Recent improvements in GPS carrier phase frequency transfer

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***Abstract*— GPS carrier phase frequency transfer is a convenient method to compare distant ground clocks. It requires multi-channel dual-frequency GPS receivers in both ground stations.**

In this paper, CNES specific software for GPS carrier phase frequency transfer is used. It overcomes the usual limitation of some GPS solutions : the day boundaries discontinuities. These discontinuities in the clock solution occur if the data are analyzed in daily independent batches. It is also possible to down sample the measurement files. These two functionalities allow us to perform a continuous GPS carrier phase frequency transfer on long durations. Results on different baselines are presented and discussed. For instance, on medium baselines, stabilities reaching 1.10^{-15} (Allan deviation) on one day are commonly obtained. On transatlantic baselines, stabilities are degraded due to the low number of satellites in common view.

In the Time/Frequency laboratory of CNES, several GPS receivers and frequency standards are available. With this technique, we can estimate CNES H-Maser frequency stability (from 3.10^{4} s on, at the level of 4.10^{-15}). Moreover, we can compare the obtained results with local comparisons, including versus a cryogenic sapphire oscillator.

Besides, the precise orbit restitution software developed at CNES (ZOOM) is able to solve the clocks of a GPS network (ground and on-board clocks) on several days. The formulation is slightly different from the previously mentioned software and the models are also different (for example the phase wind-up can be modeled). We compare and discuss some frequency transfer results obtained with both approaches. On medium baselines, very similar results are obtained. But on transatlantic baselines, better results are achieved provided that a good network geometry is chosen.

I. INTRODUCTION

Time or frequency transfers using satellites and especially GPS have been used for many years. The classical technique consists in processing the C/A code measurements of two ground stations on one single GPS satellite (in common view and chosen using a predefined schedule) to provide the comparison of the two ground clocks. This is equivalent to a single difference code measurement residual at each epoch. Such a method provides a time transfer precision of a few nanoseconds, which is not sufficient for high performance atomic clocks.

High quality geodetic GPS receivers are able to track several satellites in the same time and to record two frequencies in order to compute the so-called ionosphere-free combination. So, using all these code measurements, an extension of the classical technique is possible by averaging on all satellites in common view of both stations and by canceling out the ionosphere effects. If the receivers of the two ground stations can track the P code on both frequencies, this extension of the classical technique is called P3 [4].

Moreover, such receivers are also able to record carrier phase observables. Since the intrinsic noise of the carrier phase is much smaller than the code, it offers promising perspectives for accurate frequency transfer for integration times between several hours and several days [1-7,9].

Some GPS receivers are also able to collect code and phase data from geostationary (GEO) satellites that transmit GPS-like signals. Such satellites are very interesting thanks to their continuous observability. Unfortunately, they transmit today on a single frequency (L1), preventing from computing the iono-free combination. Furthermore, a precise orbit shall also be determined. The advantages/drawbacks of GEO with respect to GPS satellites for accurate frequency transfer have been investigated and their performances compared [7,8].

The clock solution computed by GPS carrier phase comparison may present discontinuities at day boundaries [5, 6]. They are due to the discontinuities of the phase ambiguities at the day boundaries when processing daily batches. A possible solution to generate a continuous transfer is to use the set of midnight clock parameters to link the computation batches [6].

Our new software, called here two-station algorithm, was initially developed by CNES Precise Orbit Restitution Service for EGNOS ground stations positioning and clock identification.

Being able to process several consecutive days, this algorithm overcomes the day boundaries discontinuities. The Microwave and Time/Frequency Department of CNES uses this software with GPS code and phase data coming from several GPS receivers connected to a Hydrogen Maser.

Besides, the precise orbit restitution tool developed at CNES (ZOOM) is able to solve the clocks of a GPS network (ground and on-board clocks) on several days. The formulation is slightly different from the previously mentioned software and the models are also different (for example, the phase wind-up can be modeled).

In this paper, we will first present the different GPS receivers available at the CNES Time/Frequency laboratory. Then, both algorithms (two-station and network) are detailed. Last, some results of frequency transfers on different baselines using the two algorithms are highlighted.

II. HARDWARE DESCRIPTION

A. *GPS receivers*

In the CNES Time/Frequency laboratory, we use several GPS receivers which observables are summarized in Table 1. They are time receivers, except the NovAtel OEM-3. Every receiver has their own omni directional antenna.

