Influence of Troposphere in PPP Time Transfer

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***Abstract*— PPP time transfer analysis requires the estimation of position and troposphere delay parameters. The aim of this study is to investigate the influence of troposphere modeling or of external troposphere corrections in PPP time transfer using a least-square analysis, like in the Atomium software. It is investigated using both simulated and real data. We also test the use of two external troposphere products as troposphere corrections, rather than estimate the troposphere parameter in the least-square. Results for two GPS stations are presented here. They show a significant improvement of the clock solution when using external troposphere products. Since external troposphere products are not always available for all stations, we also test a new approach for the troposphere estimation: using constraints on the troposphere parameter, reducing the sampling rate of this parameter to 15 minutes along with an evolution constraint of 1 mm between successive estimation epochs of the wet tropospheric delay. With this method, the clock solution gets the same level of precision as when the troposphere is corrected with external products rather than estimated.**

I. Introduction

The goal of GPS geodetic time and frequency transfer is to compare remote clocks using GPS observations. To that aim, station clocks are estimated based on the analysis of GPS code and carrier-phase observations with a comprehensive modeling of all perturbations acting on the GPS signal. Today, geodetic time and frequency transfer is often computed using a Precise Point Positioning (PPP) software [1-4] and IGS orbit and clock products [5]. Our study is based on the Atomium software, which proposes a least-square approach to determine the clock solutions from GPS code and carrier-phase observations.

In the GPS data analysis, other parameters that are correlated with the clock must be estimated at the same time. These are the station position, which are determined in the reference frame corresponding to the IGS products, carrier-phase ambiguities, and the delay of the signal due to the troposphere. While the position can be estimated for the whole day, the tropospheric delay varies rapidly so that it must be estimated with a higher sampling rate. The Atomium software is originally based on an estimation of a new troposphere parameter each 2 hours, with a linear interpolation between two estimation epochs. The present study aims at quantifying the errors induced in the clock solutions by this approach, and to propose an alternative approach which provides a better determination of the troposphere parameters and reduces the errors in the clock solutions.

Section II describes the model of troposphere delays used in this study. In the third section, the influence of troposphere in time transfer is studied using simulated and real data. The improvement of the clock determination using external troposphere products in order used to mitigate the influence of troposphere mismodelling is shown in section IV. The last section presents the sensitivity of the clock solution to the introduction of relative constraints in the least-square adjustment.

II. TROPOSPHERE MODELLING

The Atomium PPP software is based on a least-square analysis of the ionosphere-free GPS code and carrier-phase combinations, after correcting them for all the known effects present in the signal (earth tides, antenna phase center, …). The procedure used in Atomium is fully described in [1]. The observation equations are solved to determine the station position once a day, the tropospheric zenith wet delay (ZWD) with a 2 hours sampling rate and a linear interpolation between the estimation epochs and the station clock synchronization error with respect to the IGS time scale, with a sampling rate of 5 minutes.

In the observation equation (or signal modeling), the troposphere delay is modeled as the sum of a zenith hydrostatic delay and the zenith wet delay. In each part, it is considered as a zenith path delay (ZHD or ZWD) multiplied by a given mapping function, which accounts for the elevation dependence of the delay (due to the elevation-dependence of the signal path across the troposphere layer). This reads:

Troposphere delay = mfh * ZHD + mfw * ZWD

where mfh is the hydrostatic mapping function, mfw the wet mapping function. The Niell mapping functions [6] are used for both the hydrostatic and wet parts, the hydrostatic zenith path delay is described by an a priori Saastamoinen model [7], and the wet zenith path delay is estimated.

III. TROPOSPHERE INFLUENCE

The influence of the troposphere parameter determination is first tested on simulated data and then investigated with true GPS measurements. The GPS code and carrier-phases observations and the satellite orbits and clocks are simulated for any station position and for a given station clock. It includes the various error sources acting on the observations, i.e. the tropospheric delay, the ocean tide loading, the observation noise etc. All the data are provided in the Receiver Independant EXchange Format (RINEX) format [8].

The orbits are constructed using a keplerian model. The orbital parameters used for the GPS constellation parameters are taken from the Yuma Almanac of the week 442 [9] with an identical eccentricity for all GPS satellites, fixed to 0.01 to recover the quasi-circular characteristics of the GPS orbit. Satellite positions with a 15-min sampling rate are then written in orbit files with the appropriate sp3 format [10].

The satellite and station clocks with respect to a same reference time-scale are simulated using a clock model provided by G. Panfilo [11]. Different parameters have been defined for the different types of clocks, i.e. the satellite clocks, the station Cesium clock or H-maser. The simulated clocks are saved for further computation and written in RINEX clock files.

