REMOTE SYNCHRONIZATION EXPERIMENTS FOR FUTURE QUASI-ZENITH SATELLITE SYSTEM USING CURRENT GEOSTATIONARY SATELLITES

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Abstract

Japan's Quasi-Zenith Satellite System (QZSS) is scheduled for launching in 2010. We have been conducting research on the remote synchronization system for the onboard crystal oscillator (RESSOX), which does not require onboard atomic clocks, for the QZSS since 2003. RESSOX reduces overall cost and satellite power consumption, as well as onboard weight and volume, and is expected to have a longer lifetime than a system with onboard atomic clocks. Since a QZSS does not yet exist, we have been conducting synchronization experiments using current geostationary satellites (JCSAT-1B or IS-4 [formerly PAS-4]) to confirm that RESSOX is an excellent system for timing synchronization. For the experiments using JCSAT-1B, we have already reported that synchronization within 10 ns was achieved when feedback information was used. Since JCSAT-1B was located at an elevation angle of 46.5 degrees at our institute, however, the effect of tropospheric delay was not very large. To examine the applicability of RESSOX under more severe conditions, IS-4 was selected. IS-4 is located at an elevation angle of 7.9 degrees at our institute, which means that the effect of tropospheric delay is large (in the case of the QZSS, the smallest elevation angle at Okinawa station is approximately 10 degrees). In this paper, we will present the experimental setup, the results of uplink experiments and feedback experiments, and some discussions on the use of RESSOX with the QZSS.

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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 **[1]**. Its constellation consists of three satellites orbiting on inclined orbital planes with a geosynchronous period. The QZSS utilizes a highly 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. Therefore, users can always receive navigation signals from at least one of the QZSs 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 frequency standards that are used as time references. This is because: (1) atomic frequency standards 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. 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 a practical sense, QZSS will load two rubidium atomic standards. RESSOX is research for a future technology.

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, if multiple navigation signals are used for feedback, use of the delay models becomes unnecessary **[7, 8]**.

III. REMOTE SYNCHRONIZATION EXPERIMENTS USING GEO

Since the QZSS does not exist at the moment, we validate RESSOX techniques using geostationary satellites (GEOs) as an actual space system. Two GEOs, JCSAT-1B (the elevation angle is 46.5 degrees at our institute) and IS-4 (formerly PAS-4; the elevation angle is 7.9 degrees), have been chosen as relay satellites because the elevation angle of the QZSS at Okinawa is expected to be between 10 and 90 degrees. The experimental results using JCSAT-1B have been reported and a synchronization error of 10 ns was achieved **[9]**. In this section, first, we will introduce the equipment used in the experiments and then we will discuss briefly the experimental results of JCSAT-1B and explain in detail the experiments using IS-4.

