PPP and Phase-only GPS Time and Frequency transfer

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***Abstract*— The Royal Observatory of Belgium (ROB) developed the software *Atomium* to perform GPS-based time and frequency transfer. Originally dedicated to perform Precise Point Positioning (PPP) based on a combined analysis of dual-frequency carrier phase and code measurements, *Atomium* has recently been adapted to allow a phase-only analysis, providing a continuous solution independent of the GPS codes. In this paper, the analysis strategy used in *Atomium* is described and the clock solutions obtained through the phase-only approach are compared to the results from the PPP mode. It is shown that the continuous solution improves the stability of the time link for averaging times smaller than 7 days, but that the phase-only solution is drifting with respect to the combined code-carrier phase solution; this drift is station-dependent.**

I. Introduction

Geodetic time transfer, i.e. GPS time and frequency transfer based on a joined analysis of code and carrier phase measurements, and using a consistent modeling of these measurements, is presently widely recognized for its high precision This precision was demonstrated by different authors [1-5]. The major limitation of geodetic time transfer concerns the discontinuities at the daily batch boundaries, which are caused by the noise of the code measurements. Indeed, the carrier phase measurements contain an unknown initial ambiguity (integer number of cycles), so that they can only provide information on the clock evolution (frequency transfer). The absolute synchronization error between two clocks can be obtained from the code measurements, but its accuracy is limited by the code noise (some ns). As the GPS data are classically analyzed by daily batches, the absolute clock synchronization error is determined for each day from the code measurements gathered through that day. Due to the colored signature of the code noise, implying large and long-term temporal variations in all code measurements, the clock solutions show discontinuities at the day boundaries. The origin of this colored noise in the codes is presently not yet fully understood [6], but it reduces our ability to access the true clock signal, and stresses the necessity to develop a rigorous approach for continuous geodetic time transfer. One solution was already proposed in [7]; it consists in performing the PPP analysis on a longer data batch, reducing consequently the number of boundary jumps. A second approach was proposed in [8], where two ways of computation are tested, either a clock hand-over, analysing daily data batches with one common observation epoch between two consecutive days (midnight), or a stacking of the carrier phase ambiguities, through a stacking of normal equations for consecutive days.

In order to have at our disposal a simple tool for the rapid computation of clock solutions in a PPP mode, the ROB developed *Atomium*, based on a least square analysis of GPS code and carrier phase data. This tool has in addition been adapted to provide also a phase-only solution, based on the least squares estimation of the clock solution from the phase differences between successive epochs. The advantage of the phase-only approach is that it provides a continuous solution across the day boundaries, but the drawback is that the absolute clock synchronization errors can of course not be determined due to the presence of the carrier phase ambiguities. This means that the continuity of the clock solution is interrupted after each tracking interruption. For the computation of TAI [9] or any other time scale, each period of continuous clock solutions can be combined with a calibrated time transfer method as Two Way Satellite Time and Frequency Transfer (TWSTFT).

The first part of this paper presents the analysis procedure used by *Atomium* to produce a PPP solution for position and clocks, and it shows the results obtained for several stations in comparison with the solutions obtained by other software packages (NRCan and Bernese 5.0) as well as with the IGS solution obtained from the full IGS network analysis (IGS combined solution). The second part describes the theoretical background of the phase-only approach recently implemented in *Atomium* and its first results.

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II. PPP ANALYSIS

Precise Point Positioning consists in determining the station position, clock and tropospheric zenith path delay without using any measurement from another station as in differential positioning. The PPP approach requires the availability of precise satellite orbits and clocks provided by some external source. The PPP procedure is fully described in [10], we just recall here the main principle and how it is implemented in *Atomium*.

The observation equation for carrier phases (L_1 and L_2) and pseudoranges (P_1 and P_2) can be written as:

$$L_i = R + c(-\tau_s + \tau_r + \tau_t) - c\tau_{i,Li} + N_{Li}\lambda_{Li} + \frac{\lambda_{Li}}{2\pi}\phi_{d,Li} + n_{\Phi Li} \qquad (1)$$

$$P_i = R + c(-\tau_s + \tau_r + \tau_t) + c\tau_{i,Li} + c\tau_{d,Li} + n_{PLi} \qquad (2)$$

with R the geometric distance receiver-satellite, τ_s the satellite clock error, τ_r the receiver clock error, τ_t the tropospheric delay, τ_i the ionospheric delay, λ the carrier wavelength, N the phase ambiguity, τ_d the instrumental code delay, $\phi_{d,Li}$ the instrumental phase shift on the carrier, and n the noise.

