Application of Vondrak Filtering Method in Software Defined Receiver (SDR)-Two-Way Satellite Time and Frequency Transfer（TWSTFT）

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***Abstract*—In March 2020, Two-Way Satellite Time and Frequency Transfer based on SDR-TWSTFT (Software Defined Receiver) link data has been used in the calculation of TAI (International Atomic Time) for the first time. Improving the reliability and stability of the link is of great significance to enhance the performance of TAI. By analyzing the performance of SDR-TWSTFT link, it is found that the results show some characteristics of random noise. In this paper, a frequency domain amplitude analysis method based on Vondrak filtering theory is proposed, which can determine the filtering factor. This method is used to process the SDR-TWSTFT link measurement data between the NTSC (National Time Service Center) of the Chinese Academy of Sciences and the PTB (Physikalisch Technische Bundesanstalt). It is found that this method can improve the reliability of the link time transfer results, and significantly improve the short-term frequency and time stability of the filtered link.**

Keywords—SDR; TWSTFT; link calibration; Vondrak filtering

I. Introduction

TWSTFT (Two-Way Satellite Time and Frequency Transfer) is one of the most accurate time transfer technologies. In the calculation process of UTC (Coordinated Universal Time), the link undertakes 60% of the weight of the atomic clock data and most of the primary atomic frequency standard data transfer tasks. The traditional TWSTFT link has good long-term stability, but its medium and short-term performance is significantly affected by the diurnal effect [1]. In order to improve the medium and short-term stability of TWSTFT link, since 2016, 16 time keeping laboratories have participated in the research work related to SDR (Software Defined Receiver)-TWSTFT. The SDR-TWSTFT receiver used in the study is based on a general SDR module, which couples a fast analog-to-digital converter with a computer with high computing power (calculated by Graphic Processing Unit). As of today, 13 participating laboratories regularly report SDR data to BIPM (Bureau International des Poids et Mesures). SDR-TWSTFT link data was first used in UTC computing in March 2020.

At present, the research on SDR-TWSTFT links mainly focuses on the links within Asia and Europe, Europe and America as well as Eurasia. In order to analyze the performance of SDR-TWSTFT link, firstly, by comparing the measurement results with the original TWSTFT link, it is found that SDR-TWSTFT link can effectively reduce the influence of diurnal effect on the measurement results; Comparison with other techniques ,such as IPPP (Integer ambiguity Precise Point Positioning), the results show that the overall performance of the link is better than that of the existing TWSTFT link (some research results have been published in BIPM researcher Z. H. Jiang [2]).

In March 2018, the Asia Europe laboratory replaced the previous AM22 satellite with ABS-2A satellite to reconstruct the Ku band TWSTFT link. In order to further improve the short-term and medium-term measurement uncertainty of SDR-TWSTFT link, a frequency-domain amplitude method is proposed to select the Vondrak filter factor [3]. Firstly, the low-pass filter is used to weaken the residual diurnals of SDR-TWSTFT link and suppress the high-frequency component. Then, another parallel and independent GPS (Global Positioning System) PPP (Precise Point Positioning solutions) time transfer link is used to evaluate the reliability of the filter result. Finally, the performance of SDR-TWSTFT link before and after filtering is analyzed.

II. SDR-TWSTFT Link Calibration

A. Principle of SDR-TWSTFT

The principle of SDR-TWSTFT is shown in Fig. 1. The uplink part of the system is the same as that of the traditional TWSTFT system. The ground station A modulates the PRN (Pseudo-Random Noise) synchronized with the master clock signal to the IF (Intermediate Frequency) carrier by the way of BPSK (Binary Phase Shift Keying) through the SATRE (SAtellite Time and Ranging Equipment) [4], and then adjusts the IF signal to Ku band by the transmitting cell and transmits it to GEO (Geostationary Earth Orbit) satellite, finally, the satellite transparently transmits the time signal of ground station A. In the downlink part, at ground station B, the traditional SATRE is replaced by SDR. First, the Ku band signal is adjusted to the intermediate frequency through the receiving cell, and then the processed signal is connected to the input of the SDR. The signal analog-to-digital conversion, demodulation, filtering and other processes are completed in

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the SDR, and then the band-pass filtering is carried out at the output of the SDR to obtain the one-way time transfer results, finally, the clock difference between the two ground stations is obtained by data exchange.