For each station, the code and carrier-phase observations are simulated on a daily batch, using a 5-min sampling rate, and written in RINEX observation files. The observation equations for carrier-phase (L1 and L2) and for the pseudorange (P1 and P2) are [1]:

$$L_i = R + c(-\tau_s + \tau_r + \tau_t) - c\tau_{i,L_i} + N_{L_i}\lambda_{L_i} + n_{\phi_{L_i}} \quad (1)$$

$$P_i = R + c(-\tau_s + \tau_r + \tau_t) + c\tau_{i,L_i} + c\tau_{d,L_i} + n_{P_{L_i}} \quad (2)$$

with R the geometric distance receiver-satellite, τ_s the satellite clock synchronization error, τ_r the station clock synchronization error, τ_t the tropospheric delay, τ_i the ionospheric delay, λ the carrier-phase wavelength, N the phase ambiguity, τ_d the instrumental code delay and n the noise.

For the satellites and station clocks, we use the values previously saved. The geometric distance is computed with the same satellite position as computed before and the station motions due to the Earth tides and ocean tides are introduced following the IERS 2003 conventions [12]. The total zenith tropospheric delay (ztd) is read from the troposphere data files computed by the IGS. These files are sampled at a rate of 1 point every 5 minutes and contain the total tropospheric delay (hydrostatic + wet). We remove the hydrostatic part, which is assumed to be equal to a standard atmosphere, and keep the wet part; the hydrostatic and wet Niell mapping functions [6] are then used to account for the elevation dependence. The ionospheric delay is computed with an interpolation of the CODE IONEX TEC maps [13]. Finally, at each new passage of the satellite in the sky of the station, an integer ambiguity, randomly chosen between 1 and 1000, is given to the carrier-phase measurements. The phase wind-up is also modeled according to [14] and added to the simulated carrier-phase observations. The simulation does not allow yet the possibility to introduce cycle-slips. An (optional) white noise is added, based on the specification of the GPS/GALILEO receiver GeNeRx from Septentrio [15]. The multipath is not simulated here.

The influence of troposphere modeling is first investigated using simulated GPS data. A set of simulated data, with noise on the observables, has been analyzed with Atomium in order to determine the clock solutions, using 3 alternatives for the troposphere estimation:

1. No a priori data for the ZWD (as common)
2. Computation with the simulated ZWD used as an a priori value for the least-square adjustment
3. Computation with the simulated ZWD removed from the simulated observations, and not estimated in the least-square adjustment

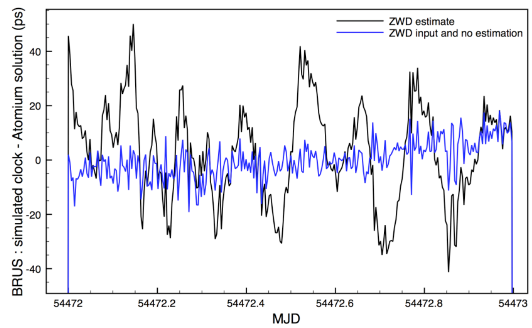

Figure 1. Difference between simulated clock and Atomium clock solution on simulated GPS data for the three cases tested (cases 1 and 2 give the same result, i.e. black curve).

The figure 1 presents the differences between the simulated station clock and the computed one, during one day, obtained with the Atomium software and the 3 analysis strategies just described. Figure 1 shows that estimating ZWD with zero or the simulated ZWD as a priori (black curve), introduces periodic peaks in the clock solution almost every two hours. This is a clear consequence of the correlation between the ZWD and the clock parameters in the least-square adjustment. The amplitudes of the peaks are significantly larger than the expected noise of GPS observations. Those peaks are not present in the third case (blue curve). Their presence in the two first cases is therefore attributed to the estimation of the ZWD together with the station clock estimation.

The results obtained with simulated data can now be compared with the clock solutions obtained when processing true GPS observations with Atomium. As no “true” clock solution is available in that case, we consider the IGS station clock solution as a reference, as it is based on the combination [16] of separate analysis center solutions computed together with satellite orbits, station positions and EOP parameters. Figure 2 presents the differences between the IGS and Atomium clock solutions. The differences show peaks similar to those observed with simulated data, with the same order of magnitude, and the similar period of recurrence of about 2 hours. We therefore expect that those differences between the Atomium and IGS clock solutions can be reduced by modifying the way the atmosphere parameter is estimated.

