Correcting Ocean Tide Loading Effect for Station Displacement in GNSS All-in-View Time Transfer

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***Summary*—Station displacements caused by geodynamic activities, e.g., tectonic motions and geophysical effect, e.g., the ocean tide loading shall be taken into account for time transfer. In Taiwan, the impact of the ocean tide loading on positioning can be larger than 3 cm. Such a 3-cm impact on GNSS time transfer has to be taken into account, especially for a long baseline link. In this work, we assess the impact of the ocean tide loading on TL and PTB station displacements, in which the station coordinates are determined using the so-called precise point positioning (PPP) technique. The station displacements between the PPP solution with and without the ocean tide loading corrections are used to estimate time corrections in the TL-PTB link using GNSS all-in-view (AV) time transfer approach. The results show that the time transfer correction due to the ocean tide loading effect is relatively small compared to the noise level given by the AV time transfer results.**

Keywords—GNSS; PPP; time transfer; All-in-view; ocean tide loading

I. INTRODUCTION

The GNSS all-in-view (AV) time transfer has been regularly used to compare the UTC time labs since 2007 [1]. In the Common Global Navigation Satellite System (GNSS) Generic Time Transfer Standard (CGGTTS) [2] procedure, the position of GNSS antenna, which is given in the International Terrestrial Reference Frame (ITRF), is considered as a precisely known coordinate with an accuracy of 3 cm in accord to the 0.1 ns precision requirement of time [2]. To maintain such a positioning accuracy, the station coordinates need to be constantly updated. In general, the station displacements due to the geophysical motions (e.g., tidal displacements) have the less impact on short baselines than that on long baselines due to the common-mode cancellation, e.g., the atmospheric condition and tidal effect [3]. In this work, we attempt to validate the impact of the geophysical effect, e.g., ocean tide loading, on the time transfer using the GNSS AV approach. We select two stations for this experiment: Physikalisch-Technische Bundesanstalt (PTB) station located in Braunschweig, Germany and TL (Telecommunication Laboratories) located in Taoyuan, Taiwan. The distance between the PTB and TL stations is roughly 8383 km. This work is helpful for understanding the impact of the ocean tide loading on the time transfer over two different areas using one month of GNSS data. In addition, we also assess the impact of the station displacements derived by the so-called precise point positioning (PPP) on the time correction. Discussion and conclusions are given based on the results presented in this work.

II. METHODS

In this work, we estimate the station displacement using the PPP technique with and without the ocean tide loading correction, namely BLQ correction [4]. The PPP technique requires the precise GNSS orbit and clock information in connection to the ITRF [5, 6] and the well-defined IGS (International GNSS Service) time scale. The station position is determined using the ionosphere-free linear combination of the GPS dual-frequency carrier phase observations. Considering the effect of the station displacement between the positioning solution with and without the BLQ correction, we first drive the following equations to estimate the change of propagation delay from GNSS satellite to receiver.

Fig. 1 shows the geometry position of the GNSS satellite and the receiver. Let the original position of the receiver is R and the corrected position is R'. The corrected path vector from satellite S to receiver R' can be expressed as

$$\overrightarrow{\mathrm{SR'}} = \overrightarrow{\mathrm{SR}} + \overrightarrow{\mathrm{RR'}}. \tag{1}$$

Since $\overrightarrow{\mathrm{RR'}}$ is very small relative to the satellite path and

$$\left|\overrightarrow{\mathrm{SR'}}\right|^2 = \left|\overrightarrow{\mathrm{SR}}\right|^2\left(1 + \frac{\left|\overrightarrow{\mathrm{RR'}}\right|^2}{\left|\overrightarrow{\mathrm{SR}}\right|^2} + \frac{2\overrightarrow{\mathrm{SR}}\cdot\overrightarrow{\mathrm{RR'}}}{\left|\overrightarrow{\mathrm{SR}}\right|^2}\right), \tag{2}$$

the corrected path can be computed by the approximation as

$$dp = \left|\overrightarrow{\mathrm{SR'}}\right| - \left|\overrightarrow{\mathrm{SR}}\right| \approx \overrightarrow{\mathrm{RR'}}\cdot\frac{\overrightarrow{\mathrm{SR}}}{\left|\overrightarrow{\mathrm{SR}}\right|}. \tag{3}$$

The position information of GNSS satellites is provided in the CGGTTS file [2]. Both the elevation (elev) and azimuth (az) of the satellite are given with respect to the receiver in the local East, North, Up (ENU) coordinate system. The relation between the local ENU coordinates and the Earth-centered, Earth-fixed (ECEF) coordinates is illustrated in [7].