B. *Frequency Standard*

These receivers are connected to our Hydrogen Maser (EFOS-16 from Neuchâtel Observatory). This active Maser has no automatic cavity tuning (ACT) in order to improve the short term stability. The drawback is that the long term stability is degraded.

In paragraph IV.A., we will try to characterize its stability by comparing GPS carrier phase frequency transfer to different local measurements.

TABLE I. OBSERVABLES OF CNES RECEIVERS

	Observables	GPS/GEO
Ashtech Z12-T	C1, P1, P2, L1, L2	GPS only
NovAtel OEM-3	C1, P2, L1, L2	GPS/GEO
NovAtel MPC	C1, P2, L1, L2	GPS/GEO
Septentrio PolaRX	C1, P1, P2, L1, L2	GPS/GEO

III. DESCRIPTION OF TWO-STATION AND NETWORK ALGORITHMS

A. *Two-station algorithm (EPO : EGNOS Performance Obervatory)*

The first algorithm used in this study was developed by CNES orbit restitution service for the positioning of GPS ground stations for EGNOS project (in the EGNOS Performance Observatory toolbox : EPO). It can perform a single station absolute positioning (relative to a given GPS clock and ephemeris). It can also perform a relative positioning between two stations using single difference measurements.

The EPO software was initially limited to one day measurements [3] (use of IGS daily ephemerides and clocks and RINEX files). A new development has been recently carried out to solve for longer durations, with also the ability to down sample the measurements and to allow phase continuity between daily files. This continuity is ensured by keeping the ambiguities from one day to the next one.

The basic design is to use elementary executables that are launched in a script, that is written by a specific front end, depending on the solution configuration.

The algorithm is composed of three main parts :

- pre-processing and partial derivatives computation, this part is common to both single and relative positioning cases.
- absolute positioning least squares filter : receiver antenna is positioned using GPS ephemerides and clocks as inputs (IGS products .sp3 and .clk). The receiver clock relative to GPS solution time is also estimated.
- relative positioning least squares filter : one station is taken as reference and the second is positioned using single differences measurements. The station receiver clocks difference (referred to as clock solution) is also obtained.

A detailed description of this algorithm is given in [9].

B. *Network algorithm (ZOOM)*

The network solution is computed using the CNES precise orbit restitution software (ZOOM). This software is for example currently used to compute the JASON precise orbits, using GPS, DORIS and Laser measurements. The GPS part is also able to process ground station measurements, for example to perform orbit restitutions on the GPS constellation.

For the present study, the GPS orbits are fixed to the IGS solution. The measurements are dual frequency code and phase measurements. They are pre-processed and down sampled with the same method as for EPO solutions. Two cases (as for EPO) are solved for :

1 – absolute positioning : GPS clocks are fixed and only ambiguities, tropospheric vertical path delay, coordinates and receiver clocks are adjusted. This configuration is very similar to the absolute positioning EPO filter presented above.

2 – relative positioning : GPS clocks, ambiguities, tropospheric vertical path delay, coordinates and receiver clocks are adjusted. A reference station is fixed (coordinates and clock).

C. Comparison of the configurations

Table II summarizes the algorithms specificities.

TABLE II. COMPARISON OF TWO-STATION (EPO) AND NETWORK (ZOOM) ALGORITHMS

	EPO	ZOOM
Observables	C1,C2,L1,L2 or P1,P2,L1,L2	P1,P2,L1,L2
Measurement elimination	Pre-processing : Cycle slip, outliers Elimination of outliers during solution	Pre-processing : Cycle slip, outliers
Phase ambiguities	Adjusted	Adjusted
Models	Earth tides (IERS) Relativistic correction for GPS clocks Tropospheric zenith delay (1/12 day, continuous segments, relative constraints) Computations in terrestrial frame Geometry of GPS (z only, no attitude)	Earth tides (IERS) Relativistic correction for GPS clocks Relativistic correction for propagation Tropospheric zenith delay (1/10 day, constant segments, no constraint) Computations in inertial frame Geometry of GPS (x,y,z complete attitude) Phase wind-up
Absolute positioning	Least squares, one station	Least squares, several stations
Relative positioning	Least squares, one station w.r.t. reference station	Least squares, several stations w.r.t. reference station
Clocks	One receiver clock, epoch by epoch	GPS and receivers clocks, epoch by epoch

IV. RESULTS WITH THE TWO-STATION ALGORITHM

In this part, we give some results obtained on different baselines with the two-station algorithm.

