IMPROVEMENT OF TWSTFT SHORT-TERM STABILITY UTILIZING FULL TIME TRANSFER NETWORK DATA

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In the Asia-Pacific Rim region, the two-way satellite time and frequency transfer (TWSTFT) links between 6 Labs, using multi-channel time transfer modems, have composed a time-transfer network. To fully utilize the data of TWSTFT network and improve the short-term stability of TWSTFT, a feasible method of processing data is proposed. We perform data analysis with practical time transfer data, and the results show that it is an effective method to improve the TWSTFT short-term stability.

INTRODUCTION

Two-way satellite time and frequency transfer (TWSTFT) is currently one of the most accurate and precise time transfer method. The procedure of TWSTFT and direct-link data processing principle is demonstrated in recommendation ITU-R TF.1153-2.

As the number of point-to-point two-way time transfer links is growing, the concept of network time transfer has been proposed [1, 2] and the utilization of the redundant data of each indirect link in the TWSTFT network becomes an important topic. In the Asian-Pacific region, multi-channel modems are used for TWSTFT. All TWSTFT measurements are performed simultaneously and hourly data with quadratic fit over 1-second measurements in 300-second duration sessions are available at the NICT's Web site. In calculating the time transfer results, the indirect redundant links may provide useful information to improve the precisions.

In this paper, we propose a feasible method to utilized full data of the TWSTFT sub-network in the Asian-Pacific region. The numerical results show that the short term stabilities of most links are improved.

METHOD OF DATA ANALYSIS

To calculate the time difference T_1-T_2 between two stations 1 and 2, the time interval readings at stations 1 and 2, i.e., TIC_{12} and TIC_{21}, can be applied. The related equation is as the following

$$\begin{aligned}(T_1 - T_2) = {} & \tfrac{1}{2}(TIC_{12} - TIC_{21}) \\ & + \tfrac{1}{2}[(TU_1 - TD_1) - (TU_2 - TD_2)] \\ & + (SCD_2 - SCD_1) \\ & - \tfrac{1}{2}(\delta_{12} - \delta_{21}).\end{aligned} \tag{1}$$

Where TU_i and TD_i are satellite propagation delays of up-link from station i and down-link to station i. SCD_i is the Sagnac correction at station i for the downlink from the satellite. The measurement noises are noted as δ_{12} and δ_{21}, correlated to the measurements TIC_{12} and TIC_{21}, respectively. Equation (1) is the formula for calculating the time difference between two TWSTFT stations.

In recent years, 8-receiving-channel NICT modems [3, 4] have been used for the Asia-Pacific TWSTFT network. TWSTFT measurements among 6 Labs, including NICT(Japan), TL(Taiwan), KRIS(Korea), NTSC(China), NMIJ(Japan), and A*STAR(Singapore), can perform simultaneously and hourly. In order to use all the time transfer data to calculate the time difference between each pair of stations, we would consider equation (1) again. Without any unpractical assumption and negligence, we preserve all items on the right side of equal sign and rewrite it as

$$
\begin{aligned}
& T_{12} = N_{12} \\
\text{where}\quad & N_{12} = \tfrac{1}{2}(TIC_{12} - TIC_{21}) \\
& \quad + \tfrac{1}{2}[(TU_1 - TD_1) - (TU_2 - TD_2)] \\
& \quad + (SCD_2 - SCD_1) \\
& \quad - \tfrac{1}{2}(\delta_{12} - \delta_{21})
\end{aligned}
\qquad (2)
$$

For the case of 3-station network, we get three linear equations

$$
\begin{cases}
T_{12} = N_{12} = Y_1 \\
T_{13} = N_{13} = Y_2 \\
T_{23} = T_{13} - T_{12} = N_{23} = Y_3
\end{cases}
\qquad (3)
$$

Equation (3) can be written in matrix notation [5] as

$$X\,T = Y\,, \qquad (4)$$

$$
\text{with}\quad X = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -1 & 1 \end{bmatrix} ; \quad T = \begin{bmatrix} T_{12} \\ T_{13} \end{bmatrix} ; \quad Y = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix} = \begin{bmatrix} N_{12} \\ N_{13} \\ N_{23} \end{bmatrix}
$$

