Remote Synchronization of Onboard Crystal Oscillator for QZSS Using L1/L2/L5 Signals for Error Adjustment

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Abstract— **A new error adjustment method for remote synchronization of the onboard crystal oscillator for the quasi-zenith satellite system (QZSS) using three different frequency positioning signals (L1/L2/L5) is proposed. The error adjustment method that uses L1/L2 positioning signals was demonstrated in the past. In both methods, the frequency-dependent part and the frequency-independent part were considered separately, and the total time information delay was estimated. By adopting L1/L2/L5, synchronization was improved by approximately 15% compared with that using L1/L2 and approximately 10% compared with that using L1/L5.**

I. Introduction

The Japanese Quasi-Zenith Satellite (QZS) System (QZSS) is a three-satellite navigation/positioning system conceived to improve the positioning performance (satellite availability and position accuracy) of the presently available global positioning system (GPS) in urban areas where high-rise buildings reduce the number of visible GPS satellites [1]. A new timekeeping method of the QZSS, named the remote synchronization system for an onboard crystal oscillator (RESSOX), has been planned by the National Institute of Advanced Industrial Science and Technology (AIST) [2]. RESSOX is a remote control method that permits synchronization between a ground station clock and QZS clocks. In its original concept, various delay models are used for the estimation of the delay of the RESSOX control signal that includes time information of QZSS-Time and is advanced with respect to QZSS-Time to compensate the delay during the transmission. Furthermore, pseudo-ranges of positioning signals obtained at the ground station, named the time management station (TMS), are used for error adjustment, where QZSS-Time is a standard time of QZSS, like GPS Time for GPS, and refers to UTC (NICT).

The proposed Japanese QZSS has the following properties regarding its timekeeping system (TKS): (1) it is possible to control the system over a 24-hour period as long as a good choice of the TMS site is made; (2) a high-stability crystal oscillator is superior to an atomic clock in terms of short-term frequency stability [3]; and (3) the QZSS employs a maximum of three satellites, which is not too many to monitor from the ground.

RESSOX reduces overall costs, satellite power consumption, onboard weight and volume, and has a longer lifetime compared with a system with onboard atomic clocks.

RESSOX ground experiments and computer simulations have been conducted since 2003. QZS will broadcast four positioning signals as availability enhancement signals; L1C/A, L1C, L2C, and L5 [4]. The tentative target of our research is synchronization within 10 ns between the ground site and the QZS site and frequency stability better than 1×10^{-13} for 100,000 s. Primary experimental results using only the L1 and L1/L2 positioning signals and experimental apparatus have been introduced in our previous papers [5-9]. We have developed a new feedback method using L1, L2 and L5 positioning signals of the QZS and proved that we could improve the performance by 15% compared with the former L1/L2 method.

. Evaluations of the effects of the range error magnitude and least-squares filter used at the ground site will also be discussed.

II. Simulation Model

To investigate this new RESSOX technique, a specific software simulator has been developed. The actual onboard crystal oscillator will be MINI-OCXO manufactured by CMAC, and it is modeled as follows:

$$f = 1.023 \times 10^{7} - 1.7795196 + 0.3324755\text{V}$$

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where f is the output frequency, and V is the applied voltage (when V = 5.352333 V, f = 10.23 MHz).

To control the MINI-OCXO using the difference between uplinked time information and MINI-OCXO time, PI control of the control voltage was employed. The following formula, which describes PI control, was used.

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

Here, v_k is the k-th output voltage, $offset$ = 5.352333 (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 and is 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.

Control repetition at the TMS is once every second, and that on the QZS is once every 1.5 seconds.

