Real time zero-difference ambiguities fixing and absolute RTK

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BIOGRAPHY

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ABSTRACT

Until recently it was believed that integer ambiguities could only be fixed on differenced measurements in order to remove biases. Recently Mercier and Laurichesse [2] have demonstrated that simple assumptions on bias stability are sufficient to fix integer ambiguities on zero-difference phase measurements.

A solution for clocks over a regional network can then be computed using these unambiguous phase measurements and precise GPS satellites ephemerides (such as IGS products), giving integer phase clocks for the satellites. These clocks have an interesting property : they allow the positioning of an independent receiver using a PPP like method, with integer ambiguities properties on the phase residuals [1].

If this zero difference ambiguity fixing is performed in real-time, it becomes possible to compute RTK solutions with centimeter accuracy without using any close reference station. In this paper, we address real time issues of zero differenced ambiguity fixing, and we present a method for absolute RTK for dual-frequency receivers.

1. INTRODUCTION

Integer ambiguity resolution is routinely applied on double differenced GPS phase measurements to achieve precise positioning. Double-differencing is very powerful because it removes most of the common errors between the different signal paths, including biases, making it easier to identify integer ambiguities. Double-differencing also minimizes the size of the problem to be solved by removing all the clock contributions. This technique is the basis for very precise differential positioning.

Precise Point Positioning (PPP) is an alternative approach to perform precise positioning. In this technique, zero-difference measurements are used in combination with precise orbits and clocks for the GPS constellation. The performance of the method is directly related to the quality of these input orbits and clocks, which are computed using data collected over a world-wide network of stations. PPP is a very powerful tool, in particular to track moving receivers, however, until recently it lacked the ability to fix integer ambiguities.

We have recently shown [1,2] that it is possible to directly fix integer ambiguities on zero-difference phase measurements. Phase measurements then become unambiguous pseudo-range-like measurements with millimeter noise level. Network solutions for orbits and integer phase clocks then acquire the ability to "reveal" the zero-difference integer ambiguities during the PPP processing of any receiver.

More precisely, the network solution for integer clock computation involves two steps. First zero difference wide-lane integer ambiguity fixing is performed independently for each receiver of the network using previously determined satellite delays [1]. This leads to ionosphere-free equations where the only ambiguity left is the ambiguity on the first frequency (for GPS, the equivalent wavelength is 10.7 cm).

These remaining ambiguities are fixed globally over the whole network using zero-differenced narrow-lane integer ambiguity fixing. Integer phase clocks for the GPS constellation are a by-product.

During PPP, the same first processing step is applied to any receiver to fix its zero-difference integer wide-lane ambiguities, using the same satellite delays as the ones used in the network solution (these delays are equivalent to ‘wide-lane clocks’). Then, integer phase clocks are used to fix the remaining ambiguities on the first frequency, leading to “absolute” centimeter level PPP [2]. Figure 1 synthesizes the key steps involved in our PPP approach.

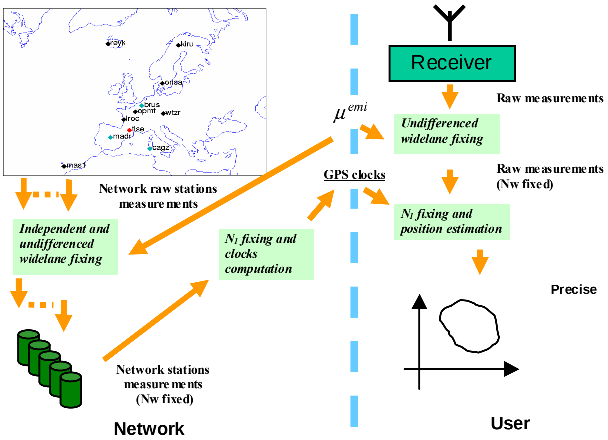

Fig. 1. Integer PPP diagram

In this paper we will demonstrate how this same technique can be applied for real-time positioning. We will not consider the problem of transmitting orbits and clocks for the GPS constellation from the reference center computing network solution to the end user, which is a transmission problem which can be dealt with in many different ways (dedicated transmission system, local or global augmentation system, internet access via GPRS, etc.). We will focus instead on the challenges posed by real-time integer ambiguity fixing.

