Comparison Study of GPS Carrier Phase and Two-Way Satellite Time and Frequency Transfer

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***Abstract*— A dual frequency GPS and a geostationary communication satellite based time and frequency transfer network have been established for the Asia-Pacific region. Some stations link to Europe with both methods. Consequently, we can compare the performance of GPS carrier phase time or frequency transfer to a two-way satellite time and frequency transfer, and vice versa. The difference between the two methods shows good consistency in the regional network. On the other hand, for intercontinental links there is an obvious variation with the diurnal and secular changes.**

I. Introduction

We have been studying new time or frequency transfer techniques for producing more accurate clock comparisons, such as the development of a new two-way time transfer modem with a binary offset carrier [1], an ultra-stable frequency transfer using a communication optical fiber [2], and a GPS carrier phase (GPS CP) time or frequency transfer.

Geodetic analysis software have been used for quite some time to conduct carrier phase observations. However, the timing community has been paying less attention to this method because the use of double difference observations has been the mainstream for carrier phase analysis. In recent years, the geodetic community has taken notice of Precise Point Positioning (PPP), because it is able to determine the receiver antenna position without a reference station. Moreover, the International GNSS service (IGS) provides us with precise satellite ephemerides, which are a vital requirement for the PPP and in deciding the position accuracy of the PPP. The PPP can estimate the receiver clock offsets and antenna position at the same time, and timing researchers are beginning to use the carrier phase observations for time transfer purposes [3]. The time transfer precision is greatly improved when using the carrier phase observations, as opposed to the use of pseudorange observations.

Some timing laboratories in the Asia-Pacific region have established time links using a dual frequency GPS and a two-way time and frequency transfer (TWSTFT). The TWSTFT observation noise is one nanosecond or less and can be reduced to a few hundred picoseconds with simple averaging within a few hundred seconds [4]. Then, we can evaluate the performance of a GPS CP by comparing it to a TWSTFT, and vice versa. The NICT (Japan) and KRISS (Korea) have also established intercontinental links to the AUS (Australia) and PTB (Germany) using both methods. We can then evaluate the time transfer precision for not only a regional network but also for intercontinental links.

We implemented a simple parameter estimation algorithm into carrier phase analysis software. We also assessed the efficacy of the algorithm in this paper.

II. Analysis Software

We came up with several methods for the receiver clock offset estimation:

1) Network-based.
2) Single-difference.
3) Precise point positioning (PPP).

The Network-based method was adopted in the IGS Analysis Centers (ACs) [5], and is able to solve the strictest of solutions in a closed network, although this requires a lot of computer resources. The single-difference and PPP methods are similar except for their use of a satellite clock offset. However, the single-difference method is preferable in a regional network, but the PPP is tolerant of the intercontinental clock comparison.

We adopted the PPP for this comparison study to evaluate the GPS CP capability for not only the Asian region, but also the Asia-Europe and Asia-Australia links. However, we had to take a couple of things into consideration before using the PPP. First, the correction models should be consistent to those of an ephemerides provider, because the PPP requires satellite orbits and clock offsets from an outside provider. Second, the sampling rate of the observations should be consistent with the satellite clock offsets. The satellite clock offsets provided by the IGS ACs were at a five minute sampling rate. This means that we cannot perform a dense clock comparison for a sampling rate over that time constraint using the PPP. Since December 17, 2006, IGS has provided us with high-rate clock offsets to avoid this limitation [6], although it still remains for the observations made before this date.

When the carrier phase observations are used, the receiver clock offset and carrier phase ambiguity are highly correlated to each other. Some sophisticated algorithms have been devised to avoid this problem [3], [7]. However, we cannot use these algorithms because the current implementation method for our software uses a classical batch estimator. Therefore, we use pseudorange observations to constrain the absolute value of the estimated clock offset. Since the use of pseudorange observations produces a day boundary problem, the software estimates all the parameters in range of overlapping solution arcs. Although this method cannot completely eliminate the discontinuity of each solution arc, it is expected to sufficiently reduce any discontinuity. Table I presents a summary of the software implementation.

