A new algorithm for GNSS precise positioning in constrained area

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BIOGRAPHIES

Sébastien CARCANAGUE graduated as an electronic engineer in 2009 from the ENAC (Ecole Nationale de l'Aviation Civile) in Toulouse, France. Since 2009, he is a PhD student at the signal processing lab of ENAC and M3SYSTEMS working on precise positioning algorithm in constrained environments.

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Willy Vigneau graduated from the "Ecole Nationale Supérieure de l'Aéronautique et de l'Espace" in 1999. He has been in charge of the Radionavigation unit at M3 Systems since 2002, and is especially managing projects related to signal processing studies applied to GPS, EGNOS and GALILEO. He is now technical director of M3 Systems and is following M3 Systems' development on GPS, EGNOS and Galileo algorithms and receivers. Recently, he has been particularly involved in several EGNOS and Galileo related projects as project manager and signal processing engineer.

Christophe MACABIAU graduated as an electronics engineer in 1992 from the ENAC in Toulouse, France. Since 1994, he has been working on the application of satellite navigation techniques to civil aviation. He received his Ph.D in 1997 and has been in charge of the signal processing lab of ENAC since 2000.

ABSTRACT

Precise Point Positioning (PPP) and Real-Time Kinematic (RTK) techniques provide a position estimate with an accuracy that is within the centimeter-level in open sky. Their basic principle is to take advantage of the high accuracy of the phase measurements made by the receiver Phase Lock Loops, compared to the delay estimate made by the receiver Delay Lock Loops.
PPP and RTK techniques are not common for mobile users travelling in difficult environment, like urban area, for several reasons: frequent carrier-phase cycle slips and loss of tracking, reduced number of visible satellites, strong multipath on carrier phase and code pseudorange measurements. Indeed, in a constrained environment, several GNSS signals can be blocked, and the received GNSS signals are usually a combination of several multipath components.
The aim of the proposed paper is to present a new precise positioning algorithm, based on single-differenced (between stations) measurement that applies to constrained environments. This technique enables a decreased convergence time of RTK in these environments, and provides a better code-only position if the rover carrier phase measurements are not available. Indeed, the contribution of the reference receiver noise to the initial position estimation is drastically reduced by using a non ambiguous carrier phase combination instead of code measurements. The new model is based on a careful management of code-phase hardware biases that keeps the rover widelane ambiguity as an integer and makes use of the newly and freely available widelane satellite biases originally intended for PPP with ambiguity resolution. The advantages of using single-differenced observations instead of double-differenced measurements are also underlined in this paper.

1. INTRODUCTION

1.1 PRECISE POSITIONING IN URBAN ENVIRONMENT

Current GNSS positioning accuracy is sufficient for most civil users. However, a number of applications need a centimeter-level position: surveying, crustal motion monitoring, precise agriculture… These applications are classically using Real-Time Kinematic (RTK) and/or Precise Point Positioning (PPP) to provide this required accuracy. They both use the accuracy of the carrier phase measurements by estimating the unknown ambiguity, as a float or an integer. The 2 techniques are very efficient in open-sky environment, with good satellite geometry, few cycle slips and reduced multipath. New applications targeting users in urban areas would significantly benefit

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from a precise positioning capability in urban area such as Intelligent Transportation System (ITS), UAV navigation system, etc... However, it is difficult to directly transpose RTK or PPP to these applications since their environment is not adapted for these methods [Kubo, et al., 2007]:

- Multipath is very high on pseudorange and carrier phase
- Cycle slips are frequent
- Carrier phase availability is low
- Satellite geometry is weak

Figure 1 shows the cumulative density function of the duration between 2 consecutive tracking losses for GPS L1 C/A data collected at 1 Hz in Bordeaux's beltway during 1 hour and 20 minutes. The antenna was mounted on the roof of a car, which was driven along the beltway. The receiver was a Septentrio PolarX2. A satellite was considered visible from the first epoch that it was tracked until the last it was tracked. During this time interval, the occurrence of data gaps and their duration on each satellite were carefully checked. All satellites above 5 degrees were considered.

