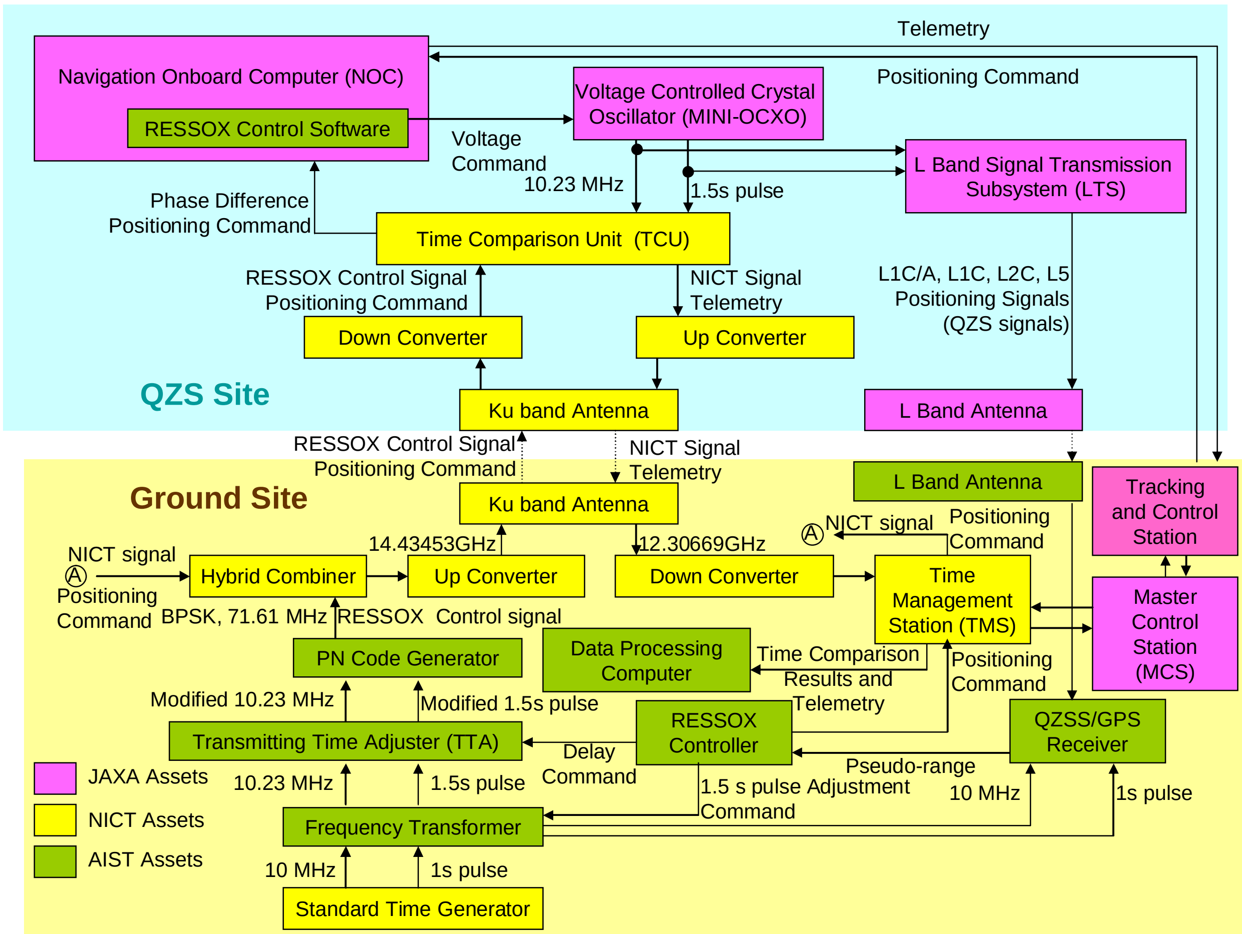

Fig. 3. System diagram of RESSOX.

Figure 4 shows the schematic of the test bed for the preliminary ground experiments. 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.

TRANSMITTING TIMING ADJUSTER (TTA) AND TIMING CONTROLLER

The TTA is an apparatus that generates advanced time to compensate the delay between the TMS and the QZS. The time adjustment files and commands for the TTA are generated and transferred by the timing controller with TCP/IP. The time adjustment files are prepared by calculating the delay models, and the time adjustment commands are given as feedback information from the QZS receiver in real time. The TTA adjusts the time between 0.1 s and 0.2 s in advance of the QZSS time because the distance between the TMS and the QZS varies in the vicinity of 40,000 km, and the time rate from -1 µs/s to 1 µs/s, which corresponds to a rate ranging from -300 m/s to 300 m/s. To realize these specifications, the direct digital synthesizer (DDS) is used.

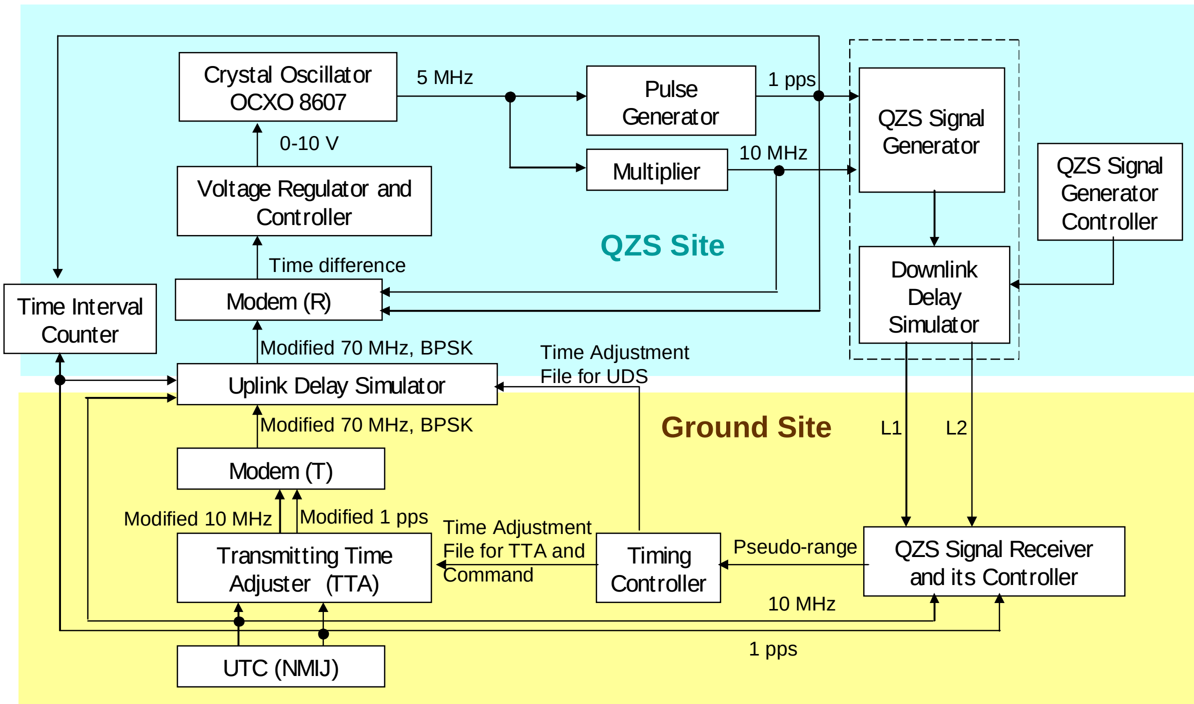

Fig. 4. Schematic of the test bed for preliminary ground experiments.

Figure 5 shows the block diagram of the TTA and timing controller for the ground test bed. To operate the TTA, first, the Ku-band estimated time advance file that describes the advanced time at a broadcasting time in coordinated universal time (UTC) at the TMS is prepared by orbit calculation and other delay simulations.