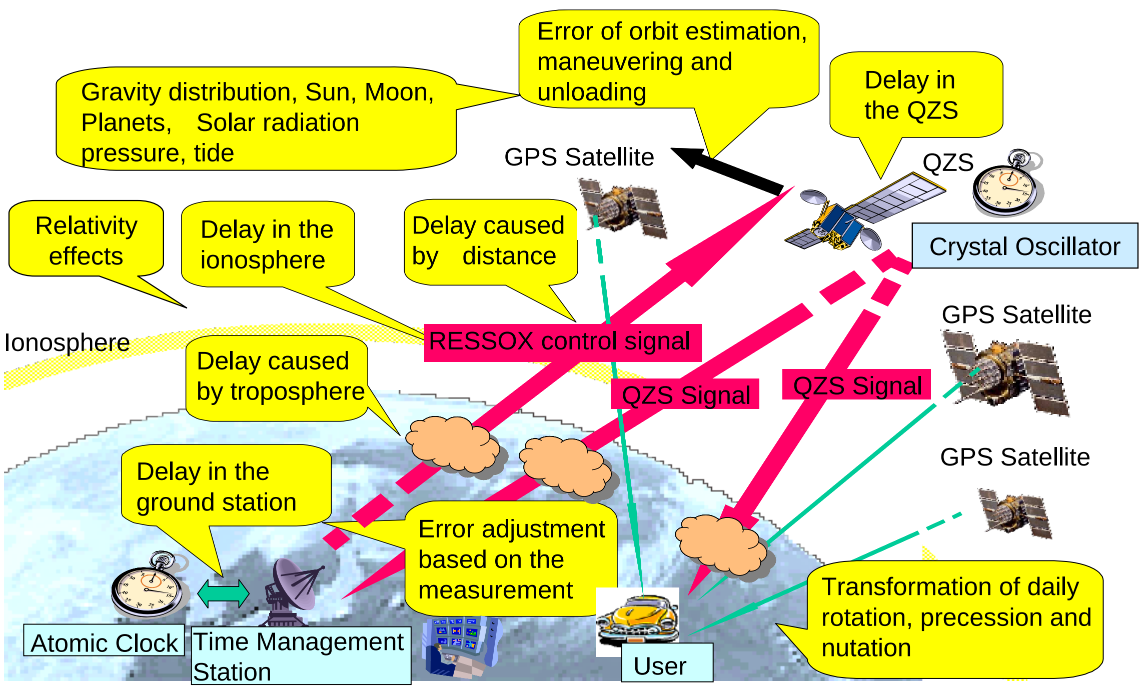

Fig. 1. RESSOX schematic.

EXPERIMENTAL SETUP

The experimental setup on the ground is common to both JCSAT-1B and IS-4. The only differences are the satellites, the antennae, and the up/down-converters to communicate with them. The concept of GEO experiments is shown in Fig. 2. The block diagram of the experiments is shown in Fig. 3. First, the apparatuses for the GROUND ground site are listed as follows.

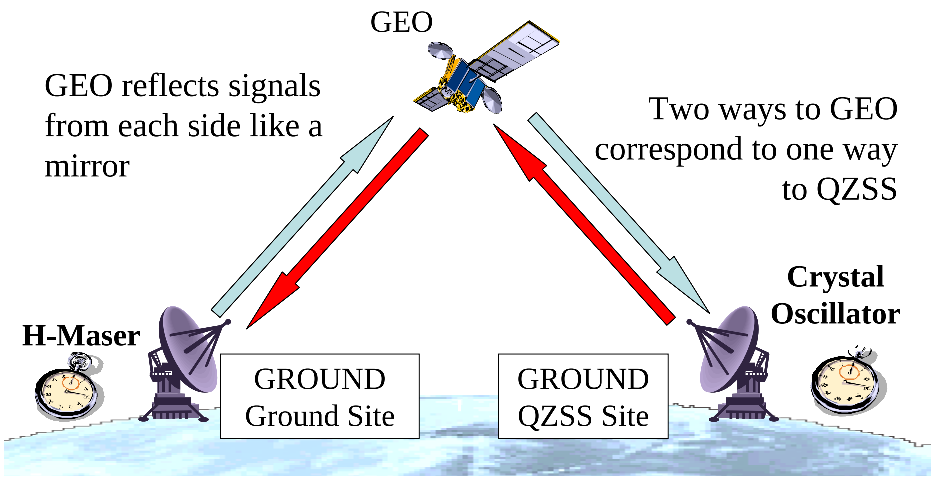

Fig. 2. Concept of GEO experiments.

Hydrogen maser (H-maser): The H-maser used in the experiments is one of the atomic clocks used to generate national time and frequency standards in Japan (UTC (NMIJ)). It was used as the atomic clock to which apparatuses on the GROUND ground site referred in the experiments.

Transmitting Time Adjuster (TTA): The TTA generates the advanced time of the H-maser and provides inverse Doppler effects to change the frequency of the two-way satellite time and frequency transfer (TWSTFT) modem, as described later. It is based on the wavefront clock principle **[10]**. In the experiments, the TTA was used to compensate the propagation time of the RESSOX control signal by means of the estimated propagation time that was computed with our simulators beforehand, which corresponded to the feed-forward control of RESSOX. The feedback commands generated by the timing controller are also received.

Modem (T): The Modem (T) is one of the three TWSTFT modems used in the experiments ("T" stands for "transmitting"). The TWSTFT modem has one transmitting channel that transmits a modulation wave of its own reference with the pseudo-noise (PN) code. It also has two receiving channels that compare the time difference between the time of input clock signal (1 pps and 10 MHz) and time of the received PN signal. In the experiments, the modem (T) was referenced to the time signal of the TTA and the RESSOX control signal was transmitted to the modem (TR) of the satellite site via the GEO.

