AI translation · View original & related papers at
chinarxiv.org/items/chinaxiv-202504.00169

# Postprint: Data Fusion Methods for Time Transfer Links under Non-uniform Sampling Conditions

**Authors:** Wang Xiang, Song Huijie, Guo Dong, Gao Zhe, Wei-Xiong Wang, Wu Wenjun, Dong Shaowu

**Date:** 2025-04-08T16:02:35+00:00

## Abstract

To fully utilize different types of time transfer links, a data fusion method based on multiresolution analysis is proposed to achieve fusion applications of time transfer link data at different sampling rates. First, wavelet decomposition is applied to the original data, decomposing it to a unified resolution to preliminarily eliminate high-frequency noise; Kalman filtering is then performed at different resolutions; finally, the fusion result is obtained through the Mallat fast reconstruction algorithm. Using this method to process time transfer data between the Chinese Academy of Sciences'National Time Service Center (NTSC) and the Physikalisch-Technische Bundesanstalt (PTB), the results demonstrate that the fusion algorithm can handle data issues caused by link anomalies or interruptions. Since the measured performance of GPS (Global Positioning System) PPP (Precise Point Positioning solutions) links is generally superior to that of TWSTFT (Two-Way Satellite Time and Frequency Transfer) links, the GPS PPP link measurement results are therefore used to evaluate the fusion algorithm gain. Using Rapid Realization of Coordinated Universal Time (UTCr) as a reference, the accuracy gain of the data fusion results is approximately 1%, and the daily frequency stability gain is better than 20%. Simultaneously, the fusion algorithm can suppress periodic noise in TWSTFT links, effectively improving the stability and robustness of the links.

## Full Text

## Preamble

**Vol. 66 No. 2**

**March 2025**

ChinaRxiv

*Acta Astronomica Sinica*

# Research on Data Fusion Method for Time Transfer Links under Unequal-Interval Measurement Conditions

WANG Xiang[1,2]†, SONG Hui-jie[1,2], GUO Dong[1,2], GAO Zhe[1,2], WANG Wei-xiong[1,2], WU Wen-jun[1,2,3], DONG Shao-wu[1,2,3]

[1] National Time Service Center, Chinese Academy of Sciences, Xi' an 710600
[2] Key Laboratory of Time Reference and Applications, Chinese Academy of Sciences, Xi' an 710600
[3] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049

## Abstract

To fully utilize different types of time transfer links, it is necessary to achieve fusion of time transfer link data under varying sampling rates. This paper proposes a data fusion method based on multi-resolution analysis. First, wavelet decomposition is applied to the original data to project it onto a unified resolution, initially eliminating high-frequency noise. Kalman filtering is then performed at different resolutions. Finally, the Mallat fast reconstruction algorithm is used to obtain the fusion result. The method was applied to process time transfer data between the National Time Service Center (NTSC) of the Chinese Academy of Sciences and the Physikalisch-Technische Bundesanstalt (PTB) of Germany. The results demonstrate that the fusion algorithm can effectively handle data issues caused by link anomalies or interruptions. Since the measured performance of the GPS (Global Positioning System) PPP (Precise Point Positioning solutions) link is generally superior to that of the TWSTFT (Two-Way Satellite Time and Frequency Transfer) link, the GPS PPP link measurements were used to evaluate the algorithm' s gain. Using Rapid Realization of Coordinated Universal Time (UTCr) as the reference, the data fusion results show an accuracy gain of approximately 1% and a daily frequency stability gain better than 20%. Simultaneously, the fusion algorithm can suppress periodic noise in the TWSTFT link, effectively improving link stability and robustness.

**Keywords:** techniques: TWSTFT, techniques: GPS PPP, techniques: time transfer, methods: wavelet decomposition, methods: Kalman filtering, methods: fusion

## 1 Introduction

Two-Way Satellite Time and Frequency Transfer (TWSTFT) and GPS PPP (Precise Point Positioning solutions) time transfer are the most commonly used techniques in international time transfer. In the time transfer network that generates Coordinated Universal Time (UTC), GPS PPP links account for 60% of the total number of links, while TWSTFT links transmit clock data representing 60% of the total atomic clocks and primary frequency standards. Statistics from July 2023 show that in Circular T 426 published by the Bureau International des Poids et Mesures (BIPM), only 7% of the total links used were composite link data, indicating substantial redundant links in the international time transfer network.

