LONG-BASELINE TWSTFT BETWEEN ASIA AND EUROPE

M. Fujieda, T. Gotoh, M. Aida, J. Amagai, H. Maeno
National Institute of Information and Communications Technology
Tokyo, Japan
E-mail: *miho@nict.go.jp*

D. Piester, A. Bauch
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

S. H. Yang
Korea Research Institute of Standards and Science, Daejeon, Korea

Abstract

A Two-Way Satellite Time and Frequency (TWSTFT) link between Asia and Europe was established in 2005 connecting the National Institute of Information and Communications Technology (NICT) and the Korea Research Institute of Standards and Science (KRISS) with the Physikalisch-Technische Bundesanstalt (PTB). In this report, we investigate factors which potentially limit the stability and accuracy of the overall measurement configuration. This includes analysis of the ionospheric effects and satellite motion, as well as the influence of the environmental conditions on the internal delays of the ground stations. Delay variations of some tenths of a nanosecond have been modeled, explaining partially the observed variations.

INTRODUCTION

During the last few years, the method of Two-Way Satellite Time and Frequency Transfer (TWSTFT) has evolved to be extensively used in the realization of International Atomic Time (TAI). The number of laboratories operating TWSTFT equipment has increased, allowing links within and in between North America, Europe, and the Asia Pacific region **[1]**. In July 2005, a TWSTFT link was established between the National Institute of Information and Communications Technology (NICT) and the Physikalisch-Technische Bundesanstalt (PTB) **[2]**, which are currently the Asian/Pacific and European nodes in the network of international time links for TAI, respectively. With the use of two transponders on the geostationary satellite PAS-4, a baseline of 8300 km is bridged. After starting regular operation (October 2005), the Korea Research Institute of Standards and Science (KRISS) has used the same link since the end of November 2005.

On intercontinental links, sources of instabilities which can be neglected for short baselines may have a significant impact on the measurement results. Potential sources have been addressed and were investigated previously **[3]**. One of them is the stability of the earth station itself, which is obviously baseline-independent. Delays of the equipment may vary caused by changes of environment, and that would degrade the accuracy of TWSTFT. Other sources are ionospheric delay, satellite motion, and the instability of the transponder configuration on the satellite, which are all not canceled out in the configuration used here.

Since the establishment of the link between NICT, KRISS, and PTB, diurnal variations with amplitude of over 1 ns have been observed in the time transfer result. In this report, we investigate the factors which potentially limit the stability of the overall measurement configuration in use. We start with a brief description of the ground stations and list operational parameters. Time transfer results characteristic for the achieved link performance are shown. Thereafter, correlations between the observed diurnals and outdoor temperature, ionospheric delay, satellite motion, and transponder configuration are investigated.

HARDWARE AND TIME TRANSFER RESULTS

In addition to the TWSTFT links operated in the Asia/Pacific region, NICT initiated the establishment of a TWSTFT link between Asia and Europe. The earth stations installed at PTB, NICT, and KRISS consist of standard telecommunication hardware. A special characteristic is the use of a multi-channel TWSTFT modem developed at NICT **[4]**. For temperature stabilization, the up- and down-converters are installed indoors and the low-noise amplifiers are mounted in temperature-stabilized boxes close to the antenna feed system. However, at PTB radio frequencies have to be transmitted over a distance of 1 km to connect the indoor equipment with the antenna. This is done by an optical fiber connection. The Ku-band radio frequencies used and the elevation angles of the antennae are listed in Table 1; for further details, see Ref. **[2]**. The telecommunication satellite PAS-4 provides different footprints for Europe and Asia. Thus, two transponders are involved for the link direction from Asia to Europe and vice versa (see Fig. 1). In principle, the NICT modem provides a continuous data stream with one measurement made every second. For the data analysis, TWSTFT data are processed for 5 minutes every hour, formatted following the recommendation ITU-R **[5]**.