TABLE I
SUMMARY OF NICT DEVELOPED SOFTWARE.

Observations:
undifference ionosphere-free combinations of
L1 and L2 carrier phase,
as well as P1 and P2 pseudorange.
Satellite ephemerides:
IGS final products.
15 min. position and 5 min. clock offset.
center of mass: Block II, II-A, II-R offsets
until 05/11/2006, and from then by ANTEX file.
Earth rotation models:
based on IERS Conventions 2003 [8].
earth rotation parameters are IGS final products.
Site displacement models:
IERS Conventions 2003.
NAO99b as ocean loading parameters.
Propagation delay correction:
dry and wet Niell mapping function [9].
relativistic correction: eccentricity and IERS Conv. 2003.
phase wind-up [10].
Estimation strategy:
solution arc: 36 hour arc (18:00 - 06:00).
weight: L3 = 1 cm, P3 = 1 m.
elevation cut off: below 15 deg.
down weight: $1/\sin x$ below 30 deg.
station position: solve each arc.
zenith path delay: solve every 2 hour.
receiver clock offset: solve every 5 min.
L3 carrier phase ambiguity: solve as a real value.

III. CLOCK COMPARISON

A. Overlapping Estimation Test

We tested the simple overlapping parameter estimation in the first step. We compared the time differences computed from P3 all-in-view [11] (P3AV) and GPS CP (referred to as link difference, henceforth). Four stations were used for this comparison; NICT, TL (Taiwan), ORB (Belgium), and USNO (USA). We used BIPM CCTF files for the P3AV, and IGS RINEX files for the GPS CP. We applied the same correction models as applied for the GPS CP to P3AV, which were the IGS satellite ephemerides and site displacement with only a solid earth tide. To reduce the P3AV's observation noise, we used Vondrak smoothing [12] as a low-pass filter. A CCTF file contains the every 16 min. observations, and the clock solutions of the GPS CP were estimated at 5 min. intervals. To align different observation epochs, linear interpolation was applied to the GPS CP solutions.

Fig. 1 shows the time differences between UTC(TL) – UTC(NICT) for the P3AV and GPS CP (upper plot), as well as the link difference (lower plot). The period of comparison was from Mar. 1 to Dec. 31 in 2006. Fig 2 shows the link differences between UTC(TL) – UTC(ORB) (upper), UTC(TL) – UTC(USNO) (middle), and UTC(ORB) – UTC(USNO) (lower). The Y-axis scale is different for Figs. 1 and 2. The link difference of UTC(TL) – UTC(NICT) is

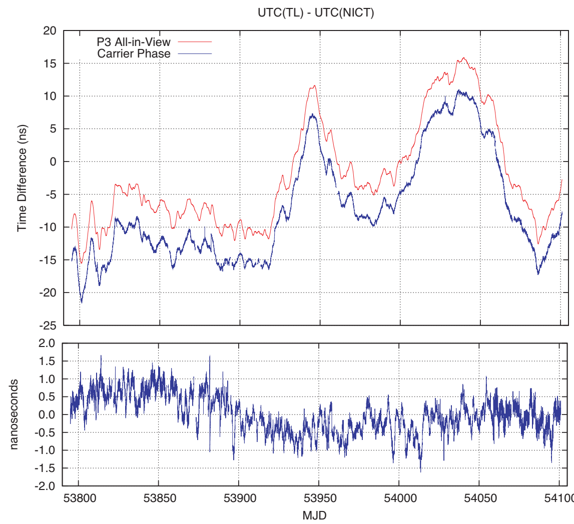

Fig. 1. Time differences between UTC(TL) – UTC(NICT) by using P3AV and GPS CP (upper plot), as well as difference between P3AV and GPS CP (lower plot).