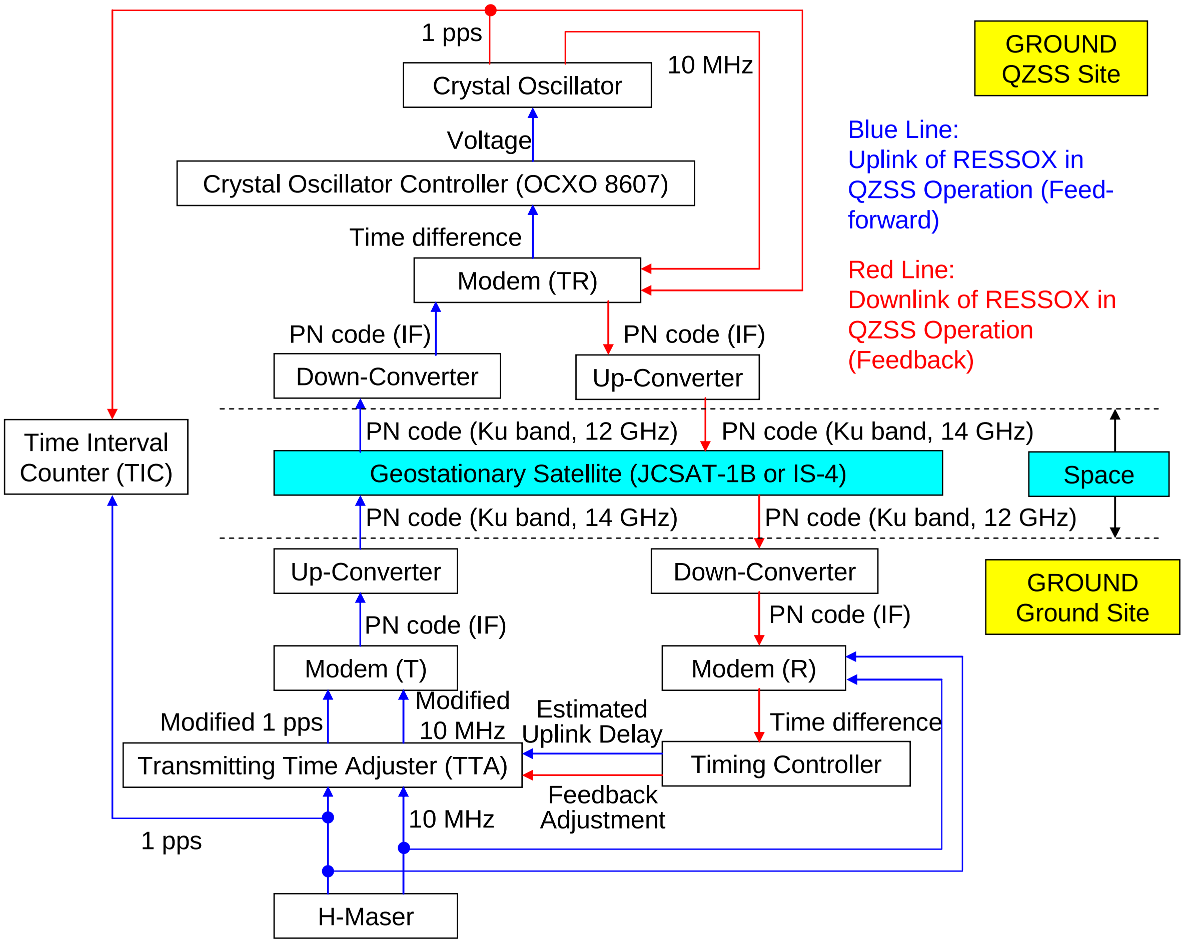

Fig. 3. Schematic of RESSOX experiments using geostationary satellites.

Modem (R): The Modem (R) is one of the three TWSTFT modems used in the experiments and has the H-maser as reference time ("R" stands for "receiving"), and corresponds to the QZSS/GPS receiver in the actual RESSOX. It receives the PN-modulated time signal of a crystal oscillator from the satellite site, which was sent from the modem (TR) via GEO. This signal corresponds to the navigation signals of the QZSS (QZS signal) in the actual RESSOX. The time difference was compared, as explained earlier, and the propagation time that corresponds to a pseudorange of a navigation signal in the actual RESSOX was observed.

Timing controller: The timing controller is a Windows XP PC. The timing controller generates estimation of the uplink propagation time and feedback commands in the form of estimation errors of the downlink propagation time, i.e. the differences between the observed propagation time with the modem (R) and the estimated propagation time with our simulators.

Apparatuses for the GROUND QZSS site are listed as follows.