In recent years, numerous studies on redundant data have supported this multi-technology fusion strategy. In 2009, Martinez et al. proposed a fusion method based on GPS code and carrier phase measurements combined with TWSTFT data. By using TWSTFT data as additional observation equations and applying least-squares analysis, they successfully improved the boundary discontinuities in GPS carrier phase, introducing new ideas and methods to the time transfer field. In 2011, Defraigne et al. successfully achieved remote time transfer through comprehensive modeling of GNSS code and carrier phase, further demonstrating the effectiveness and potential of multi-technology integration. In 2012, Jiang et al. analyzed the performance of GLONASS and GPS combinations, finding that combined data excelled in improving short-term link stability, particularly in enhancing UTC link accuracy and robustness. Following extensive related research, the Consultative Committee for Time and Frequency (CCTF) proposed to BIPM at its 21st meeting in 2017 that redundant time transfer systems should be applied in UTC generation. This recommendation reflects current trends and practical needs in time transfer. Subsequently, Verhasselt et al. in 2019 investigated time transfer performance using different combination methods across GNSS constellations, with results showing that multi-constellation combined solutions significantly outperformed single solutions, providing new directions for future time transfer technology development. In 2021, Wang et al. adopted a scheme using the derivative of GPS PPP results as the average rate of TWSTFT measurements, together with the phase data of TWSTFT measurements as observation measurements, and completed data fusion using a Kalman algorithm, improving link robustness. These studies have advanced time transfer technology and provided strong technical support for BIPM' s adoption of redundant time transfer systems in UTC generation.

In practice, different types of time transfer links have different measurement resolutions. To fully utilize the complementary information from different resolution data and achieve optimal fusion results, a fusion method capable of handling multi-resolution measurement data is required.

Wavelet multi-resolution information processing and Kalman filtering are commonly used methods for time-frequency data analysis. Wavelet multi-resolution information processing can describe different variation characteristics of random processes or signals in the short, medium, and long term. However, due to its lack of real-time capability and recursiveness, wavelet analysis can only process signal blocks obtained over a period. Kalman filters are based on the time-domain dynamic model and observation model of the target, making it difficult to obtain accurate state estimation for time transfer links with multi-scale characteristics. To fully leverage the advantages of both methods and compensate for their shortcomings, we consider combining them: first using wavelet analysis to decompose observation information from different resolutions to the same scale, then using a Kalman filter for real-time, recursive optimal estimation of the observation information, which can meet the requirement of fusing data from different measurement resolutions.

This paper derives the multi-link dynamic time measurement system and multi-link Kalman filter update equations based on wavelet decomposition, designs a data fusion scheme based on wavelet decomposition and Kalman filtering, and finally randomly selects UTC official link data (TWSTFT and GPS PPP) between the National Time Service Center (NTSC) of the Chinese Academy of Sciences and the Physikalisch-Technische Bundesanstalt (PTB) of Germany to analyze the algorithm' s effect on suppressing the TWSTFT link' s diurnal phenomenon, and evaluates the algorithm' s improvement of original measurement result performance from three aspects: stability, accuracy, and data integrity.

## 2 Multi-Link Dynamic System Based on Wavelet Decomposition

Using the idea of wavelet multi-resolution analysis and combining it with measurement data from time transfer links, an optimal dynamic multi-resolution filtering algorithm can be constructed with error variance minimization as the criterion to achieve optimal estimation.

### 2.1 Principle of Wavelet Decomposition

Wavelet decomposition breaks down a signal into a series of wavelets at different scales. These wavelets can be regarded as window functions of different frequencies and time scales. By sliding them across the signal and multiplying, information about the signal at different times and frequencies is obtained.