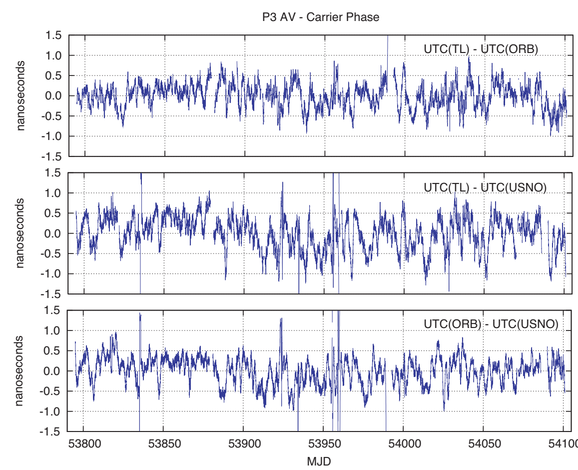

Fig. 2. Differences between P3AV and GPS CP. Stations are UTC(TL) – UTC(ORB) (upper), UTC(TL) – UTC(USNO) (middle), and UTC(ORB) – UTC(USNO) (lower).

slightly inconsistent in comparison to other baselines, and has a phase variation with long period. The cause of this variation is probably multipath in the NICT. The other baselines are consistent within ± 1 ns, and any apparent discontinuities greater than 1 ns are not seen. This means that simple overlapping estimation is admissible for clock comparison within a few hundred picoseconds of precision.

B. Short Term Comparison

We used five stations in the TWSTFT network for the comparison with GPS CP. Three stations are in Asia, NICT, KRISS, and TL, and two stations are further away, AUS and PTB. Table II shows the station information. The three stations

TABLE II
TIME LINK STATION INFORMATION.

AUS	S $33°47^m$ E $151°9^m$ GPS: Javad JPS E_GGD (IGS SYDN) Ref: UTC(AUS) Cs.
KRISS	N $36°23^m$ E $127°22^m$ GPS: ASHTECH Z-XII Metronome Ref: UTC(KRIS) H.M.
NICT	N $35°42^m$ E $139°29^m$ GPS: Septentrio PolaRX2 TR Ref: UTC(NICT) H.M.
PTB	N $52°18^m$ E $10°28^m$ GPS: ASHTECH Z-XII Metronome (IGS PTBB) Ref: UTC(PTB) Primary Cs.
TL	N $24°57^m$ E $121°10^m$ GPS: ASHTECH Z-XII Metronome (IGS TWTF) Ref: UTC(TL) H.M.

in Asia are covered by the same geostationary communication satellite transponder. On the other hand, the NICT - PTB or KRISS - PTB and the NICT - AUS or KRISS - AUS use different transponders. The TWSTFT modems output the one-way range every second. To make a short term comparison, we computed the time differences between UTC($k1$) − UTC($k2$) every second, and then a simple average was applied to these differences every 5 minutes.

Fig. 3 shows the time difference between UTC(TL) − UTC(NICT) (upper plot) in October 2006, and the link difference (lower plot). The diurnal variation of $\pm300 \sim \pm400$ ps is seen in the link difference. Fig. 4 shows the link differences of

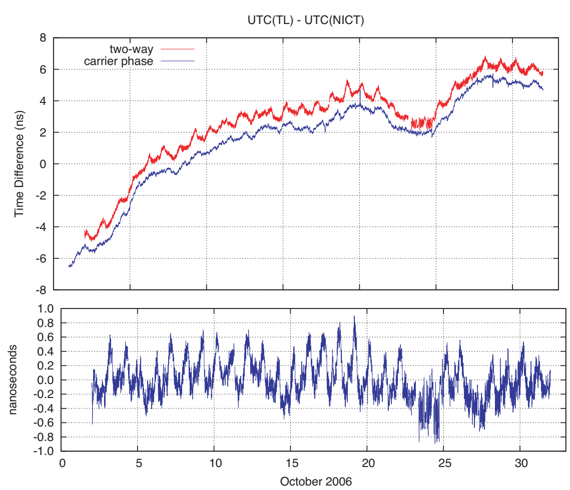

Fig. 3. Time difference between UTC(TL) − UTC(NICT) (upper) using TWSTFT (red) and GPS CP (blue), as well as its difference (lower).