Real-time implementation of the network solution raises difficult issues. The ability to perform fast zero-difference real-time wide-lane integer ambiguity fixing is strongly dependant on the quality of pseudo-range measurements. Thus, the time to fixing will depend on the quality and sampling rate of the measurements. It will also depend on the elevation of the satellites over the horizon. Zero-difference real-time narrow-lane integer ambiguity fixing requires a Kalman filter working with mixed integer and float variables, in order to fix ambiguities on the fly as new satellites come into view.

For user receivers a complex initialization step must be implemented to find the first PPP solution and the current ambiguities, assuming that the receiver is not moving. A bootstrap method is applied on an initial floating solution. The time to convergence depends on the quality of the initial state vector. It is only then that the pursuit can be started, i.e. the RTK itself. This is realized by a Kalman filter with ambiguities fixed 'on the fly'. The absolute RTK positioning solution is directly extracted from the state vector of the filter.

Examples using play-back data from the IGS or data obtained directly on the internet from the EUREF real-time network will be shown. In each case, real-time integer clocks are compared to a reference solution obtained by post-processing to assess both quality and availability. Absolute RTK positioning of a ground receiver using these real-time integer clocks is then presented. The achieved positioning is at the centimeter level.

2. GENERAL OVERVIEW OF THE APPROACH

The detailed formulation has been presented in [2] with some applications to PPP [1] or time transfer [4]. The main characteristics are summarised hereafter.

The general objective is to solve simultaneously for clocks and zero differences integer ambiguities. First the zero difference integer widelane ambiguities are estimated for each receiver. Using these values, the ionosphere free pseudo-range and phase equations are constructed.

These equations correspond to a system, without ionosphere propagation effects, and an equivalent wavelength of 10.7 cm. The remaining integer ambiguity and other parameters (clocks, troposphere delays, coordinates) can then be solved over a network of stations.

2.1. ZERO DIFFERENCE INTEGER WIDELANE AMBIGUITY SOLUTION

In a first step, integer widelane ambiguities are solved for each receiver. The code and phase widelane (Melbourne-Wubenna) combination $f(L_2 - L_1, P_1, P_2)$ is constructed for each pass. This is the ionosphere and geometry free linear combination between pseudo-range P_1 and P_2 and difference of the phases L_1 and L_2 (subscripts 1 and 2 correspond to the two frequencies). For all measurements of one pass this combination can be expressed as [2,3]:

$$f(L_2 - L_1, P_1, P_2) = -N_w + \mu_{rec} - \mu^{emi} \qquad (1)$$

where $N_w = N_2 - N_1$ is the difference of the ambiguities of the two phase measurements for the current pass and

μ_{rec}, μ^{emi} are respectively the receiver and satellite widelane biases. These biases do not depend on the pass. For the GPS satellites, their values vary slowly with time, typical variations are well below one cycle over one day. Receiver biases are generally stable for receivers in good environmental conditions. In a few cases, variations up to a few cycles per hour have been observed [1].

The fractional parts of the satellite biases μ^{emi} are solved by using a limited set of good reference receivers with stable delays μ_{rec} (only the receiver measurements are needed, no external model is necessary).

Then it is possible to construct a consistent set of widelane biases for any receiver by fixing μ^{emi} and solving equations (1) for all measurements to find a set of integer N_w values and a slowly varying value of μ_{rec}. As an example, figure 2 shows the values of $f(L_2 - L_1, P_1, P_2)$ for all passes (upper plot) and $f(L_2 - L_1, P_1, P_2) + \mu^{emi}$ for the same passes (lower plot). The integer N_w values can be directly defined, together with a global bias μ_{rec} in order to verify equations (1) in the least-squares sense.

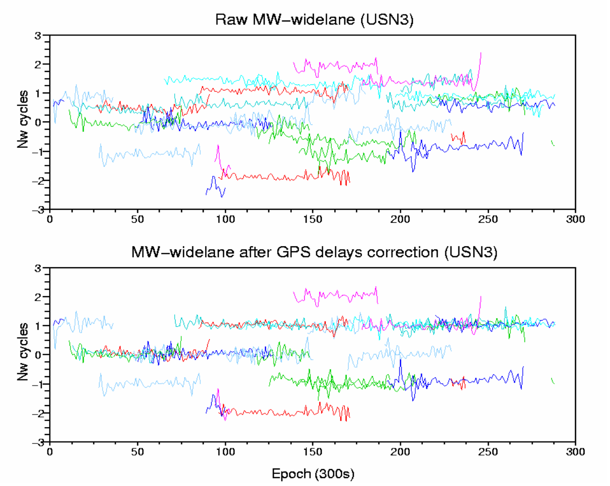

Fig. 2. Floating vs. Integer Nw residuals

With a fixed set of μ_{rec}, μ^{emi} coefficients, all the integer widelane are uniquely defined.