The first part of these results summarizes our efforts to characterize CNES Hydrogen Maser using local measurements and GPS carrier-phase. The second and third parts concern IGS stations equipped with Hydrogen Masers with good long term stability on continental baselines (IV.B and C) and on transatlantic baselines (IV.D).

A. An attempt to characterize CNES Hydrogen Maser

We compare here our Hydrogen Maser (with the NovAtel OEM-3 receiver) to another H-Maser located in the IGS station BRUS (Brussels, Belgium). The receiver in this station is an Ashtech Z12-T. The baseline is about 800 km. We processed 8 consecutive days. Fig. 6 shows the location of these two stations.

The computation of the clock solution has been performed with different elevation limitations (5°, 10°, 20°, 30° and 40°). Table III provides the mean number of satellites in common view according to the elevation limitation. On Fig.1 are presented the Allan deviations of the clock solution for 4 different elevation limitations (10° to 40°).

For clarity, we didn't plot the Allan deviation curve for a 5° elevation limitation that provides no improvement w.r.t. 10°. As expected, the transfer noise is much lower than what is usually reported for GPS P3 frequency transfer [4] on similar baselines.

TABLE III. NUMBER OF SATELLITES IN COMMON VIEW AS A FUNCTION OF THE ELEVATION LIMITATION ON CNES/BRUS BASELINE

Elevation limitation	Number of satellites for CNES/BRUS baseline
40°	3
30°	4.3
20°	5.5
10°	6.5
5°	6.6

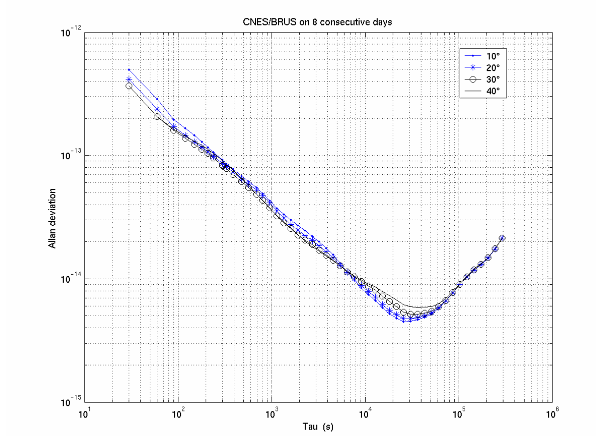

Figure 1. Frequency stability (Allan deviation) of the clock solution obtained with the two-station algorithm on BRUS/CNES baseline for different elevation limitations

With a high elevation limitation, only the "center" of each satellite pass is considered, which should provide the best solution (because this part of the satellite pass is the less noisy due to the higher signal to noise ratio). However, the number of satellites used for the computation is then lower. As the clock solution is averaged on fewer satellites, the stability may be affected. Also, the tropospheric vertical path delay is not so well identified. So there is a trade-off to perform on that point. As we are more interested in the stability in the range of 10^4 seconds and more, we can derive from this curve that the best compromise for elevation limitation is 10° on such a baseline.

Fig. 2 compares the stability obtained between our Hydrogen Maser and BRUS (with an elevation limitation of 10°, indicated by dark stars) to other characterizations of our H-Maser :

- its stability measured in 1996 at Neuchâtel Observatory by triangulation with 2 other H-Masers (indicated by a blue line)
- the stability obtained by hourly comparison with a Cesium clock Agilent 5071A-001 (indicated by dark circles)
- the stability obtained by comparison with the cryogenic sapphire oscillator SOPHIE (from University of Western Australia) located 800 m away from our laboratory (indicated by blue points). This comparison is performed at 100 MHz through optical fibers.

The reference stability is deemed to be the one obtained by triangulation in 1996 at Neuchâtel Observatory, but it can't be obtained again as it would require two other H-Masers.

The comparison of our H-Maser with a cryogenic sapphire oscillator is likely to be degraded by the transfer by fiber. This point shall be investigated further. The drift observed after 500 seconds on this curve is due to the cryogenic sapphire oscillator.

