The CNES Real-time PPP with undifferenced integer ambiguity resolution demonstrator

D. Laurichesse, *Centre National d'Etudes Spatiales, Toulouse, France*

BIOGRAPHY

Denis Laurichesse is a member of the orbit determination service at CNES. He has been in charge of the DIOGENE GPS orbital navigation filter, and is now currently involved in navigation algorithms for GNSS systems. He was the co-recipient of the 2009 ION Burka award for his work on phase ambiguity resolution.

ABSTRACT

Integer ambiguity resolution on undifferenced GPS phase data has made a lot of progress in recent years. By combining pseudo-range and phase information, it is possible to fix integer ambiguities on zero-difference phase measurements, for dual-frequency problems, without any atmospheric models. Phase measurements then become pseudo-range-like measurements with millimeter noise level. Using these measurements, and precise satellite ephemerides, it is possible to perform the synchronization of a regional network, to compute satellite clocks. These clocks have an interesting property: they allow the positioning of independent receivers using a PPP-like method, with integer ambiguity fixing. The achieved positioning accuracy is at the centimeter level.

This method can also be applied to real-time positioning [ION NTM 2008, ION ITM 2009 and ION GNSS 2010 meetings]. The core of the real-time implementation is a Kalman Filter working with both real- and integer-valued phase ambiguities. The filter produces satellite orbits and clocks compatible with integer ambiguity fixing. These products are then ingested by algorithms developed for user receivers to perform real-time positioning with accuracy comparable to standard RTK.

To demonstrate that this processing strategy is compatible with the latency constraints imposed by real-time applications, and with the level of performance typical of common personal computers, CNES has developed a complete real-time 'integer PPP' demonstrator. The paper presents the architecture of the demonstrator. It also presents results obtained within the framework of the Real-Time IGS Pilot project, as well as results from a stand-alone experiment.

In order for users to assess the potential offered by this new approach to real-time positioning, CNES provides a free user test package containing all the tools needed to perform PPP with ambiguity resolution. This test package includes an access to the CNES caster, documentation to understand the nature of the ambiguity resolution parameters, and a modified version of the BNC software which handles ambiguity fixing. This material is available on a dedicated web site (www.ppp-wizard.net).

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. The process is a two steps procedure, where the difference between the ambiguities on the two frequencies is first fixed using the four observables widelane combination (Melbourne Wübbena). No geometrical model or orbits, clocks, receiver positions, etc. are needed for this first step. Then the remaining ambiguity is fixed in a global network solution, using the models and the ionosphere free phase combination.

Once ambiguities are fixed, phase measurements become unambiguous pseudorange-like measurements with a few millimeter noise level. In addition, during the ambiguity fixing process, clock corrections associated with the ionosphere free phase combination are estimated. When phase measurements from an independent receiver are processed with these phase clocks the integer nature of the ambiguities is easily revealed. This allows the absolute precise point positioning (PPP) of this receiver with integer ambiguity fixing (‘integer PPP’). Since November 2009, such clock solutions are available in the CNES/CLS IGS analysis center solution ('grg' solution).

The extension of this method to real-time applications has been developed in [ION NTM 2008, ION ITM 2009 and ION GNSS 2010]. The core of the real-time implementation is a Kalman Filter working in mixed-mode (with both real- and integer-valued phase ambiguities). The filter produces GPS constellation states (orbits and clocks) with the ‘integer’ property. At the same time algorithms have been developed for real-time user receiver positioning. These algorithms take advantage of our orbits and clocks to perform real-time ambiguity-fixed positioning.

In order to demonstrate that these filter and algorithms are compatible with the latency constraints imposed by real-time applications when running on standard equipment (personal computers), we have developed a complete real-time ‘integer PPP’ demonstrator. As part of this demonstrator, we propose a free user test package which provides the tools needed to perform ‘integer PPP’ with any receiver. The test package includes an access to the CNES caster, an ICD to understand the nature of the ambiguity resolution parameters, and a modified version of the BNC software which handles ambiguity fixing.

This paper details how the demonstrator works, how well it performs and how users can try ‘integer PPP’ for themselves using information provided on our website.

1.1. NOTATIONS AND MODEL EQUATIONS

In this paper, we use the following notations:

$$\gamma = \frac{f_1^2}{f_2^2}, \quad \lambda_1 = \frac{c}{f_1}, \quad \lambda_2 = \frac{c}{f_2}$$

where f_1 and f_2 are the two frequencies of the GPS system and c is the speed of light. For GPS L_1 and L_2 bands, $f_1 = 154 f_0$ and $f_2 = 120 f_0$, where $f_0 = 10.23\,\text{MHz}$. Pseudorange or code measurements, P_1 and P_2, are expressed in meters, while phase measurements, L_1 and L_2, are expressed in cycles.