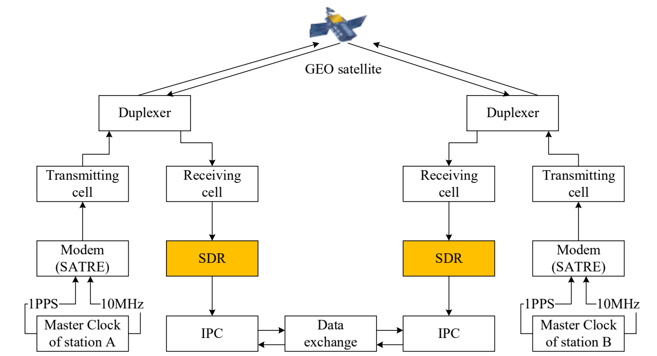

Fig. 1. Principle of SDR-TWSTFT

Equation (1) is the calculation formula of SDR-TWSTFT, where T_k is the master clockface of the ground station, K is the code of the ground station (the same below), T_{TWK} is the one-way transmission delay measured by the ground station, T_{CALRK} is the calibration delay in TWSTFT link, and $T_{ESDVARK}$ is the correction value of the ground station delay after the calibration delay, $T_{REFDLYK}$ is the time delay between the local time reference point of the ground station and the TWSTFT equipment.

$$
\begin{aligned}
T_A - T_B = &\frac{1}{2}\left(T_{TWA} + T_{CALRA} + T_{ESDVARA}\right) \\
&-\frac{1}{2}\left(T_{TWB} + T_{CALRB} + T_{ESDVARB}\right) \\
&+T_{REFDLYA} - T_{REFDLYB}
\end{aligned} \quad (1)
$$

B. Method of SDR-TWSTFT link calibration

The calibration of time transfer link can improve the accuracy of time transfer results. At present, the class A time transfer uncertainty of GPS PPP algorithm [5] has reached 0.3ns [6]. GPS PPP has the characteristics of high resolution and high precision, so when there is no calibrator to calibrate the TWSTFT link directly, the calibrated GNSS link can be used to calibrate indirectly.

As shown in Fig. 2, two independent time transfer links are established between the local station and PTB of the time transfer link hub, and the SDR-TWSTFT link is indirectly calibrated using the calibrated GPS PPP link [7]. The physical realization signals of $\mathrm{UTC}(k)$ are Pulse Per Second (1PPS) pulse and 5MHz frequency signal respectively. The frequency signal is converted to 10MHz through frequency multiplier for the use of calibrated receiver and SDR equipment to be calibrated. The receiver in GPS PPP link has been calibrated and the initial synchronization second signal of the SDR equipment in TWSTFT link to be calibrated uses 1PPS pulse signal. Using the principle of GPS PPP and SDR-TWSTFT, the deviation between $\mathrm{UTC}(k)$ and IGS System Time (IGST) is measured for GPS PPP link. The clock difference D_{PPP}