As an independent reference we chose GPS all-in-view (GPSAV) time transfer data **[6]**. At NICT and PTB, the GPS data were obtained by geodetic GPS receivers, Ashtech Z-12T. Due to a malfunction at PTB, the receiver was replaced between MJD 53912 and 53945 by a Septentrio PolaRx2. At KRISS, a Euro-80 receiver was used until March 2006 and an Ashtech Z-12T thereafter. GPS time transfer results are computed from the standard CGGTTS formatted data and averaged every hour.

In Fig. 2 (a), the time scale differences of UTC (NICT) – UTC (PTB) and UTC (KRIS) – UTC (PTB) and in (b) their Modified Allan deviations (MDEV) for TWSTFT and GPSAV are depicted, respectively. The observation period is between February and October 2006. The MDEV plot reveals that the short-term stability of TWSTFT is superior to that of GPSAV. Bumps exist at around averaging times of 40000 s and of 200000 s, revealing diurnal impacts on the time transfer data and probably steering corrections especially at KRISS, respectively.

To separate the effects of time scale variations from those related to the time transfer itself, double differences between GPSAV and TWSTFT for UTC (NICT) – UTC (PTB) and UTC (KRIS) – UTC (PTB) were calculated. Excerpts of 8 days are shown in Fig. 3. For better visibility, a 5-hour moving average is depicted, too. One can apparently see diurnal variations with amplitudes of 1 ns or even more.

INSTABILITY SOURCES

TEMPERATURE

One candidate for causing diurnal variations is the environmental temperature. To investigate correlation between the diurnal variation and the outdoor temperature following procedure is applied: Data are: 1) smoothed by a moving average, 2) separated day by day, then 3) daily fitted linear slopes are subtracted, and 4) separated data of 1 month are averaged. In Figure 4 (a) and (b), the mean spectra for UTC (NICT) – UTC (PTB) and UTC (KRIS) – UTC (PTB) are shown, respectively. Regarding UTC (NICT) – UTC (PTB), the spectra until July show strong diurnal variations with amplitudes of more than 1 ns. From August onwards, their functional forms vary and their amplitudes are reduced. It is difficult to identify the same characteristics from UTC (KRIS) – UTC (PTB) double differences. Due to fewer data points, noise fluctuations are more pronounced. However, the data provide almost the same tendency as of UTC (NICT) – UTC (PTB). It is not clear whether the diurnals are correlated with seasonal effects or not: While the amplitude of the diurnals has almost vanished since August 2006, the same period in 2005 showed clear daily variations **[2]**. The signal levels of the PTB station, both in transmission and reception, decreased during August 2006. A system check revealed a water leakage of an outdoor component, which was fixed afterwards. However, the former signal power could not be readjusted, but it increased independently again during November without any manual change of the ground station. This may point to the fact that some non-understood hardware problems exist in the PTB ground equipment.

We estimated correlation factors between the spectra in Fig. 4 and monthly mean temperatures at NICT and PTB. The results are shown in Fig. 5. The averaged correlation factors of the spectra with the temperatures at NICT and PTB are -0.1 and 0.6, respectively. One can clearly see that the correlation factors with respect to PTB temperature go down rapidly after August 2006. Figure 6 depicts two examples of monthly data (February and March 2006) with a high correlation factor with PTB outdoor temperature. Whereas the amplitude of the temperature variations in March were two times larger than those in February, the amplitude of the spectra in both months remained almost the same. The amplitude of the diurnal effect seems indeed independent of the amplitude of the temperature variation at PTB. The correlation factor with respect to the NICT station is overall small. This agrees with investigations of the NICT earth station used in the Asian network, whose delay variation mainly depends on outdoor temperature, which causes diurnal variation with amplitude of not more than 100 ps **[7]**. Temperature coefficients of components employed in the earth stations were measured using a temperature-controlled chamber and network analyzer. The results show that they do not exceed some tens of a picosecond per K and humidity dependence is smaller at least in the case of the NICT station **[7]**.