UTC(KRIS) − UTC(NICT). These plots are for June (upper), August (middle), and October (lower) of 2006. The diurnal variation in Fig. 4 is partly better than it of Fig. 3. The diurnal variation of UTC(TL) − UTC(NICT) is caused by the instability of the TL earth station. In addition, small phase variations for periods longer than few days are also seen in both figures. It seems that the multipath in the NICT causes the several days phase variation. Although small systematic offsets appear in June in Fig. 4, apparent time jumps or drifts are not seen in these figures. Fig. 5 shows the short-term stability of the link differences of UTC(k) − UTC(NICT).

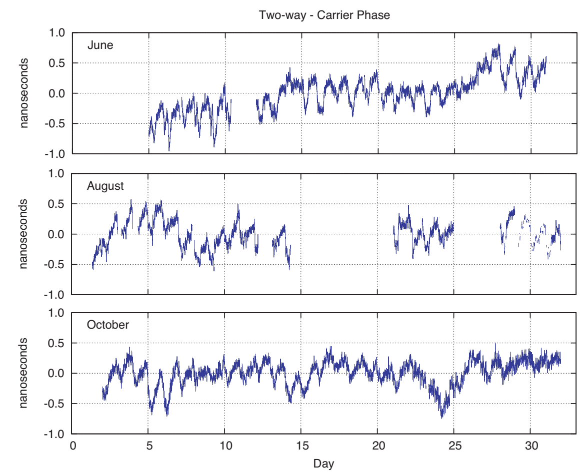

Fig. 4. Differences between TWSTFT and GPS CP in Jun. (upper), Aug. (middle), and Oct. (lower) of 2006 for KRIS and NICT stations.

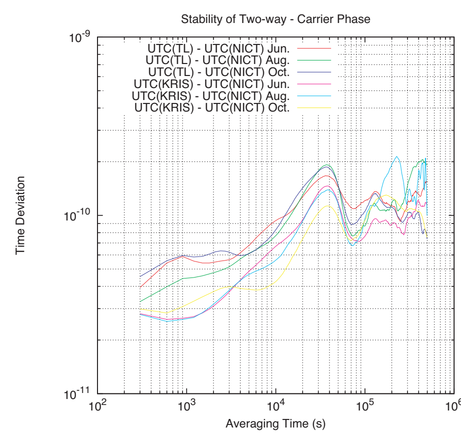

Fig. 5. Short-term stability of difference for TWSTFT and GPS CP in Asian region.

Fig. 6 shows the link differences with the intercontinental links in October 2006, and Fig. 7 shows their stabilities. Note that the Y-axis scale is different from Fig.4. The diurnal variations of these links are more obvious particularly with the Asia-Europe links.

C. Long Term Comparison

We used the ITU format data of TWSTFT [13] for a long term comparison check. Hourly data from the ITU format is generated by the NICT. The data is mid point of a quadratic fitting with a one-way range of 0^m to 5^m of every hour.