The simulation conditions used are shown in Table 1. Typical Keplerian orbit elements of the QZS, shown in Table 1, were assumed. To calculate the orbit precisely, the EGM96 geopotential model with the spherical harmonic coefficient of degree 360, the gravity effects of the sun, the moon and other planets taken from the Jet Propulsion Laboratory (JPL) ephemeris DE405, the radiation pressure, and the solid tide effects were considered. To calculate ionospheric delay, the data (COD10426.ION) from the Center for Orbit Determination in Europe (CODE) was used. The simulation period was all day, January 1, 2000. This means that the positions of the sun, the moon and other planets and ionospheric data for that day were used. The meteorological conditions for tropospheric delay calculation were assumed to be constant at 15°C, 1013.25 hPa, and 70% relative humidity, and the Saastamoinen model was used. The position of the TMS was assumed to be in Okinawa (26.5 N, 127.9 E, elevation = 0.0 m). The calculations using these parameters correspond to "Orbit/Delay Calculation (without Error)" in Fig. 1. 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, and v_z = 1,693.581 m/s in the International Celestial Reference Frame (ICRF).

For the orbit information used at the TMS, an initial error of -5 m for each axis of ICRF, that is, the initial conditions of x = -22,881,064.583 m, y = -32,625,640.367 m, and z = 19,898,917.824 m of the equation of motion (v_x, v_y and v_z are the same as the authentic values) are assumed in order to create the time adjustment file for TTA and the database of L1/L2/L5. The ionospheric and tropospheric delays were not considered.

The difference in the range between the two calculations corresponds to the range error. The maximum range error in the 24-hour simulation was about 12 m (40 ns).

TABLE I. SIMULATION 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	26.5 N, 127.9 E, 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, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto (JPL-DE405)

III. CONTROL METHOD

To realize RESSOX, The L1, L2 and L5 pseudo-ranges were considered separately, and the delay of the frequency-dependent part (i.e., ionospheric delay) and that of the frequency-independent part (i.e., range error and tropospheric delay) were estimated. The following is the simulation sequence of this new method, as shown in Fig. 1.

Step 1. Four estimated delays (L1-, L2-, L5- and Ku-bands) are prepared. These estimated delays include model errors such as those due to the orbit, ionosphere, or troposphere, and we assume that they are used at the TMS as the measurement results. The estimated delays of the L1-, L2- and L5-bands make up the database of L1, L2 and L5 delays in the timing controller to be used for comparison with the L1- L2- and L5-band pseudo-ranges in Step. 7. In contrast, the estimated delay of the Ku-band is described in the time adjustment file for the transmitting time adjuster (TTA), and is used as a feed-forward control.

Step 2. Four authentic delays (L1-, L2-, L5- and Ku-bands) are prepared. These delays do not contain any errors. Three of these delays are contained in the L1, L2 and L5 authentic delay file, and the fourth is contained in the Ku authentic delay file.

Step 3. 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 signal arrives at the QZS.

Step 4. The delay of the RESSOX control signal during transmission is realized by the Ku authentic delay file.

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. Some noise generated by the crystal oscillator and the time comparator is assumed in this step and is generated by Stable 32, a clock simulator software [10].

Step 6. The pseudo-ranges of L1, L2 and L5 are calculated using the L1, L2 and L5 authentic delay file and the onboard crystal oscillator error.

Step 7. The pseudo-ranges of L1, L2 and L5 obtained by the QZS signal receiver are compared with the database of L1, L2 and L5 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), E_2 for L2 (f_{L2} = 1.2276×10^9 Hz) and E_3 for L5 (f_{L5} = 1.17645×10^9 Hz) .

Step 8. Simultaneous equations (1), (2) and (3), which include E_1, E_2 and E_3, 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, are solved.

$$e+\frac{k}{f_{L1}^2}=E_1, f_{L1}=1.57542\times10^9[\text{Hz}] \qquad (1)$$

$$e+\frac{k}{f_{L2}^2}=E_2, f_{L2}=1.2276\times10^9[\text{Hz}] \qquad (2)$$

$$e+\frac{k}{f_{L5}^2}=E_3, f_{L5}=1.17645\times10^9[\text{Hz}] \qquad (3)$$

These equations are expressed using a matrix as follows.

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

To solve the equations, pseudo-inverse $\mathbf{x}=(\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{E}$ was used.

