Improvement GPS Time Link in Asia with All in View

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***Abstract*— GPS satellite orbits and clock offsets, which are provided by the International GPS Service (IGS), caused a major transition with GPS time transfer methods. Since a satellite clock error, which is only canceled out by the common-view method, is greatly improved by IGS products, the all-in-view method archives better precision than the common-view method when the baseline of stations is very long. The time transfer quality in the Asia-Pacific region can be improved using the all-in-view because the timing centers in this region are widely separated. This paper shows the level of improvement of the time transfer quality between stations in Asia-Pacific region using the GPS all-in-view.**

I. Introduction

The GPS common-view [1] method is widely used for international time transfer purposes because it is simple and highly precise. However, as the baseline of stations becomes longer, the error increases for several reasons. First, the number of common satellites observed by the stations decreases. Second, the elevation angle of observed common satellites becomes lower. Third, the error of propagation delay model cannot be canceled out because the propagation paths for the stations are different.

Timing stations have used single-channel, single-frequency GPS receivers. Recently, a multi-channel or dual-frequency receiver has been used due to the availability of commercial geodetic receivers. Dual-frequency receivers decreases the correction error of ionospheric delay, which is the largest error source for GPS time transfer, by almost half than single-frequency receivers because they can measure ionospheric delay [2], [3].

The International GPS Service (IGS) [4] provides precise satellite orbit and clock offset for GPS satellites [5]. These benefits reduce the advantage of the common-view. The satellite clock offset, which is one of the major errors in GPS time transfer and has so far been canceled out only using the common-view, can be corrected with IGS products. Then, the clock offset of the stations can be compared via an arbitrary satellite instead of a common satellite. In this method, called "GPS all-in-view" [6], the precision does not depend on the length of the baseline, unlike the common-view.

The international time comparison network consist 4 pivot stations are located in the U.S.A., Germany, Japan, and all other stations in each region link to the pivot stations. Since the timing stations in the Asia-Pacific region are further separated than those in Europe, link uncertainties in the region are of lower quality than those in Europe. The all-in-view would effectively improve the time transfer quality in the Asia-Pacific region because it has an independent baseline length.

II. GPS Time Transfer

The GPS observation equation is shown in (1).

$$\begin{aligned}\tau_i^k(t) &= \frac{\rho_i^k(t, t-\tau_i^k)}{c} + I_i^k + T_i^k \\ &\quad + [dt_i(t) - dt^k(t-\tau_i^k)] + e_i^k \end{aligned} \qquad (1)$$

Here, τ_i^k is the received signal on receiver i from satellite k (in units of seconds). ρ_i^k is the geometrical distance between the satellite and the receiver. I_i^k and T_i^k are the propagation delays of ionosphere and troposphere, respectively. dt_i and dt^k are the clock offsets of the receiver and the satellite, respectively, from a reference time system such as IGST or GPS Time. e_i^k is the measurement and model errors, and c is the speed of light. For time transfer purposes, the antenna position of a receiver is assigned by the surveying in advance, and all parameters except the receiver clock offset (dt_i) are corrected by models or pre-calculated values from other analyses. Then, the time transfer precision depends on the accuracy of the orbit analysis or the correction models of the propagation delay.

The common-view is the simple difference between observations of two receivers (i and j) from a common satellite (k), as shown in (2).

$$\tau_{ij}^k = \frac{\rho_{ij}^k}{c} + I_{ij}^k + T_{ij}^k + dt_{ij} + e_{ij}^k \qquad (2)$$

Here, the notation $(\bullet)_{ij} = (\bullet)_i - (\bullet)_j$ represents a common-view quantity. The satellite clock offset is eliminated by the common-view effect. In addition, the correction error of the propagation delays is probably eliminated when the baseline length of the receivers is short and the line of sight is very close. As a consequence, the common-view has high precision even though the correction models are poor.