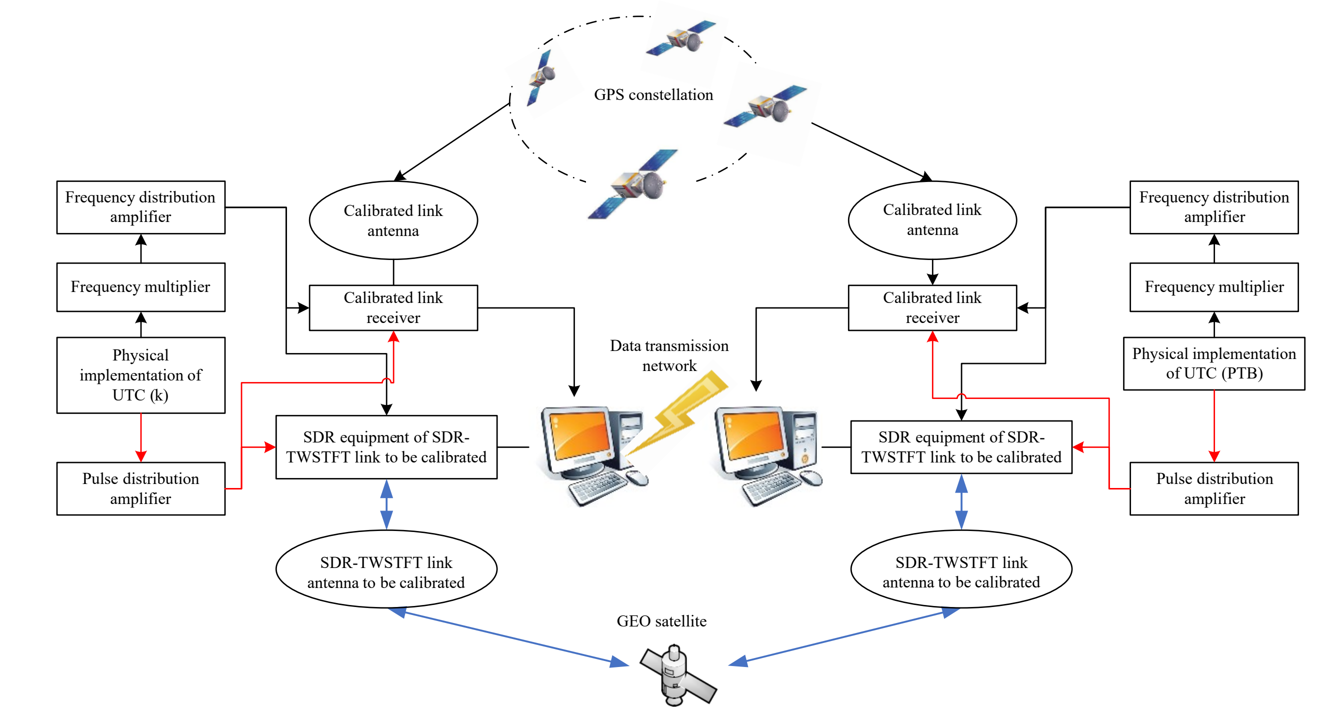

Fig. 2. SDR-TWSTFT link calibration principle

between $\mathrm{UTC}(k)$ and $\mathrm{UTC}(\mathrm{PTB})$ is obtained by interacting with the data transmission network. For SDR-TWSTFT link, according to SDR-TWSTFT principle described in the previous section, after measuring one-way data, the clock difference $D_{\text{SDR-TWSTFT}}$ between $\mathrm{UTC}(k)$ and $\mathrm{UTC}(\mathrm{PTB})$ is obtained through data transmission network interaction data. The $D_{\text{SDR-TWSTFT}}$ time series is interpolated with reference to D_{PPP} to get D_{CPPP} [8]. The difference between D_{CPPP} and $D_{\text{SDR-TWSTFT}}$ is the single calibration value, and it is recorded as $C = D_{\text{CPPP}} - D_{\text{SDR-TWSTFT}}$. The calibration value is the mean of the single calibration value. In order to improve the accuracy of calibration values, we need at least 7 days of continuous measurement data.

III. VONDRAK FILTERING METHOD

Vondrak filtering is a smooth curve which seeks a compromise between absolute fitting and absolute smoothing of measured data. The key of Vondrak filtering lies in the selection of filtering factors.