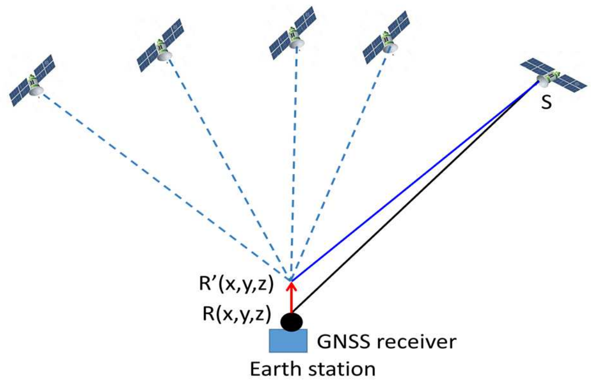

Fig. 1. Geometry position of GNSS satellites and a receiver.

Let the unit vector from the geocentric positions of the receiver to satellite is $\hat{p} = -\frac{\overrightarrow{SR}}{|\overrightarrow{SR}|}$, then we have

$$\hat{p}\cdot\hat{e} = cos(\text{elev})\cdot sin(\text{az})$$
$$\hat{p}\cdot\hat{n} = cos(\text{elev})\cdot cos(\text{az})$$
$$\hat{p}\cdot\hat{u} = sin(\text{elev}). \quad (4)$$

The station displacement $\vec{d} = \overrightarrow{RR'} = (dx,\ dy,\ dz)$ is expressed in the ECEF coordinates. We have

$$\hat{p}\cdot\vec{d} = dx\hat{p}\cdot\hat{x} + dy\hat{p}\cdot\hat{y} + dz\hat{p}\cdot\hat{z}$$
$$= dx(-sin\lambda\cdot\hat{p}\cdot\hat{e} - cos\lambda sin\phi\cdot\hat{p}\cdot\hat{n} + cos\lambda cos\phi\cdot\hat{p}\cdot\hat{u}) + dy(cos\lambda\cdot\hat{p}\cdot\hat{e} - sin\lambda sin\phi\cdot\hat{p}\cdot\hat{n} + sin\lambda cos\phi\cdot\hat{p}\cdot\hat{u}) + dz(cos\phi\cdot\hat{p}\cdot\hat{n} + sin\phi\cdot\hat{p}\cdot\hat{u}), \quad (5)$$

where λ, ϕ are the spherical longitude and latitude respectively. Thence, the corrected distance for satellite path is $dp = -\hat{p}\cdot\vec{d}$. Finally, the time correction is the distance divided by the speed of light, i.e. dp/c.

III. RESULTS

In this section, we assess the impact of the station displacement on the time transfer in terms of 1) the BLQ effect, 2) the difference between the PPP-derived station coordinates and a reference coordinate given by the CGGTTS header information and 3) the difference between the PPP-derived station coordinates and the first-day PPP-derived solution.

A. The impact of the BLQ effect

We first assess the station displacements caused by the BLQ effect on the time transfer during the period MJD 59362 to MJD 59397 (May-28-2021 to July-02-2021). The magnitudes of the station displacement vectors were plotted in Fig. 2. The station displacement of TL can be up to 40 mm. In comparison, the largest displacement of PTB is only about 10 mm. The TL station is located in Taiwan, so the tide loading effect is expected to be larger than the PTB station. Additionally, the diurnal periodic variations of the station displacements are mainly caused by the loading model component M2. The averaging time corrections corresponding to the GPS AV solutions for the station displacements of TL and PTB were computed and shown in Fig. 3. The time corrections caused by the BLQ effect for the TL and the PTB stations varied from -90 ps to 50 ps, and from -22 ps to 25 ps, respectively.