On the other hand, if sufficiently precise correction models are used, first, all parameters including the satellite clock offset can be corrected with these models, and then the clock offset can be compared between two receivers. We do not need to hope the correction error will be canceled out by the common-view. The ionospheric delay, which is the largest error source for GPS time transfer, can be eliminated by dual-frequency measurements with a geodetic receiver. The next largest error

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source is the satellite clock offset. The satellite orbits and clock offsets of the navigation message included in the GPS broadcast signal have a poor quality. The orbit determination accuracy of navigation message is 2 m, and the satellite clock offset is similar precision as 7 ns. In contrast, GPS satellite ephemerides, which are the combined solutions of ten IGS analysis centers around the world, are accurate to 5 cm and 0.1 ns. Navigation messages should be used in early stage of GPS time transfer, and dual-frequency receivers cannot be used yet. However, the common-view is no longer advantageous, as rigorous models for the all-in-view have been obtained.

The all-in-view, with rigorous delay correction, has some advantages over the common-view. First, it increases the number of satellites that can be observed at once. Second, it has small measurement error observation, which uses only high elevation satellites. Third, it reduces the systematic error due to the antenna position error, since the observed satellites are uniformly distributed in the sky.

III. Comparison between Common-view and All-in-view

To evaluate the improvement of time transfer precision when using the GPS all-in-view, I compared both – the common-view and all-in-view – method results with actual observations in the Asia-Pacific region. I used four timing stations: – NICT (Koganei, Japan), KRIS (Dajeon, Korea), TL (Taoyuan, Taiwan), and NMI (Sydney, Australia) –. The geographical location of each station is shown in Fig. 1, and the baseline lengths between stations are shown in TABLE I. All stations used Euro80 multi-channel receivers, and NICT and TL also used ASHTECH Z-12T Metronome multi-channel dual-frequency receivers. These stations used UTC(NICT), UTC(KRIS), UTC(TL), and UTC(AUS) as their respective a reference signals.

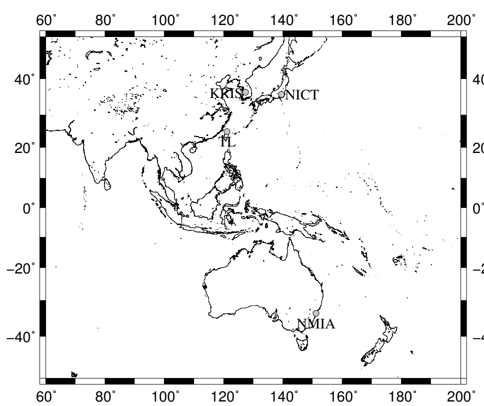

Fig. 1. Locations of timing stations in Asia-Pacific region.

I evaluated the time transfer precision, stability, and accuracy. All observations were corrected using IGS final products. IGS products were formed 15-minute intervals. Then, I computed the position or clock offset of a GPS satellite at the observation epoch using interpolation with total of 10 points before or after the epoch. I used a global ionosphere map (GIM) provided by the AIUB/CODE analysis center of the IGS [7] to correct the ionospheric delay. An ASHTECH link between NICT and TL was also used the measured ionospheric delay correction (P3 method). Even though the clock behavior and the observation noise cannot be classified clearly, high frequency components generally include most of the observation noise, and low frequency components include most of the clock behavior. Then, I used Vondrak smoothing [9] as a low-pass filter. To evaluate the time transfer accuracy, I compared two-way time transfer data measured by NICT modem [8] together with the GPS observations. I compared the GPS observations over period from Apr. 1, 2004 to May 31, 2005. However, the two-way time transfer observations with NICT modem began in Feb. 2005, and I performed accuracy evaluations from Feb. 1 to May. 31, 2005.

TABLE I

Baseline lengths and time transfer method of timing stations. MC is GPS multi-channel, P3 is GPS dual-frequency in addition to multi-channel, TW is two-way time transfer.

baseline	*length*	*method*
NMIA - KRIS	7602.5 km	MC, TW
NMIA - NICT	7307.6 km	MC, TW
NMIA - TL	6848.6 km	MC
KRIS - NICT	1092.6 km	MC, TW
KRIS - TL	1396.6 km	MC, TW
NICT - TL	2111.8 km	MC, P3, TW

A. Precision

A comparison of UTC(AUS) and UTC(NICT) using common-view is shown in Fig. 2. The upper plot shows the time difference between UTC(AUS) and UTC(NICT) measured in nanoseconds. Each point shows the averaged observation of all satellites that contributed to the common-view at a specific epoch. The lower plot shows the residuals of averaged and smoothed observations. Fig. 3 shows similar plots using the all-in-view instead of common-view. When GIM is used to correct the ionospheric delay, the time transfer precision of the all-in-view is about 1.5 times better than that of the common-view.

