Compensation of Time Alignment Error in Heterogeneous GPS Receivers

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BIOGRAPHY

Hee Sung Kim received the B.S. and M.S. degrees in School of Electronics, Telecommunication and Computer Engineering from Korea Aerospace University in 2007 and 2009, respectively. His research interests include network RTK and ITS.

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ABSTRACT

Commercial GPS receivers extensively utilize low-quality oscillators such as Temperature Compensated Crystal Oscillators (TCXO) and Ovenized Crystal Oscillators (OCXO). As widely known, if a crystal oscillator is utilized as the time reference of a GPS receiver, the resulting clock bias error grows very fast. To prevent the clock bias becoming too large, clock steering mechanism is usually utilized in commercial GPS receivers. Since the clock steering mechanism is different from one manufacturer to another, time alignment error arises inevitably if heterogeneous GPS receivers are utilized in relative differential positioning or time transfer. This paper investigates the how the clock steering mechanisms can affect the positioning accuracy in relative positioning and proposes a compensation scheme to eliminate the effects of the time alignment error.

INTRODUCTION

Atomic clocks are widely utilized for precise time synchronization in the GPS satellites and critical reference stations since they can provide stable and precise reference frequency information. However, instead of the high-quality atomic clocks, most of the commercial GPS receivers extensively utilize low-quality crystal oscillators such as Temperature Compensated Crystal Oscillator (TCXO) and Ovenized Crystal Oscillator (OCXO) due to manufacturing cost.

Since crystal oscillators have lower precision and stability than atomic clocks, they cause large clock bias. In addition, if a crystal oscillator is utilized as the time reference of a GPS receiver, the resulting clock bias usually grows very fast. To prevent the clock bias becoming too large, various clock steering mechanisms are utilized for low-cost GPS receivers.

The clock steering mechanisms are largely divided into two categories. One is the continuous steering method and the other is the clock jumping. In the first method, clock bias is sustained within a few meters by continuous steering. In the second method, if clock bias exceeds a threshold value, it is adjusted by applying a clock jump.

Since detailed procedure of each clock steering mechanism is different from one receiver type to another, a time alignment error arises inevitably if heterogeneous GPS receivers are utilized in relative differential positioning or differential time transfer.

To eliminate the undesirable effects of the time alignment error between heterogeneous GPS receivers, this paper proposes an efficient compensation method. The proposed compensation method consists of three steps; time offset removal, clock jump synchronization, and clock bias compensation. For the purpose, it is investigated how the different clock steering mechanisms can affect the accuracy of differential positioning. A real-measurement experiment result demonstrates the effectiveness of the proposed compensation method.

ALIGNEMENT ERROR COMPENSATION

Time offset removal and clock jump synchronization

To prevent clock bias becoming too large, the GPS receivers equipped with crystal oscillators utilize various clock steering mechanisms. Since the intermittent clock jumps generated by these steering mechanisms result in large clock bias change, it

Table 1 Three types of clock jumps

Type	Pseudorange	Carrier phase	Time tag
1	Jump	Jump	No
2	Jump	No jump	No
3	No jump	No jump	Clock offset