Atomium is based on the ionosphere-free combinations of L_1 and L_2 and of P_1 and P_2, named L_3 and P_3 respectively. The observations are used at the 5-minute sampling rate. The satellite orbits are obtained with a Neville interpolation on 12 points of the IGS sp3 files in which the satellite positions are given at the 15 minute sampling rate; the satellite clock corrections are taken from the IGS CLK files in which the sampling rate is of 5 minutes. The station position is corrected for its time variations due to degree 2 solid Earth tides as given in the IERS Conventions [11] and for ocean loading effects, using the FES2004 model [12]. The respectively elevation (no-azimuth) and nadir-dependent absolute corrections for the receiver and satellite antenna phase center variations as made available by the IGS (file igs05.atx) are applied and the carrier-phase measurements are corrected for phase windup taking into account the satellite attitude and eclipse events. The instrumental code delays are considered as constant, and not included in the present version of the software.

The tropospheric delay is expressed as the sum of the hydrostatic and wet delays, both being the product between a given mapping function (*mf*) and the zenith path delay (*zpd*). The hydrostatic part is introduced using the Saastamoinan a priori model [13] with the dry Niell mapping function [14] and the wet part uses the Niell wet mapping function. The wet *zpd* is estimated with a 2-hour sampling rate, with linear interpolation between the epochs of consecutively estimated *zpd*'s. Using a least squares scheme, with a weighting for the codes and carrier phases associated with the noise level of each observation type and satellite elevation, *Atomium* provides an estimation of

- the receiver clock delay, at each epoch (5 minutes sampling rate)
- the position for the whole day (optional)
- the *zpd*, with a sampling rate of 2 hours
- the phase ambiguities

Figure 1 presents the clock solution obtained with *Atomium* in a PPP mode for three IGS stations over a period of 15 days. Two of them (NRC1 and BRUS) are equipped with an H-Maser, while the station PTBB is equipped with a cesium clock. NRC1 and BRUS have been chosen for their respectively characteristic large and small day boundary jumps. Figure 1 also shows the differences between the *Atomium* clock solution and the combined IGS clock solution, and this for the period Jan.-Feb. 2007. The differences between the *Atomium* clock results and the IGS clock solution for all the stations analyzed (not all are shown here) show a constant bias ranging between 0 and 200 ps plus some small variations with an rms between 50 and 100 ps. The origin of the biases is unclear at this moment.

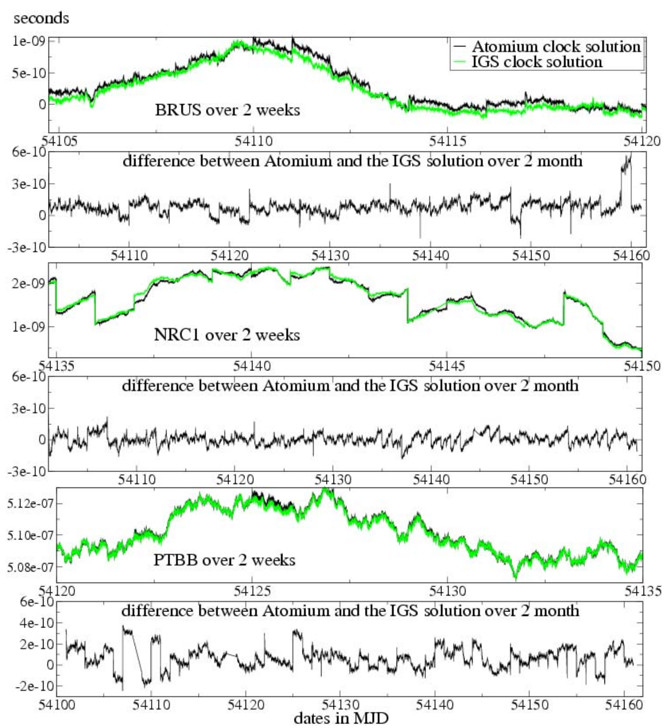

Figure 1. Comparison between *Atomium* PPP results and the IGS combined clock solutions for BRUS, NRC1 and PTBB.