Crystal oscillator: A very stable BVA-type oven-controlled crystal oscillator (OCXO) manufactured by Oscilloquartz S.A. (OCXO 8607) is used for synchronization with the H-maser. The Allan deviation of the crystal oscillator used in the experiments is shown in Fig. 4. Red and black lines show the results obtained using the H-maser and another voltage-controlled crystal oscillator (VCXO) as reference, respectively. As VCXO has better short-term stability, the latter results are better than the former when the averaging time is less than 10 s. In the experiments, OCXO 8607 was controlled to a certain offset that was intentionally given, as the time-interval counter could not display negative values, as explained later. Every apparatus in the GROUND QZSS site is referenced to OCXO 8607 time.

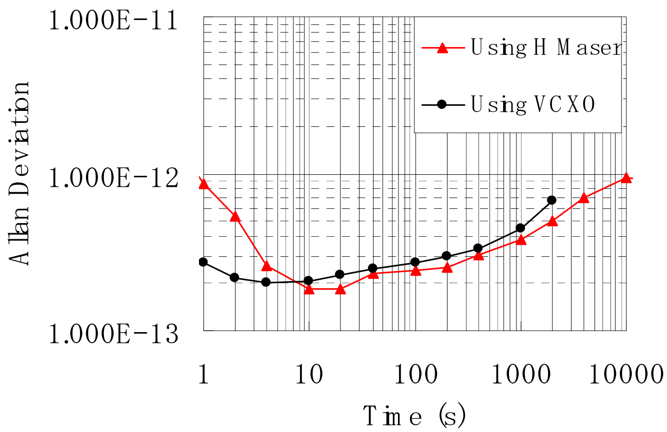

Fig. 4. The Allan deviation of OCXO 8607.

Modem (TR): The Modem (TR) is one of the three TWSTFT modems used in the experiments that were referenced to OCXO 8607 ("TR" stands for "transmitting and receiving"). It receives RESSOX control signals from the modem (T) via GEO, and the time difference between OCXO 8607 time and the RESSOX control signal, which includes the clock error of OCXO 8607 and the estimation error of uplink propagation time. Meanwhile, it also transmits a PN-modulated signal, which is a substitution of the navigation signals of the QZSS (QZS signal), to the modem (R) via GEO.

Crystal oscillator controller: The crystal oscillator controller, which consists of a Macintosh PC and a voltage generator, generates the input voltage of the crystal oscillator to reduce the observed time difference in the modem (TR). In the experiments, a kind of PI control shown in the following equation was used to control the crystal oscillator:

$$v_k = offset - \frac{k_1}{l+1}\sum_{i=k-l}^{k}\Delta t_i - k_2\sum_{i=0}^{k-l}\left(\int_i^{i+p}\Delta t dt\right) \quad (1)$$

where v_k is the k-th output voltage, $offset$ = 4.945 (V), k_1 is a proportional gain set at 7.6×10^6, 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.

Finally, apparatuses that were not categorized in either site are listed as follows.

Time-interval counter (TIC): The TIC displays the time difference of the two clocks. It displays only positive values. In the experiments, the TIC displays the time difference of the H-maser and OCXO 8607, including the offset given in OCXO 8607. Since OCXO 8607 was implemented on the ground test bed in the experiments, TIC was used only in the experiments and not in the actual QZSS operation.

Geostationary satellite (GEO): The GEO used for the experiments is JCSAT-1B operated by JSAT Corporation or IS-4 operated by the Intelsat Corporation. JCSAT-1B is drifting around the longitude of 150 degrees east, and IS-4, around the longitude of 72 degrees east. Frequency bands of 14.051 GHz (Ku band) and 12.303 GHz (Ku band) were used for the uplink and downlink signals of JCSAT-1B, and 14.610375 GHz (Ku band) and 12.661500 GHz (Ku band) for those of IS-4, respectively. The satellites are used as a mirror to reflect the signals from the GROUND ground site to the GROUND QZSS site and vice versa.

DIFFERENCE BETWEEN USING QZSS AND GEO

When the GEO is used for RESSOX experiments, the following differences should be noted.

(1) The satellite direction is not changed. This means that tropospheric and ionospheric delays will hardly change dynamically when RESSOX is operated. Moreover, the multipath condition does not change during the experiments.