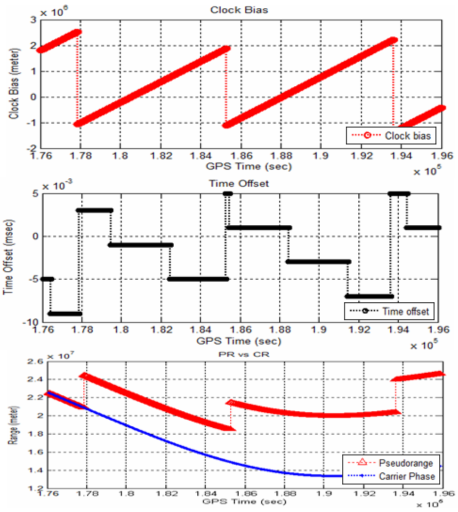

Fig. 1 Time offset, clock bias and measurement trends

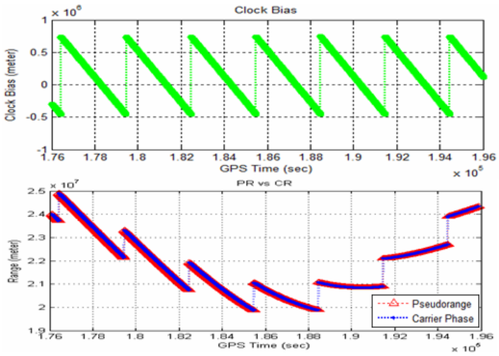

Fig. 2 Corrected clock bias and measurements

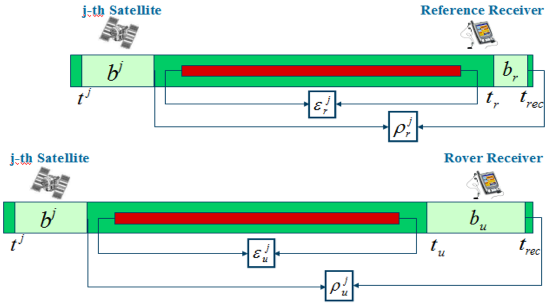

Fig. 3 Comparison of pseudorange measurements sampled by two receivers at the same location with the same time tags

becomes main source of the large positioning error in relative differential positioning.

If the clock bias exceeds a fixed threshold value, the clock steering mechanism adds an abrupt jump to the to the pseudorange/carrier phase measurements and subtracts the same amount of jump from time tag (receiver observation time). Table 1 lists three types of clock jumps adopted by various clock steering mechanisms. Rarely, some of commercial receivers adopt Type 2 and Type 3 clock jumps at the same time.

Fig. 2 illustrates clock bias, time offset and measurement trends controlled by a clock steering mechanism. This clock steering mechanism causes some minor problems to interpret by the conventional measurement modelling. First, on-time problem is caused by time offset which means that time tags are not the exact integer multiples of seconds. For the time offset removal, a simple compensation algorithm is utilized when there is a time offset but no clock jump.

$$\text{Corrected } \tilde{\rho}_k^j = \tilde{\rho}_k^j - T_{offset,k} * SPL$$
$$\tilde{\phi}_k^j = \tilde{\phi}_k^j - T_{offset,k} * SPL \qquad (1)$$

where

$\tilde{\rho}_k^j$: pseudorange measurement
$\tilde{\phi}_k^j$: carrier phase measurement
SPL : speed of light
$T_{offset,k}$: Time offset, k-th epoch

Some receiver do not show the same amount clock jumps in the pseudorange and carrier phase measurements. In this case, to synchronize clock jump phenomenon in all the measurements, it is convenient to compensate the carrier phase measurement. If the carrier phase measurement does not follow the pseudorange trend caused by the clock jump, the clock jump amount is estimated utilizing the fact that the clock jump is usually integer multiple of a fixed constant.

$$\text{Corrected } \tilde{\phi}_k^j = \tilde{\phi}_k^j - (T_{offset,k} - N_{jump}^j) * SPL \qquad (2)$$

where

N_{jump}^j : integer multiple of a fixed constant

Fig. 2 illustrates the clock bias and measurement trends after the application of correction.

Compensation of large clock bias

Fig. 3 illustrates range measurements of two heterogeneous receivers located at the same location(zero baseline). In this case, all the error terms except the receiver clock bias become the same. However, it can be seen that the signal transmission times are different for the same location and the same signal reception time tag values. The different signal transmission times, in turn, generate different satellite positions and line-of-sight vectors.