IONOSPHERIC DELAY

TWSTFT via geostationary satellites uses different frequencies for uplink and downlink; thus, ionospheric delays are not equal for both paths. They are, however, known to be small compared to the overall uncertainty and have, thus, typically been neglected. Ionospheric delays for the link between NICT and PTB are computed using the Global Ionosphere Map (GIM) **[8]** published by the Center for Orbit Determination in Europe (CODE) **[9]**. Ionospheric delays between MJD 53767 and 53790 were calculated. In Fig. 7 (a), part of the results is shown. The expected delay change due to the variation of the ionosphere is less than 100 ps. To cancel out the ionosphere effect on the TWSTFT measurements from the double differences GPSAV – TWSTFT, one has to add both data sets. Ionospheric delays are similar in form to the spectra of the diurnal variation, but the amplitudes are small compared to the observed diurnal variations.

SATELLITE MOTION

The signal propagation time from one station to the other, in combination with the rotation of the Earth, introduces the Sagnac effect. A correction is normally applied as a constant, assuming a fixed position of the ground stations and the satellite. When the satellite motion, which roughly represents an oscillation around a center position with a period of 1 day, is large and the baseline between stations is long, the variation of the Sagnac effect might not be negligible. We calculated the expected effect for the link between NICT and PTB through PAS-4. The baselines between NICT (KRISS) and PTB are about 8300 km (7800 km). Two line elements published by North American Aerospace Defense Command (NORAD) **[10]** were used in the orbit calculation of PAS-4 at 72 E degree of longitude. The Sagnac effect actually shows a daily variation of sinusoidal shape due to the satellite motion. In Fig. 7 (b), the Sagnac effect and the double differences, GPSAV – TWSTFT, of NICT – PTB are shown. It is found that the variation exceeds 0.5 ns. The impact of the high unexpected variation should be investigated in more detail. However, the Sagnac-effect variation seems to be hidden due to other causes. However, the phase and functional form of the computed Sagnac variation do not fit well with the observed diurnal variation, and at least other causes of variations must exist.

The influence of the transponder configuration used for the TWSTFT measurements between Europe and Asia was investigated by comparing time transfer data between NICT and KRISS via two TWSTFT links. Firstly, two complete intra-Asian links were compared and, secondly, one of them was replaced by a combination of two connections to PTB. As shown in Fig. 1, the connections between NICT (KRISS) and PTB are established through two transponders with separate Asian and European spot beams. Thus, the signal paths have non-reciprocity. In this standard configuration, a direct time transfer between NICT and KRISS is impossible. A direct time transfer between NICT and KRISS is regularly performed via a different geostationary satellite, JCSAT-1B. Data on this link do not show apparent diurnal variations **[11]**. To establish a second NICT-KRISS link, we changed the uplink and downlink frequencies for the Asian beam and performed direct time transfer between NICT and KRISS via PAS-4 through a different transponder with one spot beam covering both stations (see Fig. 8 (a)). Data were recorded between MJD 53975 and 53983. In Fig. 9, the time scale difference of UTC (NICT) – UTC (KRIS) via JCSAT-1B and via direct PAS-4 and double differences between them are shown. The continuously recorded data were reduced by averaging sets of 5 minutes. The double differences were computed from simultaneously recorded raw data. A diurnal component in the time transfer data is apparent just at the noise level.

We compared results NICT – KRISS via direct PAS-4 and via the normal configuration through two transponders, named via PAS-4, with PTB as the relay. The time transfer of UTC (NICT) – UTC (PTB) and UTC (KRIS) – UTC (PTB) are performed simultaneously using two separate receive channels in the modem at PTB. The time scale difference UTC (NICT) – UTC (KRIS) relayed by PTB is computed from subtraction of UTC(KRIS)-UTC(PTB) from UTC (NICT) – UTC (PTB) and is, thus, independent of instabilities of UTC (PTB). In Figure 10 (a) and (c), time scale differences by TWSTFT via JCSAT-1B and via PAS-4 are shown. Five-minute averaged data in both links were taken every hour. While the time scale differences via JCSAT-1B follow a smooth curve, those via PAS-4 sometimes show noise fluctuations. In Figure 10 (b) and (d), double differences are shown. Diurnal and longer-term instabilities become apparent. In Figure 11, the time deviation of the double differences between data via JCSAT-1B and via direct PAS-4 (recorded during 8 days), and via JCSAT-1B and via PAS-4 (recorded during 257 days) are depicted. For the direct links, the noise level, as well as the amplitude of diurnal variations, is substantially lower.