Figure 2 shows the comparison between the results obtained for IENG over one week with *Atomium* and two other softwares capable of performing PPP : NRCan [10], based on sequential least squares, and Bernese 5.0 [15] based on a least squares analysis. The Bernese software does not directly interpolate the IGS orbits, as done by the NRCan and *Atomium* software, but it fits the orbits cinematically in an inertial frame where they are interpolated and then converts the obtained satellite positions back to the earth-fixed system. In Figure 2, the NRCan solution has been corrected for a constant bias of about 4 ns with respect to the other solutions. This bias is caused by the fact that the version of the NRCan software used in this work is using relative corrections for the satellite and antenna phase center variations while the

Bernese, *Atomium* and the IGS use absolute corrections since Nov. 2006. The NRCan bias remains visible in the lower part of Figure 2 which displays the differences between the clock results obtained with each PPP software and the IGS clock solution. These differences have similar amplitudes with an rms between 30 and 100ps over the week analyzed, but note that the rms is affected both by the accuracy of the solution during the different days, and its precision.

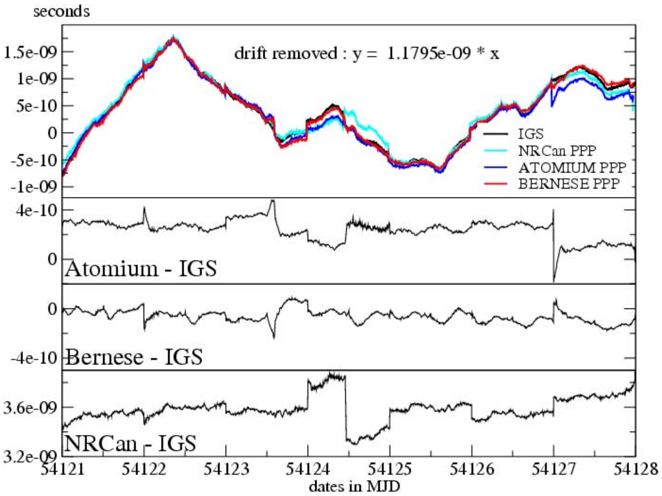

Figure 2. Comparison between the results obtained for IENG over one week with *Atomium*, NRCan, Bernese 5.0 and the IGS combined clock solution.

III. Phase-only Analysis

As we already explained, using PPP for time transfer applications is mainly limited by the presence of day boundary jumps in the clock solution, which can be important for some stations (see Figure 1 for NRC1, or [16]). One solution to suppress these day boundary jumps is to exploit the continuity of the phase measurements across midnight to provide a continuous solution without using any pseudoranges.

The phase-only approach developed here is based on this principle and has the advantage of being simple and rapid to use. It consists of using the phase differences between two consecutive epochs (with the 5-minute sampling) as basic observable, to create the normal equations accordingly, and to solve for the clock differences between the consecutive epochs.

The first derivative of equation (1) is used to generate the phase derivatives of the ionosphere-free carrier phase measurements:

$$dL_3(t) = L_3(t)-L_3(t-1) \quad (3)$$

so that

$$dL_3(t) = R(t) - R(t-1) + c(-d\tau_s + d\tau_r + d\tau_t) + n_{\Phi Li} \quad (4)$$

where $d\tau_s$, $d\tau_r$ and $d\tau_\phi$ are the differences between the satellite clock errors, the receiver clock synchronization errors and the tropospheric delays, at times *(t)* and *(t-1)*.

This new quantity does not contain any ambiguity as long as there is no tracking interruption; in case of a cycle slip the phase difference will be rejected as an outlier. The normal equations corresponding to these new observations have been written and solved in a similar way as for the PPP. The phase-only version of *Atomium* therefore provides

- the receiver clock derivative $d\tau_r$ at each epoch
- the position for the whole day (optional)
- the *zpd*, with a sampling rate of 2 hours

The phase-only clock solution is then obtained from integrating the receiver clock derivative at each epoch obtained from the least square estimation.

Similar to the strategy used in the PPP mode, the phase-only analysis is also done in daily data batches. But, the successive days are linked by computing the difference between the first observation of the day and the last observations of the day before exactly as the differences between two successive observations within a day. This guarantees the continuity of the clock solution across the day boundaries. In case of an actual tracking interruption, the phase-only solution is interrupted and the integration must be restarted.