This file is assumed to be generated from the estimated orbit information in actual operation. Using the Ku-band estimated time advance file, time adjustment files for TTA are prepared with a utility program. The format of the time adjustment file for TTA is as follows: The first line indicates the next file name. The second line specifies the number of data in the file. The third line includes the modified Julian day (MJD) and UTC of the first data. The fourth line defines the valid time of each coefficient of the file (the minimum is 0.1 s). From the fifth to the last line (the maximum number is 10,000), the fitting coefficients are given for a valid time. These coefficients are calculated by Lagrange interpolation or least-mean-squares approximation (the maximum order is 11).

In our ground test bed, the TTA receives 10 MHz and 1 pulse per second (pps) from UTC (NMIJ), which is our time standard (NMIJ stands for National Metrology Institute of Japan, one of the institutes in AIST), and UTC (NMIJ) is used as the time standard of our ground test bed instead of the QZSS-Time. The time adjustment commands are also given as the changes of the coefficients. The database of L1 and L2 delays was prepared beforehand through orbit and delay calculations and compared with the pseudo-range measured by the QZS signal receiver. The differences between them are accumulated, and using the least-mean-squares filter, the error to be compensated is calculated and output as the change of the coefficients to be adjusted.

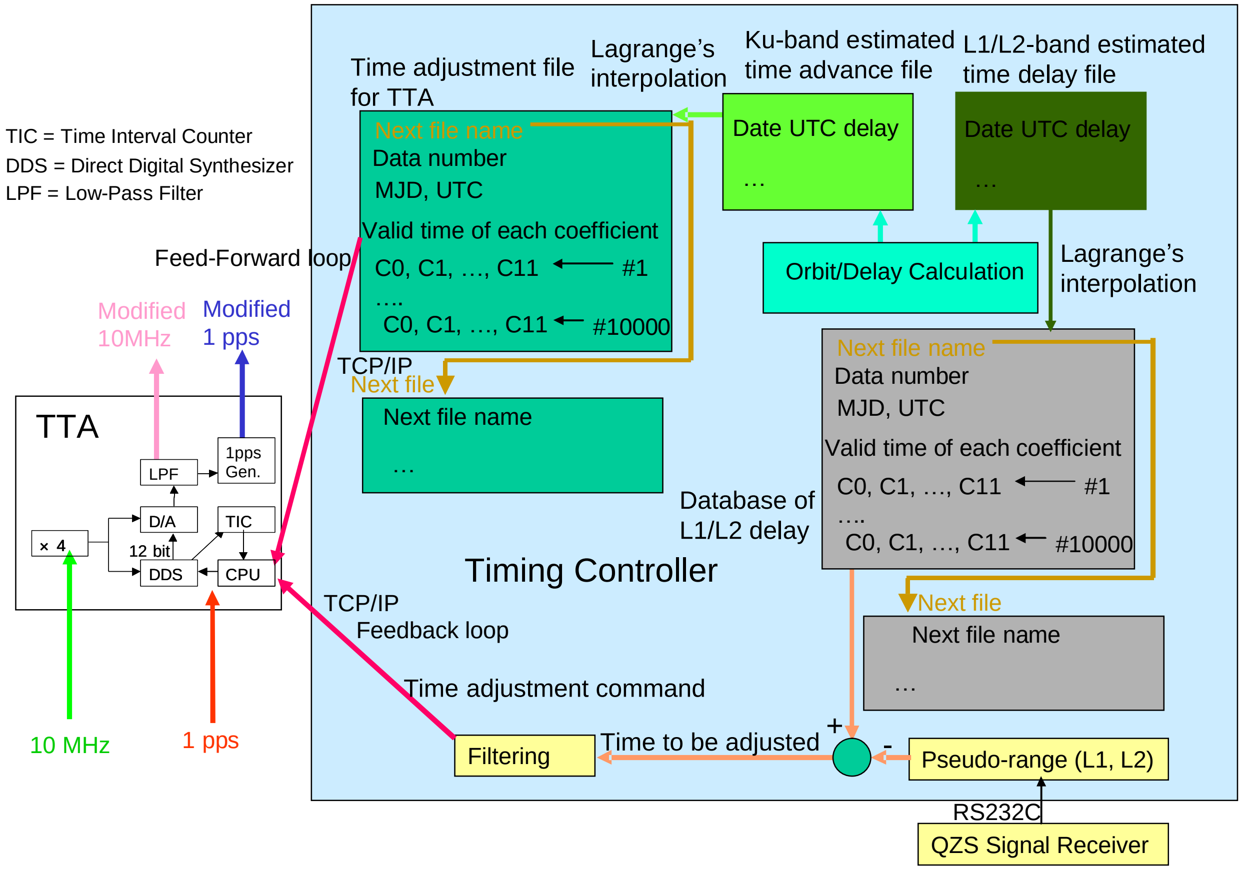

Fig. 5. Block diagram of the TTA for the ground test bed.

MODEMS (PN-CODE GENERATOR AND TIME COMPARATOR)

The principle of operation of the modem at the TMS is PN-code generation and that onboard is the time comparator. For simplicity, the modem at the TMS is called the transmitter modem (Modem (T)) and that onboard is called the receiver modem (Modem (R)). The same modem as that used in two-way satellite time and frequency transfer (TWSTFT) to compare two or more time standards all over the world is prepared for the transmitter at the ground station and for the onboard receiver in this experiment **[10]**. The RESSOX control signal is modulated and demodulated using the PN code (M-sequences), and then transmitted with 70 MHz carrier. Clearly, the simple 10 MHz signal or the relative 1 pps cannot be transmitted as is.

UPLINK DELAY SIMULATOR (UDS)

The UDS is a hardware simulator used in the ground test bed. Figure 6 shows the block diagram of the UDS. The UDS assigns offset values to the first-in first-out (FIFO) memory according to the Ku-band authentic time delay files for the UDS that have the same format as those for the TTA, and these files are assumed to be the authentic delay of the Ku band. Then, the UDS adjusts the time information of the modified 10 MHz generated by the TTA. The UDS is based on DDS technology of the TTA and FIFO memory control techniques. It receives an intermediate frequency (IF) signal that includes time information (central frequency of 70 MHz, bandwidth of 2.5 MHz), down-converts the frequency to 2 MHz, downloads the waveform of time information into FIFO memory in real time, and reads out the FIFO memory data using the modified 10 MHz generated by the TTA inside the UDS. Herewith, the UDS up-converts the frequency to 70 MHz, and outputs the modified IF signal using the time adjustment files for the UDS.

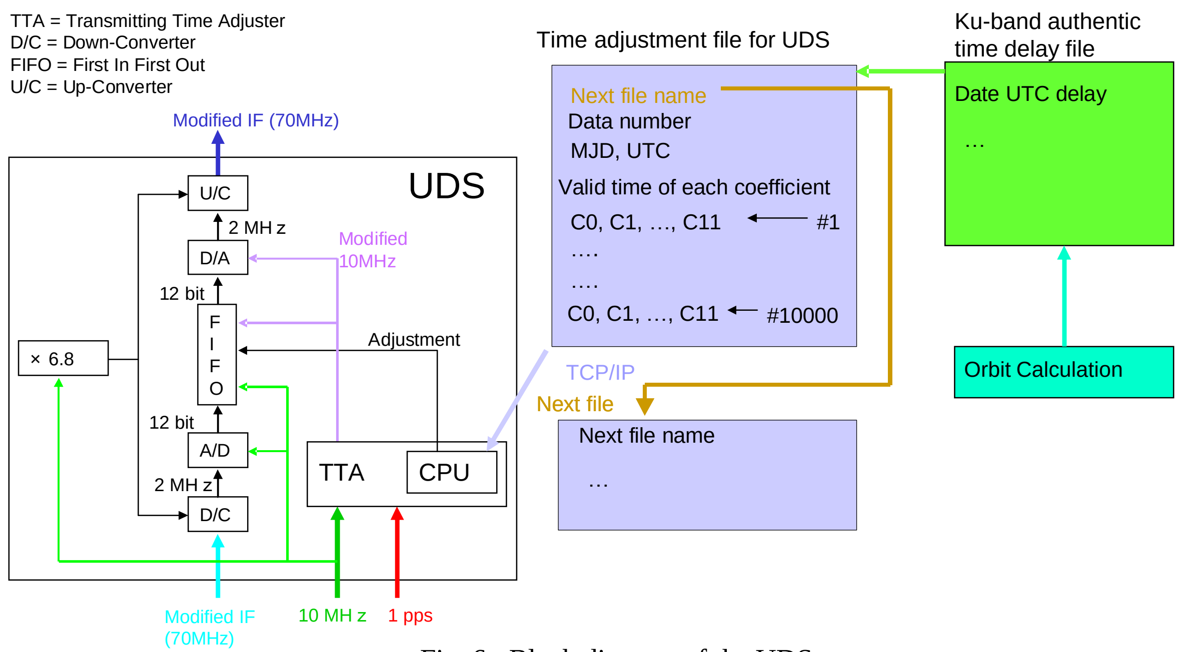

Fig. 6. Block diagram of the UDS.