Fig. 4 and Fig. 5 show a short baseline (NICT and TL link) case with the ionospheric delay corrected by actual measurements. TABLE II shows the residual R.M.S. of all baselines. Here, “# obs.” is number of all observations used for the common-view, and “# ave.” is number of observations after epoch-by-epoch averaging. The number of observations with the all-in-view shows only the averaged observations because a time comparison is performed after the averaging process. There is no significant difference between the common-view and the all-in-view in the short baseline. The residual R.M.S. of the common-view was slightly good when GIM was used, and the residual R.M.S. of the all-in-view was slightly good oppositely when the measured ionospheric delay was used.

TABLE II

BASELINE COMPARISON BETWEEN COMMON-VIEW AND ALL-IN-VIEW.

	common-view			all-in-view	
link	# obs.	# ave.	R.M.S.	# ave.	R.M.S.
NMIA - KRIS	27,539	10,539	3.986 ns	10,799	2.621 ns
NMIA - NICT	30,216	10,881	3.623 ns	11,014	2.467 ns
NMIA - TL	33,970	11,034	4.153 ns	11,087	2.735 ns
KRIS - NICT	98,482	14,950	1.533 ns	14,486	1.587 ns
KRIS - TL	96,080	15,136	1.968 ns	15,029	2.004 ns
NICT - TL	110,243	18,419	1.739 ns	18,301	1.807 ns
NICT - TL,P3	212,222	35,259	0.926 ns	35,083	0.910 ns

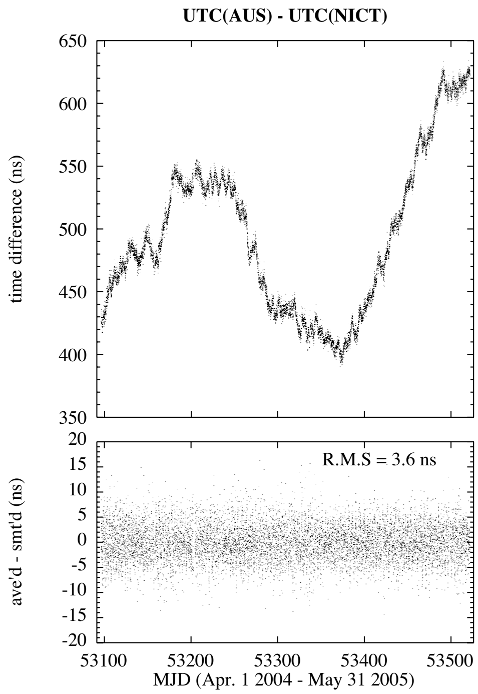

Fig. 2. Time difference between UTC(AUS) and UTC(NICT) using common-view (upper), as well as residuals of averaged and smoothed observations (lower). Each point of the upper plot shows the averaged observation with the common-view satellites at the epoch.

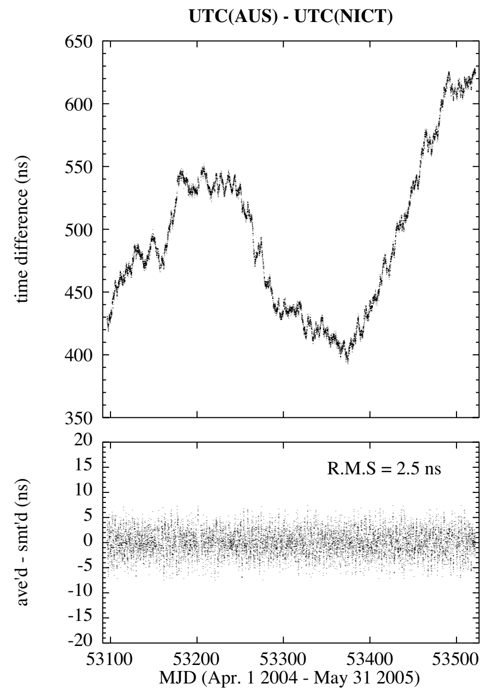

Fig. 3. Time difference between UTC(AUS) and UTC(NICT) using all-in-view (upper), as well as residuals of averaged and smoothed observations (lower).