Assume $f$ is the link data to be processed, belonging to the space of Lebesgue square-integrable functions on $\mathbb{R}$, i.e., $f \in L^2(\mathbb{R})$. For any $j$ belonging to the integer set $\mathbb{Z}$, define $f_j$ as an approximation of $f$, with $f_j \in V_j$, where $\{V_j\}_{j\in\mathbb{Z}}$ is a multi-resolution analysis generated by the scaling function $\phi$, $k$ is the translation factor, and $\phi$ is expressed as

$$\phi(x) = \sum_k h_k \phi(2x - k), \quad -\infty < x < \infty$$

where $h_k = \int_{-\infty}^{\infty} \phi(x)\overline{\phi}(2x-k)dx$, and $\overline{\phi}$ is the conjugate function of $\phi$. The wavelet function is expressed as

$$\psi(x) = \sum_k g_k \phi(2x - k)$$

where $g_k = (-1)^k \overline{h}_{1-k}$, and $\overline{h}$ is the conjugate function of $h$. Then we have

$$f_j(x) = \sum_k c_{j-1;k}\phi_{j-1;k}(x) + \sum_k d_{j-1;k}\psi_{j-1;k}(x)$$

where the scaling coefficients can be expressed as the inner product of function $f_j$ with the scaling function $\phi_{j-1;k}$ at scale $j-1$ with translation parameter $k$, $c_{j-1;k} = \langle f_j, \phi_{j-1;k}\rangle$, and the wavelet coefficients can be expressed as the inner product of function $f_j$ with the wavelet function $\psi_{j-1;k}$ at scale $j-1$ with translation parameter $k$, $d_{j-1;k} = \langle f_j, \psi_{j-1;k}\rangle$. The relationship between scaling coefficients at two levels $c_{j;k}$ and $c_{j-1;k}$ can be expressed as

$$c_{j-1;k} = \sum_{n\in\mathbb{Z}} \overline{h}_{n-2k} c_{j,n}$$

and the relationship between wavelet coefficients at two levels $d_{j;k}$ and $d_{j-1;k}$ can be expressed as

$$d_{j-1;k} = \sum_{n\in\mathbb{Z}} \overline{g}_{n-2k} c_{j,n}$$

After data decomposition processing, we obtain

$$f_j(x) = \sum_k c_{j-1;k} \sum_n h_{n-2k}\phi_{j,n}(x) + \sum_k d_{j-1;k} \sum_n g_{n-2i}\phi_{j,n}(x)$$

Then taking the inner product of both sides of the equation with $\phi_{j,n}(x)$, we get

$$c_{j,n} = \sum_k h_{n-2k} c_{j-1;k} + \sum_k g_{n-2k} d_{j-1;k}$$

Thus completing the reconstruction.

### 2.2 Multi-Link Dynamic System Description

At scale level $i$, the single-link state equation corresponding to time $t+1$ can be expressed as

$$x(i,t+1) = A(i,t)x(i,t) + w(i,t)$$

where $A(i,t) \in \mathbb{R}^{n\times n}$ is the state transition matrix, $w(i,t)$ is the system noise satisfying a normal distribution $w(i,t) \sim N(0, Q(i,t))$, and $Q(i,t)$ is its covariance matrix. The mean and variance of the initial state value $x(t)$ satisfy $E[x(0)] = x_0$ and $E\{[x(0)-x_0][x(0)-x_0]^T\} = P$, where $E$ denotes mathematical expectation.

When there are $N$ independent time transfer links, with $f$ $(f = 1, 2, \cdots, N)$ representing each link, the system measurement vector $z_f(i,t)$ at scale $i$ and time $t$ can be expressed as

$$z_f(i,t) = C(i)x(i,t) + v(i,t)$$

where $C(i)$ is the system measurement matrix, $v(i,t)$ is the measurement noise satisfying $v(i,t) \sim N(0, R(i,t))$, and $R(i,t)$ is its covariance matrix. It should be noted that $v(i,t)$ and $w(i,t)$ are independent of each other.