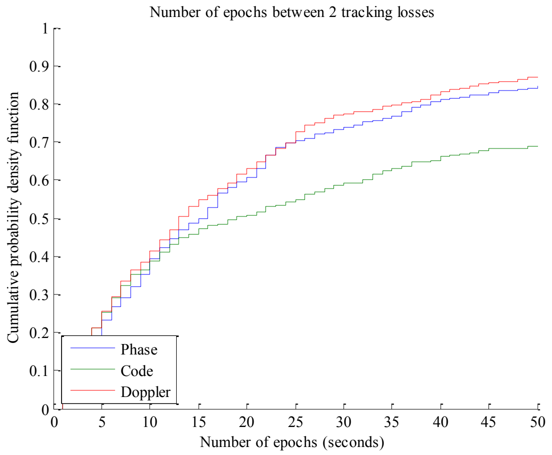

Figure 1 Cumulative density function of the duration between 2 consecutive tracking loss of GPS L1 C/A

Figure 1 shows that about 70% of the carrier phase are continuously available for a duration smaller than 25 seconds. That is why in those conditions, near-instantaneous ambiguity resolution is required [Kubo, et al., 2007] and [de Jonge, et al., 2000].

As the ambiguity resolution convergence time, typically requires at least 30 minutes for PPP, it does not seem well suited for urban environment, even with recent efforts on cycle slip correction [Banville, et al., 2009]. The weak geometry and the high multipath would lengthen convergence time just as the low carrier phase availability. RTK thus seems to be the best a priori choice for GNSS precise positioning in urban environment.

1.2 RTK IN URBAN ENVIRONMENT

RTK is more robust to signal blockage and cycle slips than PPP because its convergence time can be significantly shorter and a precise position can be obtained more quickly. It is classically based on double differences of observables to eliminate common biases. An ambiguity resolution technique is then applied to solve for ambiguities as a set (geometry-based techniques) or independently (geometry-free techniques). However, previously stated effects of urban environment are very harmful:

- **Multipath on pseudorange**. Multipath reduces the accuracy of pseudoranges. It essentially impacts the accuracy of the float solution. It will result in a longer convergence time.
- **Multipath on carrier phase**. They will mostly affect the estimation process of the ambiguities. The residuals will be larger and correct ambiguities can be rejected erroneously. Moreover, LAMBDA method [Teunissen P. , 1993] classically used for ambiguity resolution is not optimal in the presence of biases [Teunissen, 2001] since the decorrelation phase of the method amplifies their effect [Henkel, et al., 2009].
- **Frequent cycle slips/complete loss of lock**. Carrier phase tracking loop is very sensitive to dynamics and the environment surrounding the receiver which can cause complete loss of lock. Some receivers can recover from this loss of lock in one or 2 seconds but other receivers can take up to 20 seconds [de Jonge, et al., 2000]. During this time, the user won't be able to use one or several carrier phase measurements which will bring accuracy down. Cycle slips are also sometimes difficult to repair and force to estimate the ambiguity again. Moreover, in conventional RTK, a convergence time is usually required before reaching precise positioning level. Every time a cycle slip or a loss of lock occurs, the convergence time has to be restarted. Then instantaneous ambiguity resolution would be the best solution as in [de Jonge, et al., 2000] and [Wu, et al., 2003], although it requires precise code measurements.
- **Weak satellite geometry**. A weak satellite geometry impacts geometry-based ambiguity resolution technique and the accuracy of the final solution. In geometry-based ambiguity resolution technique, the float solution may not be precise enough to pass the validation test. Geometry-free ambiguity resolution techniques, which treat each satellite separately to solve for ambiguities individually are not affected by a bad geometry but are usually less efficient than geometry-based technique [Odjik, 2008].

Each of these effects makes single-epoch ambiguity resolution harder.

Under these conditions, RTK algorithms have to be improved by first denoting that double difference is not optimal in the sense that:

- Although it removes important biases, code double differencing also adds the code noise and multipath measurement errors of the reference receiver in the double difference measurements.
- Double difference further correlates the ambiguities [Enge, et al., 2nd Edition]. This is very important since the usual decorrelation step used by ambiguity resolution techniques amplifies biases when present.
- The choice of the reference satellite(s) implies problems for the RTK program designer, to pass the change both in the ambiguities value and the accumulated covariance matrix in the positioning filter [Teunissen, et al., 1998].

To improve single-epoch ambiguity resolution in difficult environment, a new positioning model referred to as Optimized Between-stations Integer WidelANe (OBIWAN) will be introduced in this paper. It is optimized in the sense that spatially correlated errors affecting observations are cancelled by differentiation, while the noise and multipath added by the reference receiver in the code measurement of the rover are negligible. It is based on single difference of observations, which present a number of advantages compared to double difference model. Finally, code-phase biases are carefully handled, to allow the resolution of the widelane ambiguity as an integer.

In the first part, the scenario will be presented. Necessary background on Melbourne-Wübbena combination and hardware biases will be presented in the second part. In the third part, the OBIWAN algorithm will be presented and detailed. Finally in the fourth part, the algorithm will be tested with real data showing that it improves single-epoch ambiguity resolution.