B. Stability and Accuracy

Fig. 6 shows the time transfer stability of a long baseline (NMIA and NICT link), and Fig. 7 shows the time transfer stability of a short baseline (NICT and TL link). Two-hour simple averaged observations were used to compute the modified Allan variance. The all-in-view with a long baseline has an apparent advantage in short-term stability with an averaging time less than 10^5s. However, the long-term stability of either over one day is similar. Clock behavior seems to be dominant over one day because NMIA and NICT are using cesium clocks as the master clock of UTC. If these stations use more stable clocks such as hydrogen maser clocks, the all-in-view would have better stability than the common-view over one day.

Fig. 8 and Fig. 9 show the comparisons of two-way time transfer and GPS. The vertical axis shows $[\mathrm{UTC}(k1) - \mathrm{UTC}(k2)]_{TW} - [\mathrm{UTC}(k1) - \mathrm{UTC}(k2)]_{GPS}$. The observation epochs of two-way time transfer and GPS are not the same. Then, we used interpolation to adjust the GPS observation epoch to the two-way time transfer epoch. The time difference between the common-view and the all-in-view with respect to the two-way time transfer was approximately consistent, though the bias is slightly shown.

IV. CONCLUSION

I investigated the improvement of time transfer precision in the Asia-Pacific region using the GPS all-in-view instead of the common-view. The residual R.M.S. of the all-in-view is better than the common-view when the baseline is long. Further improvement could be expected if the measured ionospheric delay was used, though a correction model was used in this study. We did not see an improvement of the long-term stability for more than one day. However, it could be improved

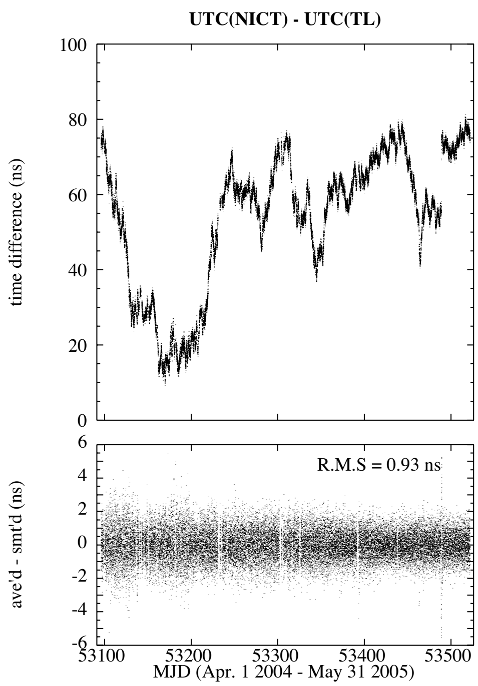

Fig. 4. Time difference between UTC(NICT) and UTC(TL) using P3 common-view.

if the reference signal of the stations were changed to a stable clock, such as a hydrogen maser. The absolute values of the common-view and the all-in-view with respect to the two-way time transfer correlated well. A few biases between the common-view and the all-in-view should be considered in future.

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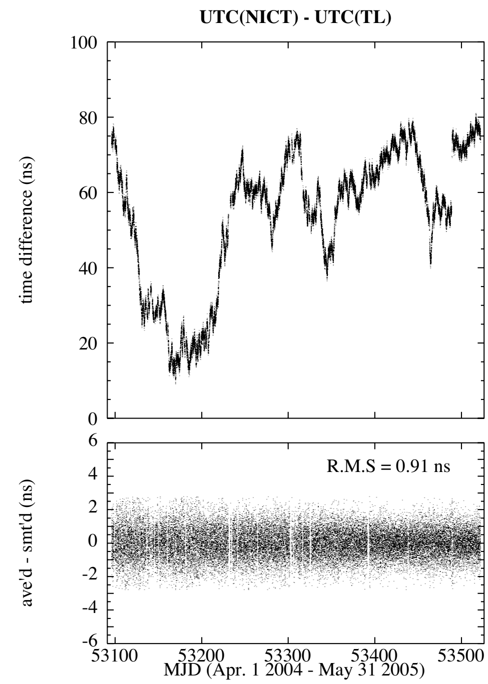

Fig. 5. Time difference between UTC(NICT) and UTC(TL) using P3 all-in-view.

