The Method of Real-time PPP Time Transfer Research

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Abstract. The accuracy of precision point position (PPP) time transfer can achieve a value below 0.3 ns. Time transfer by precise point positioning has the defect of long latency resulting from IGS products, and cannot satisfied for the high real-time user. A real-time precise point positioning time transfer algorithm using IGS products is proposed, which can improve the real-time, the feasibility of the algorithm is tested and verified in this paper. The time transfer results show that the accuracy of the new algorithm can be reach to 0.30 ns for RMS and 0.25 ns for STD. Moreover, the daily stability of the time transfer results is up to 2E-15. Experiments show that, the algorithm is real-time, and the time transfer results are coincident with IGS final clock products well.

1. Introduction
Nowadays, methods of time transfer are GPS AV (GPS All-in-view)[1], GLONASS AV (GLONASS All-in-view)[2], GPS PPP (GPS Precision Point Positioning)[3] and TWSTFT (Two way Satellite Time and Frequency Transfer) etc, which time laboratories participate to the calculation of international time scale. GPS PPP is the main method of time transfer, and has been adopted by many time laboratories around the world, accounting for about 48% of all time transmission links, and the share of recent years has been rising.

GPS PPP has its unique advantages in the remote high-precision time-frequency transfer, and the stability of remote distance can reach to E-15 or E-16. A unaccuracy of time transfer is better than 0.3 ns[5-6], but GPS PPP needs precision satellite calendar and satellite clock offset which make the real-time badly. Now BIPM uses IGR in GPS PPP, and the time delay is about 17-41 hours[7]. In addition, IGS also gives the production IGU, and the clock error is about 0.15 ns, the prediction clock error is 3ns, the high precision real-time time transfer is not be satisfied.

There are many researches on GPS PPP time transfer in China, and mainly focusing on afterwards high time transfer[8-9]. The time laboratories use the result of time transfer as the reference of the local time signal, but the real-time clock difference monitoring of time-frequency signals is not possible, in particular, there is no mature results and application experience in real-time delivery of nanosecond. In this paper, GPS PPP is researched in detailed, and the high precision real-time time transfer method is given. Last, the test analysis is given by using the real compare data, and the feasibility is verified by the results.

2. IGS RTS Production

2.1 The real-time precision satellite orbit
RTS production is the correction of satellite calendar, the precision orbit and clock error can be got with the correction. The correction of satellite orbit is the correction on radial, tangent, and normal in
satellite-solid coordinate system, if the correction of satellite position and satellite velocity is
\[
\begin{bmatrix}
\delta O_x \\
\delta O_y \\
\delta O_z
\end{bmatrix}
\text{ and }
\begin{bmatrix}
\delta \dot{O}_x \\
\delta \dot{O}_y \\
\delta \dot{O}_z
\end{bmatrix},
\]
then the correction of satellite position is followed[12].

\[
\begin{bmatrix}
\delta x \\
\delta y \\
\delta z
\end{bmatrix} =
\begin{bmatrix}
\delta O_x \\
\delta O_y \\
\delta O_z
\end{bmatrix} +
\begin{bmatrix}
\delta \dot{O}_x \\
\delta \dot{O}_y \\
\delta \dot{O}_z
\end{bmatrix} (t - t_0)
\] (1)

The correction of satellite position need to be transfer to earth-solid coordinate system because of
the satellite calendar using earth-solid coordinate system. The position \( \mathbf{r} \) and velocity \( \mathbf{\dot{r}} \) of satellite
can be got using the broadcast satellite calendar, the rotate matrix from satellite-solid coordinate to
earth-solid coordinate is followed.

\[
\mathbf{R} = \begin{bmatrix}
\mathbf{r} \\
\mathbf{r} \times \mathbf{\dot{r}} \\
\mathbf{r} \times (\mathbf{r} \times \mathbf{\dot{r}})
\end{bmatrix}
\] (2)

At \( t \) time the satellite position in earth-solid coordinate system is followed.