QZS SIGNAL GENERATOR AND CONTROLLER

In the ground test bed, the QZS signal generator is required to simulate the QZS signal. Although the QZSS broadcasts L1C/A, L1C, L2C, and L5 signals, since we do not have a generator generating all signals at the moment, a GPS signal generator (Spirent GSS4730) that can generate four channels of L1C/A and L2P positioning signals is used. To simulate one QZS, only one channel of L1C/A and L2P signals is used. Because commercially available software that comes with the GSS4730 supports only simple orbit models and ionosphere delay, we have developed a new delay simulation method called SimQZ that uses the simulation data file made by us. Figure 7 shows the block diagram of the QZS signal generator. The simulation data file includes the 14 data values described in Fig. 7, with one time step record per line. The time step is 100 ms and the file must be in the comma separated value (CSV) format. The simulation data files are read by SimQZ in real time, and SimQZ controls the signal generator hardware to output the simulated QZS signal.

QZS SIGNAL RECEIVER AND CONTROLLER

Because the QZS signal includes time information of the onboard crystal oscillator, the time information coming from the QZS is adopted as the pseudo-range. To calculate the pseudo-range, an exclusive QZS signal receiver is used. The block diagram of the QZS signal receiver is shown in Fig. 8. The QZS signal receiver calculates the pseudo-range using UTC (NMIJ) and outputs it to the timing controller. The timing controller generates the time adjustment commands using the pseudo-range.

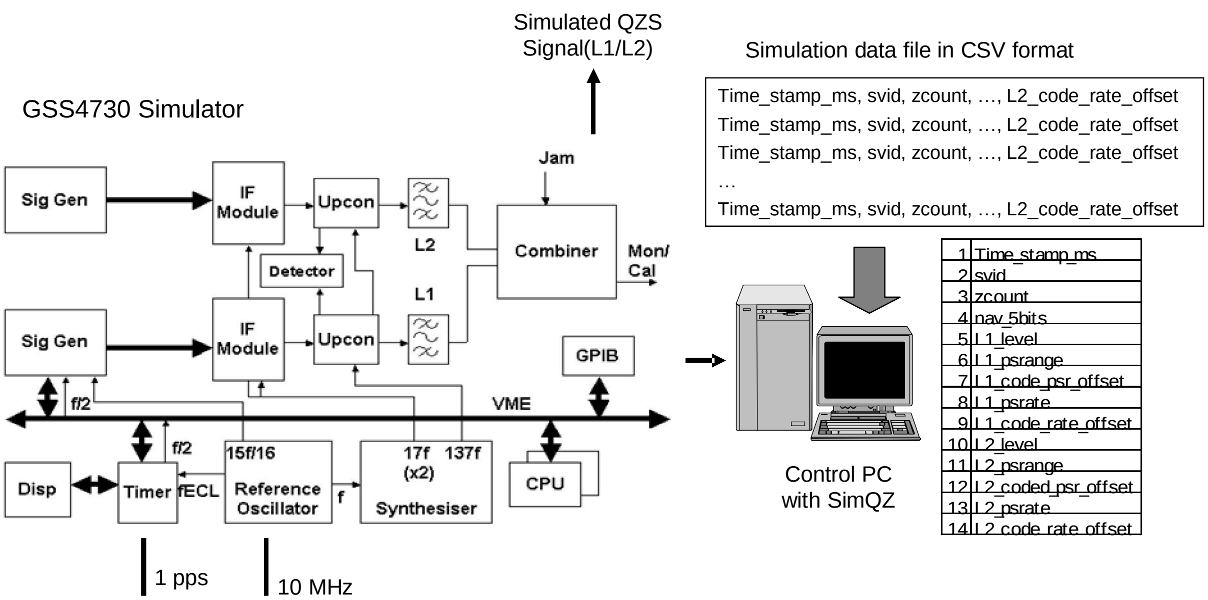

Fig. 7. Block diagram of the QZS signal generator.

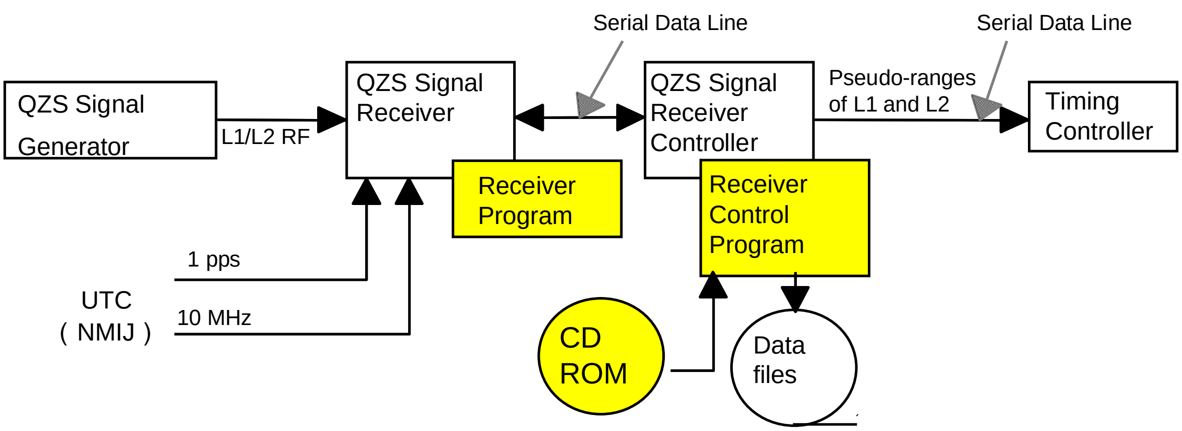

Fig. 8. Block diagram of the QZS signal receiver.

CRYSTAL OSCILLATOR

If continuous synchronization between the QZSS-Time and the onboard crystal oscillator were possible, the requirements for the crystal oscillator would have been less severe; the same specifications as those for the GPS (stability of 10^{-12} within 100 s) would be more than sufficient. However, in the case of the QZSS, when a QZS reaches the equatorial region, communication using the Ku band between the QZS and the TMS should be stopped for approximately 11 minutes (660 s) in order to avoid interference with geostationary satellites; this is done twice a day. For this reason, the crystal oscillator should have stability higher than 7×10^{-12} per 660 s. This specification could cause desynchronization of approximately 5 ns during the interruption period.

Two kinds of crystal oscillators are used for the ground experiments. One is a very stable BVA-type oven-controlled crystal oscillator (OCXO) manufactured by Oscilloquartz S.A. (hereafter, OCXO 8607), and the other is an engineering model of the onboard OCXO (same specifications as the onboard OCXO) manufactured by C-MAC Micro Technology (hereafter, MINI-OCXO). The former was selected because it was one of the most stable crystal oscillators in the world at the time when we began the research and the specifications of the onboard crystal oscillators were not determined.