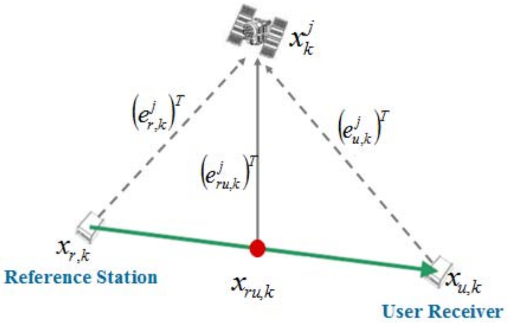

Fig. 4 Geometry of relative positioning if there is no large clock bias

Fig. 4 shows a geometry of relative differential positioning if the baseline is non-zero vector and there is no large clock bias. If the distance between the reference and the rover are within 10 km, a single-differenced pseudorange measurement can be modeled as follows under benign atmospheric environments.

$$\begin{aligned}\bar{\rho}^j_{ru,k} &= \tilde{\rho}^j_{r,k} - \tilde{\rho}^j_{u,k} \\ &= (e^{j,u}_{ru,k})^T x_{ru,k} + (b'_{ru,k}) + v'_{j,k}\end{aligned} \tag{3}$$

where

$\bar{\rho}^j_{ru,k}$: Single-differenced pseudorange

$x_{ru,k} = x_{u,k} - x_{r,k}$: baseline vector

$b'_{ru,k}$: Single-differenced clock bias

$v'_{j,k}$: Single differenced measurement noise

If difference between two clock bias values is small, it is possible to utilize Eq. (3). However, if the clock bias value becomes too large, the position of each satellite computed by the rover is different from that computed by the reference. Fig. 5 shows a more general geometry of relative positioning considering large clock bias values.

By the large difference in satellite positions caused by the large clock bias, difference a more detailed equation should be utilized instead of Eq. (3) to account for the effects of large clock bias.

$$\begin{aligned}\tilde{\rho}^j_{ru,k} &= \tilde{\rho}^j_{r,k} - \tilde{\rho}^j_{u,k} \\ &= (e^{j,u}_{ru,k})^T [x_{u,k} - x_{r,k}] + b'_{ru} + v'_{j,k} \\ &\quad + [(e^{j,u}_{ru,k})^T - (e^{j,r}_{ru,k})^T] x_{r,k} \\ &\quad + (e^{j,r}_{ru,k})^T x_k^{j,r} - (e^{j,u}_{ru,k})^T x_k^{j,u}\end{aligned} \tag{4}$$

where

$x_k^{j,r}$: Satellite position calculated by reference

$x_k^{j,u}$: Satellite position calculated by rover

$e^{j,r}_{ru,k}$: Line of sight vector with respect to $x_k^{j,r}$

$e^{j,u}_{ru,k}$: Line of sight vector with respect to $x_k^{j,u}$

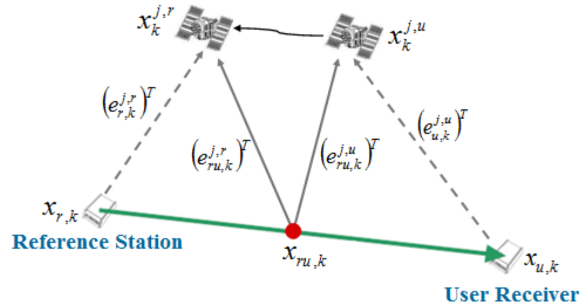

Fig. 5 Geometry of relative positioning considering large clock bias

By Eq. (4), the corrected pseudorange measurerment $\rho^j_{ru,k}$ can be obtained from the original pseudorange measurement $\tilde{\rho}^j_{ru,k}$ as follows.

$$\begin{aligned}\rho^j_{ru,k} &= \tilde{\rho}^j_{ru,k} - C^j_k \\ &= (e^{j,u}_{ru,k})^T [x_{u,k} - x_{r,k}] + b'_{ru} + v'_{j,k}\end{aligned} \tag{5}$$

where the correction term is defined as follows.