The pseudorange and phase measurements are modeled as:

$$\begin{array}{rlllll} P_1 = & D_1 & +\Delta h_p & +\left(e+\Delta\tau_p\right) & & \\ P_2 = & D_2 & +\Delta h_p & +\gamma\left(e+\Delta\tau_p\right) & & \\ \lambda_1 L_1 = & D_1+\lambda_1 W & +\Delta h & -\left(e+\Delta\tau\right) & -\lambda_1 N_1 & \\ \lambda_2 L_2 = & D_2+\lambda_2 W & +\Delta h & -\gamma\left(e+\Delta\tau\right) & -\lambda_2 N_2 & \end{array} \tag{1}$$

Where:

- D_1 and D_2 are the geometrical propagation distances between the emitter and receiver phase centers at f_1 and f_2 including troposphere elongation, relativistic effects, etc.

- W is the contribution of the wind-up effect (in cycles).

- e is the ionosphere elongation in meters at f_1. This elongation varies with the inverse of the square of the frequency and with opposite signs between phase and code.

- $\Delta h = h_i - h^j$ is the difference between receiver *i* and emitter *j* ionosphere-free phase clocks. Δh_p is the corresponding term for pseudorange clocks.

- $\Delta\tau = \tau_i - \tau^j$ is the difference between receiver *i* and emitter *j* offsets between the phase clocks at f_1 and the ionosphere-free phase clocks. By construction, the corresponding quantity at f_2 is $\gamma\Delta\tau$. Similarly, the corresponding quantity for pseudorange is $\Delta\tau_p$ (Time Group Delay).

- N_1 and N_2 are the two carrier phase ambiguities. By definition, these ambiguities are integers. Unambiguous phases measurements are therefore $L_1 + N_1$ and $L_2 + N_2$.

These equations take into account all the biases related to delays and clocks. The four independent parameters $\Delta h, \Delta\tau, \Delta h_p, \Delta\tau_p$ are equivalent to the definition of one clock per observable. However, our choice of parameters emphasizes the specific nature of the problem by identifying reference clocks for pseudorange and phase (Δh_p and Δh) and the corresponding hardware offsets ($\Delta\tau_p$ and $\Delta\tau$). These offsets are assumed to vary slowly with time, with limited amplitudes.

1.2. GENERAL OVERVIEW OF THE METHOD

The key characteristics of the method are summarized hereafter.

According to [1, 2], the measured widelane $\tilde{N}_w$ (also called the Melbourne-Wübbena widelane) can be written as:

$$\left\langle \tilde{N}_w \right\rangle = N_w + \mu_i - \mu^j \qquad (2)$$

where N_w is the integer widelane ambiguity, μ^j is the constant widelane delay for satellite j, μ_i is the widelane delay for receiver i (fairly stable for good geodetic receivers). The symbol $\langle \ \rangle$ means that all quantities have been averaged over a pass.

Integer widelane ambiguities N_w are then easily identified from averaged measured widelanes corrected for satellite widelane delays. Once integer widelane ambiguities N_w are known, the ionosphere-free phase combination can be expressed as

$$Q_c = D_c + \lambda_c W + h_i - h^j - \lambda_c N_1 \qquad (3)$$

where $Q_c = \dfrac{\gamma\lambda_1 L_1 - \lambda_2 (L_2 + N_w)}{\gamma - 1}$ is the ionosphere-free phase combination computed using the known N_w ambiguity, D_c is the propagation distance, h_i is the receiver clock, h^j is the satellite clock. N_1 is the remaining ambiguity associated to the ionosphere-free wavelength λ_c (10.7 cm).

The complete problem is thus transformed into a single frequency problem with wavelength λ_c and without any ionosphere contribution.

Many algorithms can be used to solve equation (3) over a network of stations. If D_c is known with sufficient accuracy (typically a few centimeters, which can be achieved using a good floating ambiguity solution), it is possible to simultaneously solve for N_1, h_i and h^j.

The properties of such a solution have been studied in details. A very interesting property of the h^j satellites clocks is, in particular, the capability to directly fix the N_1 values of a receiver which has not been part of the initial network [1, 2].

1.3. REAL TIME IMPLEMENTATION OF THE METHOD

As shown in figure 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, leading to “absolute” centimeter level PPP.