Table 1 shows the specifications of the OCXO 8607 and the MINI-OCXO, and Fig. 9 shows the Allan deviations of them. To measure the Allan deviation, TSC5110A time-interval analyzer of Timing Solutions is used. In our test bed, since the available frequency is only 5 or 10 MHz, we use the configuration shown in Fig. 10 for the MINI-OCXO in our experiments. The Allan deviation of the combination of the MINI-OCXO and its phase locked loop (PLL) for 5 MHz is also shown in Fig. 9. The Allan deviation between 2 s and 10,000 s of the MINI-OCXO is worse than that of the OCXO 8607; however, both have stability much lower than 7×10^{-12} at 660 s. When PLL for 5 MHz is used with the MINI-OCXO, the Allan deviation between 1 s and 4 s is worse than that of the MINI-OCXO alone. This is because the time constant of PLL is of several seconds order, and seems to affect the stability.

Table 1. Comparison between VCXO and OCXO.

Manufacturer	Oscilloquartz S.A.	C-MAC
Name	OCXO 8607	MINI-OCXO
Standard Frequency	5.000 MHz	10.23 MHz
Range of Control Voltage	0-10 V	0-10 V
Weight	900 g	200 g
Size	138 x 73 x 88 mm	47 x 60 x40 mm
Adjustment	0.03 Hz / V	0.33 Hz/V

TIME-INTERVAL COUNTER (TIC)

To measure and evaluate the time difference between the OCXO 8607 or the PLL/MINI-OCXO and the ground atomic clock, the universal time interval counter (TIC) SR620 of Stanford Research Systems is used. One-pps signals are input to the TIC directly for the evaluation of synchronization accuracy.

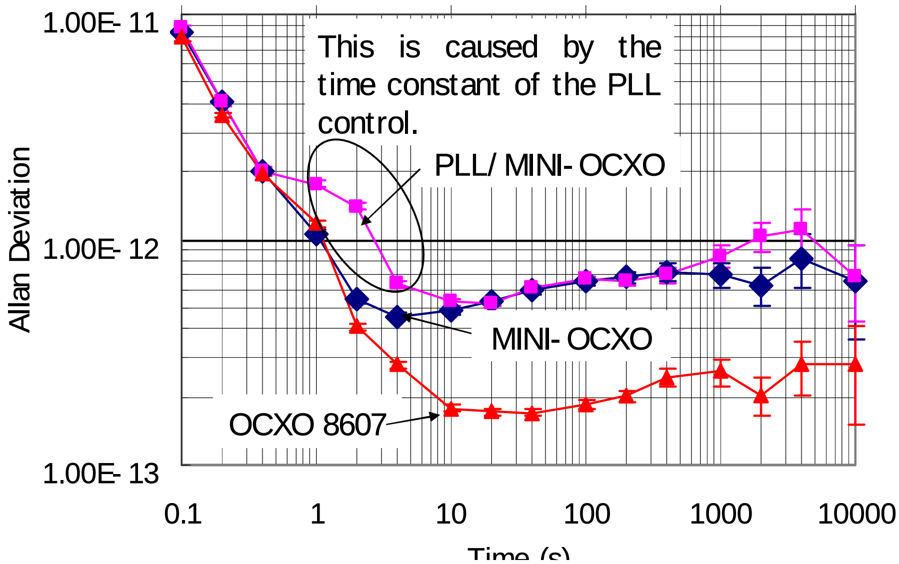

Fig. 9. Allan deviation of the OCXO 8607, and of the MINI-OCXO and combination of the MINI-OCXO and its PLL for 5 MHz used in our test bed.

IV. CONTROL METHODS

To investigate this new RESSOX technology, ground experiments are conducted. The L1 and L2 pseudo-ranges are considered separately, and the delay of the frequency-dependent part (i.e., ionospheric delay) and that of the frequency-independent part are estimated, respectively. The following is the sequence of this new technology:

<u>Step 1.</u> Three estimated delays 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. These delays, which are contained in the L1/L2-band estimated time delay file shown in Fig. 5, include the times (date and UTC) that the L1/L2 signal is received and the estimated delays of L1 and L2. Another delay, which is contained in the Ku-band estimated time advance file, includes the time (date and UTC) that the Ku signal is transmitted from the TMS and the estimated delay of the Ku signal. These files are converted into database of L1/L2 delay and the time adjustment file for TTA, respectively.

<u>Step 2.</u> Three authentic delays that do not contain any errors are prepared. Two of these delays are contained in the L1/L2 authentic delay file, and one is contained in the Ku-band authentic time delay file in Fig. 6. These files are converted into simulation data file in CSV format for SimQZ and the time adjustment file for UDS, respectively, and are used to generate authentic delays of the L1/L2/Ku signal in the experiments.

<u>Step 3.</u> The time adjustment file for TTA is fed into the TTA as feed-forward control. The timing for transmitting time information using the RESSOX control signal is adjusted to give the time comparator the correct time when the RESSOX control signal arrives at the QZS.

<u>Step 4.</u> The UDS delays the RESSOX control signal according to the time adjustment file for UDS.

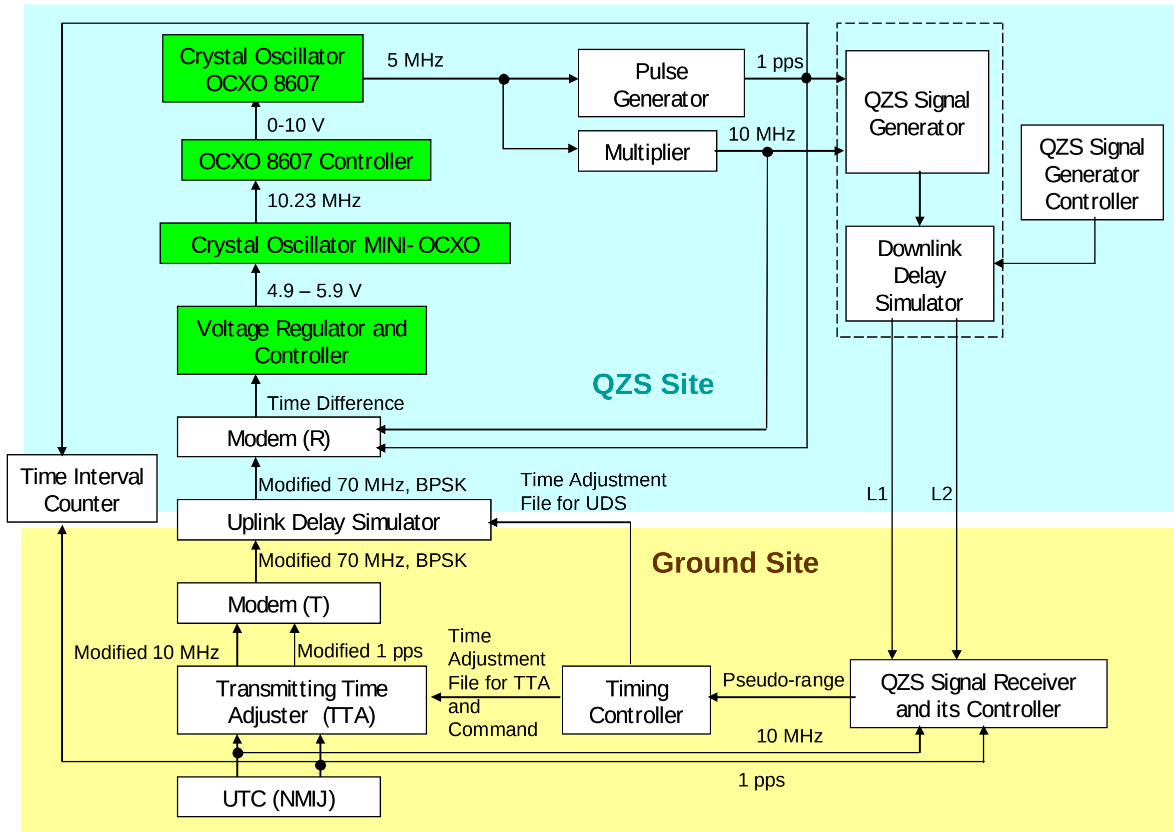

Fig. 10. Setup configuration of the MINI-OCXO in our experiments.