$$C^j_k = [(e^{j,u}_{ru,k})^T - (e^{j,r}_{ru,k})^T]\, x_{r,k} + (e^{j,r}_{ru,k})^T x_k^{j,r} - (e^{j,u}_{ru,k})^T x_k^{j,u} \tag{6}$$

For improved estimation of the baseline vector between the reference and the rover, an efficient filter is required. By previous study, it was found that position-domain carrier-smoothed-code filtering is beneficial in real-time kinematic applications where receiver movements are dynamical [3]. Extending the position-domain filtering concept, a filter is designed for more improved accuracy. The filter states are selected as follows.

$$X_k = \begin{bmatrix} x_{ru,k} & N^{21}_{ru} & N^{31}_{ru} & \cdots & N^{J1}_{ru} \end{bmatrix}^T \tag{7}$$

The time-propagation part of the designed filter inherits the characteristics of the conventional position-domain filter as follows.

$$\begin{aligned}\widehat{\Delta x}_{u,k} &= (L_k^T M_k^{-1} L_k)^{-1} L_k^T M_k^{-1} W_k \\ \widehat{\Delta X}_k &= \begin{bmatrix} \widehat{\Delta x}_{u,k} & 0 & 0 & \cdots & 0 \end{bmatrix}^T \\ \hat{X}^-_{k+1} &= \hat{X}^+_k + \widehat{\Delta X}_k \\ P^-_{k+1} &= P^+_k + Q_k\end{aligned} \tag{8}$$

where

$$W_k = \begin{bmatrix} (\Delta\tilde{\phi}^2_{ru,k} - \Delta\tilde{\phi}^1_{ru,k}) - (\Delta C^2_k - \Delta C^1_k) \\ (\Delta\tilde{\phi}^3_{ru,k} - \Delta\tilde{\phi}^1_{ru,k}) - (\Delta C^3_k - \Delta C^1_k) \\ \vdots \\ (\Delta\tilde{\phi}^J_{ru,k} - \Delta\tilde{\phi}^1_{ru,k}) - (\Delta C^J_k - \Delta C^1_k) \end{bmatrix} \tag{9}$$

$$L_k = \begin{bmatrix} e^2_{ru,k} - e^1_{ru,k} \\ e^3_{ru,k} - e^1_{ru,k} \\ \vdots \\ e^J_{ru,k} - e^1_{ru,k} \end{bmatrix}, \quad M_k = r_\phi (DD_k)(DD_k)^T$$

The measurement update part takes the form of the conventional Kalman filter as follows.

$$\begin{aligned} K_k &= P_k^- H_k^T \left(H_k P_k^- H_k^T + R_k \right)^{-1} \\ \hat{X}_k^+ &= \hat{X}_k^- + K_k \left(Y_k - H_k \hat{X}_k^- \right) \\ P_k^+ &= \left(I - K_k H_k \right) P_k^- \left(I - K_k H_k \right)^T \\ &\quad + K_k R_k K_k^T \end{aligned} \tag{10}$$

Where

$$H_k = \left[\begin{array}{c|c} L_k & O \\ \hline L_k & I_{J-1} \end{array} \right], \quad R_k = \left[\begin{array}{c|c} r_\rho M_k & O \\ \hline O & r_\phi M_k \end{array} \right] \tag{11}$$

$$Y_k = \left[\begin{array}{c} (\tilde{\rho}^2_{ru,k} - \tilde{\rho}^1_{ru,k}) - (C^2_k - C^1_k) \\ \vdots \\ (\tilde{\rho}^J_{ru,k} - \tilde{\rho}^1_{ru,k}) - (C^J_k - C^1_k) \\ \hline (\tilde{\phi}^2_{ru,k} - \tilde{\phi}^1_{ru,k}) - (C^2_k - C^1_k) \\ \vdots \\ (\tilde{\phi}^J_{ru,k} - \tilde{\phi}^1_{ru,k}) - (C^J_k - C^1_k) \end{array} \right]$$

EXPERIMENT

To verify the effectiveness of the proposed compensation method, a zero baseline experiment was performed. In the experiment, a Septentrio PolaRx2e receiver and a U-blox AEK-4T receiver were utilized as the reference and the rover, respectively.