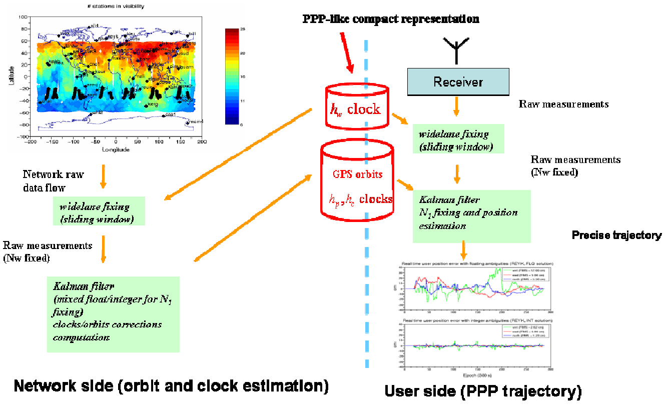

Fig. 1. Integer PPP diagram

The real-time implementation of the method has been described in [6]. The network-side is mainly based on a Kalman filter fed by measurements. Widelane ambiguities are fixed during preprocessing. Narrowlane ambiguities are fixed in the filter, using network connectivity considerations. The user-side is based on a similar Kalman filter where the position of the antenna is estimated as a parameter.

A standard state space representation consists mainly in orbits and clocks as defined in a sp3 file for example [4]. In [6], we have proposed to add new quantities, adapted to our method. These new quantities can be sent to a user either in a specific standard like RTCM, or directly in a text file for slowly varying quantities like widelane biases.

2. THE CNES DEMONSTRATOR

In order to validate the pertinence of the method in actual real-time, CNES has developed a full scale demonstrator which has been partially described in [6].

2.1. SYSTEM SIDE ARCHITECTURE

Figure 2 describes the architecture of the system side of the demonstrator. This part is in charge of:

1) collecting network measurements
2) computing state-space products
3) disseminating them over the network

A ftp interface is used to retrieve IGS measurements [5] on a daily basis to compute widelane clocks, and on a 6 hour basis to compute real-time orbits. An NTRIP interface, associated with the BNC tool [3], is used to collect network measurements in real time. It is estimated that the latency of these measurements is about 2 or 3 seconds on average. The GNSS engine processes these data and outputs the state space representation. The products are then disseminated over the internet, on a NTRIP caster, using a RTCM message or text file. The current sampling rate is 5 seconds, while the overall average latency is estimated between 6 to 8 seconds. All this process is implemented on a machine running under the Linux operating system.

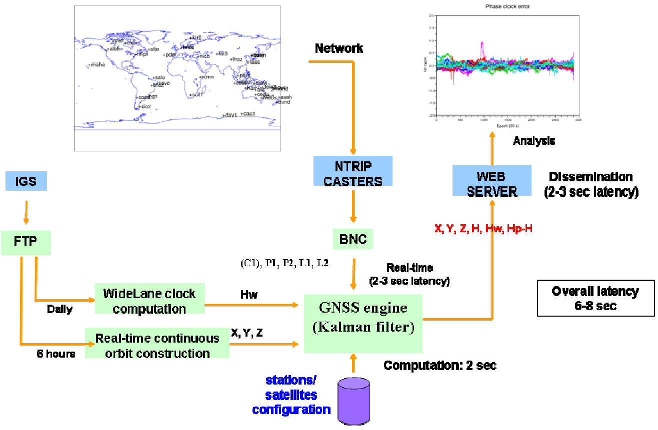

Fig. 2. System side demonstrator architecture

2.2. USER SIDE ARCHITECTURE

The architecture of the user side of the demonstrator is described in figure 3. State space representation is received from a NTRIP caster. The dual frequency observables are read directly from a local or distant receiver via NTRIP. The PPP software is a version of BNC [3], modified for ambiguity resolution. The integer PPP algorithms use the same Kalman filter as the network side. In this case, satellite clocks are not estimated, and the receiver position is estimated instead. The ambiguity fixing process remains the same in both cases. Results can be compared to an accurate reference for monitoring purposes.