A. *Basic principles*

Record the measured data as $x(t_i)$, where $i = 1:\ \mathrm{N}$. The basic formula [9] of Vondrak filtering is shown in (2),

$$Q = F + \lambda^2 S = \min \tag{2}$$

λ^2 is between 0 and ∞, which is the undetermined coefficient, used to adjust the relationship between fitting degree and smoothness. When $\lambda^2 \to 0$, it needs $F \to 0$ to get the minimum value of Q. on the contrary, when $\lambda^2 \to \infty$, it needs $S \to 0$ to get the minimum value of Q. F and S are shown in (3) and (4),

$$F = \sum p_i \left[x'(t_i) - x(t_i) \right]^2 \tag{3}$$

$$S = \sum_{i=1}^{\mathrm{N}-3} \left[\Delta^3 x'(t_i) \right]^2 \tag{4}$$

where $x'(t_i)$ is the filtering value, p_i is the weight of $x(t_i)$. F is greater than 0, which is the fitting degree of Vondrak filter. S is greater than 0, which is the constraint condition for the sum of the squares of the cubic difference of the filtering value, and reflects the smoothness of the filtering curve.

B. *Determination the filter factor*

The uncertainty introduced by time transfer link is the main source of uncertainty in $\mathrm{UTC}(k)$ calculation. According to the results of long-term statistical analysis, the daily stability of $\mathrm{UTC}(\mathrm{NTSC})$ quantity class is at 10^{-15}, and the medium and short-term stability within 24 hours quantity class is at 10^{-14} to 10^{-13}. In order to corresponding improve the medium and short-term stability of $\mathrm{UTC}(k)$, the frequency domain amplitude analysis method is used to select the filter factor. The measurement interval of SDR-TWSTFT is short, and the short-term stability is significantly affected by the measurement noise. In the data post-processing, it is necessary to suppress the short-term noise while preserving the medium and long-term characteristics of the signal. We focus on the analysis of the amplitude curves of filtering results at 48, 36, 24, 12, 8, 4 and 2 hours under different filtering factors. The factors that can make the frequency domain amplitude as high as possible in 48 and 36 hours and the amplitude as low as possible in 24, 12, 8, 4 and 2 hours are selected to filter the measured data.

IV. DATA PROCESSING AND ANALYSIS

A. *Data calibration results*

GPS PPP link and SDR-TWSTFT link between NTSC and PTB are independent of each other, so comparing the measurement results of the two links, if their maximum deviation is within the measurement uncertainty range, it can be considered that their measurement results are consistent and the calibration is effective. According to the propagation rate of measurement uncertainty, the combined uncertainty of two independent links is the arithmetic square root of the sum of their respective uncertainties. This paper selects the data of 30 days from MJD 59175 to 59205 for analysis. The measurement uncertainty [10] of NTSC-PTB SDR-TWSTFT link is about 1.59ns, and that of NTSC-PTB GPS PPP link is about 1.48ns. The calculation shows that when the absolute value of the maximum deviation of the two links is less than 2.17ns, the indirect calibration of SDR-TWSTFT link using GPS PPP is effective.

Fig. 3 shows the comparison between the results of time transfer links between NTSC and PTB in this period and that of Circular T (Cirt.) published by BIPM. The data trend of the two links is basically consistent with that published by Cirt.396.

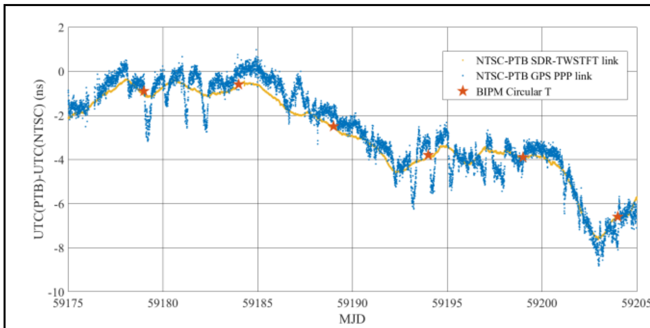

Fig. 3. Comparison between NTSC-PTB time transfer link and Circular T

Fig. 4 shows the maximum deviation distribution of the measurement results of the two links before and after filtering. Obviously, the maximum deviation is within 2.17ns, and the measurement results of the links are consistent.