Given the nature of the problem, the receiver bias is clearly only determined modulo one cycle. The same is true for satellite biases. As a consequence all the integer widelane ambiguity values are consistent with a choice of biases. A set of global integers remains unknown (one for each emitter and each receiver). One can also note that any widelane double difference combination is by construction equal to 0 up to measurement noise .

When mixing different receivers technologies the problem is somewhat more complex, and different sets of widelane biases are observed [2]. However, using specific inter-calibrations on short baselines, it is possible to construct consistent widelane solutions for heterogeneous networks.

2.2. ZERO-DIFFERENCE PHASE AND PSEUDO-RANGE IONOSPHERE FREE COMBINATIONS

Using the N_w values determined previously, the global ionosphere-free combinations of pseudo-ranges P_1, P_2 and phases L_1, L_2 can be expressed as :

$$\begin{aligned} P_c &= D_c && +\Delta h + \Delta\tau \\ Q_c &= D_c + \lambda_c N_{windup} && +\Delta h \qquad - \lambda_c N_1 \end{aligned} \tag{2}$$

where

$$P_c = \frac{\gamma P_1 - P_2}{\gamma - 1}$$

$$Q_c = \frac{\gamma \lambda_1 L_1 - \lambda_2 (L_2 + N_w)}{\gamma - 1}$$

$$\lambda_c = \frac{\gamma \lambda_1 - \lambda_2}{\gamma - 1}$$

- λ_1, λ_2 are the wavelengths for the two frequencies, γ is the squared frequency ratio.
- $\Delta h = h_{rec} - h^{emi}$ corresponds to the receiver and satellite clock difference, referenced to the ionosphere-free phase combination, expressed in meters.
- $\Delta\tau$ is the corresponding code-phase delay for the ionosphere-free combination, expressed in meters. These delays are assumed to have limited variations. These delays are not critical here, as precise positioning relies mostly on phase measurements.
- D_c is the geometrical propagation distance including the troposphere delay. It is computed between the ionosphere free centre of phase of the transmitting and receiving antennas.
- N_{windup} is the windup effect in cycles. Antenna phase correction maps are not used, their small contribution does not change the performance of the ambiguity fixing process (values well below one cycle).

Note that in these equations the remaining ambiguity N_1 is associated to the ionosphere-free wavelength λ_c (10.7 cm) and not to λ_1. The complete problem is thus transformed into a single frequency problem with a wavelength λ_c, and without any ionosphere propagation effect.

Many algorithms are applicable to solve the set of equations (2) (it is even possible to use standard double differences methods). If D_c is known with a sufficient precision (typically a few centimeters, which can be achieved using a good floating ambiguities solution), it is possible to solve simultaneously for N_1, h_{rec} and h^{emi} [1,4].

As in the case of equation (1), there is a global indetermination between the clocks and the ambiguities: each clock is known only up to an integer multiple of λ_c. We will see below that this leads to very interesting properties. These clock solutions are named 'integer phase clocks' hereafter.

2.3. INTEGER PHASE CLOCKS PROPERTIES

A first interesting property is the integer overlap property of integer phase clocks: for a given set of widelane biases, clock jumps between adjacent solutions can only be integer multiples of λ_c. In practice, the magnitude of λ_c is large enough to identify and correct all jumps in the overlaps [4].

The satellites integer phase clocks also contain all the necessary information for the zero-differenced N_1 ambiguities solution [1], [2]. Any receiver outside of the network can fix its own integer ambiguities with only the knowledge of the μ^{emi} biases (which can be understood as 'widelane clocks') and of the corresponding satellite integer phase clocks.

3. REAL TIME IMPLEMENTATION: NETWORK INTEGER CLOCK SOLUTION

As shown in [1] our PPP approach involves the following steps:

- On the network side, raw data are collected, zero-difference widelanes are fixed for each receiver, then N1 ambiguities are fixed for the network and 'integer' clock by-products are generated and broadcast to users.

- On the user side, zero-difference widelanes are fixed, and then 'integer' clocks are used to fix N1 ambiguities and to estimate the stochastic position of the receiver.