Instabilities might be induced when signals pass through two transponders and between the satellite and PTB, which, however, should cancel out completely due to the perfect simultaneous measurements UTC (NICT) – UTC (PTB) and UTC (KRIS) – UTC (PTB). In the two comparisons, two different receive channels in the modem at PTB are used, and different PRN codes have been used. Further studies will try to reveal any potential influence of this nonreciprocity.

SUMMARY

We have studied the origin of diurnal variations observed in the TWSTFT time transfer data of UTC (NICT) – UTC (PTB) and UTC (KRIS) – UTC (PTB) via PAS-4. We found rather strong correlation coefficients between the double difference GPSAV – TWSTFT for the link UTC (NICT) – UTC (PTB) and outdoor temperature at PTB up to 0.8. However, sometimes the correlation is much weaker or has an opposite sign. Unaccounted delay variations due to the ionosphere are at the 0.1 ns level, and thus may only explain a small part of the observed diurnals. From the NORAD model, the influence of the satellite movement on the Sagnac effect is significant (amplitude 0.5 ns), but its phase is different from the observed diurnals. Concluding, the instabilities might be caused by multiple sources, some of which might be induced in the path between the satellite and PTB or when signals pass through the satellite.

For future investigations, we propose quantifying the influence of the troposphere, rain, and humidity. Variations of the link quality should be carefully monitored and the influence of the earth stations on the instability can be investigated when additional laboratories join the Europe-Asia link in the near future.

REFERENCES

[1] E. F. Arias, 2005, *“The metrology of time,”* **Philosophical Transactions of the Royal Society, A363,** 2289-2305.

[2] H. Maeno, M. Fujieda, D. Piester, A. Bauch, M. Aida, Q. T. Lam, T. Gotoh, and Y. Takahashi, 2006, *“Establishment of a TWSTFT link between Asia and Europe connecting NICT and PTB,”* in Proceedings of the 20th European Frequency and Time Forum (EFTF), 27-30 March 2006, Braunschweig, Germany, pp. 575-579.

[3] T. E. Parker and V. Zhang, 2005, *“Sources of Instabilities in Two-Way Satellite Time Transfer,”* in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE 05CH37664C), pp. 745-751.

[4] M. Imae, T. Suzuyama, T. Gotoh, Y. Shibuya, F. Nakagawa, Y. Shimizu, and N. Kurihara, 2003, *“Two Way Satellite Time and Frequency Transfer,”* **Journal of the National Institute of Information and Communications Technology, 50** (1/2), 125-133.

[5] Recommendation ITU-R TF.1153-2, *“The operational use of two-way satellite time and frequency transfer employing PN timing codes”* (ITU, Geneva), last update 2003.

[6] T. Gotoh, 2005, “*Improvement of GPS Time Link in Asia with All in View,”* in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE 05CH37664C), pp. 707-711.

[7] M. Fujieda, M. Aida, H. Maeno, L. Q. Tung, and J. Amagai, 2006, *"Delay Difference Calibration of TWSTFT Earth Station using Multi-channel Modem,"* in Digest of the Conference on Precision Electromagnetic Measurements (CPEM), 9-14 July 2006, Turin, Italy, pp. 602-603.

[8] *http://www.cx.unibe.ch/aiub/ionosphere.html.*

[9] *http://www.aiub.unibe.ch/igs.html.*

[10] *http://www.norad.mil/* and *http://www.space-track.org/perl/login.pl.*

[11] M. Fujieda T. Gotoh, M. Aida, H. Maeno, and J. Amagai, *"Two-Way Satellite Time and Frequency Transfer with Long Baseline,"* in Proceedings of the Asian Time Forum (ATF), to be published.