(2) The downlinked signal is transmitted with Ku band. This means that ionospheric delay cannot be estimated by using multiple frequencies; however, Ku-band signals are not sensitive to ionospheric delay due to the short wavelength.

OVERVIEW OF JCSAT-1B EXPERIMENTS

JCSAT-1B was launched on 3 December 1997 from Guiana with an Ariane 4 rocket, and is located at 150 degrees east longitude. The experiments were performed in three phases **[9]**:

(1) In the preliminary experiments, the two-way propagation time between the ground and the GEO was measured. Then it was compared with the estimated propagation time that was calculated with the simulators beforehand. The estimation error was confirmed to be between 4,700 ns to 4,800 ns in all experiments, and was due mostly to instrumental constants.

(2) In the uplink experiments, OCXO 8607 was controlled only with the feed-forward loop of the ground site. We confirmed that the crystal oscillator controller succeeded in converging OCXO 8607 phase to the offset configured beforehand. However, since OCXO 8607 was steered to eliminate clock error as well as estimation error observed in the previous experiment, the time difference of OCXO 8607 and the H-maser observed in TIC was confirmed to be close to the estimation error calculated afterwards.

(3) In the end-to-end experiments of RESSOX, OCXO 8607 was controlled by a combination of feed-forward and feedback loops. The estimation error that remained in the clock error in the previous experiments was confirmed to be reduced by the feedback control. However, since the delays caused by the passage of the uplink and downlink signals in different media were not perfectly estimated in the experiment, they remained as the offset of 32 ns in the clock error. Therefore, numerical simulation was conducted with consideration of error sources, and it was confirmed that OCXO 8607 was synchronized to the H-maser within an error of 10 ns. Since OCXO 8607 and the H-maser were connected with signals that travel in outer space, the feasibility of synchronizing the onboard crystal oscillator to the ground clocks was confirmed by the validation experiments of RESSOX using the GEO.

PRELIMINARY GROUND EXPERIMENTS

Before the experiments using IS-4, preliminary ground experiments were conducted. The experimental setup is demonstrated in Fig. 5. A delay simulator that causes 0.01 s delay is used for downlink simulation, because the Modem (R) does not work when the time difference is smaller than 0.006 s.

Feed-forward Control Experiments

To simulate the feed-forward control, the TTA was set to zero-second advance and OCXO 8607 was controlled to make the time difference between OCXO 8607 and the uplink signal 60 μs (since TIC displays only positive values, synchronization offset was given). The result is shown in Fig. 6. The time difference measured with the Modem (TR) was controlled to exactly 60.0 μs; however, the time difference measured with TIC was 56.9760 μs. This means that the TTA has an internal delay of 3.0240 μs.