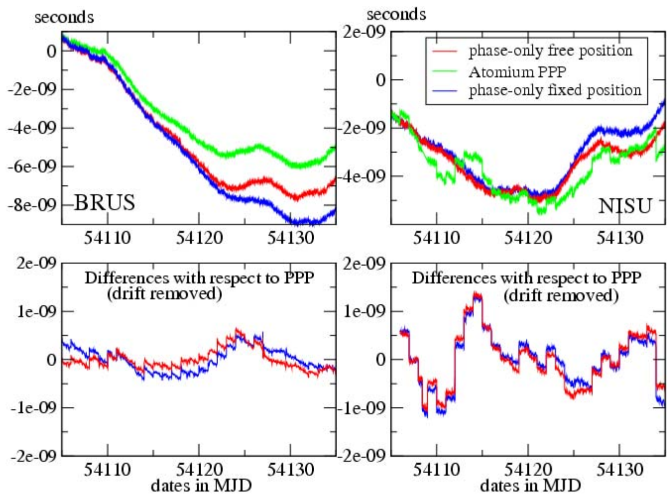

Figure 3. Comparison phase-only solution and PPP solutions for BRUS and NISU during one month.

Figure 3 compares the *Atomium* phase-only solution obtained on one hand by estimating the station position for each daily data batch, and on the other hand by keeping the position to its average value extracted from the weekly combined IGS SINEX files over the 2 months considered. We can observe a significant drift between the clock results obtained with the phase-only analysis (position fixed or not) and the PPP clock solution. The amplitude of the drift is clearly station-dependent, and amplified when fixing the position. Note that in that case, we observed that an error of 1 cm on the station position can lead to a drift of 100 ps in the clock solution over one day, leading to a disagreement of 3 ns after one month. As the PPP solutions are affected by the pseudorange noise and variations, due to some external cause like near-field antenna effect, internal multipath (reflections in the connectors) or variations of internal delays, the question could arise: is the drift correct in the phase-only solution or in the IGS and PPP solutions? The answer is given by comparing the PPP or IGS solutions with the independent time and frequency transfer method, the TWSTFT: it shows a good agreement between both [17]. Consequently, the drift in the phase-only analysis is therefore an artifact of the approach. The results confirm the drift also obtained in the approaches proposed in [8] and documented in [17]. The drifts are presently different, but a rigorous comparison of the results based on the same data and a priori positions must be done before drawing a final conclusion. Besides the effect of the position precision, the drift can also be due to some mismodeling of the observations, leading to an accumulation of errors in the continuous solution.

After removing the phase-only drift over one month, the differences between the phase-only solution and the PPP (or IGS) solution are mainly due to the day boundary jumps (see Figure 3). For a station having small day boundary jumps, like BRUS, the differences are less than 0.5 ns. Figure 4 presents the modified Allan deviation of the phase-only solution and of the daily-independent PPP solution for the time link BRUS-NISU. The continuous solution improves the stability of the time link for averaging times up to 7 days, which confirms the results obtained in [8]. Of course, the size of the improvement depends on the size of the day boundary jumps in the PPP solution.

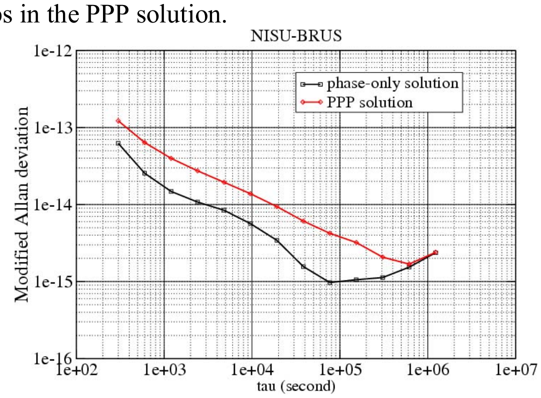

Figure 4. Modified Allan deviation of the phase-only solution and of the daily-independent PPP solution for the time link BRUS-NISU.

Another point to be mentioned is that while the phase-only analysis should provide a continuous solution, still some jumps appear at some day boundaries. These jumps are geographically correlated between the stations and they have amplitudes up to 120 ps. They are due to the non-perfect overlapping of the IGS CLK files at midnight. The amplitude of the jump depends on the visible satellites at midnight (in GPS time). This is illustrated in Figure 5 where clearly the stations in Europe show small jumps while stations in North-America show a large jump (above 100 ps).