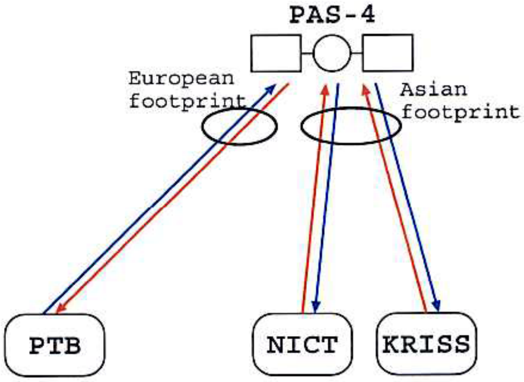

Figure 1: Schematic of the TWSTFT links between NICT, KRISS and PTB via the geostationary satellite PAS-4.

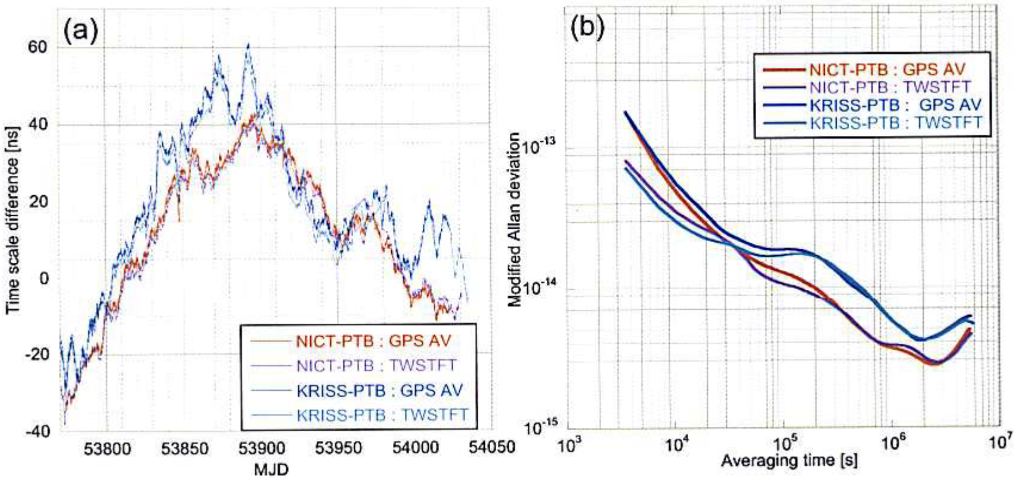

Figure 2: (a) Time scale differences and (b) modified Allan deviations of UTC(NICT)-UTC(PTB) and UTC(KRIS)-UTC(PTB) by TWSTFT and GPSAV. Observation period is between Feb 2006 and Oct 2006.