We will now show how these operations can be performed in real time.

3.1. REAL TIME WIDELANE AMBIGUITY FIXING

Zero-difference widelane integer ambiguity fixing is based upon computing the Melbourne-Wübbena widelane from raw measurements and subtracting predefined satellites biases. In order to reduce measurement noise, an averaging over some time period is required. In the real-time process, this is obtained using a sliding averaging window. The drawback of this method is that the integer widelane is only known after a certain period of time (equal to the length of the window). The optimal window length is thus the result of a trade-off between the delay of the estimation and the success rate of the ambiguity fixing.

This success rate is also highly correlated to the quality of the pseudo-range measurements, which is itself directly related to the elevation angle. This is the reason why we consider two options, one which includes all available measurements, the other which only deals with measurements with an elevation above 30°.

Indeed, when a user turns on his receiver, it is likely that a few satellites will be seen at high elevation angles, and thus are in a better configuration in term of pseudo-range noise. On the other hand, on the network side, and in converged mode, new satellites always appear with low elevation angles. Thus different window lengths should be used in user mode and in network mode.

Figure 3 shows statistics of widelane fixing with various window lengths (between 5 minutes and 1 hour) and for a representative set of 30 stations, compared to a reference post-processed solution.

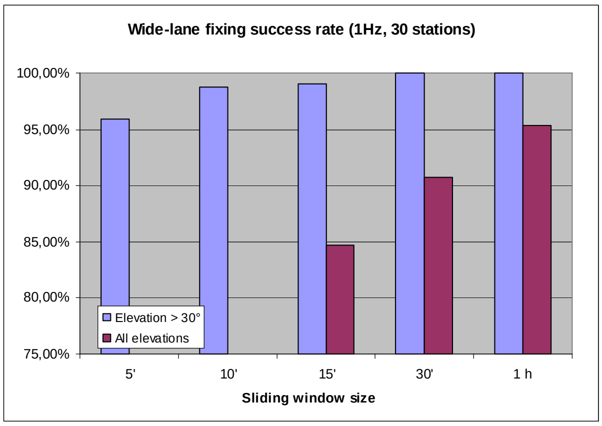

Fig. 3. Wide lane fixing success rate

Our experience shows that 30 minutes and 5 minutes are good window lengths for widelane fixing, for contemporary receivers, for low and high elevation angles respectively.

In the following paragraphs, we will assume that the widelane is fixed during preprocessing, and we will focus on real time N1 fixing and integer clocks generation.

3.2. REAL TIME CLOCK GENERATION OVER THE NETWORK

An extended Kalman filter is used to compute the clocks over the network. The state vector of the filter contains all the satellite and station clocks, a zenith troposphere delay for each station, and a floating ambiguity per pass.

We use phase measurements (from which we can compute h^{emi} without biases according to our model). Pseudo-ranges are included with very low weight to stabilize the filter. The filter works in the floating domain for all its parameters except for N_1 ambiguities that are fixed to their integer value once they are known with enough confidence.

At the beginning of a pass, neither N_w nor N_1 are known, so the covariance of the ambiguity is set to an initial value (typically 10 m), and the filter works in floating mode. After 30 minutes, the preprocessing module fixes N_w to its integer value. N_1 can be then fixed in the filter. At this stage, 2 different configurations may arise:

1) The pass is between a satellite and a station that are already linked by other measurements with fixed ambiguities (fig 4). Because of the implicit closure of the equations the covariance on N_1 is already close to the phase measurement noise (typically 1 cm). In this case, N_1 should be already close to an integer, but not yet fixed. It is then fixed to this integer value.

2) The new pass is not constrained by other fixed measurements (this is detected by testing the covariance of the ambiguity parameter in the filter). N_1 can than be set to any integer.

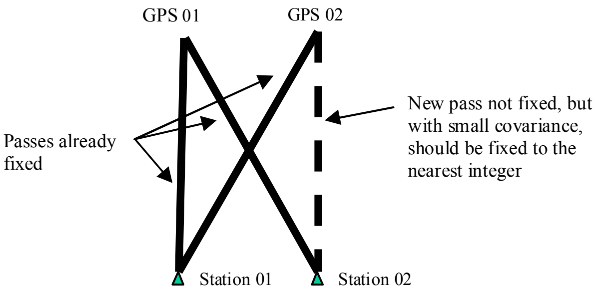

Fig. 4. connected ambiguities

The ambiguity fixing process is performed by adding a constraint equation to the filter (new measurement with a noise equal to 0). The fixing of one ambiguity can impact the whole network. It can trigger by continuity the fixing of other ambiguities not yet fixed.