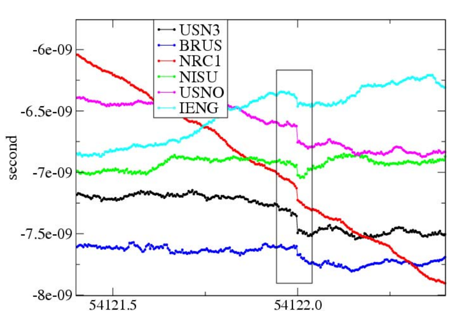

Figure 5. Jumps in the phase-only solution due to discontinuities in the satellite daily clock products

We finally compared our phase-only analysis with the continuous solution obtained with the NRCan software, which is able to analyse a data batch of several days with sequential least squares, using both code and phase observables.

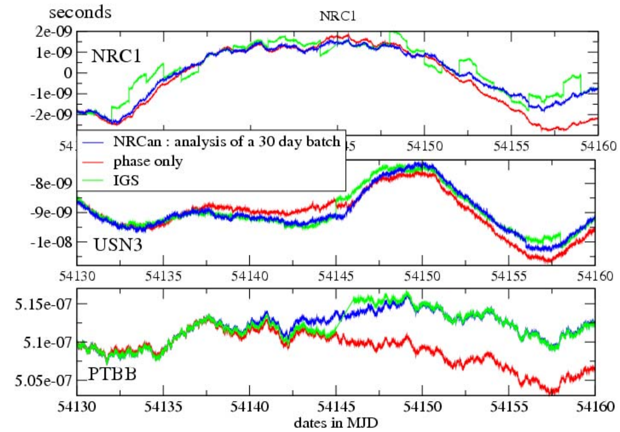

Figure 6. Comparison between the phase-only results and the NRCan results obtained through an analysis of a 30 day data batch.

Figure 6 presents the comparison between the *Atomium* phase-only results and the NRCan continuous solution for 30 days, computed for the stations NRC1, USN3 and PTBB. For NRC1 and USN3, we clearly see that the continuous solution of NRCan, which still uses the code measurements, does not contain any drift with respect to the IGS solution in a period where the IGS jumps have a normal distribution around zero, while the drift in the *Atomium* phase-only results is clearly visible, especially for NRC1. For PTBB, a large jump occurs in the IGS solution between mjd 54144 and 54146; we have verified that it is due to a code jump in the code data at mjd 54145.4, not due to a clock phase jump. As the phases are continuous at that epoch and as the codes are not used at all, our phase-only analysis ignores this jump, while in the continuous NRCan results, the jump is distributed over several days inducing an artificial drift of the solution during these days. This is also confirmed by the comparison with TWSTFT measurements between PTBB and another station (USN3 in our case, see Figure 7): neither a discontinuity nor a frequency drift is present in the TWSTFT solution, while they exist in the solutions obtained using GPS code measurements.

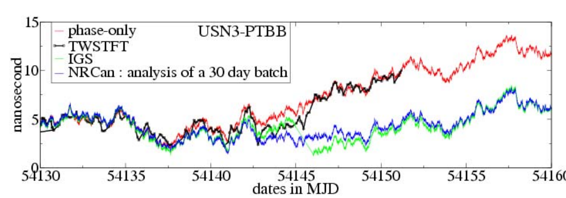

Figure 7. Comparison of the time link USN3-PTBB obtained through GPS phase-only and NRCan (30 day batch) and with TWSTFT.

IV. CONCLUSIONS

A new tool for precise GPS time and frequency transfer is presented in this paper. It is called *Atomium* and is based a least-square analysis of GPS measurements. A PPP solution can be obtained using both codes and carrier phases, and a phase-only solution is proposed in order to reduce the day-boundary jumps or intra-day jumps which are due to the use of the code measurements. The accuracy of the results obtained in the PPP mode has been deduced from the comparison of these results with the IGS combined clock products. The bias between the *Atomium* clock solution and the IGS ones is station-dependent, and remains below 200 ps. Besides this constant bias, some small variations are present, with an rms between 50 and 100 ps. This rms is similar to what is obtained with two other software performing PPP: Bernese 5.0 and NRCan.

The phase-only solution within *Atomium* is based on the analysis of the differences between the phase measurements taken at successive epochs. The analysis is performed in daily data batches, but the successive days are linked by computing the differences between the first observations of the day and the last observations of the day before. The comparison between the phase-only solution and the PPP (or IGS) solution shows a station-dependent drift, of which the origin is not yet understood. This drift can be due to either an error in the station position when this parameter is fixed within the analysis, or a mismodeling of the observations, which accumulates in the continuous solution, or some imperfections in the IGS orbits, which could explain why the drift shows small long-term variations when the position is re-estimated each day. This will be the subject of further investigations. The continuous solution improves the stability of the time link for averaging times up to 7 days, the amplitude of the improvement depends of course on the amplitude of the day boundary discontinuities in the PPP solution.