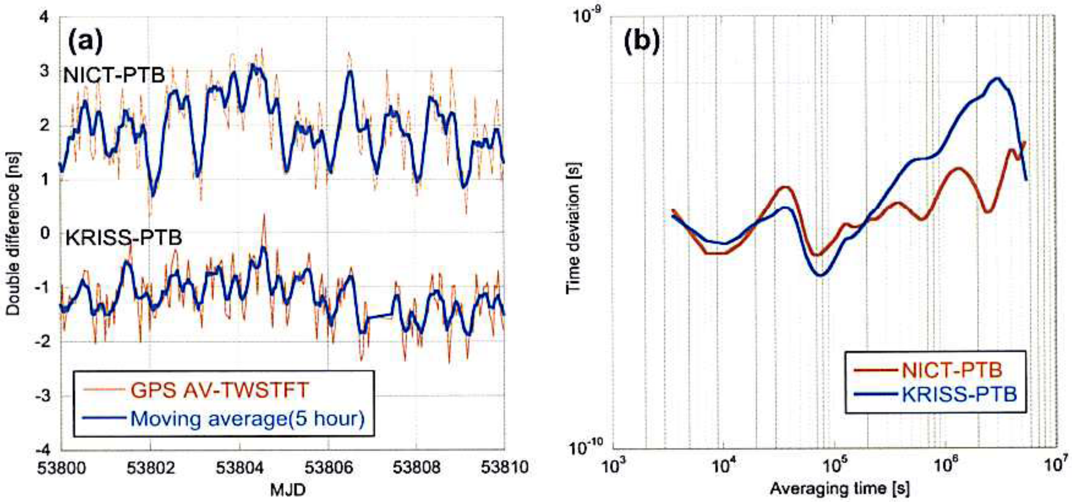

Figure 3: (a) Time plots (8 days in March 2006) and (b) time stabilities (whole period Feb 2006 to Oct 2006) of GPSAV-TWSTFT for UTC(NICT)-UTC(PTB) and UTC(KRIS)-UTC(PTB).

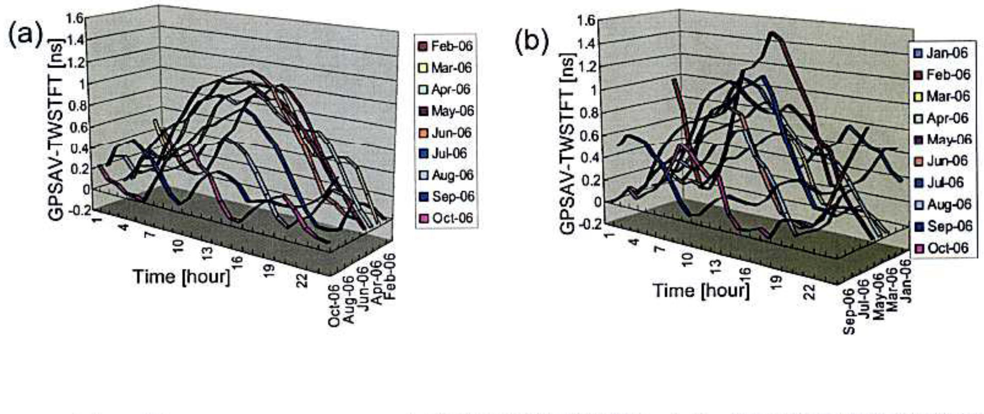

Figure 4: Monthly mean spectrum of GPSAV-TWSTFT. (a): UTC(NICT)-UTC(PTB), (b): UTC(KRIS)-UTC(PTB).

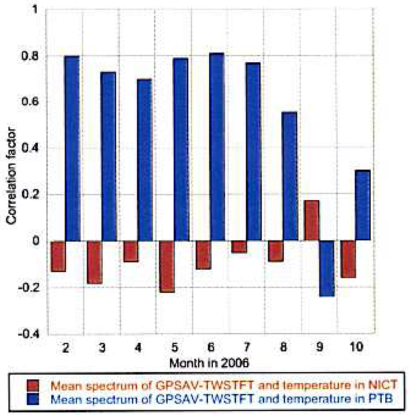

Figure 5: Correlation factors between mean spectra of GPSAV-TWSTFT for UTC(NICT)-UTC(PTB) and temperatures at NICT (red) and PTB (blue).