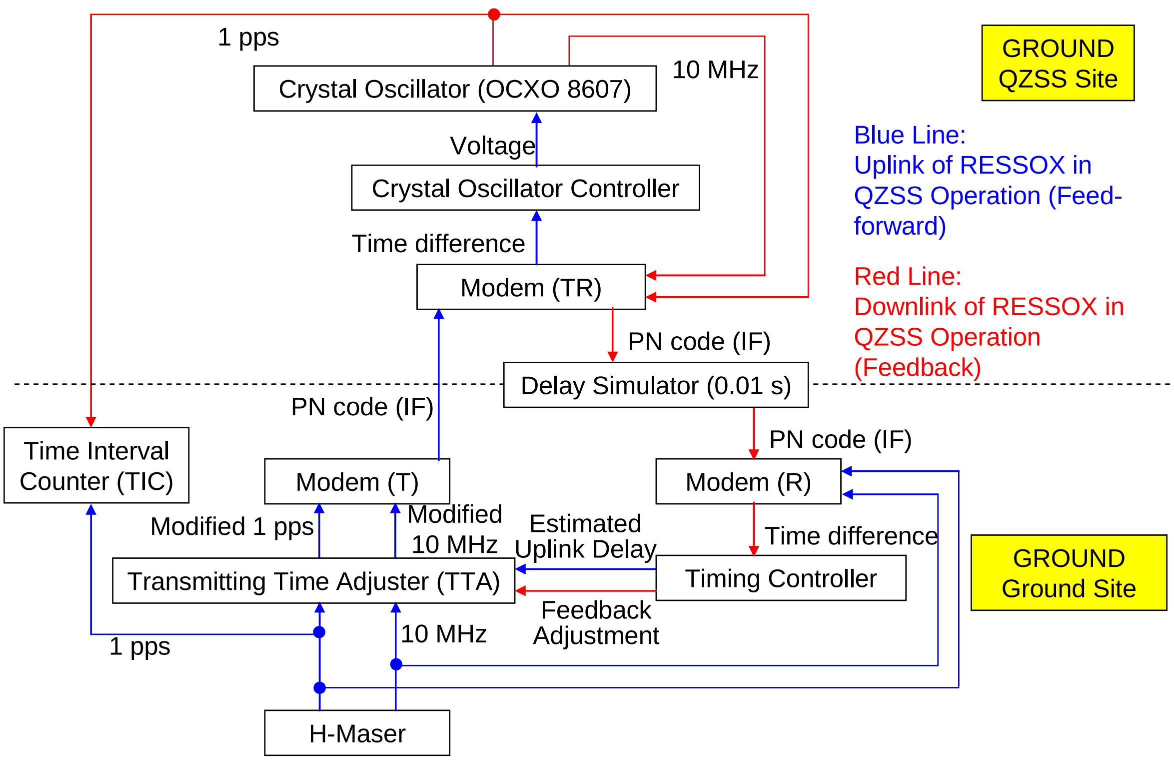

Fig. 5. Preliminary ground experiment setup.

To compensate the internal delay of the TTA, the TTA advanced the H-Maser time by 3.0240 μs. The result is shown in Fig. 7. The time difference measured with the TIC coincides with that measured with the Modem (TR). This means that the feed-forward control in which the TTA advances the H-Maser time by 3.0240 μs is successful.

Feedback Control Experiments

Next, experiments of feedback control, which compensated the feed-forward control error, were executed on the ground. As shown before, there is no error in the feed-forward control in which the H-Maser time is advanced by 3.0240 μs and this calibration was conducted throughout. The result is shown in Fig. 8. First, as the feed-forward command, 30 ns error was given (left figure; it means that the distance between the QZS and the ground station is overestimated by 9 m [=30 ns]). Therefore, in the feed-forward phase, the time difference was 30 ns. Then, feedback control was conducted. As the feedback adjustment, the command of 30 ns delay was given. As a result, the feed-forward control error was cancelled. Second, the feed-forward control error of uplink delay, zero at 0 s, and the change rate of 1 ns/s were used (light blue line in the right panel of Fig. 8). When only the feed-forward control was executed, the time difference followed the feed-forward command, which means that the pink line corresponds to the light blue line. Then, when the feedback was executed, the pink line converged to 60 μs.

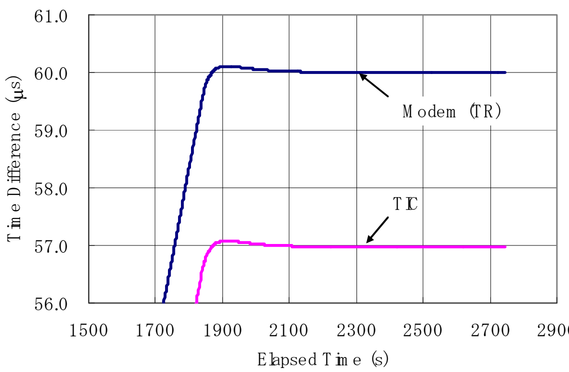

Fig. 6. Feed-forward control result without TTA internal delay consideration.

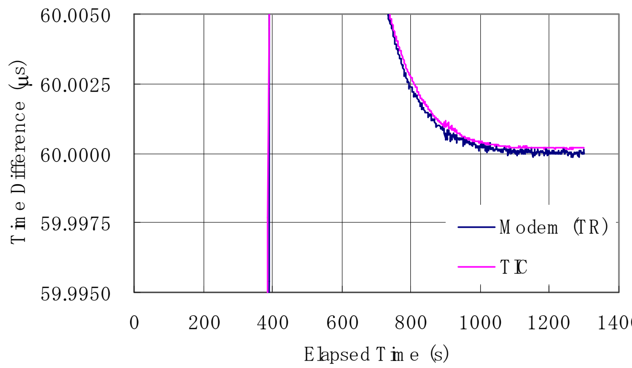

Fig. 7. Feed-forward control result with TTA internal delay consideration.