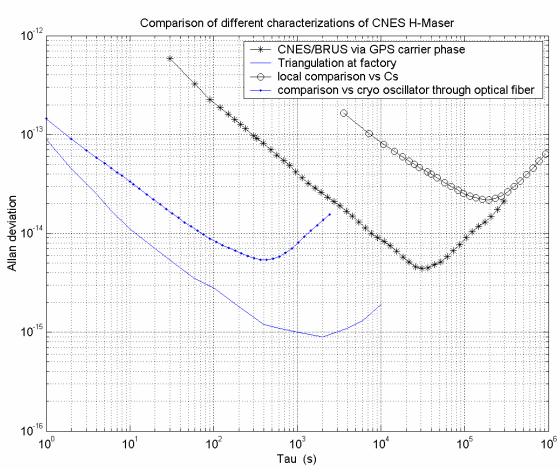

Figure 2. Different characterizations of CNES Hydrogen Maser

The frequency comparison with BRUS by GPS carrier phase is obviously limited in the short term by the stability of the link. However, if we extrapolate the triangulation results, we obtain an excellent agreement with GPS carrier phase. The local comparison with a Cs clock is of course affected by the stability of the Cs clock in the short and mid term. But, in the long-term, it is also in very good agreement with GPS carrier phase.

Therefore, we can conclude that our H-Maser can be characterized by GPS carrier phase frequency transfer at the level of 4.10^{-15} (Allan deviation) from $\tau = 3.10^4$ s on.

B. Results on continental baselines

It is also interesting to look into other baselines involving Hydrogen Masers with Automatic Cavity Tuning in order to investigate stability up to one day without being limited by the frequency drift. In this part, we used three different baselines with IGS stations BRUS, OPMT (Paris, France) and WSRT (Westerbork, The Netherlands). OPMT is equipped with an Ashtech Z-12T, while WSRT has an AOA SNR-12 ACT.

Fig. 6 shows the location of these 3 stations. The lengths of the baselines are given in Table IV.

The different results are summarized in Fig. 3. The site limitation was 10° and we processed 4 consecutive days. We get a very good result, approaching 1.10^{-15} in Allan deviation on one day.

TABLE IV. LENGTH OF THE OPMT/BRUS/WSRT BASELINES

	OPMT/BRUS	OPMT/WSRT	BRUS/WSRT
Baseline	260 km	540 km	280 km

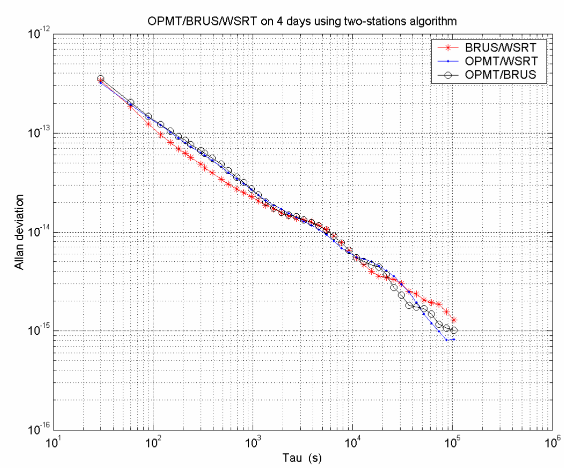

Figure 3. Frequency stability (Allan deviation) of the clock solution obtained with the two-station algorithm on BRUS/WSRT, OPMT/WSRT and OPMT/BRUS baselines

A possible control consists in comparing the clock solution obtained on OPMT/WSRT baseline to the difference of the clock solutions obtained on OPMT/BRUS and BRUS/WSRT. We get a very good agreement between them. Fig. 4 shows their difference (known as closure) on 2 days. This seems to be a good result, however the offset is striking and is worth further investigations.

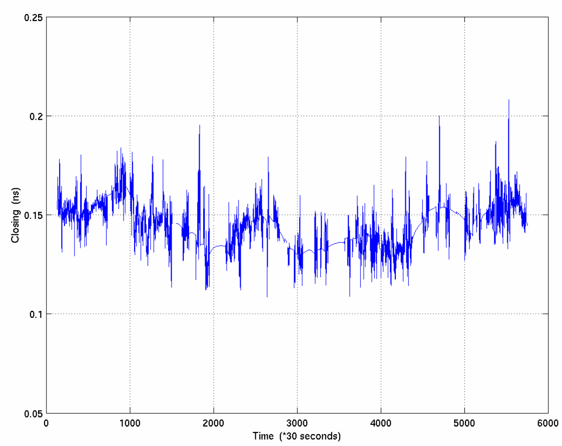

Figure 4. Closing of the clock solutions obtained with the two-station algorithm on OPMT/WSRT, OPMT/BRUS BRUS/WSRT baselines

C. *Single pass analysis on continental baseline*

The overall clock solutions presented above are simple average of the clock solution provided by each satellite in common view at each epoch. We can also compare the above stabilities to individual clock solution provided by a single satellite (hereafter referred to as pass). All geometry (coordinates) and propagation (troposphere) parameters are the same as in the overall solution.