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 positioning signals according to simulation data file in CSV format for SimQZ.

Step 7. The pseudo-ranges of L1/L2 obtained by the QZS signal receiver are compared with the database of L1/L2 delay and the differences between the pseudo-range and the database are designated E_1 for L1 (frequency f_{L1}=1.57542×10^9 Hz) and E_2 for L2 (f_{L2}=1.2276×10^9 Hz).

Step 8. The system of equations (1) and (2), which includes E_1, E_2 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 solved.

$$\begin{cases} e+\dfrac{k}{f_{L1}^2}=E_1,\ f_{L1}=1.57542\times10^9[\text{Hz}] & (1)\\ e+\dfrac{k}{f_{L2}^2}=E_2,\ f_{L2}=1.2276\times10^9[\text{Hz}] & (2)\end{cases}$$

Step 9. Using the solutions of the system of equations, we obtain the time to be adjusted, equation (3), of the RESSOX control signal using the Ku band (f_{Ku}=1.43453×10^10 Hz) for the TTA.

$$e+\frac{k}{f_{Ku}^{2}},\ f_{Ku}=1.43453\times10^{10}[\mathrm{Hz}] \quad (3)$$

Step 10. By combining the time adjustment file in Step 3 and the time adjustment command based on the time to be adjusted, the 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 time adjustment command is conducted every second.

V. EXPERIMENTS

CRYSTAL OSCILLATOR CONTROL METHOD

To control the OCXO 8607 or the MINI-OCXO using the difference between unlinked time information and OCXO 8607/MINI-OCXO time, PI control of control voltage was utilized. The following formula, which describes PI control, was used.

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

where v_k is the k-th output voltage, $offset$ = 4.945 (V), k_1 is a proportional gain set at 7.0×10^6, k_2 is an integral gain set at 3.0×10^4, 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 2, and t_{RESSOX} is time information of the received RESSOX control signal.

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. 5. The filter was constructed using 100 data of time to be adjusted (result of formula (3) using the difference between measured pseudo-ranges of L1/L2 and estimated pseudo-ranges of L1/L2 prepared as the database of L1/L2 delay) from 6 s before to 105 s before every second. 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. 11. To calculate the filtering result and send it to the TTA as the time adjustment command, six seconds are required.

EXPERIMENTAL CONDITIONS

The experimental conditions are shown in Table 2. The simulated date was 1 January 2000, and data for that day of ionospheric conditions and other celestial bodies conditions were used. In Table 2, typical Keplerian elements of the QZS are shown as the initial conditions (i.e., on 1 January 2000, 00:00:00 in UTC). These conditions can be expressed as x = -22,881,059.583 m, y = -32,625,645.367 m, z = 19,898,922.824 m, v_x = 2,207.153 m/s, v_y = -839.448 m/s, v_z = 1,693.581 m/s in the International Celestial Reference Frame (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 Ku-band authentic time delay file in Fig. 6 and the CSV file for SimQZ were prepared.

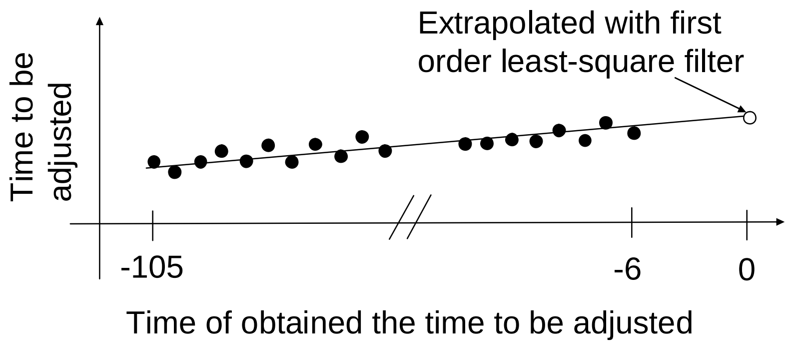

Fig. 11. Control method at TMS.

EXPERIMENTAL RESULTS

CASE OF -5 M ERROR FOR EACH AXIS USING OCXO 8607

First, we used OCXO 8607 as the controlled crystal oscillator and gave the system a measurement error of -5 m for each axis of the ICRF, i.e., we used x = -22,881,064.583 m, y = -32,625,640.367 m, and z = 19,898,917.824 m as the initial values of the motion of equation (v_x, v_y and v_z are the same as the authentic values) to create the time adjustment file for TTA and the database of L1/L2. The synchronization result between OCXO 8607 and UTC (NMIJ) is shown in Fig. 12. Most of the time during the experiment, the synchronization error was less than 2 ns. The maximum error was 5.4 ns. Therefore, the target of less than 10 ns was achieved.

Table 2. Experimental conditions.

Items	Values	Items	Values
Simulation period	2000.1.1 00:00:00UTC-2000.1.2 00:00:00UTC	Satellite mass, kg	3000.0
Semi-major axis, m	42164170.0	Satellite cross section, m^2	30.0
Eccentricity, m	0.099	CODE Data of Ionosphere	COD10426.ION
Inclination, deg	45.0	Meteorological condition	15 ˚C, 1013.25 hPa, 70% (relative humidity)
Right ascension of the ascending node, deg	205.0	Radiation pressure coefficient (Cr)	4.56× 10^{-6} N/m^2 (McCarthy 1996), Cr=1.2
Argument of perigee, deg	270.0	Position of ground station	26.5N, 127.9E, Height = 0.0 m (Okinawa)
Mean motion, deg	120.0	Solid Earth tide	Moon and Sun are considered, k2=0.3 (IAG 1999)
Geopotential model	EGM96 ,n,m=360	Other celestial bodies	Moon, Sun, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto (JPL-DE405)

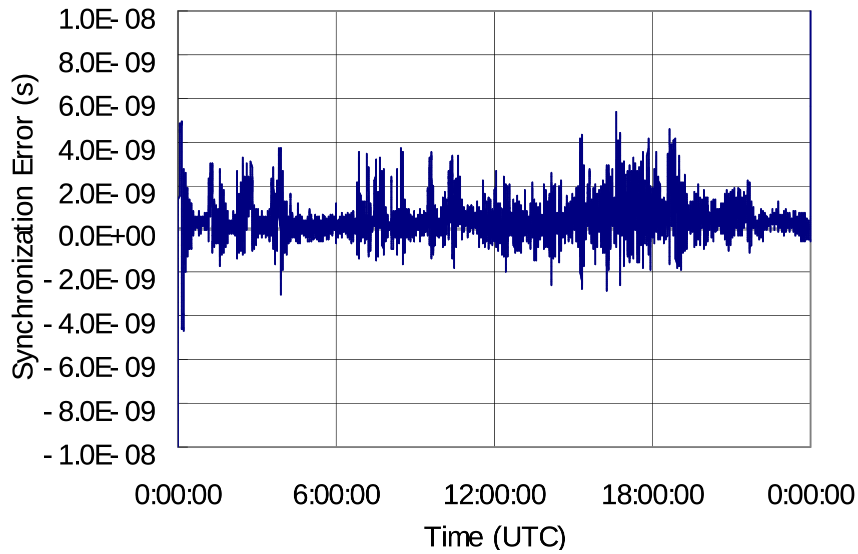

Fig. 12. Synchronization results.

Fig. 13 shows the delays of the Ku band, which include range error plus tropospheric delay and ionospheric delay, and the elements of the time to be adjusted using formula (3). In formula (3), *e* represents the sum of the range error and the tropospheric delay, and k / f_{ku}^2 represents the ionospheric delay of the Ku band. These elements of the time to be adjusted are also shown in Fig. 13. These delays and the elements of the time to be adjusted completely correspond to each other.