\[
\begin{bmatrix}
X_t \\
Y_t \\
Z_t
\end{bmatrix} =
\begin{bmatrix}
X_{\text{bc}} \\
Y_{\text{bc}} \\
Z_{\text{bc}}
\end{bmatrix} - \mathbf{R} \begin{bmatrix}
\delta x \\
\delta y \\
\delta z
\end{bmatrix}
\] (3)

CoM (Center of Mass) and APC (Antenna Phase Center) are two type reference point of the
correction satellite position. IGS01 and IGS02 can be calculated used the modified precision satellite
orbit which relative to APC. The correction of antenna phase center need to be considered if the
reference is CoM, such as IGC01.

2.2 Real-time precision satellite clock error

If the polynomial coefficient are \( C_0 \), \( C_1 \) and \( C_2 \) at \( t_0 \). Then the correction of satellite clock error
distance at \( t \) is followed.

\[
\delta C = C_0 + C_1 (t - t_0) + C_2 (t - t_0)^2
\] (4)

The precision satellite clock error at \( t \) is followed.

\[
dt^i = dt^\text{sat} + \frac{\delta C}{c_{\text{light}}}
\] (5)

Where, \( dt^\text{sat} \) is the broadcast calendar clock error at \( t \) which is modified by the relativistic effects,
\( c_{\text{light}} \) is the speed of light in vacuum.

3. PPP time transfer based RTS

3.1 GPS PPP time transfer

Usually, GPS PPP time transfer method uses the model which includes ionospheric.

\[
P_3 = \rho + c dt' - c dt' + T + b_{p3} - b_{p3} + \varepsilon_{p3}
\] (6)

\[
\Phi_3 = \rho + c dt' - c dt' + T + b_{q3} - b_{q3} + \lambda_3 N_3 + \varepsilon_{q3}
\] (7)

Where, \( P_3 \), \( \Phi_3 \) are the no ionospheric combination observation pseudo distance and carrier phase;
\( \rho \) is the distance between satellite and the receiver; \( c \) is the speed of light; \( dt' \) and \( dt' \) are receiver
clock error and satellite clock error respectively; \( T \) is the delay of troposphere; \( b_{p3} \), \( b_{q3} \) are
combination code delay of receiver and satellite respectively; $\lambda_3$ is narrow lane wavelength; $\epsilon_{p_3}$ and $\epsilon_{\Phi_3}$ are the effect which the error is no model.

Make formula and simple get the followed model.

$$P_3 = \rho + c dt'_{p_3} - c dt''_{p_3} + \epsilon_{p_3}$$ \hspace{1cm} (8)

$$\Phi_3 = \rho + c dt'_{\Phi_3} - c dt''_{\Phi_3} + T + \lambda_3 N_3 + \epsilon_{\Phi_3}$$ \hspace{1cm} (9)

Where, $dt'_{p_3} = dt'_{b_3} + b'_{p_3} / c$, $dt''_{p_3} = dt'_{b_3} + b''_{p_3} / c$, $N_3 = (-b'_{p_3} + b'_{b_3} + b'_{b_3} - b''_{b_3}) / \lambda_3 + N_3$.

Use Kalman filter could get the receiver clock error from formula and. Because of using different IGS ephemeris can get the difference receiver clock error which have different reference time. Such as IGR is the reference of BIPM GPS PPP which under the IGRT time scale; if using the last IGS ephemeris, the reference time is IGST.

3.2 Analysis for test

For proving the feasibility of the high precision real-time time transfer using the RTS production, in this paper take PTBB, BRUX, IENG and OPMT which have BIPM and IGS station as sample, and download sixteen observation data. The precision ephemeris data use IGR and IGC01 respectively. In Figure 1 give the time transfer result which using filter (150min): the black is the clock error transfer results of IGR, and pan 0.5ns up; the green is PPP(IGC01) time transfer result; the red is the PPP (IGR) time transfer result, and pan 0.5 ns down.