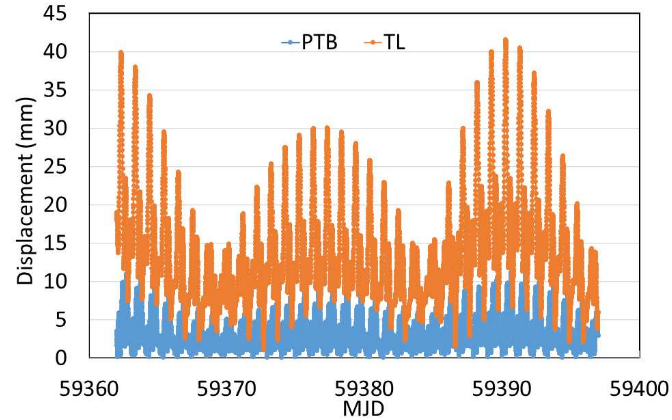

Fig. 2. Station displacements of the PTB and TL

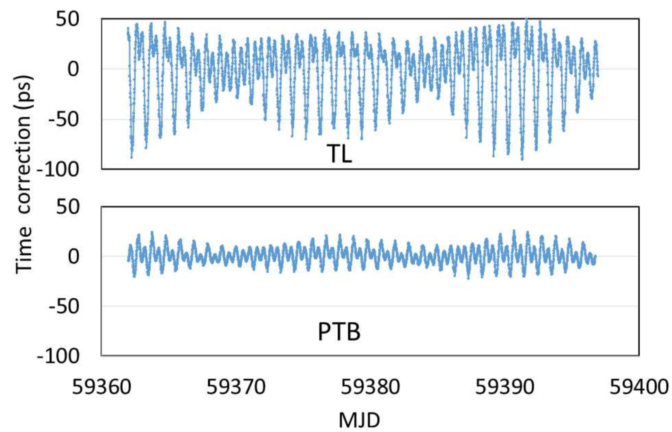

Fig. 3. Time corrections of GPS AV for TL and PTB stations

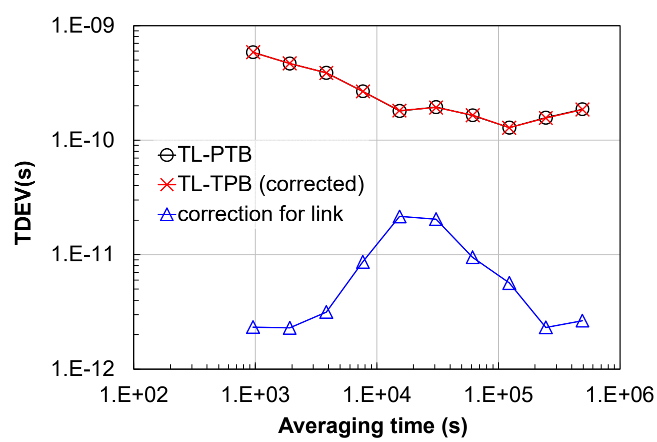

Fig. 4. Time deviation of TL-PTB AV reults: Original results(black circle), corrected results(red cross) and the correction data (blue triangle)

The time deviations (TDEVs) of GNSS AV time transfer results for TL-PTB link were plotted in Fig. 4. The time transfer solution in black circle indicates a solution derived by the ionosphere-free linear combination of the dual-frequency code observations for both the TL and PTB stations. The solutions with the time corrected by the BLQ were shown in red. The time correction caused by the BLQ-only is in blue and indicates the TDEV is 0.01 time smaller than the black curve around the averaging time of 10^3-10^4 s and 10^6. Again, the blue curve over the averaging times 10^4-10^5 s is mainly caused by the tidal loading model M2 component. The red curve with the correction is almost overlapped with the black curve, implying that the amplitude of the correction is about in tenths of the noise of the GNSS P3 AV results. In the other word, such a code-derived time solution is not sensitive to the BLQ effect.