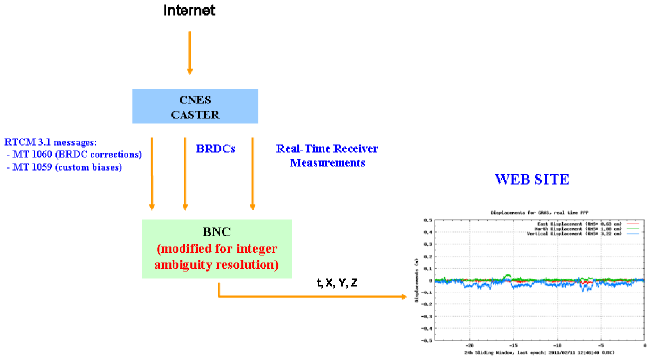

Fig. 3. User side demonstrator architecture

2.3 REAL TIME IGS PILOT PROJECT PARTICIPATION

In 2010, CNES joined the Real Time IGS Pilot Project.

The main objective is to process data from the real time IGS network and to participate as an analysis center by providing the orbit and clock solution generated by the demonstrator.

The second objective is to disseminate ‘integer’ products on a pre-operational basis to demonstrate the potential of integer clocks for user PPP. This should help support the evolution of the RTCM standard in order to allow the dissemination of phase-code biases and clocks. It should be noted that with the current RTCM standard a workaround has to be found to broadcast the different clock solutions needed by our method (for example, disseminating widelane biases in a separate file). This is the reason why 2 different solutions are generated: one solution dedicated to the RTIGS pilot project, and the other dedicated to ambiguity resolution. Even if the first solution is the only one taken in account in the real-time combination, both solutions are monitored by the RTIGS pilot project.

The CNES first solution is available on the products.igs-ip.net caster with the prefix CLK9x, while the other one is only available via the CNES caster.

2.4 WEB SITE AND STREAM USER ACCESS

CNES has set-up a web site dedicated to the demonstrator. Its internet address is http://www.ppp-wizard.net. ppp-wizard is an acronym for “PPP With Integer and Zero-difference Ambiguity Resolution Demonstrator”. This web site provides all the material to monitor the demonstrator and to perform user side integer ambiguity resolution:

- A description of the caster used by the demonstrator (IP address, different stations and products mountpoints).

- A network monitoring feature by means of a Java applet which shows the network of stations (updated in real-time) as well as the current active satellites and some statistics about the number of fixed widelane and narrowlane ambiguities.

- A set of PPP monitoring stations. For each of these stations, an instance of the PPP software modified for ambiguity resolution is running. The web site displays the errors of the obtained solution with respect to an accurate reference. The displays are updated in real-time and reflect the current performance of the demonstrator, from the user side.

- A “user test package” freely available for download which consists in:
    - o A PPP software modified for real time ambiguity resolution. This is a freeware, available in source code, as well as a precompiled version for windows.
    - o An anonymous access to the orbits/clocks stream dedicated to ambiguity resolution, from the CNES caster (CLK93 mountpoint).
    - o A link to the current widelane biases compatible with this orbits/clocks stream.
    - o A quick guide (ICD) on how to perform ambiguity resolution using CNES products.

  With this package, everyone should be able to reproduce the results obtained in the PPP monitoring section.

- There is also the possibility to download the daily consolidated products, to perform ambiguity resolution off-line.

3. EXPERIMENTAL RESULTS

3.1. RTIGS PRODUCTS PERFORMANCE

CNES started sending its solution to the real-time IGS pilot project in January 2011. Performance analysis reports and combined solutions are generated by ESOC [7, 14], the RTIGS pilot project coordinator. The CNES solution was introduced in the real-time combination in February 2011.

Figure 4 shows the orbit performance (RMS) of the different real-time analysis centers, as computed by ESOC [7, 14] (the reports are produced from real-time streams). The reference is the IGS rapid solution.

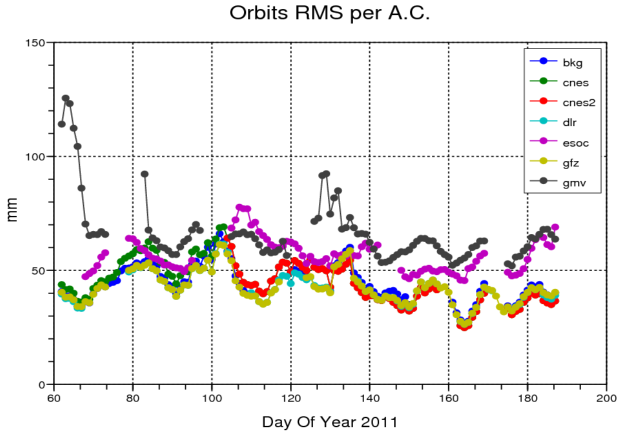

Fig. 4. Orbit quality for various rtigs analysis centers

Orbit accuracy is very good for all centers (better than 5 cm on average). Orbits from many centers are very close to each other, probably because they all use IGU solutions as inputs in the same way. In our solution the orbit error is dominated by the 6-hour extrapolation period. One possible improvement is to use orbits computed more often (2-hour or even 1-hour batch) [12]. Another possibility is to estimate orbit corrections in the real-time filter.