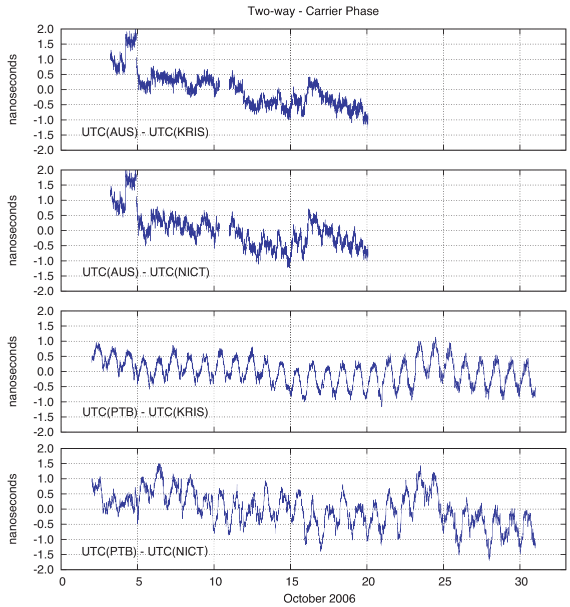

Fig. 6. Differences between TWSTFT and GPS CP in October 2006. The plots show UTC(AUS) − UTC(KRIS), UTC(AUS) − UTC(NICT), UTC(PTB) − UTC(KRIS), UTC(PTB) − UTC(NICT) in descending order.

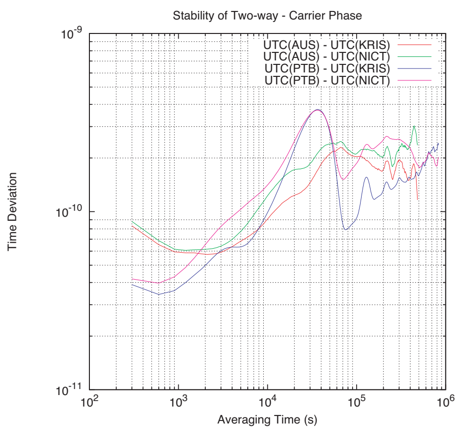

Fig. 7. Short-term stability of intercontinental links in October 2006.

Fig. 8 shows the link differences of all the baselines. The first three plots are the Asian links, and the next two plots are the Asia-Australia links, and the last two plots are the Asia-Europe links. Note that the Y-axis scale of the last two plots are different from the other plots. The span of the time comparison over a five month period from Jun. 1 to Oct. 31, 2006. The PTB receiver was replaced a few times up until July 25, 2006, and, as a result, we were unable to decide an accurate time offset. Therefore, the time comparisons with the PTB station were done with the observations made after July 25, 2006. The Asia and Asia-Australia links are consistent within ±2 ns. The observation noises are different in each link. The UTC(KRIS) − UTC(NICT) link had the best consistency, and the variation converged within ±1 ns. On the other hand, the Asia-Europe links have time jumps and drifts of about 2 ns.