At each time step, we select in our state vector the satellite clocks whose covariance are close to the phase measurement noise. These clocks are said to be 'integer' clocks while the others are 'floating' clocks.

3.3. REAL TIME STATE SPACE REPRESENTATION

The state space representation described in [1] has to be slightly modified to work properly in real time. Besides its own receiver phase jumps, the user has to be aware of any possible discontinuity in the satellite clocks, in order to reset its ambiguity estimation.

This is the reason why we need to introduce an indicator of discontinuity along with the clock solution (for example the number of time steps since the last clock reset). This indicator is computed on the network side, and broadcast with the clocks. The user can then use this indicator to decide if its ambiguities have to be re-estimated or not.

One advantage of this indicator is the added robustness of the system to transmission losses between the network solution and the user receiver.

The updated real time state space representation in given in Table 1.

Table 1. Real time state space representation

Nature	Quantity	Occurrence
μ^{emi}	1 value/satellite/ receiver family (around 4 families)	Several months
GPS Orbits + Clocks	3+1 value/satellite (same definition as IGS/sp3 standards)	Each epoch
Last clock discontinuity	1 value/satellite	Each epoch

3.4. INFLUENCE OF ORBIT ERROR

The position of the satellites is an input to the previous filter. As the precision of the available real-time satellite ephemeris is limited, this is clearly a limitation to the validity of our solution. In practice, in real time, only the

IGU predicted orbits are widely available from the IGS. The maximum error of these orbits is around 20 cm [7], theoretically not accurate enough to fix ambiguities. However, over a local area, and due to projection effects, most of the geometrical errors will be compensated by the estimated clocks.

Let us consider the geometry described in figure 5 where O is the barycentre of the network, S is the location of the user receiver, "b" is the distance between the two, θ is the elevation angle in O, and δr and δt are respectively the satellite errors on the radial and perpendicular components.

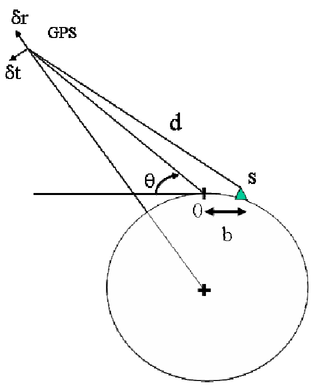

Fig. 5. Geometrical errors set-up

Figure 6 gives the satellite ephemeris error contribution not absorbed by the satellite clock, for various elevation angles θ, assuming a baseline b equal to 1000 km, and ephemeris errors δr and δt equal to 1 m.

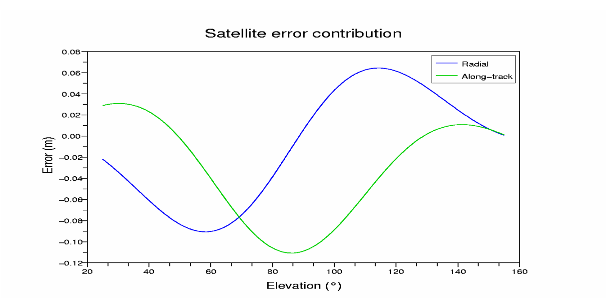

Fig. 6. Geometrical errors results

The maximum error on the distance is around 10 percent of the orbit error. For a conservative orbit error of 20 cm, the maximum error would be 2 cm, less than a quarter of λ_c, which is an admissible error.

So for our experiment, we can use local areas up to 1000 km in radius and IGU predicted orbits, without worrying about orbits errors. If we wanted to extend the area, orbit correction parameters would have to be included in the filter.