Step 9. Using the solutions of the simultaneous equations, we obtain the time to be adjusted, formula (5), of the RESSOX control signal using the Ku-band (f_{Ku} = 1.43453×10^{10} Hz) for the TTA.

$$e+k/f_{Ku}^2, f_{Ku}=1.43453\times10^{10}[\text{Hz}] \qquad (5)$$

Step 10. As a result of combining the delay estimation file in Step 3 and the time to be adjusted for the TTA, the TTA is controlled. We consider some filters in this step, as described later. We now go back to step 4. The calculation of the time to be adjusted was conducted every second. The default filter was constructed using 100 data values of time to be adjusted (result of formula (5) using the difference between measured pseudo-ranges of L1/L2/L5 and estimated pseudo-ranges of L1/L2/L5 prepared as the database of L1/L2/L5 delay) from 6 s to 105 s before every second. The 100 data values 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. 2. To calculate and send the filtering result to the TTA as the time adjustment command, six seconds are assumed to be required.

In Fig. 1, the three pink blocks indicate the key parts of this method.

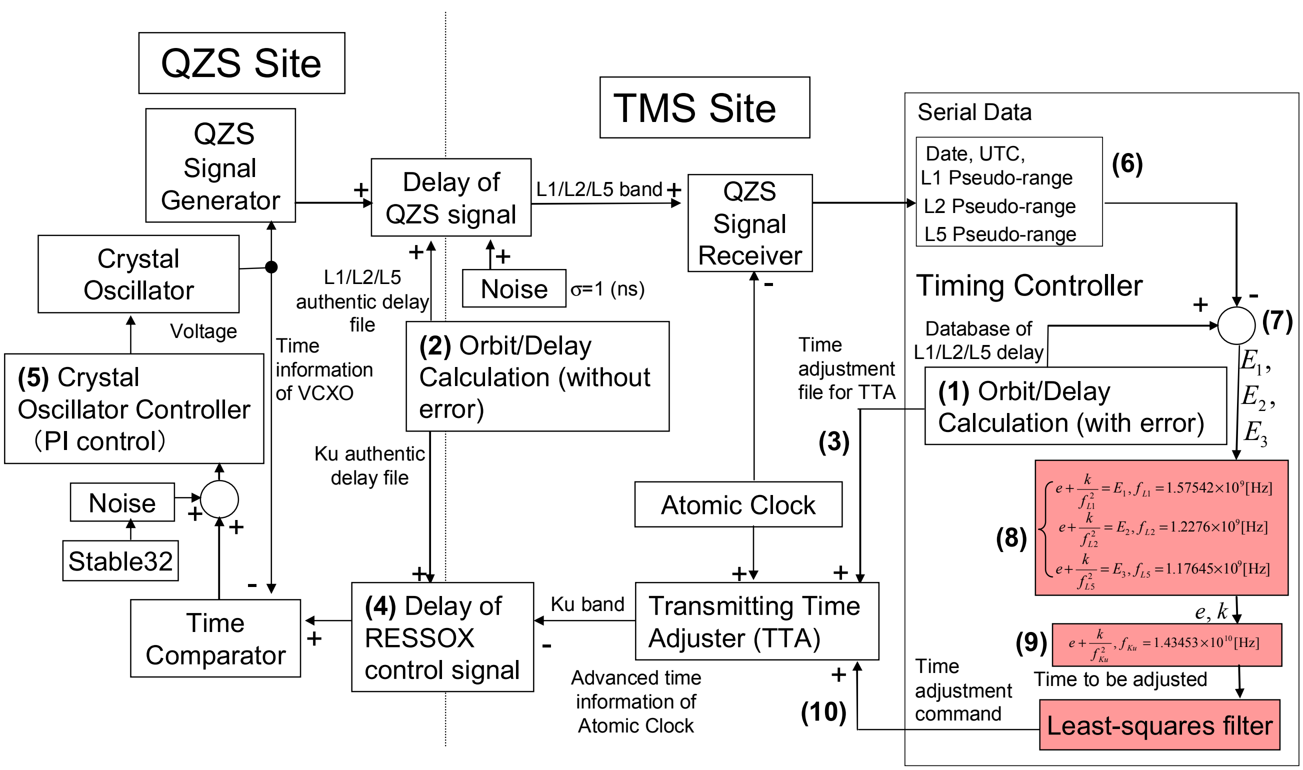

Figure 1. Simulation block diagram. Parenthetic number indicates the step explained in the text. The goal is synchronization between atomic clock and crystal oscillator.