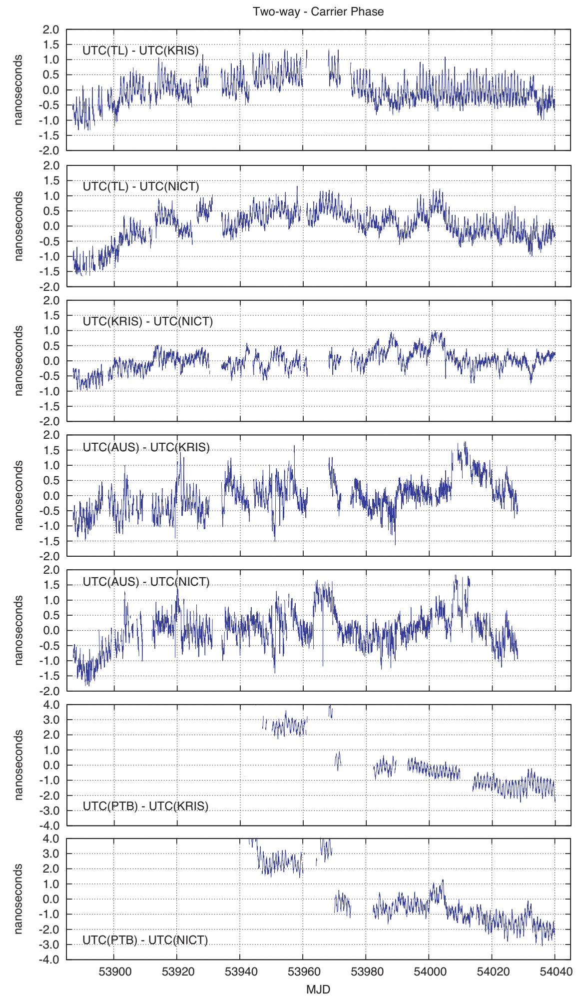

Fig. 8. Differences between TWSTFT and GPS CP. The span is from Jun. 1 to Oct. 31, 2006. The plots shown here are the UTC(TL) − UTC(KRIS), UTC(TL) − UTC(NICT), UTC(KRIS) − UTC(NICT), UTC(AUS) − UTC(KRIS), UTC(AUS) − UTC(NICT), UTC(PTB) − UTC(KRIS), UTC(PTB) − UTC(NICT) in descending order.

D. Discussion

The difference between TWSTFT and GPS CP was consistent within ±1 ns in a regional network. There weren't any systematic drifts or time jumps found in these links even though a diurnal variation with a few hundred picoseconds was seen. The variation in the Asia-Australia links was slightly more degraded than those in the Asian network, although an apparent systematic drift was not seen. On the other hand, a systematic drift was seen in the Asia-Europe links.

To investigate this drift, we performed an additional test. We computed the time difference between UTC(NIST) and UTC(NICT) or UTC(KRIS) using different methods. The NIST is a timing laboratory in the USA, and has a TWSTFT link to PTB. The NIST is also one of the NASA GDGPS networks [14], and receives the GPS carrier phase observations. We made the time difference between UTC(NIST) and UTC(k) as follows:

1) Direct comparison by using GPS CP.
2) Relay comparison with
   a) TWSTFT only.
   b) TWSTFT for UTC(NIST) and UTC(PTB), P3AV for UTC(k) and UTC(PTB).

Fig. 9 shows the time difference between UTC(NIST) and UTC(NICT) using three different methods, and Fig. 10 shows the link differences between UTC(NIST) − UTC(KRIS) (upper two plots) or UTC(NIST) − UTC(NICT) (lower tow plots). The first and third plots show the differences between the GPS CP and TWSTFT + P3AV, and the second and fourth plots show those of the GPS CP and TWSTFT only. Systematic drifts are only seen in the TWSTFT only links. Consequently, the drifts in the Asia-Europe links would be caused by the TWSTFT links.

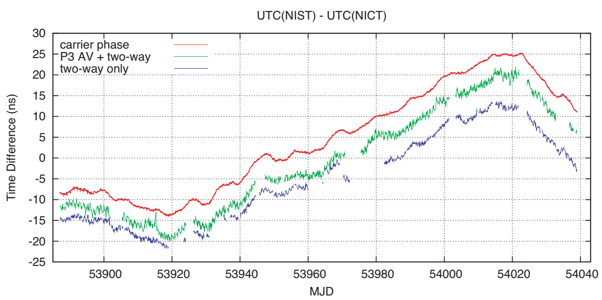

Fig. 9. Time difference between UTC(NIST) and UTC(NICT) using three different methods.

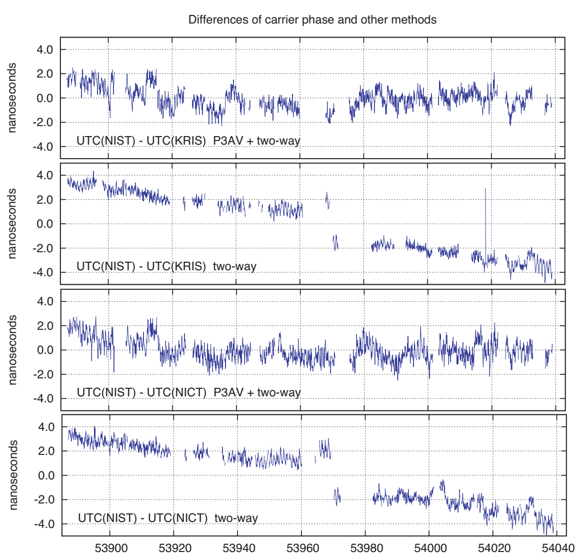

Fig. 10. Differences between GPS CP and TWSTFT only or TWSTFT + P3AV.