![Figure 1](image_url)

The results of Figure 1 show that IGR is better than PPP (IGR) and PPP (IGC01), PPP (IGR) and PPP (IGC01) have a good consistency. IENG has a 2 ns jitter. DOY253, DOY254 and DOY260 are no results because of on data of observation during the time.

Now give the PPP results between different IGS production. The precision of IGR is high, is about 0.075 ns, so take IGR time transfer results as the reference and analysis the result. Figure 2 gives the time transfer residuals relative to IGR between PPP (IGC01) and PPP (IGR). In table 1 give the statistic values of residuals between three time transfer link.
Figure 2. Difference between the time transfer solutions obtained with PPP (IGC01) or PPP (IGR) with respect to IGR (Green: PPP (IGC01). Red: PPP (IGR)).

Table 1. The statistic of difference between the time transfer solutions obtained with PPP (IGC01) or PPP (IGR) with respect to IGR (Unit: ns)

| Transfer Link | IGS | Min  | Max  | Ave  | RMS  | STD  |
|---------------|-----|------|------|------|------|------|
| PTBB-BRUX     | IGR | -0.38| 0.22 | -0.07| 0.12 | 0.09 |
|               | IGC01| -0.38| 0.22 | -0.08| 0.14 | 0.11 |
| PTBB-IENG     | IGR | -0.76| 0.38 | -0.17| 0.28 | 0.22 |
|               | IGC01| -0.88| 0.33 | -0.21| 0.32 | 0.25 |
| PTBB-OPMT     | IGR | -0.36| 0.19 | -0.04| 0.12 | 0.11 |
|               | IGC01| -0.42| 0.20 | -0.09| 0.16 | 0.13 |

The results of Figure 2 and Table 1 show that three time transfer link have a good consistency with PPP (IGR) and PPP (IGC01). Where the time transfer precision of PTBB-BRUX and PTBB-OPMT is close, RMS is about 0.15 ns, STD is about 0.12 ns. The time transfer precision of PTBB-IENG is lower than the other two links, RMS is about 0.30 ns, STD is about 0.24 ns.

The frequency stability index of time transfer link is very important. The analysis is only to PTBB-IENG and PTBB-BRUX, because the observation of OPMT is not exist, IGR is not clock error, the frequency stability of PTBB-IENG and PTBB-BRUX are calculated using Allan variance.

\[
\sigma_\alpha^2(\tau) = \frac{1}{2(N - 2m)\tau^2} \sum_{i=1}^{N-2m} (x_{i+2m} - 2x_{i+m} + x_i)^2
\]

(10)

Where, \(x_i\) is clock error, \(N\) is the length of clock error sequence, \(\tau = m\tau_0\), \(\tau_0\) is the sample interval, and this is 5min. The time transfer frequency stability results of PTBB-IENG and PTBB-BRUX with three difference methods is given in Figure 3 and Figure 4.
4. Conclusion

1) The precision and availability of RTS are analyzed. Radial direction RMS of IGC01 satellite orbit is about 13mm, the tangent direction RMS is about 32mm, and the normal direction RMS is about 26mm. the STD of satellite deviation is about 20 mm, the RMS of satellite deviation is about 44 mm. the STD of satellite clock error is about 0.12 ns, the RMS of satellite deviation is about 0.3 ns, the availability rate of IGC01 production is about ninety three point eight percent.

2) GPS PPP time transfer is a long time delay and the real-time is bad, GPS CV time transfer is low precision, so a new real-time high precision time transfer method is proposed. The feasibility of the algorithm is tested and verified using four time laboratories observation data, and the time transfer result RMS is better than 0.30 ns, STD is better than 0.25 ns, and the day frequency stability can reach to 2.0E-15.

3) the real-time high precision time transfer method based on RTS is beyond on the production of RTS, the observation data interruption, clock error data lack, network outages which are could get
time transfer failure, how to get the requirement of real-time and improve the stable of the method is the important of future research.

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