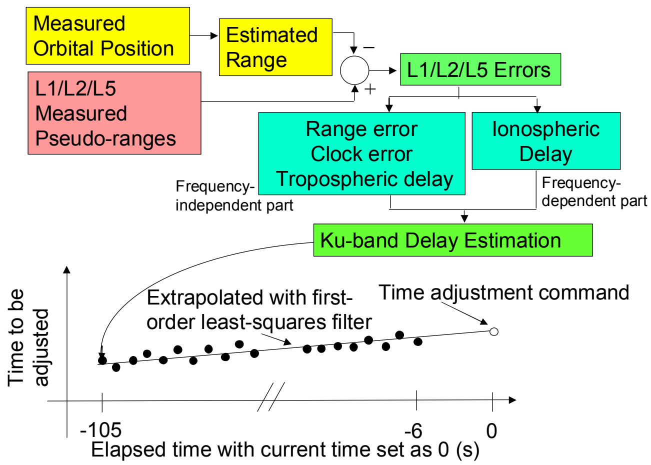

Figure 2. Default control method at TMS.

IV. Simulation Results

The simulation was conducted according to the block diagram shown in Fig. 1.

The atomic clock at the TMS and the onboard crystal oscillator can be synchronized to within 1 ns throughout 24 hours, even though the noise of the pseudo-range has a 1 ns standard deviation, as shown in Fig. 3. Even though the range error (i.e., orbit estimation) is considerably large (0-12 m), the proposed method functions correctly.

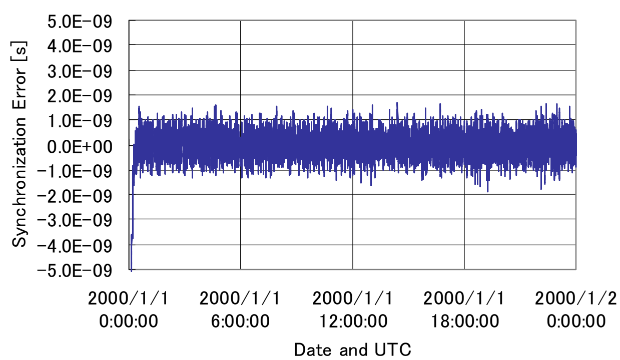

Figure 3. Synchronization result. The synchronization is within 1 ns.

Using the solutions of e and k of simultaneous equations (1) and (2), the time to be adjusted was calculated. The two terms of the time to be adjusted, that is, e and k/f_{Ku}^2, correspond to delays other than ionospheric delay and to the ionospheric delay of the RESSOX control signal using the Ku-band. As shown in Fig. 4, although e and k/f_{Ku}^2 of the time to be adjusted vary by about ±20 ns and ±0.5 ns, respectively, because of the noise of the pseudo-range, the results of these solutions show good coincidence with the actual delays of these origins, that is, the range error plus tropospheric delay and the ionospheric delay shown in Fig. 5.