Figure 5 shows the clock standard deviations for the different real-time analysis centers. The reference is the IGS rapid solution.

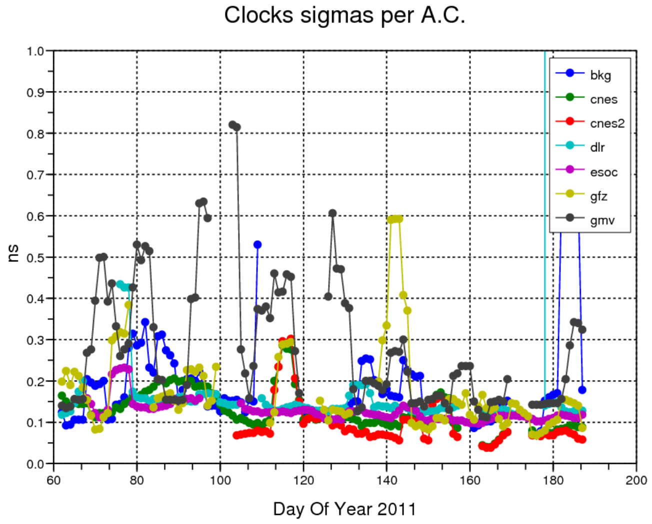

Fig. 5. Clocks sigmas for various rtigs analysis centers

Despite some outliers, the performance of the solutions tends to converge towards 0.1 ns for the majority of analysis centers, which is far better than the initial target of the project (0.3 ns). The red plots (CNES solution for integer ambiguity resolution) are regularly among the best ones. The average standard deviation of the CNES solution is 0.12 ns.

Another approach to evaluating real-time orbits and clocks precision is to use them in PPP solutions. This “user side” PPP (where ambiguities are estimated as floating quantities) is monitored by BKG with the BNC tool [3] for several RTIGS analysis centers and is available on the following link: http://igs.bkg.bund.de/ntrip/ppp. In general, the IGS FFMJ station is the preferred choice for monitoring. An example of the monitoring of the quality of the CNES solution (floating ambiguities) as seen by a user is represented on figure 6:

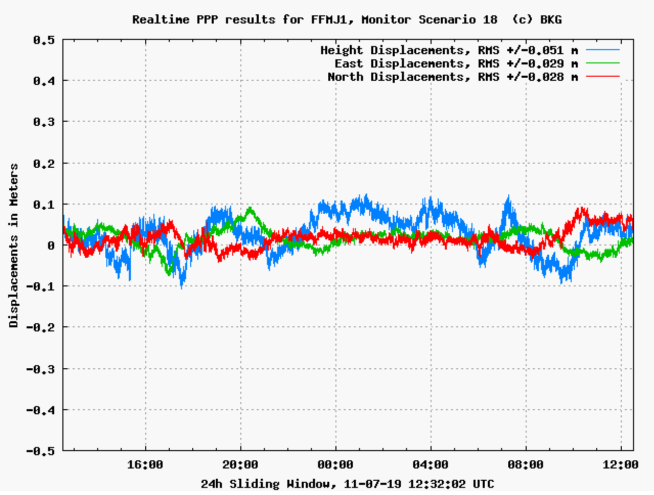

Fig. 6. PPP accuracy for FFMJ using CNES solution (standard BNC software)

3.2. ‘INTEGER’ PRODUCTS PERFORMANCES: PPP MONITORING

Figure 7 presents a typical example of station monitoring using the CNES orbits/clocks stream and the PPP software provided on the web site, using the integer ambiguity resolution feature. In this example, the performances (centimeter accuracy on the horizontal component) are equivalent to those obtained in simulations or in previous studies.