B. *Differences between PPP solutions and a reference coordinate given in CGGTTS file*

Subsequently, we assessed the station displacements with respect to the reference coordinate given by the header information of CGGTTS file. Fig. 5 shows the station displacements for both the TL and PTB stations. The PPP solution is derived by the ionosphere-free linear combination of the dual frequency phase observations. Here the BLQ effect is corrected in the PPP solution. Table I shows the statistic information of Fig. 5. The station displacement of TL is 53 mm for the mean and 26 mm for the standard deviation (SD). In comparison, PTB has a significantly large mean of 215 mm and a relatively large SD of 33 mm. Such a relatively large difference in the mean and SD is mainly due to the fact that the receiver position in the PTB's CGGTTS header was updated in 2019 and that in TL's header was updated in December of 2020. This suggests that the station coordinates require to be constantly updated in the CGGTTS file in minimizing the coordinate inconsistence.

TABLE I. THE STATISTIC INFORMATION OF THE STATION DISPLACEMENTS

	Mean (mm)	SD[a] (mm)
TL	53	26
PTB	215	33

[a] SD: standard deviation

Fig. 6 shows the time corrections caused by the station displacements and the statistic information is shown in Table II. The time correction for the TL is 13 ps and 103 ps for the mean and the SD, respectively. However, the PTB has a relatively large -407 ps and 79 ps for the mean and the SD, respectively. Such the large mean value is mainly caused by the large inconsistence between the PPP solution and the reference coordinate given in the CGGTTS file.

The TDEVs of GNSS AV time transfer results for TL-PTB link were plotted in Fig. 7. The solution with the time corrected is slightly worse than that without the time corrected (in black). The blue curve in Fig. 7 is affected by the large difference between the PPP solution and the reference coordinate. This was evidenced in Tables I and II and Figs 5 and 6. The TDEV shows a peak of 93 ps at the averaging time around 1.5×10^4 s.

TABLE II. THE STATISTIC INFORMATION OF THE TIME CORRECTIONS CAUSED BY THE STATION DISPLACEMENTS

	Mean (ps)	SD (ps)
TL	13	103
PTB	-407	79

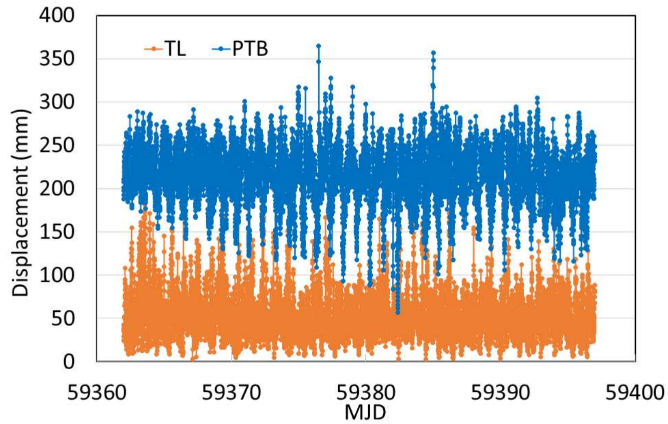

Fig. 5. Station displacements of the TL and PTB with respect ro the receiver position in the CGGTTS header