To unify time transfer link data under non-equal-interval measurement conditions to the same scale, it is necessary to achieve conversion of the link state equation and measurement equation from scale $i$ to scale $i-1$. According to the principle of wavelet decomposition, decomposing the system state from scale $i$ to scale $i-1$ yields

$$x(i-1,t-1) = \sum_k h_k x[i, 2(t-1)-k]$$

$$= \sum_k h_k \{A(i)x[i, 2(t-1)-k-1] + w[i, 2(t-1)-k-1]\}$$

$$= \sum_k h_k A(i)x[i, 2(t-2)-k] + \sum_k h_k w[i, 2(t-1)-k-1]$$

$$= A(i)A(i)\sum_k h_k x[i, 2(t-2)-k] + A(i)\sum_k h_k w[i, 2(t-2)-k] + \sum_k h_k w[i, 2(t-1)-k-1]$$

$$= A_i(i-1)x_i(i-1,t-2) + w_i(i-1,t-2)$$

where the summation symbol $\sum_{k\in\mathbb{Z}}$ is omitted, and the same applies below. That is, after decomposing the system state from scale $i$ to scale $i-1$, it can be expressed as

$$x_i(i-1,t-1) = A_i(i-1)x_i(i-1,t-2) + w_i(i-1,t-2)$$

where

$$x_i(i-1,t-2) = \sum_k h_k x[i, 2(t-2)-k]$$

$$A_i(i-1) = A(i)A(i)$$

$$w_i(i-1,t-2) = A(i)\sum_k h_k w[i,2(t-2)-k] + \sum_k h_k w[i,2(t-1)-k-1]$$

and the system noise mean also satisfies $E[w_i(i-1,t-2)] = 0$, with the system noise covariance satisfying

$$Q(i-1,t-2) = A(i)\sum_k Q[i,2(t-2)-k]A^T(i) + \sum_k Q[i,2(t-1)-k-1]$$

Using the same method to decompose the measurement vector from scale $i$ to scale $i-1$, we have

$$z_i(i-1,t-1) = C_i(i-1)x_i(i-1,t-1) + v_i(i-1,t-1)$$

where

$$C_i(i-1) = C(i)$$

$$v_i(i-1,t-1) = \sum_k h_k v[i,2(t-1)-k]$$

and it follows that $E[v_i(i-1,k-1)] = 0$, with $R(i-1,k-1) = \sum_l R(i-1,2k-2-l)$.

## 3 Multi-Link Kalman Filter Update Equations

TWSTFT and GPS PPP links are independent of each other, with different measurement intervals and different noise types in their measurement results. To weaken the influence of systematic errors and measurement errors from single links and improve time transfer accuracy, we attempt to fuse data from multiple links.

Wavelet decomposition is a binary algorithm. With each decomposition, the frequency band of the approximation component is halved. During decomposition, low-frequency coefficients (scaling coefficients) correspond to low-resolution approximation components, while high-frequency coefficients (wavelet coefficients) correspond to high-resolution detail components. After decomposition, low-resolution components of the links at the same scale can be obtained. At this point, applying threshold processing to the corresponding wavelet coefficients can reduce the influence of link random noise.

In the Kalman filtering process, we first weight data from different links using the error covariance matrix of the measurement model, then fuse low-frequency coefficients based on the error covariance matrix of the observation model, and finally reconstruct the time transfer link data fusion through the Mallat reconstruction algorithm.

Deriving the Kalman filter update equations for parallel processing of $N$ link data, we define the system state equation as

$$X_m = \Phi_{m;m-1} X_{m-1} + W_{m-1}$$

where $X_m$ and $X_{m-1}$ represent the system state at times $m$ and $m-1$, respectively, $\Phi_{m;m-1}$ is the state transition matrix from time $m-1$ to $m$, and $W_{m-1}$ is the process noise with covariance matrix $Q_m$. The measurement equation is

$$Z_m = H_m X_m + V_m$$

where $Z_m$ is the system measurement at time $m$, $H_m$ is the measurement matrix, and $V_m$ is the measurement noise with covariance matrix $R_m$.