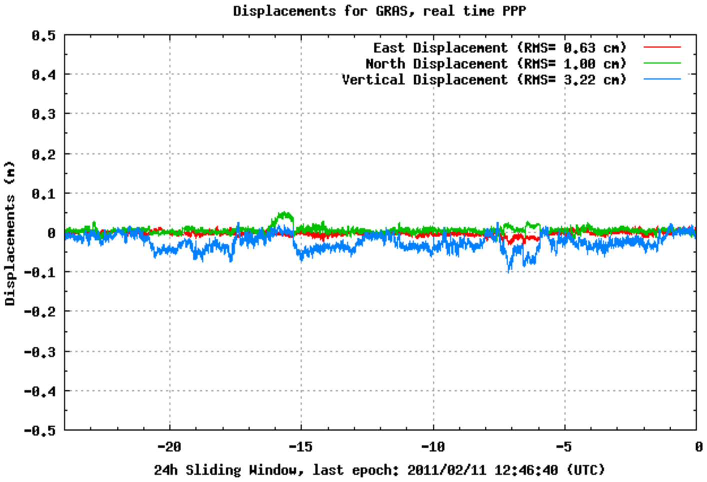

Fig. 7. PPP accuracy for FFMJ using CNES “integer” solution (BNC software modified for ambiguity resolution)

3.3 USERS ACCESS

Some statistics can be drawn about the users’ access to the web site and the demonstrator.

In particular, since January 2011, there have been 1298 visits to the web site, 567 absolute unique visitors and 4187 pages views. The PPP software has been downloaded about 100 times and the clocks stream dedicated to ambiguity resolution has been accessed about 50 times.

3.4 USERS FEEDBACK

An experiment using the demonstrator was conducted by GMV (Ricardo Piriz). This experiment took place on the roof of the GMV headquarters building in Madrid. The set-up consisted of a dual-frequency receiver (TopCon) connected to a MacBook (see Fig. 8) running the freeware version of BNC modified for ambiguity resolution.

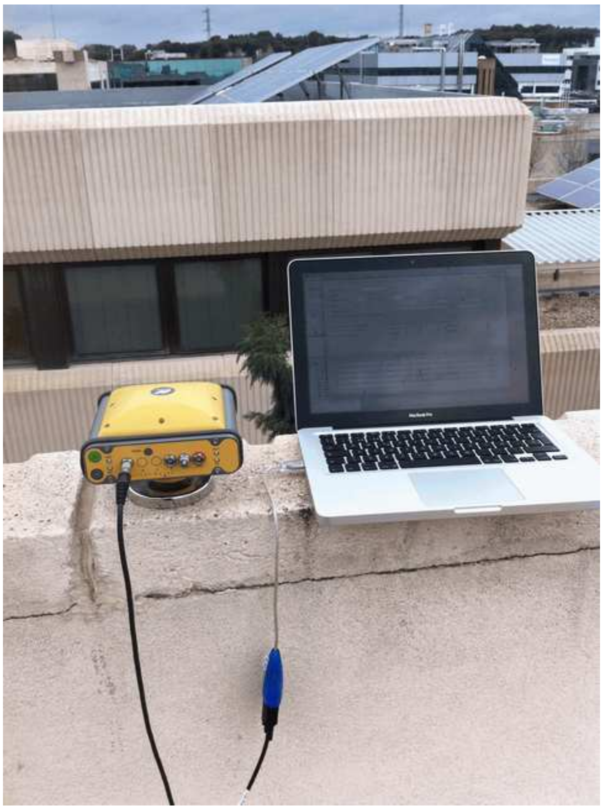

Fig. 8. GMV experimental set-up

The receiver was kept static during the initialization phase. Later on the receiver described a loop trajectory around the initial position (see Fig. 9).

Fig. 9. Receiver trajectory (distant view)

Raw measurements were recorded in real-time, as well as the trajectory computed by the demonstrator. The accurate trajectory reconstruction was performed using the RTKLib tool [8] and a reference station located near-by on the same roof. Figure 10 shows the two trajectories, the reference (in green) and the one computed using the ppp-wizard demonstrator (in red). The output rate of the measurements was set to 1 Hz so reference positions are given at 1 Hz (green dots).

The ppp-wizard trajectory is only available every 5 seconds, at the rate of the clocks. This is the reason why there is only one red dots every five green dots. The red dots on the lower left of the figure correspond to the initialization phase.

During the moving phase of the experiment, the two trajectories (relative and absolute) were within centimeters of each other.