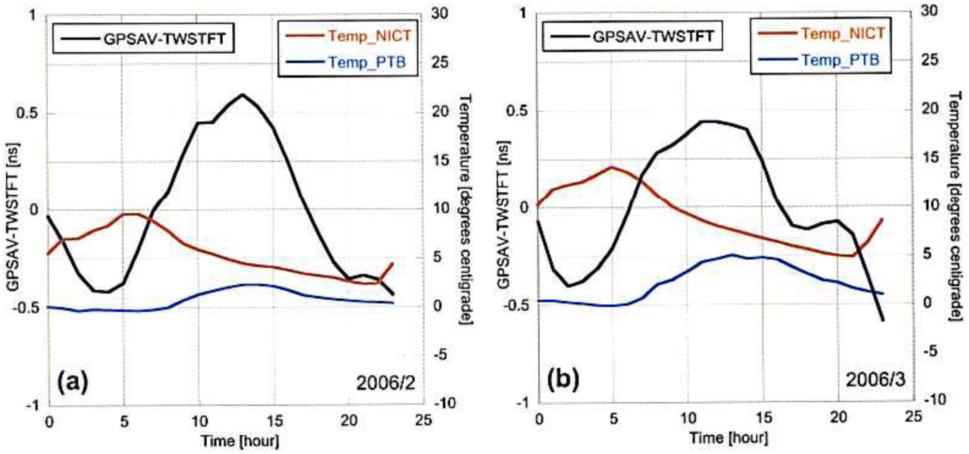

Figure 6: Mean spectrum of GPSAV-TWSTFT for UTC(NICT)-UTC(PTB) and mean temperatures at NICT and PTB. ((a): Feb 2006, (b): Mar 2006.)

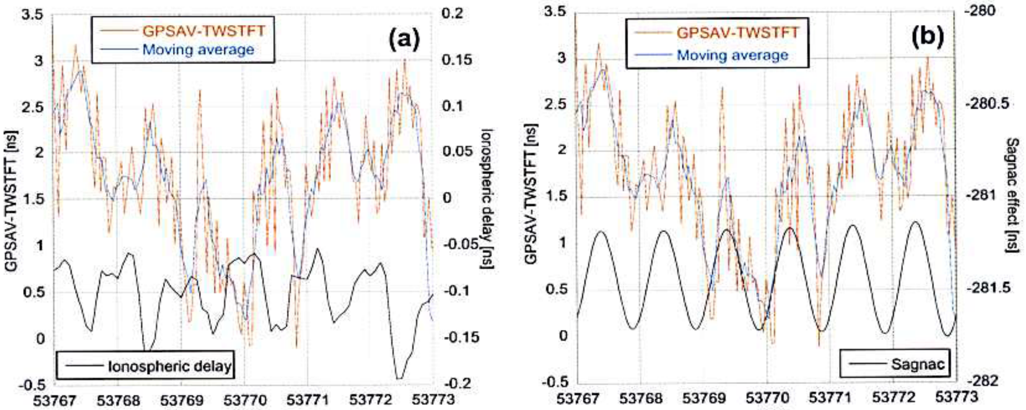

Figure 7: Impact of the ionosphere (a) and the satellite motion (b) on the time transfer data computed for 6 days starting from Feb 1st 2006. Double differences GPSAV-TWSTFT for UTC(NICT)-UTC(PTB) are shown, too.

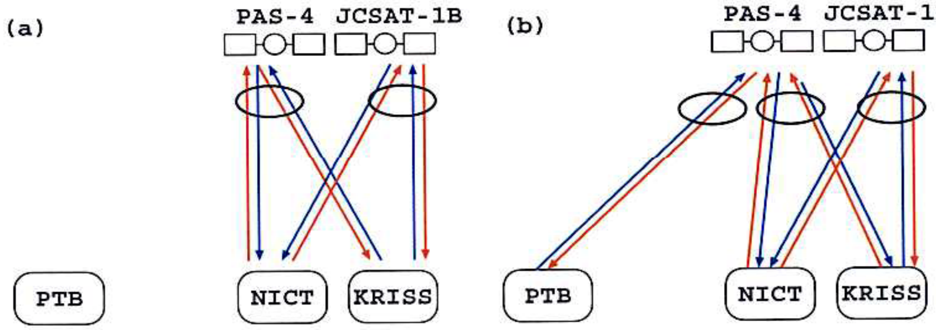

Figure 8: TWSTFT between KRISS and NICT via two satellites (PAS-4 and JCSAT-1B) with a single transponder (a) and via JCSAT-1B and via PTB (with regular configuration on PAS-4) (b).