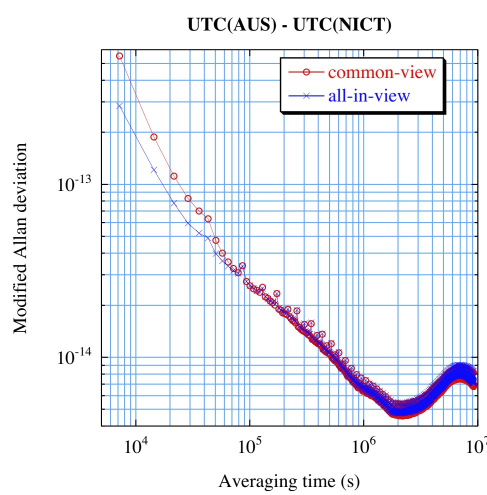

Fig. 6. Modified Allan deviation of long baseline (NMIA and NICT link). Red line shows the common-view stability, and blue line shows the all-in-view stability.

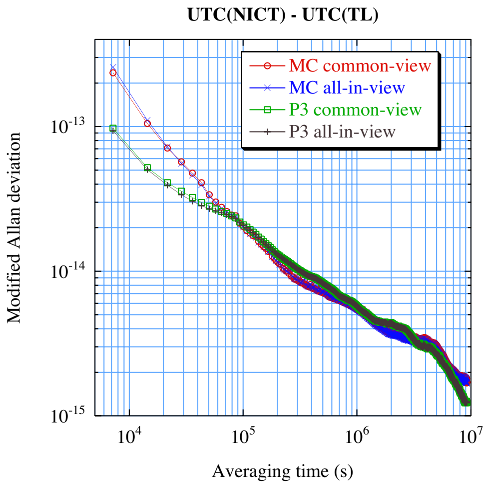

Fig. 7. Modified Allan deviation of short baseline (NICT and TL link). Red and green lines show MC and P3 common-view stabilities, as well as blue and black lines show MC and P3 all-in-view stabilities.

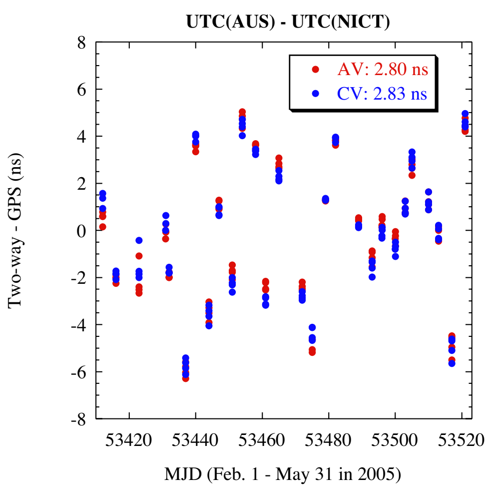

Fig. 8. Comparison between two-way time transfer and GPS with NMIA and NICT link. Blue points show the differences with common-view, and red points show those with all-in-view.

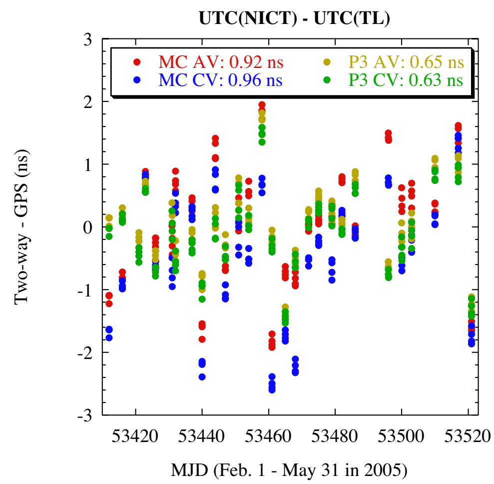

Fig. 9. Comparison between two-way time transfer and GPS with NICT and TL link. Blue and green points show the differences with MC and P3 common-view, respectively, as well as red and yellow points show those with MC and P3 all-in-view, respectively.