Finally, the phase-only solution still presents some small day-boundary discontinuities, of which the amplitude can reach the 120 ps level. These jumps are due to the non-perfect overlapping of the IGS CLK files at midnight; their amplitudes are geographically correlated between the stations, as they depend on the visible satellites at midnight. Modifying the weighting with respect to the satellite orbits/clock quality should solve a part of that problem.

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REFERENCES

[1] Th. Schildknecht, G. Beutler, M. Rotacher, "Towards sub-nanosecond GPS time transfer using geodetic processing technique". In: Proceedings of the 4th European Freq. and Time Forum, 1990, pp 335-346.

[2] C. Dunn, S. Lichten, D. Jefferson, JS Border, "Sub-nanosecond clock synchronization and precision deep space tracking". In: Proceedings of the 23th Precise Time and Time Interval Meeting, NASA Conference Publ. 3159, 1991, pp 89-101.

[3] F. Overney, L. Prost, G. Dudle, Th. Schildknecht, G. Beutler, JA Davis, J.M. Furlong, P. Hetzel, "GPS Time Transfer using Geodetic Receivers (GeTT): Results on European Baselines". In: Proceedings of the 12th EFTF, 1998, pp 94-99.

[4] K.M. Larson, J. Levine, L.M. Nelson, T. Parker, "Assessment of GPS carrier-phase stability for time-transfer applications". IEEE Trans. Ultrason., Ferroelect., Freq. Contr., 47(2), pp 484-494, 2000.

[5] C. Bruyninx, P. Defraigne, "Frequency Transfer Using GPS Codes and Phases : Short and Long Term Stability". In: Proceedings of the 31th PTTI meeting, Dana Point, California, decembre 1999, ed. L.A. Breakiron, 2000, pp 471-478.

[6] C. Bruyninx, P. Defraigne, "On the link between GPS pseudorange noise and day-boundary discontinuities in geodetic time transfer solutions", GPS solutions, 2007, in press.

[7] D. Orgiazzi, P. Tavella, F. Lahaye, "Expermiental assessment of the time transfer capability of Precise Point Positioning (PPP)", in: Proc. of the 2005 IEEE Internat. Freq. Contr. Symp., pp. 337-345.

[8] R. Dach, T. Schildknecht, U. Hugentobler, L.-G. Bernier and G. Dudle, "Continuous Geodetic Time Transfer Analysis method", in: Proc of the IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 2005, pp 329 – 336.

[9] Z. Jiang, G. Petit, P. Defraigne, "Combination of GPS Carrier Phase Data with a Calibrated Time Transfer Link", 2007, this issue

[10] J. Kouba, and P.Héroux, "Precise Point Positioning using IGS orbits and clock products", GPS Solutions, 5, p 12-28, 2001.

[11] D. McCarthy, G. Petit, "IERS conventions 2003", IERS Technical note, 32.

[12] T.Lettelier, F. Lyard, F. Lefebre, "The new global tidal solution : FES2004". Jason SWT Meeting Abstracts, St Petersburg, Florida, Nov.2004.

[13] J. Saastamoinen, "Atmospheric correction for the troposphere and stratospherein radio ranging of satellites", Geophys. Monogr. 15, Use of Artificial Satellites for Geodesy, pp. 247-251, AGU, 1972.

[14] A.E. Niell , "Global mapping functions for the atmospheric delay at radio wavelengths", Journ. of Geophys. Res. 101(B2), pp. 3227-3246, 1996.

[15] U. Hugentobler, R. Dach, P. Fridez, M. Meindl (eds.) "Bernese GPS software version 5.0". Astronomical Institute University of Berne, 2004.

[16] K. Senior, J. Ray, "Using IGS clock products to monitor GPS station performance", IGS Mail #660, 15 october 2005; http://igscb.jpl.nasa.gov/mail/2004/msg00342.html.

[17] G. Petit, Z. Jiang, "Stability of geodetic GPS time links and their comparison to two-way time transfer", Proc. 36th PTTI, 2004, pp. 31-39

[18] Z. Jiang, R. Dach, T. Petit, T. Schildknecht, U. Hugentobler, "Comparison and combination of TAI time links with continuous GPS carrier phase results", Proc. EFTF 2006, on CD_rom.