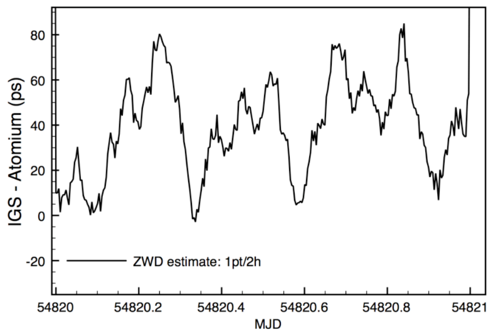

Figure 2. Difference between IGS clock and Atomium clock solution for the station BRUS over one day.

IV. USING IGS AND ROB E-GVAP TROPOSPHERIC PRODUCTS

A first way to improve the clock determination within Atomium is to introduce troposphere ZWD products rather than to estimate this parameter. Two different troposphere products have been used at this level: the new IGS troposphere product [17], referred here as IGS, and the troposphere product produced by ROB in post-processing in the frame of E-GVAP [18], referred here as ROB. In both cases, the differences between the Atomium clock solutions and the IGS clock solutions are significantly reduced as shown in Figures 3 (a) and 4 (a).

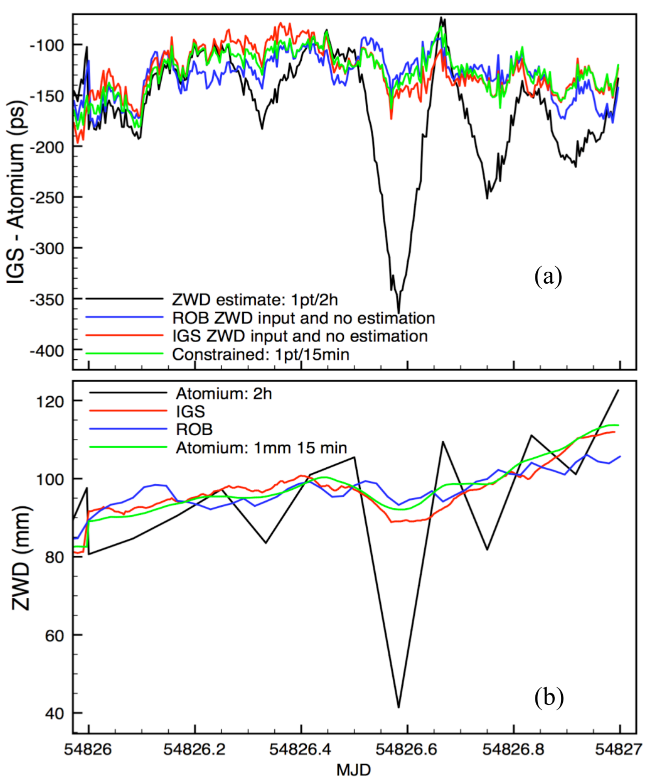

Figure 3. (a) Differences between IGS and Atomium clock solutions for TLSE on 1 day. (b) ROB's ZWD (blue), IGS ZWD (red), Atomium estimated ZWD without constraints (black) and with constraints (green).

For station TLSE, the classical computation, i.e. estimation of both clock and troposphere ZWD (black curve) leads to differences up to 200 picosecond with respect to the IGS clock solution. In parallel, the Atomium estimation of ZWD are far (up to 50 mm) from the IGS and ROB estimations, as shown in Figure 3 (b). Note that the IGS troposphere product (red curve) is given with a 5-min sampling rate while ROB E-GVAP troposphere product [18] (blue curve) is given with a 30-min sampling rate. This last product is used with a linear interpolation between two values to get a ZWD value every 5 minutes when modeling the code and carrier-phase measurements in the least-square analysis.

The results for BRUS (Figure 4 (a)) also show improvements when using troposphere products rather than estimating ZWD. The differences with respect to the IGS clock solution are smaller than for TLSE, even if the troposphere variations are larger during the day of computation, as shown in Figure 4 (b).