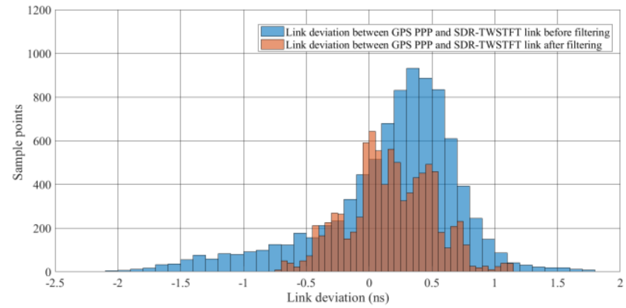

Fig. 4. Maximum deviation distribution between NTSC-PTB time transfer links

B. *Example of selecting filter factor*

The Vondrak filter has good low pass performance. The smaller the filter factor, the smoother the data after filtering. In order to avoid excessive data distortion, SDR-TWSTFT data is filtered in a certain range, and then the initial scan filter factor with less distortion is selected by analyzing the spectrum of the filtering results. In this paper, the filter factor is in the range of 0 to 50000, and the data is filtered in 100 steps. It is found that the characteristic distortion of the link within 24 hours is very large and does not meet the requirements when the filter factor is less than 7500. Therefore, the filter factor is set between 7500 to 15005500, and the calibrated SDR-TWSTFT measurement data is filtered by Vondrak in 1000 steps. Fig. 5 shows the amplitude curves of different components in frequency domain after filtering with different filtering factors. Obviously, choosing different filtering factors has no significant effect on the amplitude of 12, 8, 4, 2 hours components in frequency domain, the 48-hour component decreased monotonously, the 32-hour component increased monotonously, there is an inflection point in the 24-hour component.

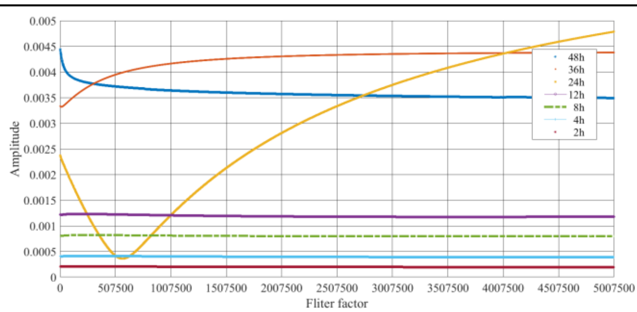

Fig. 5. Selection of filter factors for NTSC-PTB SDR-TWSTFT link-1

In order to determine the filter factor that meets the conditions, S_j is defined as the sum of the amplitudes of 48, 32 and 24 hour components when the filter factor is j, V_{48j} is the ratio of the amplitudes of 48-hour component when the filter factor is j to S_j, V_{32j} is the ratio of the amplitudes of 32-hour component when the filter factor is j to S_j, V_{24j} is the ratio of the amplitudes of 24-hour component when the filter factor is j to S_j, Then the filter factor satisfying the condition will make V_{48j} and V_{32j} as large as possible and V_{24j} as small as possible. As shown in Fig. 6, when the filter factor is 576500, it meets the requirements.

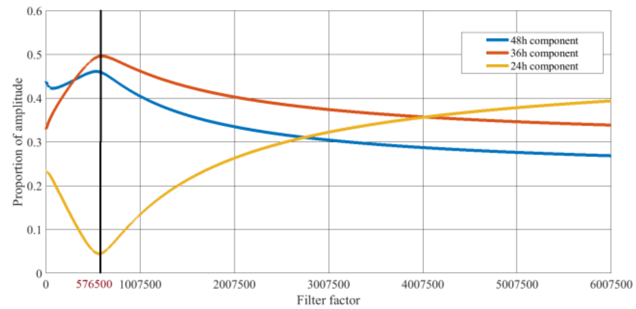

Fig. 6. Selection of filter factors for NTSC-PTB SDR-TWSTFT link-2

C. *Link performance analysis*

This section will analyze and discuss the link performance from the stability and spectrum distribution of link time transfer results before and after filtering.