Fig. 5 compares the stability previously obtained on OPMT/BRUS (indicated by dark circles) to the stability obtained with only PRN 20 (indicated by red lines) on the same baseline. In the very short term, the overall stability is better than the individual passes with a ratio close to the square root of the number of satellites in common view. But after around 600 seconds, several passes present a better stability than the overall clock solution, which shows that the latter is affected by a noise that corresponds to the connection of the different passes even on continental baselines.

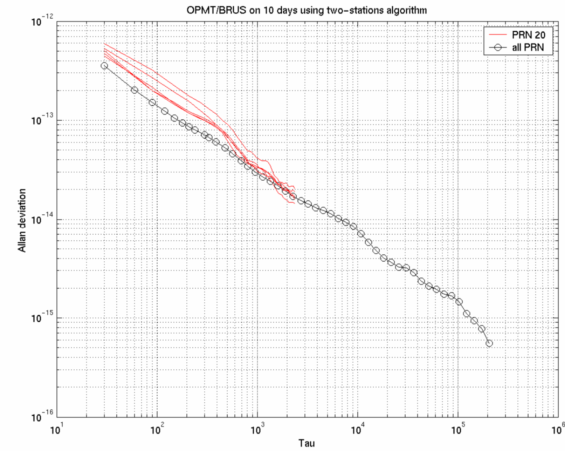

Figure 5. Comparison of the stability of the different passes with PRN 20 to overall clock solution stability on OPMT/BRUS baseline

D. *Results on transatlantic baselines*

We used three different baselines with IGS stations OPMT, BRUS and USNO (US Naval Observatory, USA). These stations are all equipped with Ashtech Z12-T and Hydrogen Masers.

Fig. 6 shows the location of these 3 stations. The lengths of the baselines are given in Table V.

The different results are summarized in Fig. 7. The elevation limitation is 10° on OPMT/BRUS. On transatlantic baselines, slightly better results have been obtained with an elevation limitation of 5°. This allows to increase the mean number of satellites in common view from 2.3 to 3.2.

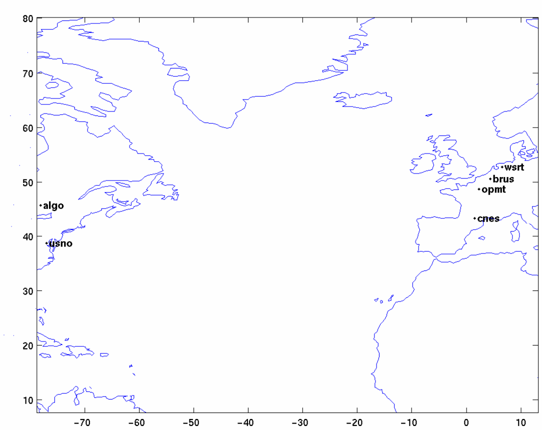

Figure 6. Map of the different stations

TABLE V. LENGTH OF THE OPMT/BRUS/USNO BASELINES

	OPMT/BRUS	OPMT/USNO	BRUS/USNO
Baseline	260 km	5940 km	5990 km

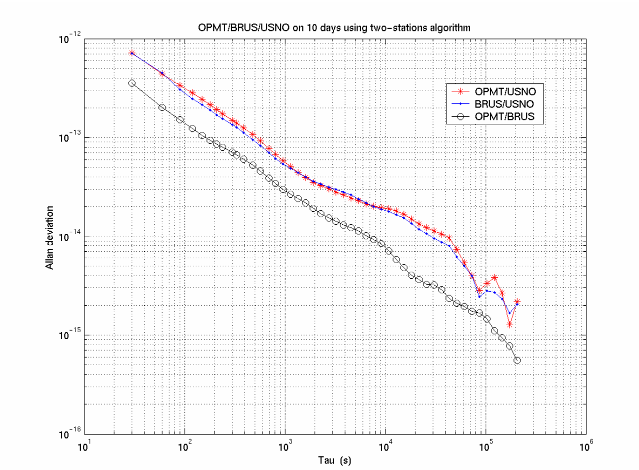

Figure 7. Frequency stability (Allan deviation) of the clock solution obtained with the two-station algorithm on OPMT/USNO, BRUS/USNO and OPMT/BRUS baselines

This clearly shows the impact of the length of the baseline : on both transatlantic baselines, the stability is degraded for several reasons. The first reason is the mean number of satellites in common-view of both stations. As we average on fewer satellites, the clock solution is not as good as on shorter baselines.