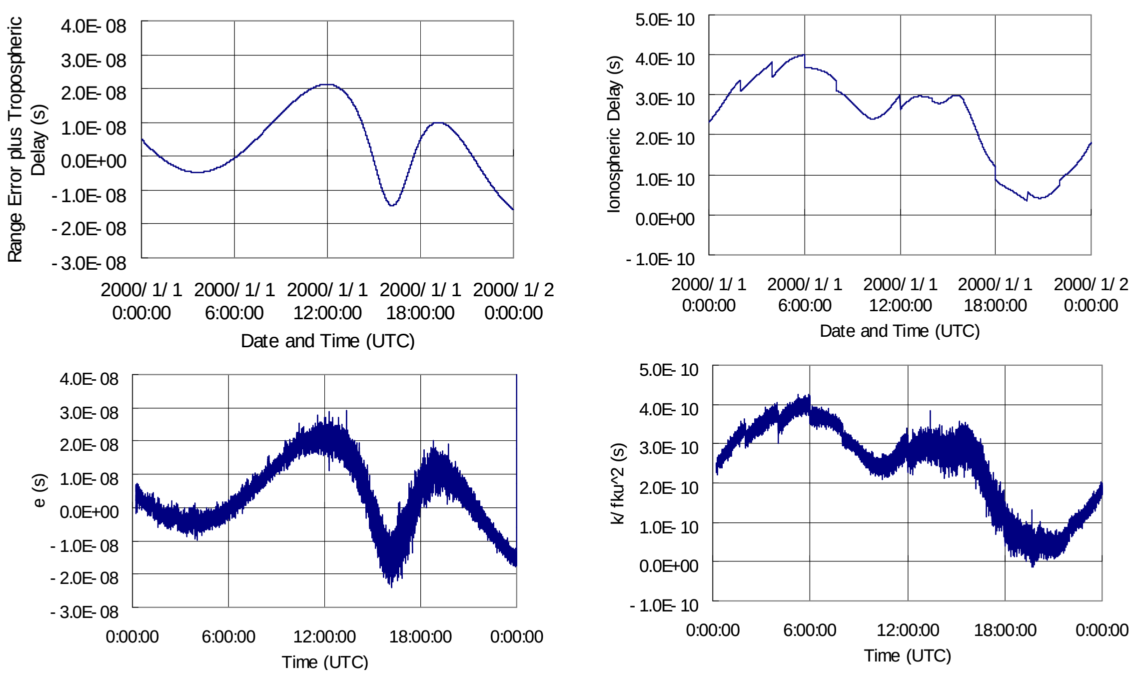

Fig. 13. Delay and elements to be adjusted using formula (3).

If we use only the delay estimation file and not the elements of the time to be adjusted in the TTA, the up-linked signal will include the error. The synchronization result for such a case is shown in Fig. 14. Although the result is noisy, it includes the range error and the tropospheric and ionospheric delays. The synchronization error is similar to the range error plus tropospheric delay; however, it includes ionospheric error, which is two orders of magnitude smaller than the range error plus tropospheric delay.

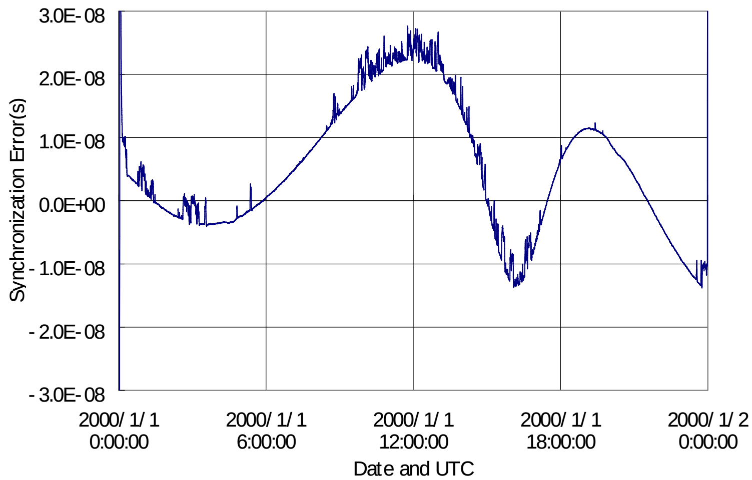

Fig. 14. Synchronization error when no adjusting elements are used.

CASE OF 5 M ERROR FOR EACH AXIS USING OCXO 8607

Next, we used OCXO 8607 and gave the system a measurement error of 5 m for each axis of the ICRF, i.e., we used x = -22,881,054.583 m, y = -32,625,630.367 m, and z = 19,898,927.824 m as the initial values of the motion of equation (v_x, v_y and v_z are the same as the authentic values) to create the time adjustment file for TTA and the database of L1/L2. The synchronization result between OCXO 8607 and UTC (NMIJ) is shown in Fig. 15. Most of the time during the experiment, the synchronization error was less than 1 ns. The maximum error was 4.38 ns in this case. Therefore, the target of less than 10 ns was achieved.

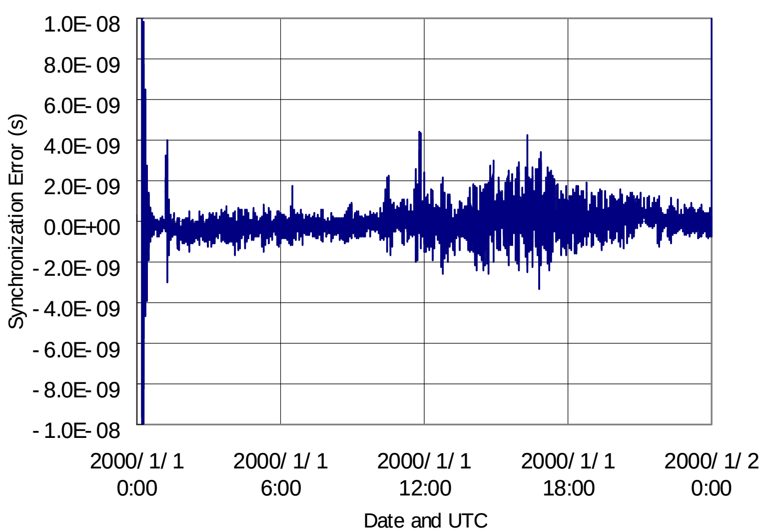

Fig. 15. Synchronization result.

Fig. 16 shows the delay of the Ku band and the elements of the time to be adjusted using formula (3), corresponding to Fig. 13. These delays and the elements of the time to be adjusted also completely correspond to each other.

Fig. 17 corresponds to Fig. 14, the case that we use only the delay estimation file and not the elements of the time to be adjusted in the TTA. Again, the synchronization error is similar to the range error plus tropospheric delay; however, it includes ionospheric error.