Fig. 7 shows the link frequency stability analysis results represented by Allan deviation before and after filtering. The dotted line shows the analysis results of NTSC-PTB SDR-TWSTFT link before filtering. The solid line shows the analysis results of the link after filtering. Tau is the average time. It can be seen that the link frequency stability is improved when the average time is within 307000 seconds, the short-term stability of 300 seconds is improved by 99%, and the medium-term stability of 76800 seconds is improved by 27%.

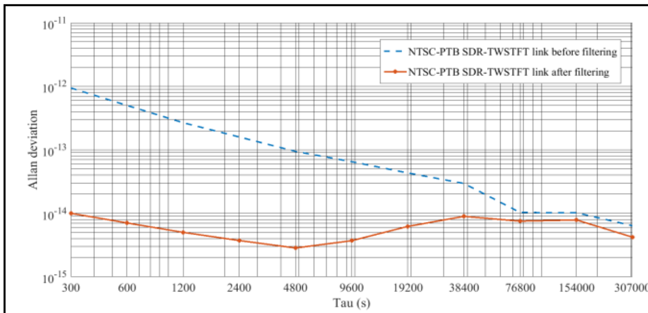

Fig. 7. Analysis of link frequency stability before and after filtering

Fig. 8 is the analysis result of link time stability characterized by time deviation before and after filtering. The dotted line is the result of the link before filtering. The solid line is the result of the link after filtering. Tau is the average time. It can be seen that the link time stability is also improved when the average time is within 307000 seconds, the short-term stability of 300 seconds is improved by 99%, and the short-term stability of 76800 seconds is improved by 4%. Since 768000 seconds, the short-term frequency stability and time stability of the link are greatly reduced, which also shows the effectiveness of the filter factor, that is to say, the performance characteristics of the link within 24 hours have been preserved.

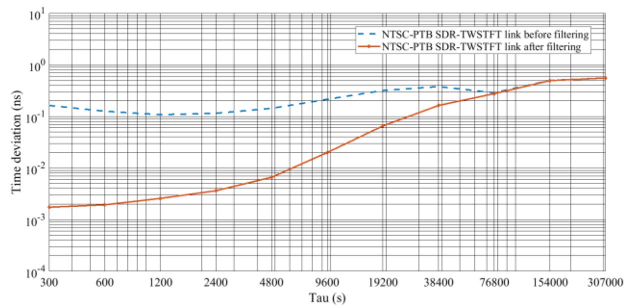

Fig. 8. Analysis of link time stability before and after filtering

Each frequency component of the time link transfer result is quantitatively analyzed by using spectrum analysis, and the result is shown in Fig. 9. Blue is the result of spectral analysis after filtering, and red is the result before filtering. The energy of each component of the signal is normalized before and after filtering. The 24-hour frequency component is marked in the figure. Obviously, the amplitude of the frequency component increases significantly after filtering. This is because we are concerned about the concentration of energy distribution to the low frequency band after filtering the high frequency component. This shows that the high-frequency component in the time transfer result is obviously suppressed and the properties of low-frequency component is more obvious after using our selected filter factor.