The state equation and measurement equation for the $f$-th link system ($f = 1, 2, \cdots, N$) can be expressed as

$$X_m^f = \Phi_{m;m-1}^f X_{m-1}^f + W_{m-1}^f$$

$$Z_m^f = H_m^f X_m^f + V_m^f$$

where $X_m^f$ and $X_{m-1}^f$ represent the state of the $f$-th link system at times $m$ and $m-1$, respectively, $\Phi_{m;m-1}^f$ is the state transition matrix of the $f$-th link system from time $m-1$ to $m$, $W_{m-1}^f$ is the process noise of the $f$-th link system with covariance matrix $Q_m^f$, $Z_m^f$ is the measurement of the $f$-th link system at time $m$, $H_m^f$ is the measurement matrix of the $f$-th link, and $V_m^f$ is the measurement noise of the $f$-th link with covariance matrix $R_m^f$.

Let the measurement information of the 1st link be $Z_{1m}^T$, the 2nd link be $Z_{2m}^T$, and so on, with the $N$-th link being $Z_{Nm}^T$. The measurement information of multiple links can be expressed as

$$Z_m = \begin{bmatrix} Z_{1m}^T & Z_{2m}^T & \cdots & Z_{Nm}^T \end{bmatrix}^T$$

Since the measurement processes between links are independent, assuming that the link state $X_m^f$ is part of the total system state $X_m$, we have $X_m^f = M_f X_m$, where $M_f = [1\ 0]$ corresponds to the phase part of the measurement data. The centralized filtering process can be expressed as

$$\hat{X}_{m|m-1} = \Phi_{m;m-1} \hat{X}_{m-1}$$

$$P_{m|m-1} = \Phi_{m;m-1} P_{m-1} \Phi_{m;m-1}^{T} + Q_{m-1}$$

$$\hat{X}_m = \hat{X}_{m|m-1} + K_m^f [Z_m^f - H_m^f \hat{X}_{m|m-1}]$$

$$K_m^f = P_{m|m-1} (H_m^f)^T [H_m^f P_{m|m-1} (H_m^f)^T + R_m^f]^{-1}$$

$$P_m = [I - K_m^f H_m^f] P_{m|m-1}$$

where $\hat{X}_{m|m-1}$ represents the prior state estimate of the $f$-th link at time $m$, $\hat{X}_{m-1}$ is the posterior state estimate at time $m-1$, $P_{m|m-1}$ is the covariance matrix of the prior state estimate at time $m$, $K_m^f$ is the Kalman gain matrix at time $m$, and $P_m$ is the covariance matrix of the posterior state estimate at time $m$. It should be noted that the measurement update of centralized filtering is expressed using local filtering, but the time update still uses the global filter equation. This makes the global filter optimal, and the local filters are also optimal relative to their sub-links, with the local filters operating in parallel.

## 4 Time Transfer Link Data Fusion Scheme

The GPS PPP link has a standard frequency of 1/300 Hz, while the TWSTFT link has a standard frequency of 1/1800 Hz. Due to the binary nature of wavelet decomposition, to ensure that the frequency bands of the approximation components are the same after wavelet decomposition and to maximize retention of the GPS PPP link' s short-term characteristics, the GPS PPP link data is first extracted at a 1/900 Hz sampling rate. According to the Nyquist sampling theorem, to avoid distortion, the initial frequency for wavelet decomposition of the extracted GPS PPP link data is 1/1800 Hz, and the initial frequency for TWSTFT link data decomposition is up to 1/3600 Hz. The extracted GPS PPP data then undergoes second-order wavelet decomposition, while the TWSTFT link data undergoes first-order wavelet decomposition, obtaining low-resolution components of both links at the same scale. After each decomposition, high-frequency coefficients are set to zero to eliminate corresponding high-frequency noise. Subsequently, Kalman filtering is performed on the low-frequency coefficients at each scale, and finally, the fusion result is obtained through the Mallat fast reconstruction algorithm.

Using second-order Daubechies wavelets, the GPS PPP link data and TWSTFT link data are decomposed to the same scale. For GPS PPP data, data is first extracted at a 1/900 Hz sampling rate, then decomposed twice. For TWSTFT data, one decomposition is performed, resulting in a frequency band of 1/3600 Hz for the corresponding results. The combined measurement uncertainty of two independent links can be expressed as the arithmetic square root of the sum of squares of their measurement uncertainties. According to the uncertainty propagation law, if the maximum deviation between link measurement results is within the uncertainty range, the link measurement results can be determined to be consistent.