The low number of satellites in common view has also another consequence. With some potential mismodelling, this makes difficult the connection between different satellite passes and therefore induces a worsening of the stability. The low number of satellites in common view on transatlantic baselines also prevents from excluding the boundaries of the passes (that are usually noisier), otherwise continuity may be lost. Moreover, zenith tropospheric delay is not as accurately identified as on shorter baselines.

V. RESULTS WITH NETWORK ALGORITHM

A. *Comparison of clock solutions obtained with two-station and network algorithms*

The same data are now processed in one set. The measurements from IGS stations OPMT, BRUS, USNO and ALGO (Algonquin, Canada) are processed with a 5 minutes sampling. BRUS is chosen as the reference station.

Fig. 8 shows the stability of the clock solution obtained with the network algorithm on OPMT/BRUS baseline, and compares it to the stability obtained with the two-station algorithm on the same baseline, on the same 7 days.

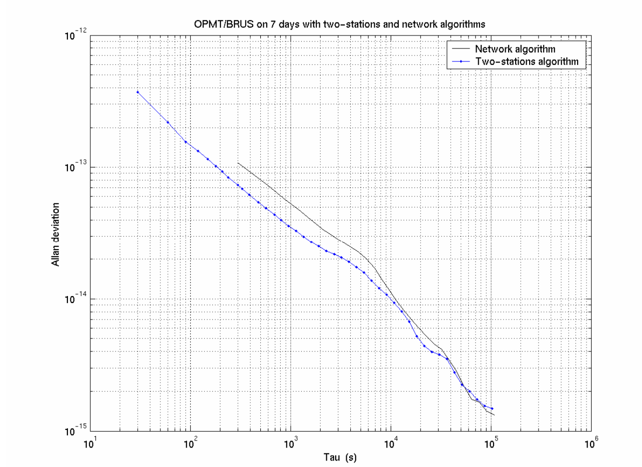

Figure 8. Frequency stability (Allan deviation) of the clock solutions obtained with both algorithms on OPMT/BRUS baseline on 7 days (Network : OPMT/USNO/BRUS/ALGO)

Fig. 8 shows an excellent agreement between both clock solution stabilities from 10^4 seconds onwards. Before that, the network algorithm clock estimation is not as good as the two-station algorithm clock : this is due to a specific process of low site measurements elimination for the clock estimation in the EPO algorithm. Also, the tropospheric modelling is not so smooth in the global case (discontinuities between the 1/10 day constant segments).

The same comparison is performed on USNO/BRUS baseline on Fig. 9.

Fig. 9 shows clearly that the network algorithm provides a better clock solution on such a transatlantic baseline. We assume this is due to the presence of ALGO close to USNO, which stabilizes the USNO related parameters (troposphere, coordinates…).

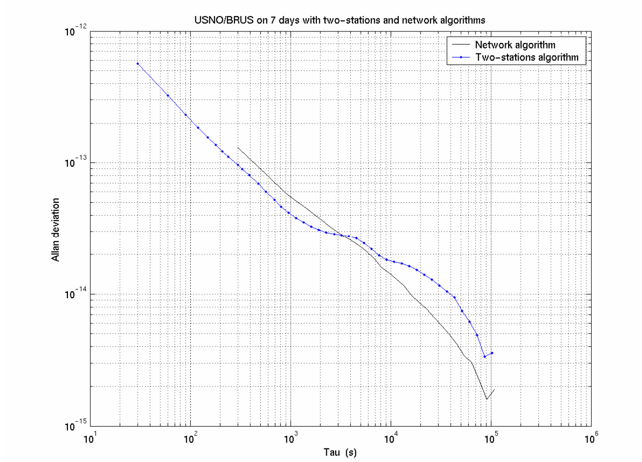

Figure 9. Frequency stability (Allan deviation) of the clock solutions obtained with both algorithms on USNO/BRUS baseline on 7 days (Network : OPMT/USNO/BRUS/ALGO)

B. *Effect of network geometry*

To confirm this, we replace in the network ALGO with WSRT and process a batch of 3 days. BRUS is still the reference station. Fig. 10 presents the Allan deviations obtained in this case with the network algorithm.