4. EXPERIMENTATION WITH REAL-TIME NETWORK CLOCK SOLUTIONS

4.1. EXPERIMENT WITH IGS DATA

For our experiment, we have chosen the following set-up:

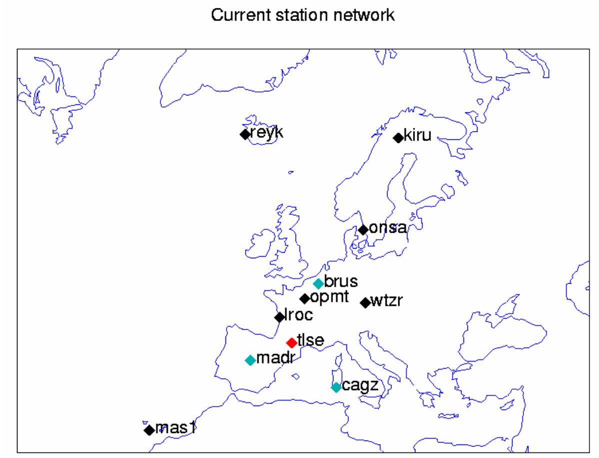

Fig. 7. IGS main network

- A local network of 10 IGS stations located in Western Europe (Figure 7) is used to compute the reference integer clocks.

- Among these stations, 3 are used for the real-time clock experiment. These stations are MADR, BRUS and CAGZ (in blue).

The experiment was conducted from 2 July 2007 to 4 July 2007. Data were downloaded from the IGS ftp site [7].

A reference integer clocks solution was generated from the network measurements using the process described in [1]. Real-time clocks were computed from the 3 real-time stations using the method described previously.

The upper plot on figure 8 shows the phase measurement residuals for one of the stations in the real-time network (MADR), expressed in cycles at the λ_c wavelength. The RMS is around 7 mm and is far below one cycle. Thus, there are no erroneous N1 integer ambiguity estimation for that station. The other 2 stations behave in the same way.

The lower plot on figure 8 shows the number of satellites in view, at raw measurements level (in blue), after widelane ambiguities are fixed (in green), and after both widelane and N1 ambiguities are fixed (in red). There are between 4 and 10 satellites in view with all ambiguities fixed, for 6 to 12 satellites in view initially (raw measurements). A daily pattern is clearly visible in this plot.

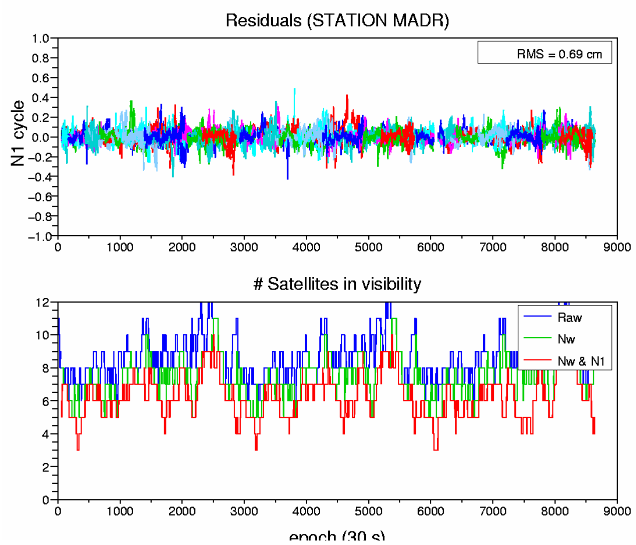

Fig. 8. IGS network measurement residuals

Figure 9 shows the result of the comparison between the real-time clocks and the reference clocks. The 2 set of clocks are very close, with an RMS around 1 mm.

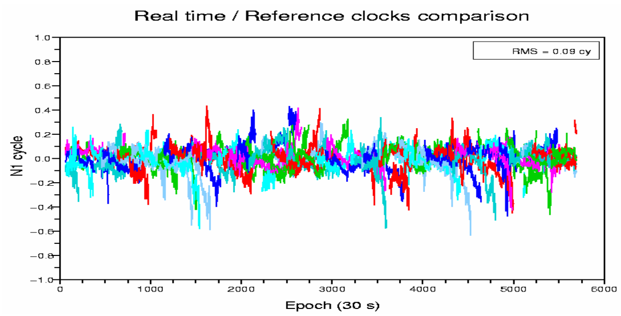

Fig. 9. Real time/reference clocks comparison

The real-time process performs as well as the post-processing in terms of clock precision. The main concern is not the accuracy of the clocks, but their availability (related to the number of satellites in view of a station for which clocks are available at a given time).

4.2. EXPERIMENT WITH REAL-TIME EUREF-IP DATA

The BKG NTRIP Client (BNC) is a program for retrieving, decoding and converting real-time GNSS data streams over the internet from NTRIP broadcasting sites like http://www.euref-ip.net/home or http://www.igs-ip.net /home. BNC has been developed for the Federal Agency for Cartography and Geodesy (BKG) within the framework of the EUREF-IP Pilot Project (EUREF-IP, IP for Internet Protocol) and the Real-Time IGS Working Group (RTIGS WG). Fig 10 shows a map of participating stations in Europe [5]. The data stream is freely accessible and the BNC program is a freeware.