Fig. 6 illustrates clock bias trends of the reference and rover receivers. Both receivers seem to utilize the clock jumping as the clock steering mechanism. The difference between the two receivers is that the reference receiver generates Type 1 clock jumps summarized in Table 1 and the rover receiver generates clock jumps in combination of Type 2 and Type 3.

Fig. 7 shows difference in the satellite positions related to the reference and the rover, respectively.

By Fig. 6 and Fig. 7, it can be verified that large differential clock bias generates large difference in the satellite positions related to the reference and the rover, respectively.

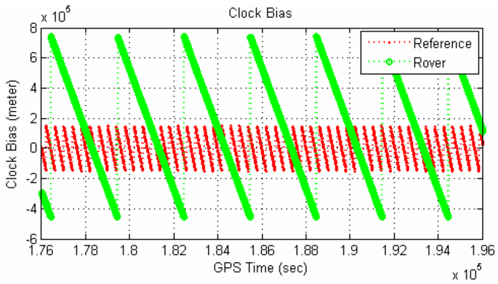

Fig. 6 Clock bias trends of reference and rover receivers

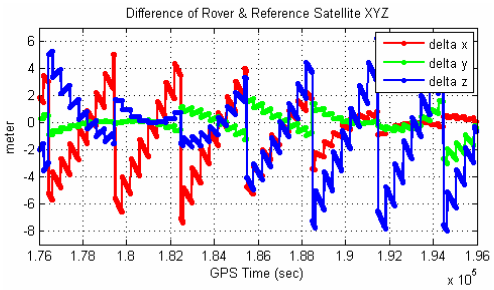

Fig. 7 Difference of the satellite positions related to the reference receiver and the rover receiver

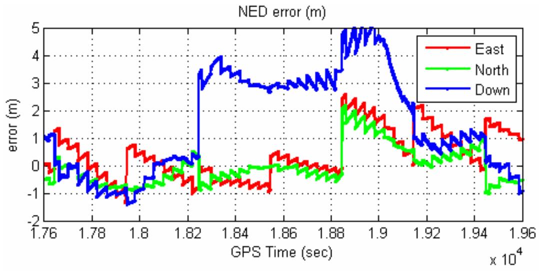

Fig. 8 Non-compensated positioning error

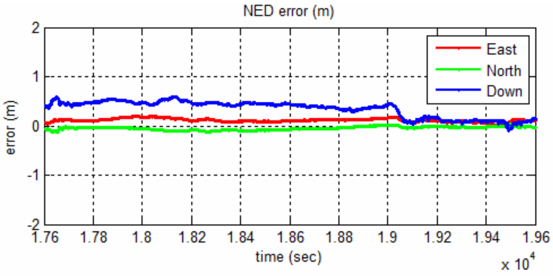

Fig. 9 Compensated positioning error

Fig. 8 and Fig. 9 illustrate the error distance profiles with respect to the locally-level NED frame before and after applying the proposed compensation method, respectively.

Fig. 8 shows that large difference between two clock bias values enlarges positioning error. In addition, it can also be seen that discontinuities of position estimates generated by the filter are synchronized with clock jumps.

Fig. 9 shows that the undesirable effects caused by the time alignment errors are effectively eliminated by the proposed compensation method.

CONCLUSION

In this paper, effects of time alignment error caused by large differential clock bias between heterogeneous receivers are analysed. An efficient compensation method of the time alignment error is proposed. By an experiment, it was verified that the proposed concept can effectively eliminate these undesirable effects of the time alignment error between heterogeneous GPS receivers.

ACKNOWLEDGEMENTS

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