The low-frequency coefficients from wavelet decomposition correspond to approximation components. The reconstructed results are shown in Figure 2 [Figure 2: see original paper]. The maximum deviation between the two link measurement results is approximately 1.88 ns, and the combined uncertainty between links is about 2.27 ns, indicating consistent link measurement results. The distribution of high-frequency coefficients from wavelet decomposition, corresponding to detail components, is shown in Figure 3 [Figure 3: see original paper], both following a normal distribution.

## 5 Data Analysis

Independent GPS PPP and TWSTFT time transfer link data between NTSC and PTB were selected for processing. Using UTCr as the reference, the accuracy and stability of the fusion results were analyzed, and the algorithm' s effect on measurement noise was further discussed.

### 5.1 Wavelet Decomposition of Link Data

Data from the NTSC-PTB link during MJD (Modified Julian Day) 60214–60249 were randomly selected for analysis. The measured data are shown in Figure 1 [Figure 1: see original paper]. Compared with the GPS PPP link, the TWSTFT link has larger measurement noise and obvious diurnal variations.

### 5.2 Link Data Fusion Based on Kalman Filtering

The Kalman filter fusion algorithm processes scaling coefficients under the same frequency band for both links, establishing a two-state equation for phase deviation and frequency deviation of link data. For the GPS PPP link, the state transition matrix and measurement matrix are

$$\Phi_{m;m-1} = \begin{bmatrix} 1 & 1/4 \\ 0 & 1 \end{bmatrix}, \quad H = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

For the TWSTFT link,

$$\Phi_{m;m-1} = \begin{bmatrix} 1 & 1/2 \\ 0 & 1 \end{bmatrix}, \quad H = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

The Allan variance with interval $\tau$ is

$$\sigma_f^2(\tau) = \frac{3q_f^0}{\tau^2} + q_f^1 + \frac{q_f^2\tau}{3} + \frac{q_f^3\tau^2}{3}$$

where $q_f^0$, $q_f^1$, $q_f^2$, and $q_f^3$ represent the spectral densities of phase modulation white noise, frequency modulation white noise, frequency modulation random walk noise, and frequency drift random walk noise, respectively. From $\sigma_f^2(\tau)$, the estimation of the observation model error covariance matrix $Q_m^f$ is

$$Q_m^f = \begin{bmatrix} q_f^1\tau + q_f^2 & q_f^2\tau \\ q_f^2\tau & q_f^2\tau \end{bmatrix}$$

The estimation of the measurement model error covariance matrix $R_m^f$ is

$$R_m^f = q_f^0$$

The noise parameters in the link state equation and measurement equation are shown in Table 1 . The measurement noise of the GPS PPP link is smaller than that of the TWSTFT link for the corresponding measurement period. The state noise of the GPS PPP link is also smaller than that of the TWSTFT link for the corresponding measurement period. Neither link data shows frequency modulation random walk noise within the corresponding measurement period.

### 5.3 Performance Analysis of Fusion Results

The comparison between data fusion results and original measurement data is shown in Figure 4 [Figure 4: see original paper]. Using UTCr as the reference, the GPS PPP link has a standard deviation of approximately 0.32 ns, the TWSTFT link has a standard deviation of 0.42 ns, and the fusion result has a standard deviation of approximately 0.31 ns. Defining $\sigma_a$ as the standard deviation of the original data and $\sigma_b$ as the standard deviation of the fused data, the accuracy gain after data fusion processing is $(\sigma_a - \sigma_b)/\sigma_a$. The TWSTFT link gain is about 24%, while the GPS PPP link gain is about 1%. The fusion algorithm provides significant gain for the TWSTFT link but not for the GPS PPP link, because the GPS PPP link has smaller measurement errors, which is also confirmed by the high-frequency coefficient distribution in Figure 3. This demonstrates that the fusion algorithm optimizes the performance of both TWSTFT and GPS PPP links.

The frequency stability of the fusion results and original link measurement data is shown in Figure 5 [Figure 5: see original paper]. Since the measurement intervals of the links and the data intervals set by the fusion algorithm differ, the $\tau$ values of the frequency stability curves also differ. For convenient comparison, the inset highlights the frequency stability curves of both links and the fusion result at the same time. The overall stability of the TWSTFT link is weaker than that of the GPS PPP link, so the frequency stability gain of the fusion result relative to the GPS PPP link is used to evaluate the algorithm. The results are shown in Table 2 . The frequency stability of the fusion results is generally better than that of the GPS PPP link.