We have processed 5 days of EUREF-IP real time data retrieved with BNC on the 4 stations circled in blue on Figure 10. The processing of these data demonstrates the robustness of the method with respect to a variety of problems that appear in real-time (stations off-line, missing samples, network problems, etc.).

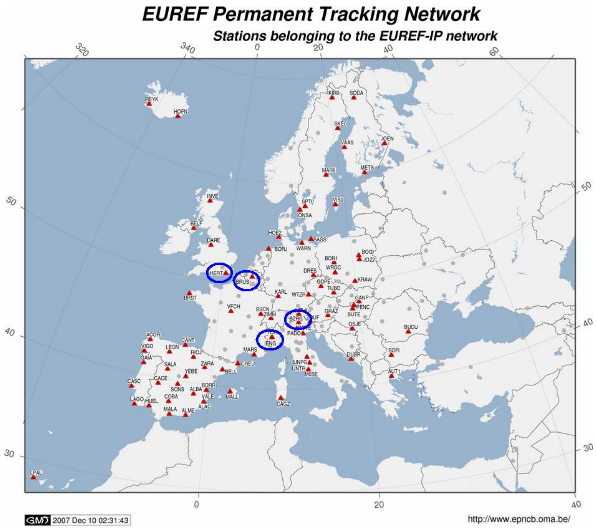

Fig. 10. EUREF-IP network

The phase measurement residuals and the number of satellites in view for station BZRG are presented on Figure 11. The results are similar in quality and availability to those obtained with data retrieved later from IGS. This proves that we can generate good quality real-time clocks with high availability using representative real-time data streams.

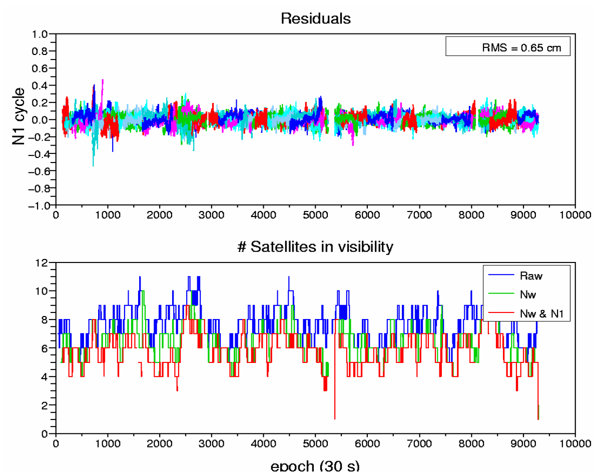

Fig. 11. EUREF-IP network measurement residuals

5. USER RECEIVER PROCESSING

5.1. FLOAT INITIALIZATION

The initialization phase is performed by a standard least squares filter. Typically, data are collected during a certain period of time (between 5 min and 120 min) and then processed.

The adjusted parameters are:

- a constant or stochastic receiver position (depending on whether the receiver is moving or not).
- a constant zenith troposphere propagation delay.
- a stochastic receiver clock.
- a floating ambiguity per pass.

The performance of this first step does not depend on the nature of the satellite clocks, i.e. whether they are integer or not. Figure 12 shows the accuracy of the positioning in term of horizontal error as a function of the duration of the processing window.

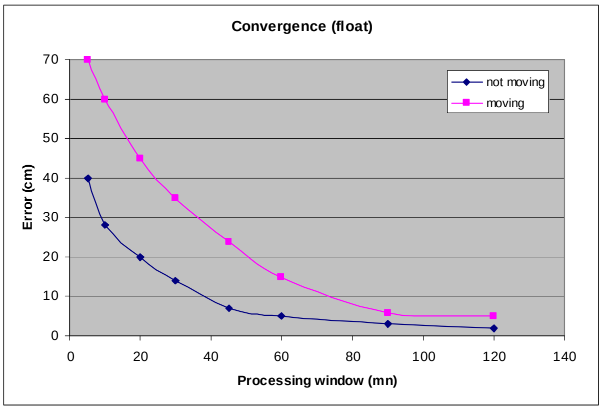

Fig. 12. Convergence accuracy (float)

The convergence time is rather long, even if the receiver is not moving. This is partly due to the fact that the observability comes from the slowly moving geometry of the GPS satellites. This resolution is phase-only (because we use phase clocks), the pseudo-range is not used here because we do not have a good estimate of the range/phase biases on the ionosphere free combination (i.e. the $\Delta\tau$ parameter of equation (2) is not known).