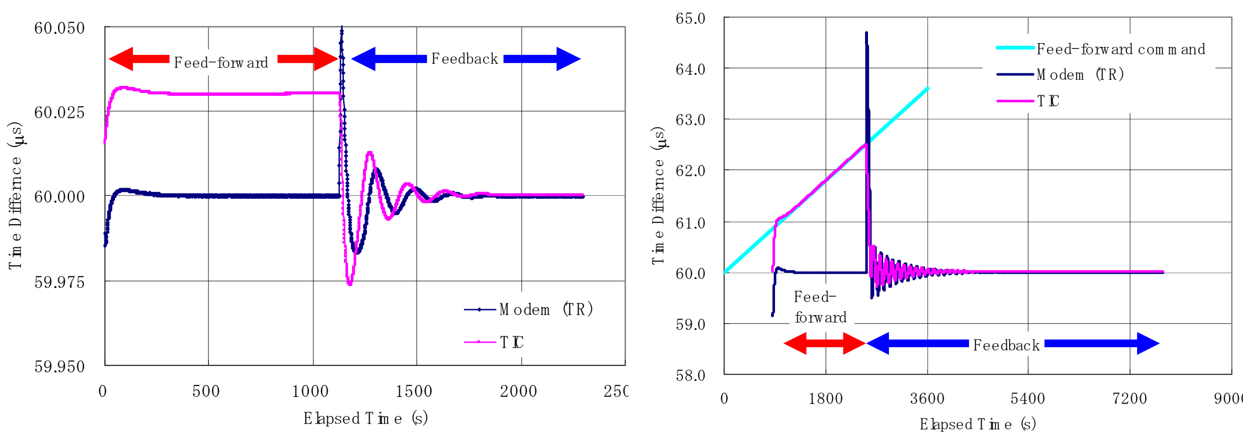

Fig. 8. Feedback control result of ground experiments.

EXPERIMENTS OF IS-4

IS-4 (formerly PAS-4) was launched on 3 August 1995 from Guiana with an Ariane 4 rocket, and is located at 72 degrees east longitude. The elevation angle from our institute is 7.9 degrees, so that large tropospheric and ionospheric delays are expected.

Feed-forward Control Experiments

Figure 9 shows the feed-forward experimental results using IS-4. As the delay estimation, the transmitting delay (approximately 0.27 s) and the TTA internal delay (3.0240 μs) were considered and the total delay was advanced at the TTA. However, the obtained time difference measured by the TIC is approximately 21.3 μs (approximately 38.7 μs difference). It is surmised that the origin of the difference is the internal delay of the up-converter, the down-converter, cables, antennas, and so on and the error of satellite orbit estimation.

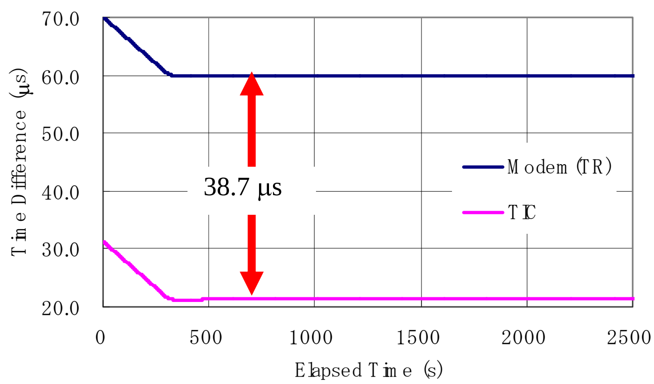

Fig. 9. Feed-forward control result using IS-4.

Feedback Control Experiments

Figure 10 shows the feedback experimental results using IS-4. As the uplink signal, the TTA advanced the standard time as the sum of transmitting delay (approximately 0.27 s), the TTA internal delay (approximately 3 μs), and other estimated delays (38.7 μs). In the case of feed-forward phase, approximately 50 ns delay was observed (left figure of Fig. 10). In the case of feedback phase, most of the feed-forward error was cancelled; however, a 4 ns-offset of the time difference remained (right figure of Fig. 10). Although a 4 ns-offset is acceptable, the origin should be investigated.