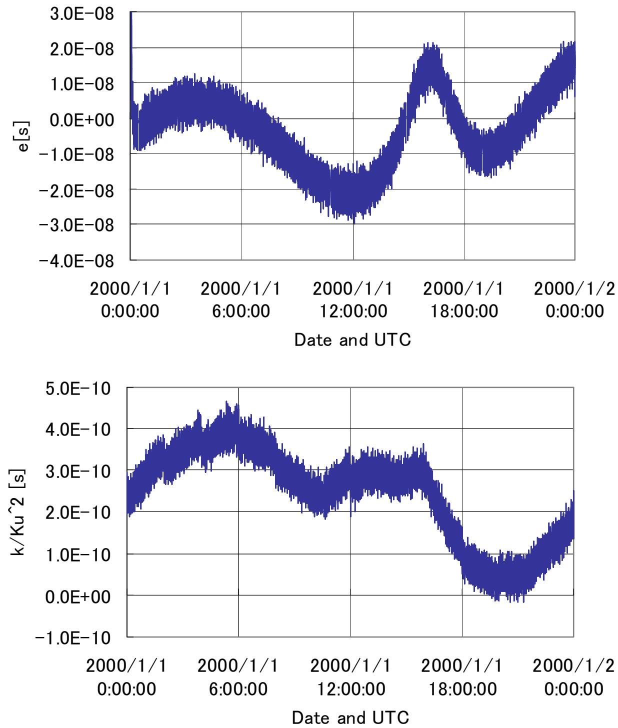

Figure 4. Elements of time to be adjusted. e and k/f_{Ku}^2 correspond to the range error plus tropospheric delay and the ionospheric delay shown in Fig. 5, respectively.

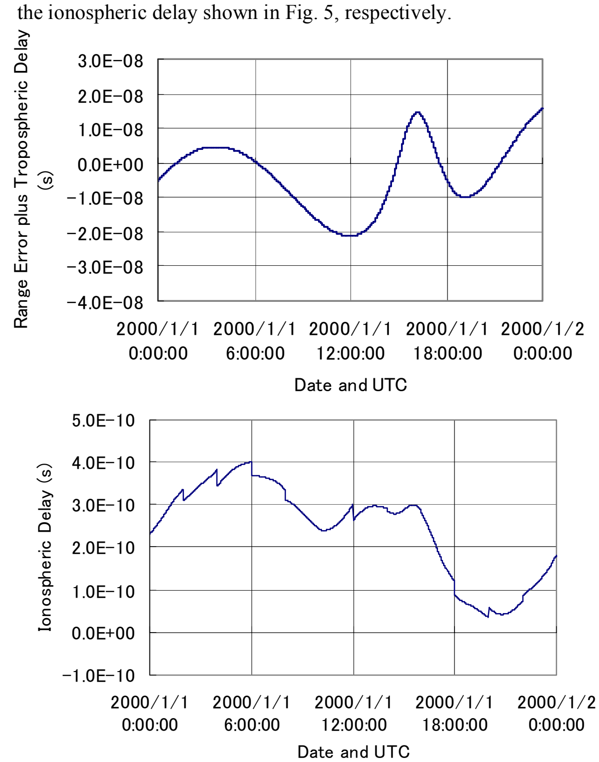

Figure 5. Authentic delay of range error plus tropospheric delay and ionospheric delay.

The actual time adjustment command calculated using a combination of 100 elements of time to be adjusted and the first-order least-squares filter shown in Fig. 2 is shown in Fig. 6. Since the element of time to be adjusted, k / f_{Ku}^2, is approximately two orders smaller than that of time to be adjusted, e, the graph shape is similar to that for e in Fig. 4; but the filter has the effect of reducing the noise.

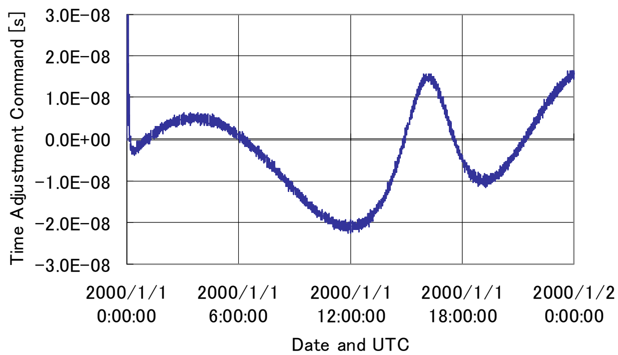

Figure 6. Actual time adjustment command calculated using combination of 100 elements of time to be adjusted and first-order least-squares filter shown in Fig. 2.