5.2. INTEGER INITIALIZATION

The initialisation phase is performed with a standard OLS filter as in the float case. After a first float estimation, a bootstrap method is applied to fix the N1 ambiguities: ambiguities which have the lowest covariance and are close to an integer are fixed iteratively.

This filter can be tuned for 3 distinct configurations (from the most favourable to the least):

1) The position of the receiver is fixed and known. No position has to be estimated in the filter. This case is very favourable but is unlikely to occur !
2) The position of the receiver is fixed but unknown, in this case, a constant position has to be estimated in the bootstrap process.
3) The receiver is moving and his position is unknown. In this case, a different position has to be estimated at each time step.

Table 2 shows the success rate for correct initial ambiguity estimation during this phase, for the 3 configurations, and for various initialization periods (these statistical results come from more than 500 different runs).

Table 2. Integer initialization success rate

Configuration	5’	10’	15’	30’	45’	1 h	1 h 30’
Receiver fixed and position known	75 %	82 %	87 %	90 %	-	-	-
Receiver fixed but position unknown	-	-	61 %	80 %	88 %	91 %	-
Receiver moving	-	-	17 %	43 %	62 %	76 %	81 %

As in the float case, and for the same reasons, the convergence time is rather long.

5.3. PURSUIT

The pursuit phase in the user’s receiver is performed by an extended Kalman filter. The estimated parameters are:

- The receiver clock.
- The receiver position.
- The zenith troposphere propagation delay.
- A floating ambiguity per pass.

Like in the network clock solution, N1 ambiguities are fixed ‘on the fly’, once the integer ambiguity for Nw is known. An efficient way to determine if the position is identified with fixed measurements or not is to test its covariance in the filter.

5.4. PPP RESULTS WITH REAL-TIME DATA

The TLSE station, in red in figure 7, which is not part of the network used to compute real-time and reference clocks, was used to evaluate PPP performance. Data used in this test were IGS data, replayed in real-time, as described in paragraph 4.1.

Figure 13 shows the real-time positioning accuracy for the TLSE station in the horizontal plane using the end-to-end real-time method. The results are around 2 cm RMS and are comparable to those obtained by standard RTK, except that in this case it is not a differential positioning with respect to a local reference station.

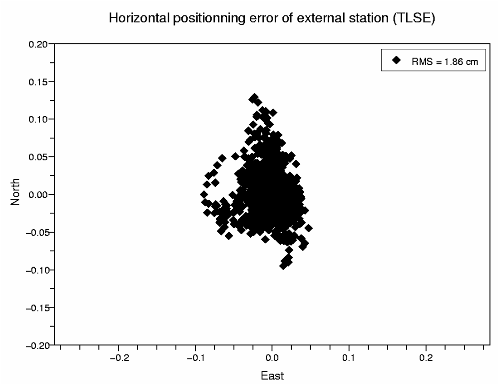

Fig. 13. Absolute RTK performance

The user can also decide to simply use the integer clocks instead of standard clocks without integer ambiguity fixing at his level, using standard receiver PPP software. The use of our integer clocks in a floating positioning leads to a 5 cm RMS accuracy.

6. CONCLUSION AND FUTURE WORK

In [1] we have presented a method to fix integer widelane ambiguities on zero-difference GPS measurements. at receiver level. Then, narrow-lane integer ambiguities can be fixed over a network of stations. The GPS integer phase clocks estimated during this process can then be used by any receiver outside of this network for improved accuracy PPP.

This zero-difference integer fixing method has been extended to real-time, and tested successfully over a European-wide area. We have shown that a real-time local network can be used to compute integer phase clocks for the GPS satellites in view, with a precision of about 1 cm. We then demonstrated that these clocks can be used by any receiver in this area to perform absolute real time kinematic positioning with about 2 cm accuracy.

Although initialization of the ambiguity resolution filter in the user receiver can be rather long (close to 1 hour), and still need to be improved, some potential applications already emerge. These applications include precise site survey, meteorology, or offshore positioning (buoys, oil rigs).

ACKNOWLEDGMENTS

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