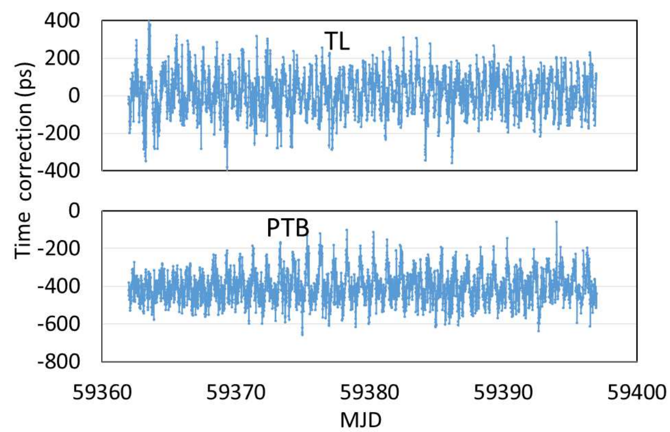

Fig. 6. Time corrections of GPS AV for TL and PTB stations

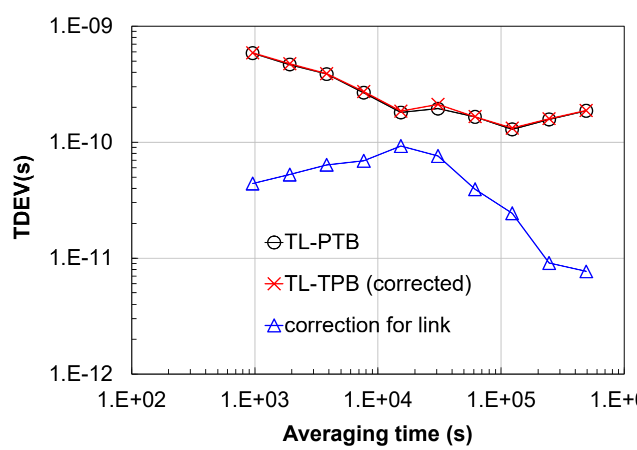

Fig. 7. Time deviation of TL-PTB AV reults: Original results(black circle), corrected results(red cross) and the correction data (blue triangle)

C. Differences between PPP solutions and the first-day PPP solution

In this section, we assess the PPP-derived station displacements with respect to the first-day solution of the one-month data. Fig. 8 shows the station displacements, and the statistic information is shown in Table III. The displacement in the TL station is 45 mm and 28 mm for the mean and the SD, respectively, whereas that in the PTB station is 34 mm and 23 mm for the mean and SD, respectively.

In contrast to Table I, Table III shows a consistent solution for the TL station. However, this is not the case for the PTB station. The result in Table III is greatly improved for the PTB station, in particular for the mean, which is reduced from 215 mm to 34 mm. This improvement leads to the PTB displacement bias consistent with the TL displacement bias. As such, we may conclude that the reference coordinate in the CGGTTS file requires to be constantly updated.

TABLE III. THE STATISTIC INFORMATION OF THE STATION DISPLACEMENTS

	Mean (mm)	SD (mm)
TL	45	28
PTB	34	23

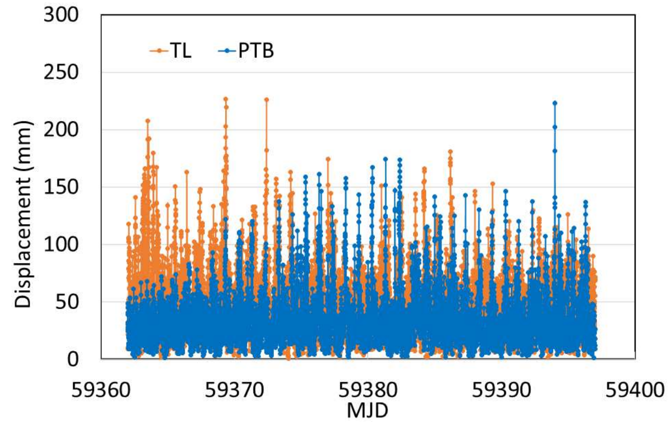

Fig. 8. Station displacement with respect to the first-day PPP solution of the one-month data

Fig. 9 shows the time correction caused by the station displacement with respect to the first-day PPP solution. Table IV shows the statistic information. The time correction for the TL station is -9 ps for the mean and 100 ps for the SD, whereas that for the PTB station shows 18 ps and 70 ps for the mean and SD, respectively.

In contrast to Table II, the statistic information for the TL in Table IV is similar. However, the statistical mean for the PTB is improved by ~95%. This is because the PTB coordinates are updated by the PPP solution. Noticeably, the SD of PTB in Table IV is similar to that in Table II. This can be attributed to the Eqs. (4) and (5), where the elevation and azimuth of the satellite are used for conducting this work. As a result, we do not recommend that the reference coordinate in the CGGTTS file is used for the station displacement in the time transfer. On the other hand, we find the periodical variations of the time corrections in the PTB station, most likely caused by the M2 component in the tidal loading model. The higher peaks appeared on MJD 59377 and MJD 59390 in Fig. 9, which happened on the same dates as in Fig. 3.