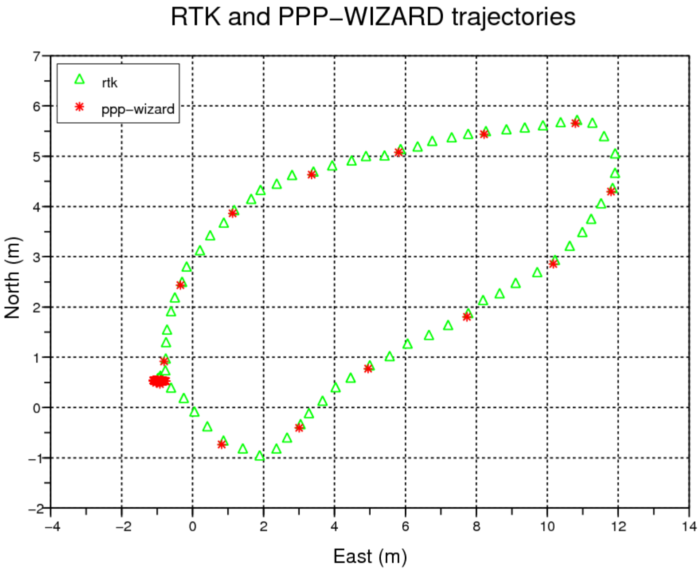

Fig. 10. Antenna trajectories (rtk and ppp-wizard)

4. FUTURE WORK

Several improvements of the demonstrator are under study. These improvements are detailed hereafter:

4.1. GLONASS/GALILEO INTEGRATION

Glonass orbits and clocks computation is requested by the RTIGS pilot project, and will be implemented by end of year 2011. Unfortunately, due to the complex nature of hardware biases in Glonass [13], the integer ambiguity resolution feature is not supported in the demonstrator for the moment. The Glonass clocks arel be processed as standard ones.

Galileo clocks computation is planned for future integration, upon request from the RTIGS pilot project and when the SSR representation and external tools like BNC and BNS are updated.

4.2. ORBIT QUALITY

A recurrent problem with the demonstrator is the quality of input orbits. The demonstrator currently uses the portion of IGU orbits which is available in real-time, i.e. 3 to 9 hours after the date of the last measurement used to compute the orbits. This extrapolation period is quite long. Under specific conditions such as a large number of satellites in eclipse season, the quality of these extrapolated orbits may be such that the D_c quantity of equation (3) exhibit errors above one N_1 wavelength λ_c (10.7 cm), thus possibly leading to wrong ambiguity fixing.

The best strategy to improve input orbit quality is not yet known. Obviously orbits computed more frequently (for example every one or two hours instead of six hours for the IGUs) would shorten the extrapolation period and improve results, but the operational burden induced by such an approach is very high. The estimation of an orbital correction in the Kalman filter appears as a promising solution however it is not very robust with respect to data gaps in real-time streams, in particular from those coming from isolated stations in key locations (middle of the Pacific Ocean).

4.3. THREE-CARRIER AMBIGUITY RESOLUTION

Two satellites already broadcast on a the third frequency (f_5), and, with the modernization of GPS, a full constellation will broadcast civil signals on f_1, f_2 and f_5 in the future. There have been many studies on optimal three frequencies combinations [9], and TCAR (Three Carrier Ambiguity Resolution) techniques, mainly in the RTK framework [10]. These studies can be transposed to the undifferenced case and some preliminary conclusions can already be drawn:

- The widelane between L_5 and L_2 (extra widelane) has a wavelength of about 5.9 m. Given the noise level of pseudorange measurements, the traditional Melbourne-Wübbena technique can be used to solve instantaneously for the ambiguity of this widelane .

- The knowledge of this extra widelane ambiguity is of little help to solve for N_w using the traditional technique. However, we can introduce a new phase observable combination ℓ_w, which is the linear combination of (L_2-L_1) and (L_5-L_2) which eliminates the ionosphere contribution. It can be shown that, if the extra widelane ambiguity is known, the wavelength of N_w on ℓ_w is about 3.4 m. Using the pseudorange measurements to form an initial positioning solution, solving for N_w should be relatively easy. Then, when all the widelane ambiguities are known, the ℓ_w combination becomes the equivalent to an undifferenced measurement with a noise of about 10 cm, leading to a positioning accuracy better then 50 cm without the need to fix the N_1 ambiguity.

- When all the widelanes ambiguities are known, one can compute the combination of phase measurements which eliminates both the geometry and the ionosphere contribution. This combination gives an estimate of N_1, the only remaining unsolved ambiguity. It can be shown that the theoretical noise of this combination is about 2 N_1 cycles, which can be easily solved by averaging over several epochs. Unfortunately, the huge phase noise amplification factor of this combination amplifies time-correlated errors like multipath that can lead to an averaging process much longer that expected. Other approaches using the geometry-dependent combination may also be considered.