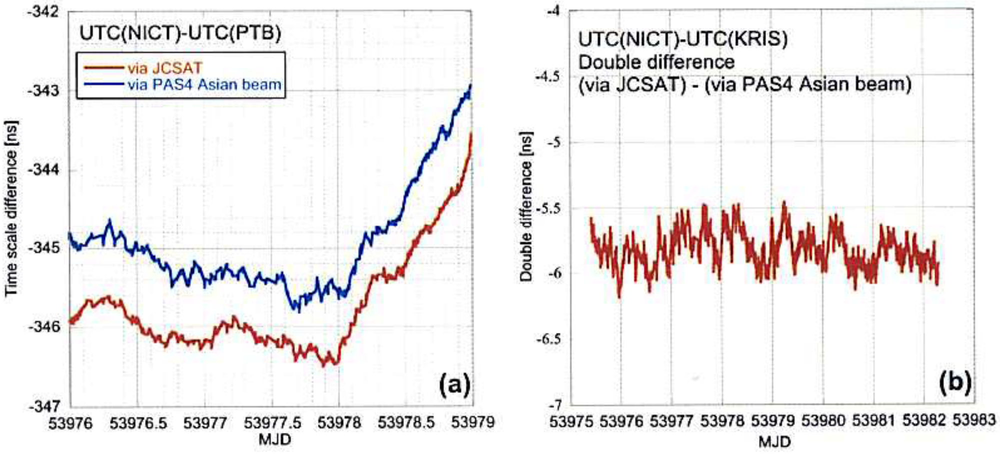

Figure 9: (a): Time scale difference of UTC(NICT)-UTC(KRIS) via JCSAT-1B (red) and via direct PAS-4 (blue). (b): Double differences, (via JCSAT-1B)-(via direct PAS-4). For visibility, offset is inserted into data.

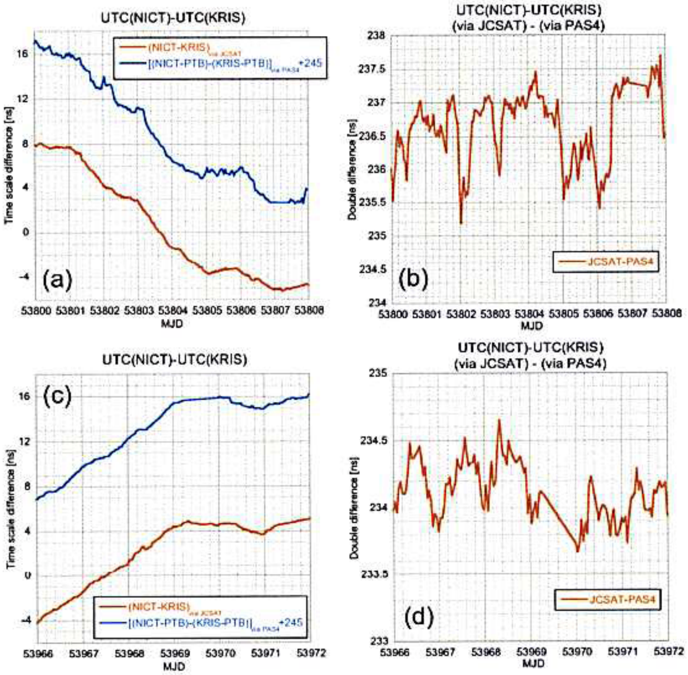

Figure 10: UTC(NICT)-UTC(KRIS) via JCSAT-1B and via PTB for two sets of data in March (a) and August 2006 (c) and their corresponding double differences (b), (d).

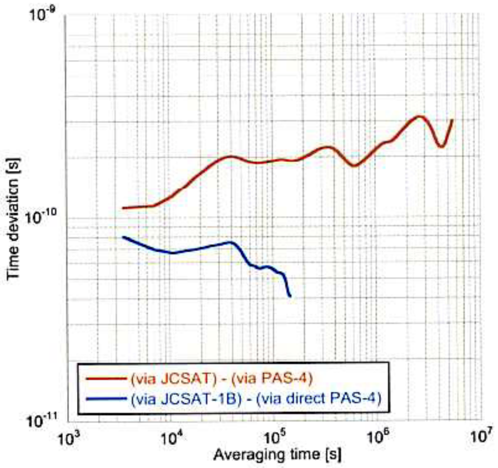

Figure 11: Time deviations of double differences as depicted in Fig. 9(blue) and Fig. 10 (red).