When n stations perform the TWSTFT time transfer, equation (4) is still applicable, with its element extended as the following

$$
X = \begin{bmatrix}
1 & 0 & 0 & \cdots & 0 & 0 & \\
0 & 1 & 0 & \cdots & 0 & 0 & \\
\cdots & & & & & & \cdots \\
0 & 0 & 0 & \cdots & 0 & 0 & 1 \\
-1 & 1 & 0 & \cdots & 0 & 0 & 0 \\
-1 & 0 & 1 & \cdots & 0 & 0 & 0 \\
\cdots & & & & & & \cdots \\
-1 & 0 & 0 & \cdots & 0 & 0 & 1 \\
0 & -1 & 1 & \cdots & 0 & 0 & 0 \\
0 & -1 & 0 & \cdots & 0 & 0 & 0 \\
\cdots & & & & & & \cdots \\
0 & -1 & 0 & \cdots & 0 & 0 & 1 \\
\cdots & & & & & & \cdots \\
0 & 0 & 0 & \cdots & -1 & 1 & 0 \\
0 & 0 & 0 & \cdots & -1 & 0 & 1 \\
0 & 0 & 0 & \cdots & 0 & -1 & 1
\end{bmatrix}_{\frac{n(n-1)}{2}(n-1)}
; \quad T = \begin{bmatrix} T_{12} \\ T_{13} \\ \vdots \\ T_{1n} \end{bmatrix}
; \quad Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_{\frac{(n-1)n}{2}} \end{bmatrix}
= \begin{bmatrix} N_{12} \\ \vdots \\ N_{1n} \\ N_{23} \\ \vdots \\ N_{2n} \\ \vdots \\ N_{(n-1)n} \end{bmatrix}
$$

However, it is well known that the performance (precision or the stability) of each TWSTFT link is not the same. In considering different performances of every TWSTFT links, we would propose a feasible method, take the stability into account and provide a weighting value for each link to solve equation (4).

Since Y_{ij} is the single channel (between stations i and j) TWSTFT result, we can record the time transfer data and related information (such as Sagnac correction) for some periods, and then calculate the time deviation (TDEV) value of Y_{ij} to evaluate its short-term stability. According to the TDEV value at averaging times of 1 hour, we determine the weighting value as

$$w_i = \frac{1/\sigma_i^2}{\sum_{k=1}^{M}\left(1/\sigma_k^2\right)} \tag{5}$$

where $\sigma_i = TDEV\ [Y_i\ (1h)]$ and M= n(n-1)/2. Applying the weighting to Equation (4), we get

$$\mathrm{WX\,T} = \mathrm{WY}\ , \tag{6}$$

where $$\mathrm{W} = \begin{bmatrix} w_1 & 0 & 0 & 0 \\ 0 & w_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & w_{n(n-1)/2} \end{bmatrix}$$

By doing this, those links with higher short-term stabilities can have more contribution in solving equation (4). The short-term stabilities of most links may be improved. Note that Equation (6) can be solved by the weighted least squares method:

$$\mathrm{T} = (\mathrm{X}^{\mathrm{T}}\mathrm{WX})^{-1}\mathrm{X}^{\mathrm{T}}\mathrm{WY} \tag{7}$$

NUMERICAL RESULTS

By using the method proposed above, we calculate the stabilities of 3-station and 4-station cases with practical time transfer data of the Asia-Pacific TWSTFT network from Modified Julian Day (MJD) 55069 to MJD 55129 (about 2 months).

3-station case: Let us consider the links between three stations, NICT, TL, and KRIS (simply notated with 1, 2, and 3, respectively). The first row in Table-I shows the TDEV values of direct NICT-TL, NICT-KRIS, and TL-KRIS links. According to these values, the weighting values can be obtained by equation (5). After solving the T_{12} and T_{13} for NICT-TL and NICT-KRIS, their TDEV values are evaluated again to check improvement of the short-term stabilities. The last row of Table-I shows that the TDEV of NICT-KRIS is obviously improved.
With equation (6) being modified, T_{21} and T_{23} (time differences of TL-NICT and TL-KRIS links) can also be solved, and one can find that $T_{21}= -T_{12}$.