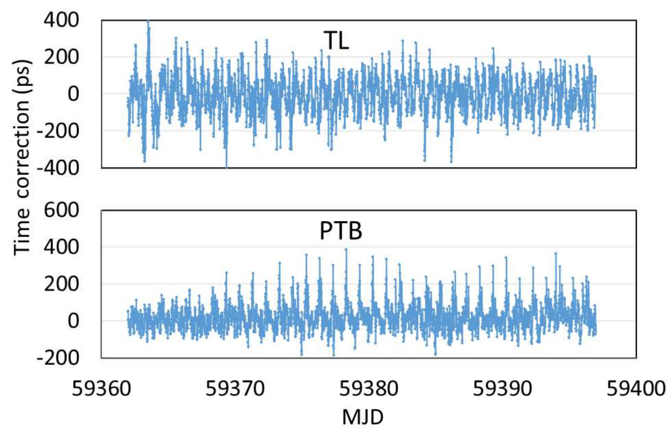

Fig. 9. Time corrections of GPS AV for TL and PTB stations

The TDEVs of GNSS AV time transfer results for TL-PTB link were plotted in Fig. 10. The black curve is almost overlapped with the red curve. The blue curve is higher than that in Fig. 4 and is slightly lower than that in Fig. 7. The TDEV shows a peak of 80 ps at the averaging times around 1.5×10^{4} s.

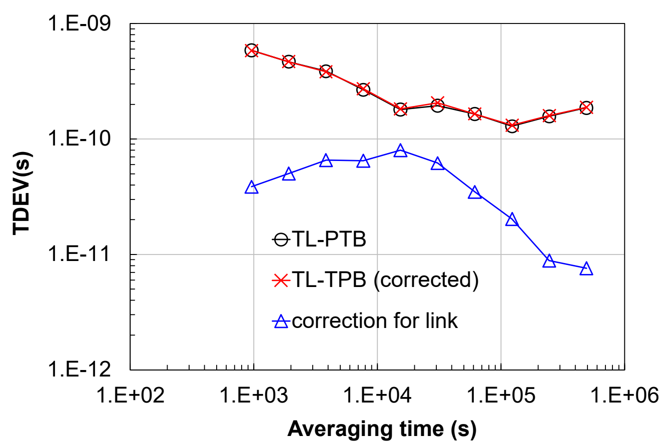

Fig. 10. Time deviation of TL-PTB AV reults: Original results(black circle), corrected results(red cross) and the correction data (blue triangle)

TABLE IV. THE STATISTIC INFORMATION OF THE TIME CORRECTIONS CAUSED BY THE STATION DISPLACEMENTS

	Mean (ps)	SD (ps)
TL	-9	100
PTB	18	70

IV. DISCUSSIONS

In this study, we consider the effect of the station displacement only on the change of propagation delay from the GNSS satellite to the receiver. However, other effects and error source should be considered together. For a clock at a station, 1-cm change in height on Earth's surface is equivalent to the relativistic redshift effect of 10^{-18} [8]. Thus, a 3-cm variation may accumulate at most a phase difference of 0.13 ps for a half day. Several studies have characterized the GNSS errors in time transfer at sub-daily level [9]. For example, the multipath delay may have a deviation of 40 mm and tropospheric delay accuracy of the IGS final product is about 4 mm. Such errors must be taken into account carefully for the time transfer results.

V. CONCLUSIONS

The correction of station displacement is relatively small compared to the noise level of GNSS AV time transfer. We did not find the significant difference between the AV results with and without the BLQ correction. This is mainly attributed to the fact that the PPP-derived station coordinates are resulted from the ionosphere-free linear combination of dual-frequency phase observations. However, the solution of AV time transfer in this work is resulted from the P3 solution, whose noise level is much higher than the PPP-derived station coordinates. In addition, the time corrections caused by the BLQ effect for the TL and the PTB stations varied from -90 ps to 50 ps, and from -22 ps to 25 ps, respectively. As such, the AV time solution is not sensitive to this geophysical effect. On the other hand, the station coordinates require to be constantly updated in the CGGTTS file in minimizing the coordinate inconsistence.

The station displacement due to the geodynamic activities, e.g., tectonic motion and the geophysical effect, e.g., the ocean tide loading should be taken into account for the time transfer. For example, the yearly movement of the TWTF IGS station is about 33 mm [8], the displacements over 2-4 years may become significant in time transfer results. Therefore, the time transfer solution is geographic-dependent. We will discuss the long-term effect of the station displacement and also test the effectiveness of the correction on the upsampled common view results of the GNSS P3 code time transfer [11] in the future work.

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