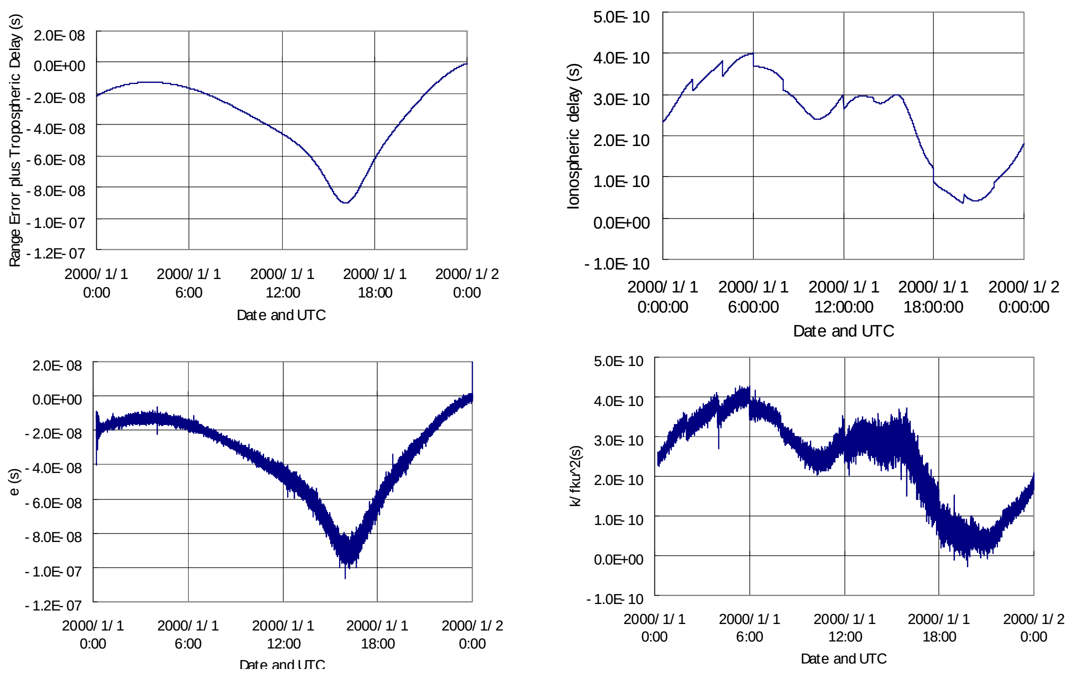

Fig. 16. Delay and elements to be adjusted using formula (3).

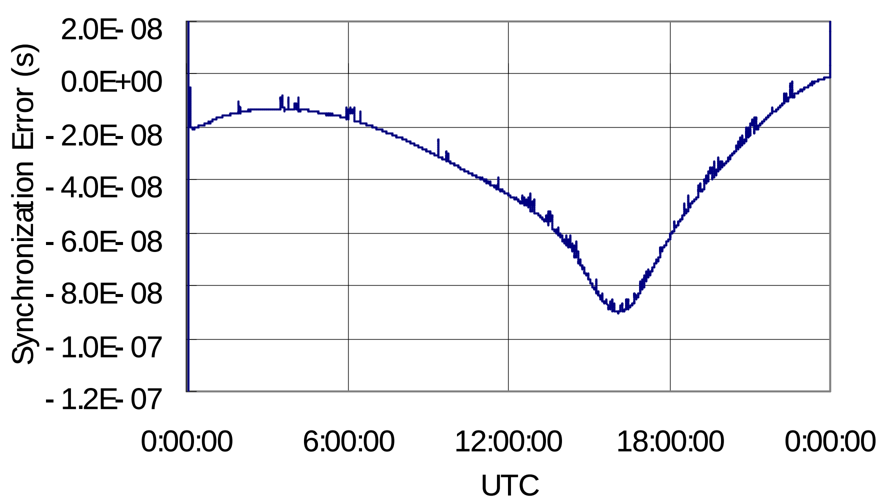

Fig. 17. Synchronization error when no adjusting elements are used.

CASE OF -5 M ERROR FOR EACH AXIS USING MINI-OCXO

Finally, we used MINI-OCXO and gave the system a measurement error of -5 m for each axis of the ICRF, i.e., we used x = -22,881,064.583 m, y = -32,625,640.367 m, and z = 19,898,917.824 m as the initial values of the motion of equation (v_x, v_y and v_z are the same as the real values) to create the time adjustment file for TTA and the database of L1/L2. The synchronization result between MINI-OCXO and UTC (NMIJ) is shown in Fig. 18. Most of the time during the experiment, the synchronization error was less than 1 ns. The maximum error was 4.31 ns.

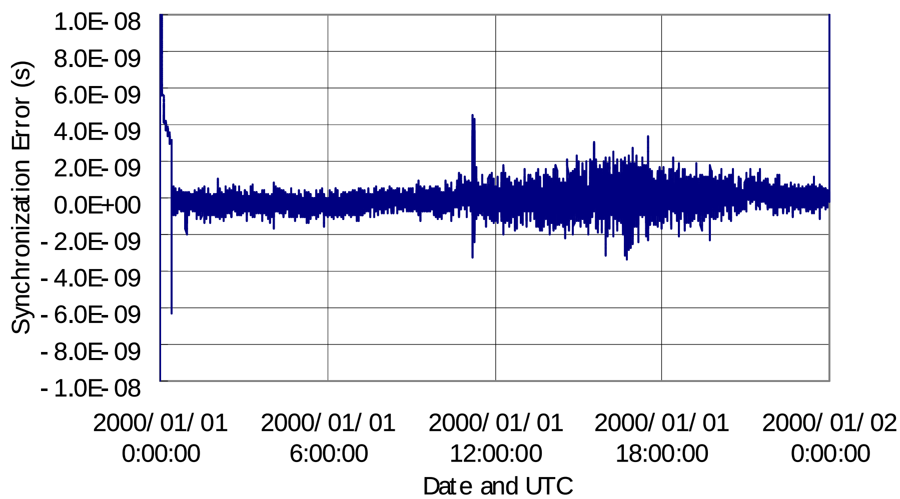

Fig. 18. Synchronization results.

Fig. 19 shows the elements of the time to be adjusted using formula (3). Again, these delays and the elements of the time to be adjusted completely correspond to each other.

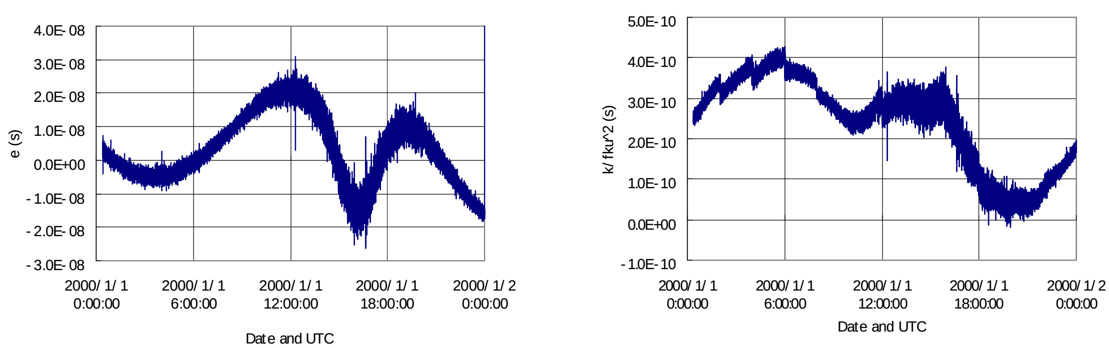

Fig. 19. Delay and elements to be adjusted using formula (3).

Fig. 20 corresponds to Fig. 14. The noise using MINI-OXCO was smaller than that using OCXO 8607. Again, synchronization error is similar to the range error plus tropospheric delay; however, it includes ionospheric error.

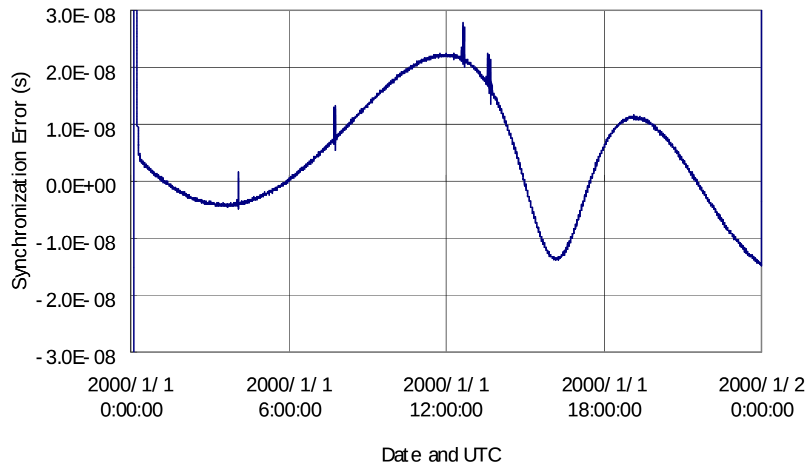

Fig. 20. Synchronization error when no adjusting elements are used.