Table-1 TDEVs of direct and network results in 3-station case

Link / TDEV(1h) (ps)	TL-NICT	TL-KRIS	NICT-KRIS
Direct	**89.5**	**94.7**	**153**
3-station network	**88.4**	**97.0**	**118**

4-station case: With one more station, say NTSC(china), be included, we have 6 time-differences (of NTCT-TL, NICT-KRIS, NICT-NTSC, TL-KRIS, TL-NTSC, and KRIS-NTSC links) to be soled. The calculation results are shown in Table-2. One can find that most of the short-term stabilities are improved.

From the above numerical analysis, we found that NICT, TL and KRIS use hydrogen masers as the master clocks, so the TDEV values of the links between each other are low. The proposed method can effective improve the relative medium short-term stability of NICT-KRIS link. However, the master clock of NTSC is cesium clock and its performance may dominate the stability of time transfer at one-hour period, so the improvements in the short-term stability of those links with NTSC are smaller. The TDEVs of UTC(NICT)-UTC(KRIS) links in direct and 4-station network cases are shown in Fig.1.

Table-2 TDEVs of direct and network results in 4-station case

Link / TDEV(1h) (ps)	TL-NICT	TL-KRIS	NICT-KRIS	TL-NTSC	NICT-NTSC	KRIS-NTSC
Direct	**89.5**	**94.7**	**153**	**325**	**328**	**333**
4-station network	**88.2**	**97.1**	**118**	**316**	**325**	**329**

CONCLUSIONS

In this paper, we propose a feasible method to improve the short-term stability of TWSTFT network by using full time transfer network data. Since the performance of the cesium master clock may dominate the stability of time transfer at one-hour period, the improvements in the short-term stability of those cesium-maser links are smaller. However, the method is confirmed to be effective by using practical TWSTFT measurement data, especially for the maser-maser links with medium stability.

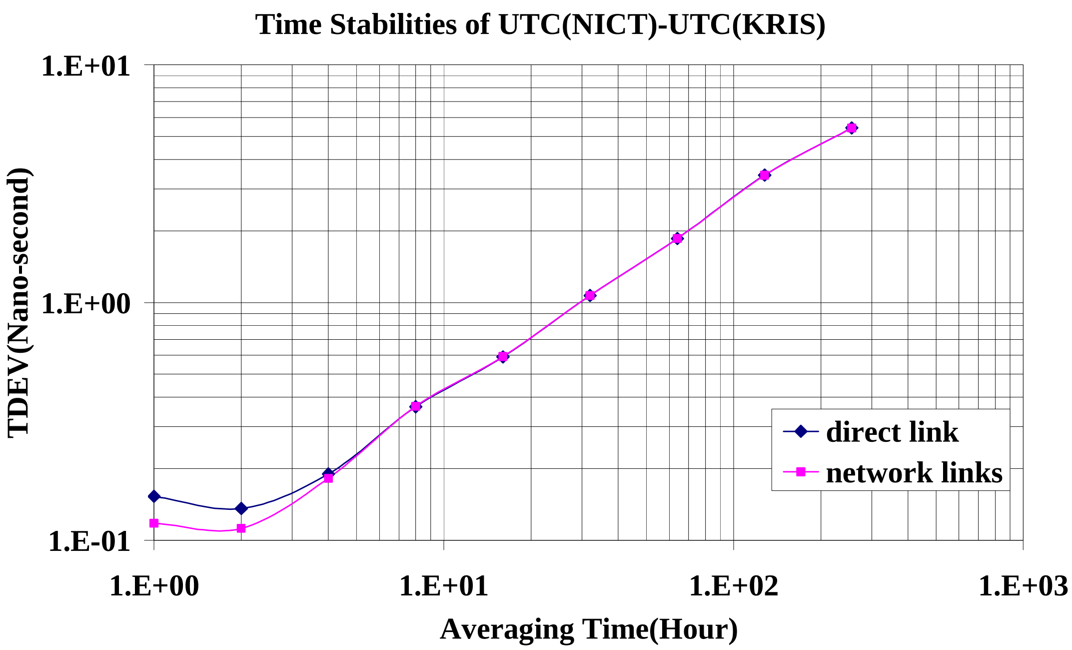

Fig. 1 TDEVs of UTC(NICT)-UTC(KRIS) links in direct and in 4-station network case

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