V. Effect of Adopting Three Frequencies

To compare the effects of using three frequencies, synchronization error was evaluated. Three different combinations were investigated: L1 and L2, L1 and L5, and L1, L2 and L5. The combination of L1 and L2 means the current usable combination, and that of L1 and L5 means the most separate frequencies, for which small error is expected. First, we consider the optimum number of data values with the first-order least-squares filter. The number of data values was increased to 1,000. The tendency of the number of data values being greater with smaller synchronization error was confirmed, and the best results were obtained in the case of using three frequencies, as shown in Fig. 7. In any case, when the number of data values is smaller than 50, the maximum synchronization error is larger than 10 ns, and the smallest synchronization error is obtained when the number of data values is 1,000. Synchronization using L1/L2/L5 was improved by approximately 15% compared with that using L1/L2 and by approximately 10% compared with that using L1/L5.

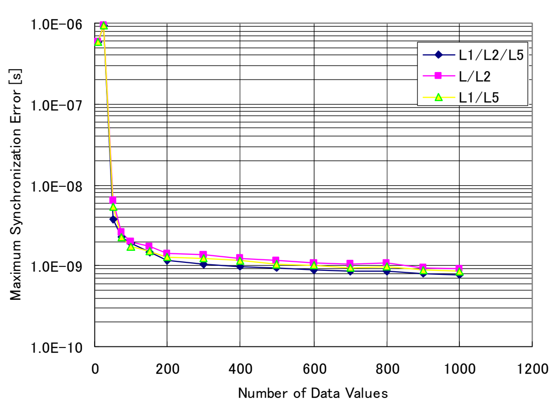

Figure 7. Relationship between number of data values and maximum synchronization error. Three different combinations were investigated.

Next, we compared the effect of the order of the filter, using three frequencies; the results are shown in Fig. 8. In the case of using the zeroth-order filter, even for a small number of data values, the maximum synchronization error is lower than 3 ns, however, it increases when the number of data values is more than 200. In the case of a first- or higher-order filter, when the number of data values is small, the maximum synchronization error becomes unacceptably large. The smallest maximum synchronization error was obtained when the first-order filter and 1,000 samples were used.

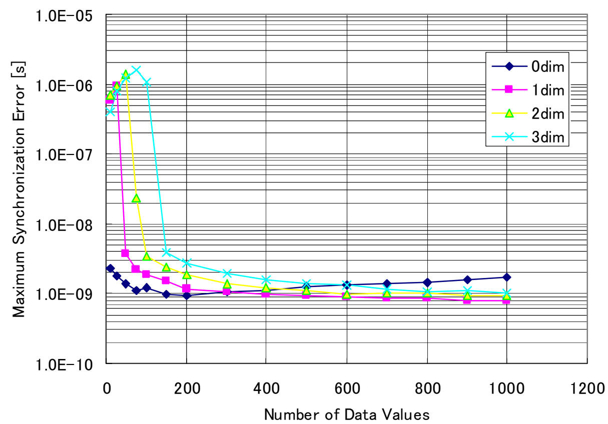

Figure 8. Relationship between number of data values and maximum synchronization error. The effect of the order of the filter is compared.

VI. Conclusions

This study is summarized below.

(1) A new tuning method of the QZS remote synchronization system for an onboard crystal oscillator (RESSOX) using L1, L2 and L5 positioning signals was demonstrated by simulation.

(2) Synchronization within 1 ns between the onboard crystal oscillator and the ground standard time was achieved in a 24-hour simulation.

(3) The ionospheric delay and the combination of tropospheric delay and range error of the RESSOX control signal were estimated in the calculation and efficiently compensated.

(4) On the ground, the number of data values and the order of the least-squares filter can be changed. The first-order least-squares filter using 1000 data values and three frequencies is the best, yielding a synchronization error of less than 0.77 ns.

Acknowledgment

This study was carried out as part of the ”Basic Technology Development of Next-Generation Satellites” project promoted by the Ministry of Economics, Trade and Industry (METI) through the Institute for Unmanned Space Experiment Free Flyer (USEF).

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