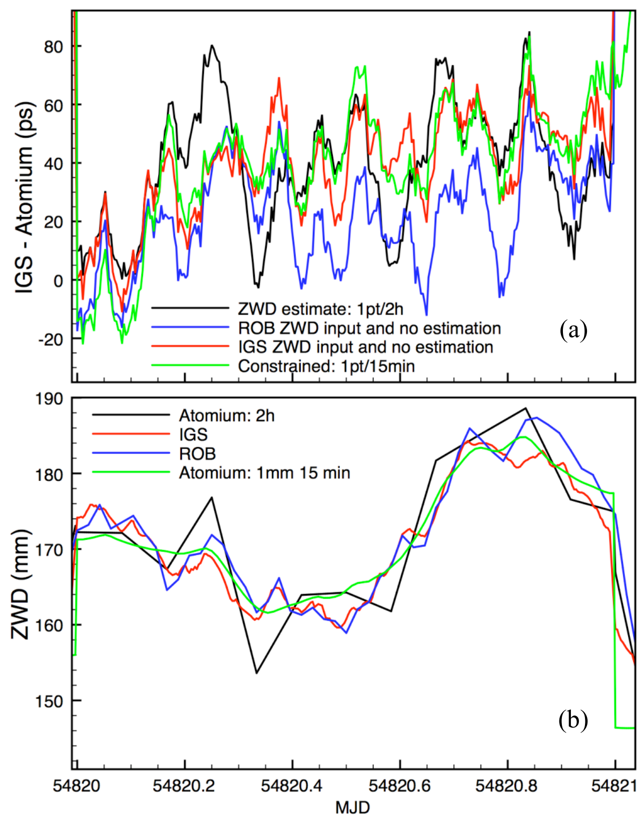

Figure 4. (a) Differences between IGS and Atomium clock solutions for BRUS on 1 day. (b) ROB ZWD (blue), IGS ZWD (red), the Atomium estimated ZWD without constraints (black) and with constraints (green).

Figure 4 (a) also shows that there are small differences in the clock solutions computed when using IGS troposphere products or ROB E-GVAP troposphere products for the ZWD. Theses differences are up to 20 picoseconds, with the two troposphere products used here, which are in good agreement within the centimeter, as we can see in Figure 4 (b). Influence of the product on the solution is not studied further here but this example shows the order of magnitude of the difference we can get using different troposphere products (or estimation) and therefore, gives an order of magnitude of the limitation from the troposphere to the clock solution precision that can be obtained for the clock solution in PPP .

V. CONSTRAINING ZENITH WET DELAY

The two stations considered in the previous section have both troposphere values computed by the IGS and ROB, but not all the stations are integrated by an analysis center providing precise zenith troposphere delay. It is therefore necessary to be able to determine the parameter ZWD together with the clock, but with a higher quality than what is obtained with the present version of Atomium. To that aim, relative constraints between successive ZWD parameters are introduced in the least-square adjustment, and simultaneously the sampling rate of the ZWD estimations is reduced to better fit the characteristic time of wet tropospheric delay variations. Reducing the sampling rate of the estimations could not be done without constraining the ZWD due to the high correlation between the clock and the troposphere parameters in the observation equations which increases as the clock and troposphere parameters are estimated with a similar or nearly similar sampling rate. Keeping the 2-hour sampling rate with constraints on the parameters could also not improve our solution, as the constraints would not be significant due to the large possible variations of the parameter ZWD at this timescale.

The relative constraints are introduced as new observation equations, imposing the rate of variation of the parameter ZWD between two successive epochs of estimation. The normal equations are then modified accordingly and the least-square inversion as well.

Several sampling rate for the ZWD estimation and several relative constraints (i.e. standard deviation of the variations of ZWD between two successive epochs of estimation) have been tested. A sampling rate of 15 minutes was finally chosen along with relative constraint fixed at 1 mm. The green curves in Figures 3 (a) and 4 (a) show the differences between the IGS and Atomium clock solutions obtained with a constrained ZWD estimation. ZWD estimated with relative constraints (green curves in Figures 3 (b) and 4 (b)) are close to the IGS or the ROB E-GVAP solutions. The Atomium clock solutions do not suffer anymore from large variations as it was the case with the ZWD estimated every 2 hours (back curve in Figures 3 (a) and 4(a)), both the clock and troposphere parameter solutions are improved.

VI. CONCLUSIONS

In least-square adjustment, estimating simultaneously the clock synchronization error and the troposphere parameters ZWD can lead to important errors in the clock solutions due to strong correlations between the two estimated parameters. This study sets up in the Atomium software a new analysis strategy, which reduces the errors in clock solutions due to the imperfect troposphere estimation.. This strategy is based on a short sampling rate for the troposphere parameters estimation (rather than 2 hour previously) and introducing relative constraints on the variations of the troposphere parameter between two successive epochs of estimation. We found the highest quality of the clock estimation for a ZWD estimation sampling rate of 15 minutes and relative constraints fixed at the 1 mm/15 min. The new strategy improves the clock solutions leading to smaller differences between the Atomium and the IGS clock solutions, up to a factor of 10 between the previous and the present differences for some stations.

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