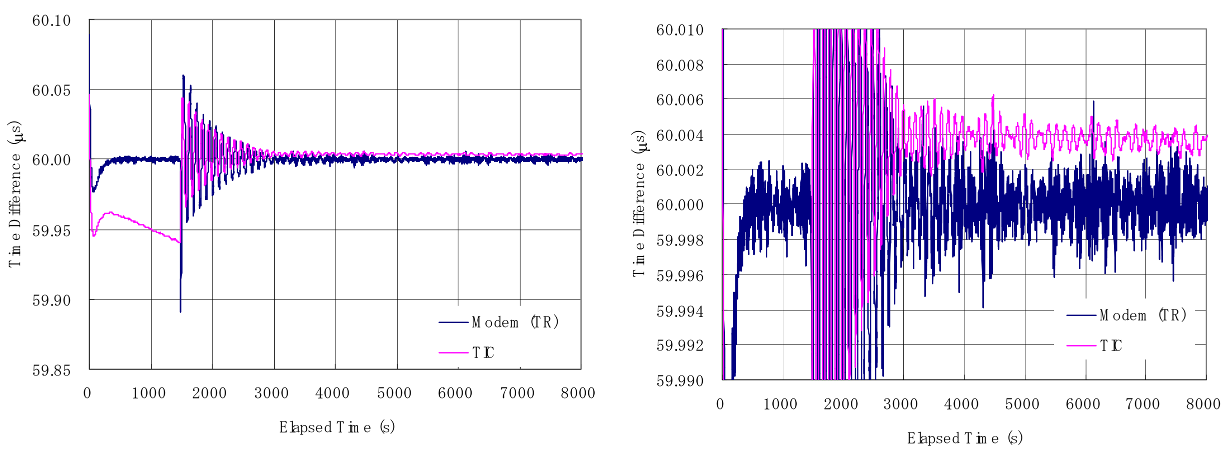

Fig. 10. Feedback experimental results using IS-4.

Precipitation Attenuation Effects

Since precipitation attenuates Ku band (12-15 GHz), in particular, at small elevation angle, our experiment was unintentionally interrupted. Figure 11 shows experimental data that indicate signal loss due to precipitation, and Fig. 12 shows the precipitation data at that time from a Web site. From Fig. 12, much precipitation was observed between IS-4 and the ground site during the experiment.

This means that special attention should be given to precipitation at small elevation angle when the QZSS is controlled by RESSOX.

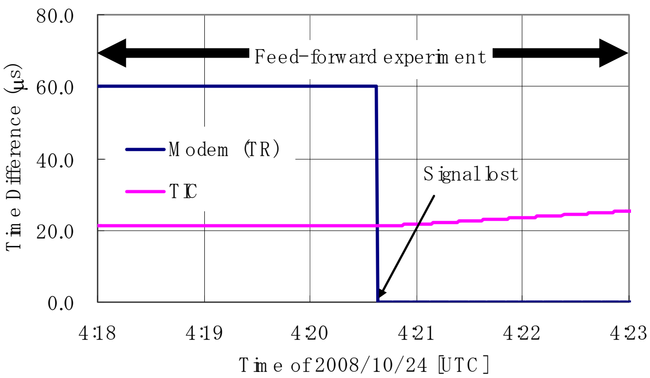

Fig. 11. Experimental data showing signal loss due to precipitation.

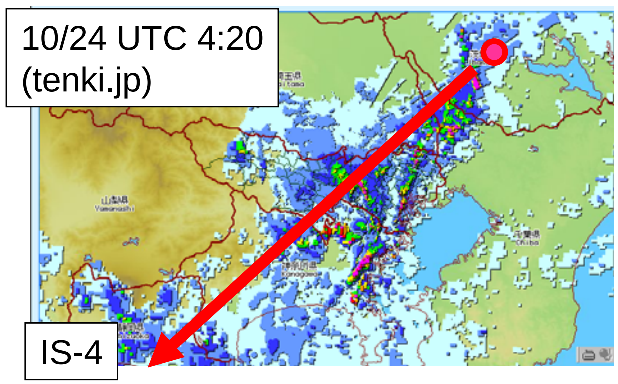

Fig. 12. Precipitation data from a Web site.

IV. CONCLUSIONS

This study is summarized as follows:

(1) The apparatuses used in this research were introduced.

(2) Feed-forward and feedback control results of preliminary ground experiments were introduced. Feed-forward control worked well if the TTA delay (3.0240 μs) was compensated. Feedback control worked well and compensated the time offset and the delay change rate.

(3) Feed-forward and feedback control results using IS-4 were introduced. In the experiment, delay other than the TTA delay was approximately 38.7 μs. Feedback control compensated most of feed-forward error; however, 4 ns-offset remained.

(4) Signal loss due to precipitation was observed. Special attention should be given to precipitation at small elevation angle when the QZSS is controlled by RESSOX.

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