These preliminary results show that the entire ambiguity resolution process may be reduced to a few minutes, maybe less, depending on the quality of the pseudorange and phase measurements and of the receiver’s environment. An intermediate observable where only the widelane ambiguities are solved may be of particular interest. A more detailed study of undifferenced ambiguity resolution with three frequencies observables can be found in [11].

5. CONCLUSION

In [1] a method to fix integer ambiguities on zero-difference GPS measurements was introduced.

This zero-difference integer fixing method has been since extended to real-time, and tested successfully over a global network. A full scale demonstrator using this method was developed in the RTIGS framework and has been running operationally since January 2011.

The CNES RTIGS solution shows promising results in term of orbits/clocks accuracy and user PPP, and has been introduced in the real-time combination by the RTIGS pilot project coordinator.

A PPP software modified for ambiguity resolution as well as a compatible clocks stream is provided by the demonstrator. Some users have reproduced CNES results (absolute horizontal centimeter accuracy) using this material.

Some improvements are already under study: the introduction of the Glonass and the future Galileo constellations for the RTIGS project, the improvement of the quality of the GPS orbits, and the addition of the GPS third frequency to reduce the convergence time of user PPP, which is the main limitation of this promising method.

ACKNOWLEDGMENTS

The author wishes to thank Loukis Agrotis, Mark Caissy and Georg Weber for their help on the different RTIGS pilot project components and tools, Ricardo Piriz and Oscar Colombo for their feedback and helpful comments about the demonstrator’s products and software.

REFERENCES

[1] D. Laurichesse, F. Mercier, J.P. Berthias, P. Broca, L. Cerri, “Integer Ambiguity Resolution on Undifferenced GPS Phase Measurements and its Application to PPP and Satellite Precise Orbit Determination”, Navigation, Journal of the institute of Navigation, Vol. 56, N° 2, Summer 2009

[2] F. Mercier, D. Laurichesse “Receiver/Payload Hardware Biases Stability Requirements for Undifferenced Widelane Ambiguity Blocking”, proceedings of the 1st Colloquium, Scientific and Fundamental Aspects of the Galileo Programme, October 2007

[3] G. Weber, “Real-Time GNSS - EUREF-IP”, Symposium of the IAG Subcommission for Europe (EUREF) , June 6 – 9, 2007, London, England

[4] G. Wübbena, M. Schmitz, A. Bagge, “PPP-RTK: Precise Point Positioning Using State-Space Representation in RTK Networks”, Proceedings of the ION GNSS 2005 Meeting, September 13-16, 2005, Long Beach, California.

[5] J.M. Dow, R.E. Neilan, G. Gendt, "The International GPS Service (IGS): Celebrating the 10th Anniversary and Looking to the Next Decade," Adv. Space Res. 36 vol. 36, no. 3, pp. 320-326, 2005. doi:10.1016/j.asr.2005.05.125

[6] D. Laurichesse, F. Mercier, J.P. Berthias, CNES “Real-time PPP with undifferenced integer ambiguity resolution, experimental results” Proceedings, of the ION GNSS 2010, September 2010, Portland, Oregon

[7] M. Caissy, G. Weber, L. Agrotis, G. Wübbena, and Manuel Hernandez-Pajares “The IGS Real-time Pilot Project - The Development of Real-time IGS Correction Products for Precise Point Positioning” Presentations of the EGU11 Vienna, Austria, April 6, 2011

[8] T. Takasu, “RTKLIB: An Open Source Program Package for GNSS Positioning”, http://www.rtklib.com/

[9] M. Cocard, “A systematic investigation of optimal carrier-phase combinations for modernized triple-frequency GPS”, J Geod (2008) 82:555–564

[10] W. Werner, J. Winkel, “TCAR and MCAR Options With Galileo and GPS”, Proceedings of the ION GNSS 2003

[11] J. Geng “Towards Global Instantaneous Centimeter-level Positioning Based on GNSS”, University of Nottingham, UK, this issue

[12] Y. Mireault, P. Tétreault, F. Lahaye, P. Collins, M. Caissy, NrCan, “Real-Time and Near Real-Time GPS Products and Services from Canada”, IGS Analysis Center Workshop 2008, June 2-6, 2008, Miami Beach, Florida, USA

[13] A. E. Zinoviev “Using GLONASS in Combined GNSS Receivers: Current Status“, Proceedings of the ION GNSS, 13-16 September 2005, Long Beach, CA

[14] ESOC RTPP REPORTS: ftp://cddis.nasa.gov/gps/products/rtpp/