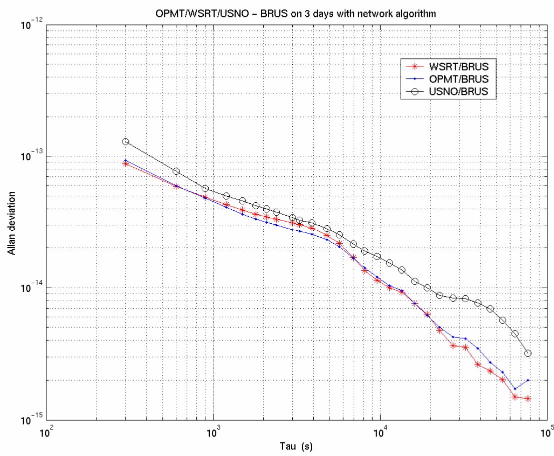

Figure 10. Frequency stability (Allan deviation) of the clock solutions obtained with the network algorithms (Network : OPMT/USNO/BRUS/WSRT)

We get very similar results on OPMT/BRUS and WSRT/BRUS with previous experiments (Fig. 3 and 8) . But the stability of USNO/BRUS is degraded because of the absence of the ALGO station close to USNO. We can deduce that the choice of the network geometry is very important and should avoid having one station very far away from the rest of the network.

C. *Wind-up effects*

In this paragraph, the same set of measurements is used for a network solution, with or without wind-up modelling. There is an important effect on the absolute solution, because the modelling must be consistent with the one used for the GPS clock solutions.

Fig. 11 shows the differences between the two clock solutions for the four stations (ALGO, OPMT, BRUS, USNO). There are important effects at 24 hours period and linear errors.

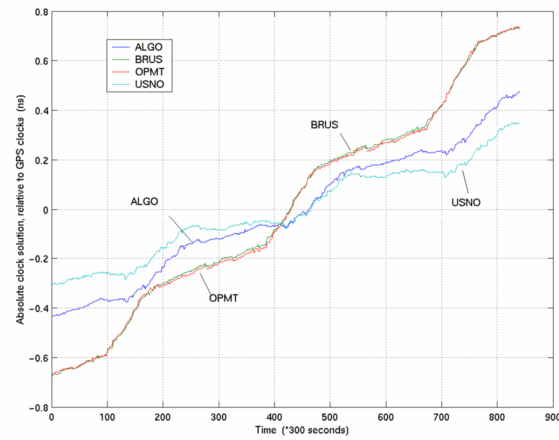

Figure 11. Differences between absolute solutions with and without wind-up modeling (network algorithm).

The effects are similar on OPMT and BRUS on one hand and on ALGO and USNO on the other because the GPS relative geometries are almost the same. 24-hour periods are observed due to the periodicity of the geometry of the problem.

For the relative solution, the effect of wind-up is not so important because the GPS clocks are identified in a consistent way with the measurement modelling. The difference between the clocks referenced to BRUS clock is below 50 ps.

CONCLUSIONS

In this paper, we presented several frequency comparisons using GPS carrier phase over short and long baselines using two different algorithms. Both algorithms can handle batches of several days in order to produce a continuous clock solution over that period. Moreover, for longer periods, a down sampling of the data can be easily performed to avoid too long a computation time.

Over continental baselines, the two-station algorithm and the network algorithm provide very consistent results approaching an Allan deviation of 1.10^{-15} on one day.

Over transatlantic baselines, the two algorithms provide different results. The two-station algorithm is limited to an Allan deviation of $3\text{-}4.10^{-15}$ on one day, due to the low number of satellites in common view. Conversely, the network algorithm provides a stability closer to what is obtained on continental baselines, provided a good network geometry is chosen.

The upcoming of Galileo will increase the number of satellites in common view (on condition that bi-system receivers are used). This should increase the performance of GNSS frequency transfer, especially with the two-station algorithm. However one must be careful to the consistency of the reference frames of both constellation solutions and to inter-system biases in the measurements.

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