To further determine the source of the gain, the wavelet decomposition algorithm was skipped, and the GPS PPP data was directly downsampled according to the TWSTFT data measurement interval, followed by data fusion using the Kalman data fusion method described in the paper. The results are shown in Table 3 , where Fusion (+) represents the fusion result using wavelet decomposition, and Fusion (−) represents the fusion result without using wavelet decomposition. The data show that the effect of preliminary noise reduction using wavelet decomposition is evident, maintaining gains within an averaging time of 1917 minutes. As the sampling interval increases, the uncertainty of the analysis results also increases. The reason for not observing continuous gain is speculated to be related to the increase in sampling interval, but this speculation requires further research for verification.

In summary, wavelet decomposition plays a key role in preprocessing high-frequency noise, thereby initially improving the short-term stability of link data. Subsequently, through dynamic weight allocation and effective suppression of frequency modulation and phase modulation white noise, along with fusion processing using the Kalman algorithm, more stable and reliable data fusion is further achieved.

The spectral analysis results of the fusion results and original link measurement data are shown in Figure 6 [Figure 6: see original paper]. The TWSTFT link time transfer results show a significant 24-hour component, while the GPS PPP link shows no obvious periodic component. Compared with the TWSTFT link, the 24-hour component amplitude in the fusion result is reduced by approximately 87.8%, indicating that the fusion algorithm can mitigate the bias caused by the diurnal effect in two-way satellite time transfer links.

From the perspective of data integrity, the impact of data fusion results on link reliability is shown in Figure 7 [Figure 7: see original paper]. Red dots mark missing or anomalous data, with two data segments enlarged: the MJD 60214–60245 segment has missing data, and the GPS PPP data at MJD 60218 are discontinuous. The fusion algorithm can use TWSTFT link data for estimation during data missing periods and can also handle anomalous jumps in data.

Different types of time transfer links have different measurement resolutions and noise characteristics. To improve their accuracy, stability, and robustness, we need to reduce the influence of various noises. Considering sampling rate differences, we first use wavelet decomposition to decompose TWSTFT and GPS PPP link data with different sampling rates to a unified scale, reduce random noise by zeroing high-frequency coefficients, then use the Kalman filter algorithm to fuse the low-frequency coefficients, and finally reconstruct the low-frequency coefficients to obtain the fusion result. The results show that the fusion algorithm performs excellently in multiple aspects, including reducing the diurnal variation of the TWSTFT link, improving the short-term stability of the GPS PPP link, suppressing phase modulation white noise and frequency modulation white noise, and handling data anomalies and missing data, which is of great significance for improving data quality and performance.

## References

[1] Martinez M C, Defraigne P. IEEE International Frequency Control Symposium 2009. Besancon, France: IEEE, 2009: 670

[2] Defraigne P, Baire Q. AdSpR, 2011, 47: 265

[3] Jiang Z, Lewandowski W. International Journal of Navigation and Observation, 2012, 2012: 353961.1

[4] Verhasselt K, Defraigne P. Metrologia, 2019, 56: 065003

[5] Wang W X, Dong S W, Wu W J, et al. GPS Solutions, 2021, 25: 138

[6] Song H J, Dong S W, Wu W, et al. Metrologia, 2018, 55:

[7] Song H J, Dong S W, Wang X, et al. Acta Physica Sinica, 2020, 69: 9

[8] Yang Y X, Gao W G. Geo-spatial Information Science, 2007, 010: 200

[9] Wang X, Song H J, Wang W X, et al. Acta Astronomica Sinica, 2020, 61: 14

[10] Wang X, Song H J, Wang W X, et al. ChA&A, 2020, 44:

[11] Wang X, Song H J, Guo D, et al. Journal of Time and Frequency, 2022, 45: 8

[12] Zucca C, Tavella P. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 2005, 52: 289

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv —Machine translation. Verify with original.*