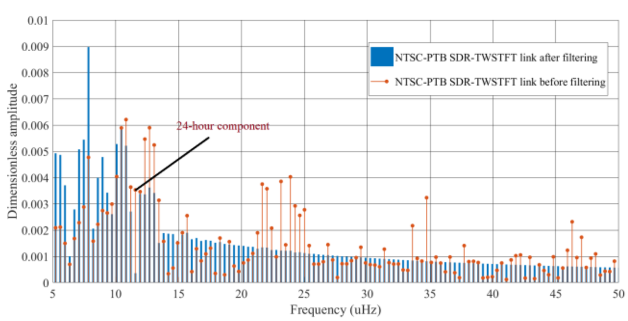

Fig. 9. Spectrum analysis of NTSC-PTB SDR-TWSTFT link before and after filtering

V. CONCLUSIONS

SDR-TWSTFT was officially used in the calculation of UTC and TAI in March 2020. Its daily frequency stability and time stability can reach 10^{-15} and 1ns. In order to improve its short-term stability, this paper uses the Vondrak filtering method, comprehensively considers the characteristics of time transfer data in different frequency points, and uses the frequency domain amplitude method to select the filtering factor, which can realize the low-pass filtering of time transfer results. Using the method introduced in this paper to process and analyze the measured data of NTSC-PTB SDR-TWSTFT link, the following conclusions are drawn.

Firstly, Vondrak filtering method can not only improve the medium and short-term frequency stability of the link, but also improve the medium and short-term time stability of the link.

Secondly, the filter factor selected by frequency domain amplitude curve is not sensitive to the frequency component of time transfer result within 12 hours, so the filter factor can be selected flexibly according to this characteristic. This method is effective for filtering the high frequency noise of the link average time within 24 hours. While filtering the noise, it retains the low frequency characteristic component of the time transfer result.

Thirdly, by comparing the residual distribution of the SDR-TWSTFT link and GPS PPP link before and after filtering, the measurement results after filtering are distributed in the range of link measurement uncertainty. This method improves the reliability of SDR-TWSTFT link time transfer results.

REFERENCES

[1] Jiang Z, Petit G, “Redundancy in the TAI TWSTFT time transfer network,” in Proc. the 20th European Frequency and Time Forum (EFTF), 2006, pp. 469–475.

[2] Jiang Z, Zhang V, Huang Y J, Achkar J, Piester D et al, “Use of software-defined radio receivers in two-way satellite time and frequency transfers for UTC computation,” Metrologia, Vol. 55, no. 5, pp. 685–698, 2018.

[3] Y. Y. Wu, “The criterion and the application of Vondrak filter,” Doctoral dissertation, Central South University, pp. 7–14, May 2012.

[4] X. Wang, H. J. Song, W. X. Wang, Z. Gao, J. H. Zhang et al, “Performance optimization method of Two-Way satellite time and frequency transfer link based on conditional adjustment,” Acta astronomica Sinica, pp. 25-1–25-14, May 2020.

[5] KOUBA J, HEROUX P, “Precise point positioning using IGS orbit and clock products,”. GPS Solutions, Vol. 5, no. 2, pp. 12–28, 2001.

[6] Jiang, Z, Czubla, A, Nawrocki, J, Lewandowski, W, Arias, E F, “Comparing a GPS time link calibration with an optical fibre self-calibration with 200ps accuracy,” Metrologia, Vol. 52, no. 2, pp. 384–391, 2015.

[7] Yao J, Weiss M, Curry C , Levine J, “GPS Jamming and GPS Carrier-Phase Time Transfer,” in Proc.2016 Precise Time and Time Interval Meeting, pp. 173–183.

[8] W. J. Wu, Z. G. Li, X. H. Yang, H. Lei, L. Chen et al, “Sagnac effect on Two-way satellite time and frequency transfer,” Journal of Astronautics, Vol. 33, no. 7, pp. 936–941, 2012.

[9] Y. Lei, D. N. Zhao, “Filtering random noise from PPP time transfer based on Vondrak,” Engineering of Surveying and Mapping, Vol.22, no. 6, pp. 18–21, 2013.

[10] W. J. Wu, M. Jiang, X. Wang, J. H. Zhang, W. Guang et al, “Two-way satellite time and frequency transfer based on software defined receiver,” Journal of Time and Frequency, Vol.43, no. 2, pp. 94–100, 2020.