IV. Conclusion

We compared GPS carrier phase observations to TWSTFT to evaluate time transfer precision. A PPP with pseudorange observations and a simple overlapping parameter estimation can be used to ensure there is consistency within ± 1 ns with respect to the TWSTFT in a regional network. Diurnal variations are clearly seen in the regional and intercontinental links, and it are additionally evident in the intercontinental links. The cause of these diurnal variations within a few hundred picoseconds is probably introduced by the TWSTFT earth stations [15], although the cause of larger variations is not yet known, and should be investigated in the future. The Asia-Europe links of the TWSTFT include a systematic drift, such as seasonal or secular variation. To assess whether it is a drift or just a periodical variation with an annual cycle, we need to perform a multiple year comparison.

Although the GPS time transfer equipment is simple and less expensive than those for TWSTFT, it doesn't provide a straightforward analysis and the software is not very user friendly for time transfers. In the future we hope to develop an analysis method that will be popularly used in the timing community.

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References

[1] J. Amagai, "Two-way satellite time and frequency transfer using a pair of pseudo random noises," in *Proc. of ATF 2006*, New Delhi, India, Dec. 2006.
[2] M. Fujieda, M. Kumagai, T. Gotoh, M. Hosokawa, "First experiment of ultra-stable frequency distribution system via optical fiber in NICT,", in this proceedings.
[3] D. Orgiazzi, P. Tavella, F. Lahaye, "Experimental assessment of the time transfer capability of precise point positioning (PPP)," in *Proc. of IFCS-PTTI 2005*, Vancouver, Canada, Aug. 2005.
[4] M. Fujieda, M. Aida, J. Amagai, H. Maeno, T. Gotoh, "Long baseline TWSTFT between Asia and Europe," in *Proc. of 38th PTTI*, Virginia, USA, Dec. 2006.
[5] J. Kouba, "A guide to using international GPS service (IGS) products," available from http://igscb.jpl.nasa.gov/.
[6] Combined IGS clocks with 30 second sampling rate, IGS Mail, available from http://igscb.jpl.nasa.gov/mail/igsmail/2007/msg00005.html.
[7] R. Dach, L. G. Bernier, "Precise continuous time and frequency transfer using GPS carrier phase," in *Proc. of IFCS-PTTI 2005*, Vancouver, Canada, Aug. 2005.
[8] D. D. McCarthy, G. Petit, IERS Conventions (2003), IERS Technical Note no. 32, 2003.
[9] A. E. Niell, "Global mapping functions for the atmosphere delay at radio wavelengths," Journal of Geophysical Research, vol. 101, no. B2, pp. 3227–3246, 1996.
[10] J. Wu, C. Wu, G. Hajj, W. Bertiger, S. M. Lichten, "Effects of antenna orientation on GPS carrier phase," Manuscripta Geodaetica, vol. 18, pp. 91–98, 1993.
[11] Z. Jiang, G. Petit, "Time transfer with GPS satellite all in view," in *Proc of ATF 2004*, Beijing, China, Oct. 2004.
[12] J. Vondrak, "A contribution to the problem of smoothing observational data," Bull. Astron. Inst. Czech, vol. 20, no. 6, pp. 349–355, 1969.
[13] The operational use of two-way satellite time and frequency transfer employing PN codes, Recommendation ITU-R TF.1153-2, 1995-1997-2003.
[14] The NASA global differential GPS system, available from http://www.gdgps.net/.

[15] M. Fujieda, M. Aida, H. Maeno, L. Q. Tung, J. Amagai, “Delay difference calibration of TWSTFT earth station using multichannel modem,” IEEE Trans. on Inst. and Meas., vol. 56, no. 2, pp. 346–350, 2007.