VI. DISCUSSION

FEEDBACK FILTERING EFFECT

The experimental results presented so far were obtained using 100 prior data of time to be adjusted and their extrapolation, as shown in Fig. 11. This process, however, requires quite a long time, approximately 6 s. Therefore, we confirmed the results by conducting experiments without using filtering, i.e., the time to be adjusted was used for the feedback as quickly as possible (3 s). All other experimental conditions were the same as the case of -5 m error for each axis using OCXO 8607. The synchronization result between OCXO 8607 and UTC (NMIJ) is shown in Fig. 21. Most of the time during the experiment, the synchronization error was less than 1 ns. The maximum error was 2.63 ns. Although this method is very robust in the noisy conditions, its performance is slightly better than that of the 100 data filtering method.

Fig. 22 shows the elements of the time to be adjusted using formula (3). The results are almost the same as those shown in Fig. 13.

VII. CONCLUSIONS

This study is summarized as follows:

(1) The apparatus used in ground experiments was introduced.
(2) A new adjustment method of the QZS remote synchronization system for an onboard crystal oscillator (RESSOX) using both L1 and L2 positioning signals was demonstrated.
(3) Synchronization within 2 ns between OCXO 8607/MINI-OCXO and the standard time was achieved in a 24-hour ground experiment.
(4) The ionospheric delay and the combination of tropospheric delay and orbit error of the RESSOX control signal were estimated in the calculation and efficiently compensated.

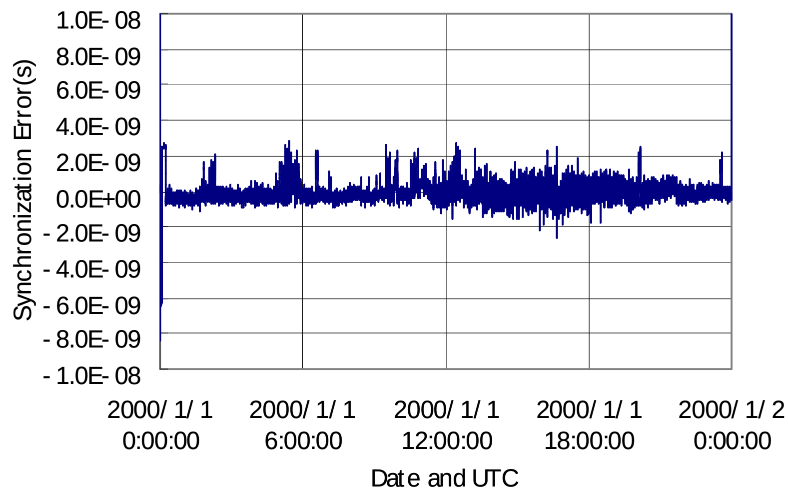

Fig. 21. Synchronization results.

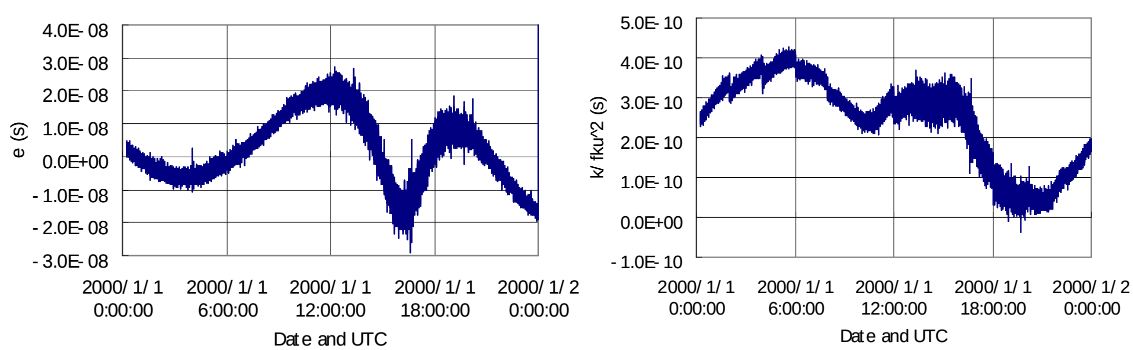

Fig. 22. Delay and elements to be adjusted using formula (3).

VIII. ACKNOWLEDGMENT

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REFERENCES

[1] I. Kawano, M. Mokuno, S. Kogure, and M. Kishimoto, 2004, "*Japanese Experimental GPS Augmentation Using Quasi-Zenith Satellite System (QZSS)*," Proceedings of the Institute of Navigation (ION) GNSS Meeting, 17th International Technical Meeting of the Satellite Division, 21-24 September 2004, Long Beach, California, USA (ION, Alexandria, Virginia), pp. 175-181.

[2] L. A. Breakiron, 1992, "*Timescale Algorithms Combining Cesium Clocks and Hydrogen Masers,*" in Proceedings of the 23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1991, Pasadena, California, USA (NASA CP-3159), pp. 297-305.

[3] J. J. Suter, L. J. Crawford, B. G. Montgomery, and W. E. Swann, 2000, "*Syntonics LLC APL-Developed Technology Makes Its Commercial Debut*," Johns Hopkins APL Technical Digest, Vol. 22, No. 2, pp. 168-175.

[4] P. A. Koppang, D. Matsakis, and M. Miranian, 2000, "*Alternate Algorithms for Steering to Make GPS Time*," Proceedings of ION GPS 2000, 13th International Meeting of the Satellite Division, 19-22 September 2000, Salt Lake City, Utah, USA (Institute of Navigation, Alexandria, Virginia), pp. 933-936.

[5] D. W. Allan, N. Ashby, and C. C. Hodge, 1997, "*The Science of Timekeeping, Application Note 1289*," (Hewlett Packard), p. 60.

[6] T. Iwata, A. Iwasaki, Y. Fukuyama, F. Tappero, K. Hagimoto, T. Ikegami, and H. Murakami, 2004, "*Ground Testbed for Quasi-Zenith Satellite Remote Synchronization System for On-board Crystal Oscillator*," Preprint of 24th Symposium on Space Technology and Science, 30 May-6 Jun 2004, Miyazaki, Japan (JSASS, Tokyo), ISTS 2004-f-16.

[7] T. Iwata, F. Tappero, M. Imae, Y. Fukuyama, K. Hagimoto, H. Murakami, T. Ikegami, A. Iwasaki, K. Nakajima, and Y. Takahashi, 2005, "*Research on Remote Synchronization System for Onboard Crystal Oscillators of Quasi-Zenith Satellites*," Proceedings of the International Symposium on GPS/GNSS, 6-8 December 2004, Sydney, Australia.

[8] T. Iwata, F. Tappero, M. Imae, Y. Fukuyama, T. Suzuyama, H. Murakami, Y. Ikemoto, A. Iwasaki, and T. Masubuchi, 2005, "*Ground Experiments of Remote Synchronization System for Onboard Crystal Oscillators of Quasi-Zenith Satellites*," Proceedings of AIAA Guidance, Navigation, and Control Conference, 15-18 August 2005, San Francisco, California, USA (AIAA, Reston, Virginia), Paper No. AIAA-2005-6468.

[9] H. C. Rawicz, M. A. Epstein, and J. A. Rajan, 1993, "*The Time Keeping System for GPS Block IIR*," Proceedings of the 24th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 1-3 December 1992, McLean, Virginia, USA (NASA CP-3218), pp. 5-16.

[10] M. Imae, M. Hosokawa, K. Imamura, H. Yukawa, Y. Shibuya, N. Kurihara, P. T. H. Fisk, M. A. Lawn, L. Zhigang, L. Huanxin, Y. Nakadan, and K. Hagimoto, 2001, "*Two-Way Satellite Time and Frequency Transfer Networks in Pacific Rim Region*," **IEEE Transactions on Instrumentation and Measurement, IM-50,** 559-562.