2. ASSUMPTIONS ON THE TARGET USER ENVIRONMENT

The technique described in this paper is based on the following assumptions:

- The system is composed of at least **2 stations**: 1 reference receiver and 1 rover receiver
- The **reference receiver is of good quality in an open-sky environment**, and is a dual-frequency receiver (L1/L2 or L1/L5) with only rare, if any, cycle slips. The rover receiver can be of a much lower quality and/or in a less friendly environment. However, it has to be dual-frequency and track the same signals as the reference receiver.
- The **2 stations are very close (short baseline case: <10km)**. The tropospheric delay and the ionospheric delay affecting the observables of the 2 receivers are almost the same. Then, if we difference the observables from the 2 receivers, the residual ionospheric delay and the tropospheric delay remain at centimeter-level.

In practice, those requirements are not very restrictive. For instance, the city of Paris (intra-muros) is approximately contained in a circle with a diameter of 10km. 1 single good quality receiver could be used to improve positioning accuracy of thousands of potential users. Moreover, the price of dual frequency receivers is expected to drop in the upcoming years, with the full availability of L2C signal.

3. BACKGROUND FOR THE PROPOSED ALGORITHM

The code and phase measurement model associated to one satellite for a signal at the frequency L_i can be written as:

$$\begin{cases} P_i = \rho + c(dt - dT) + I_i + T + b_{r,P_i} - b^s_{P_i} + \varepsilon_{P_i} \\ \phi_i = \rho + c(dt - dT) - I_i + T + b_{r,\phi_i} - b^s_{\phi_i} + N_i\lambda_i + \varepsilon_{\phi_i} \end{cases}$$

where ρ is the geometric range, dt is the receiver clock offset, dT is the satellite clock offset, I_i is the ionospheric delay on frequency i, T is the tropospheric delay, b_{r,P_i} and b_{r,ϕ_i} are the receiver hardware delay of the code and carrier phase respectively, $b^s_{P_i}$ and $b^s_{\phi_i}$ are the satellite hardware delay of the code and the carrier phase, N_i is the carrier phase integer ambiguity, λ_i is the wavelength of the signal, ε_{P_i} and ε_{ϕ_i} are noise/multipath of code and carrier phase.

Because it is difficult to solve for the integer ambiguities of the raw phase measurements due to the very small wavelength of the carrier, many applications first go through the use of phase measurements combinations that create new measurements with extended wavelength. This is for instance the case for the widelane phase combination given by:

$$\phi_{WL} = \left(\frac{\phi_1}{\lambda_1} - \frac{\phi_2}{\lambda_2}\right)\lambda_{WL} \text{ with } \lambda_{WL} = \frac{1}{\frac{1}{\lambda_1} - \frac{1}{\lambda_2}} = 86.1\ cm$$

where ϕ_i is the carrier phase observable on the frequency i.

The resulting widelane phase measurement is also ambiguous, but has kept an integer ambiguity with an longer associated wavelength.

The so-called Melbourne-Wübbena combination ([Melbourne, 1985] and [Wübbena, 1985]) uses the widelane phase observable and the narrowlane code observable to isolate the widelane ambiguity.

The narrowlane code combination is given by:

$$P_{NL} = \left(\frac{P_1}{\lambda_1} + \frac{P_2}{\lambda_2}\right) \cdot \lambda_{NL} \text{ with } \lambda_{NL} = \frac{\lambda_1\lambda_2}{\lambda_1 + \lambda_2} = 10.7\ cm$$

and P_i the code observable on the frequency i.

The Melbourne-Wübbena combination can then be obtained through [Banville, et al., 2008]:

$$\phi_{WL} - P_{NL} = (N_1 - N_2)\lambda_{WL} + b_{r,MW} - b^s_{MW} + \varepsilon_{P_{NL}} + \varepsilon_{\Phi_{WL}} \quad (1)$$

with $b_{r,MW}$ and b^s_{MW} the Melbourne-Wubbena biases for receiver and satellite respectively, $\varepsilon_{P_{NL}}$the noise of the code narrowlane combination and $\varepsilon_{\Phi_{WL}}$ the noise of the carrier phase widelane combination.

The resolution of the widelane ambiguity $N_{WL} = (N_1 - N_2)$ using the Melbourne-Wübbena combination has been at the center of PPP algorithm developers for a few years, as it is the key of undifferenced ambiguity resolution. The reader might refer to [Laurichesse, et al., 2009], [Collins, 2008] and [Ge, et al., 2008] for more details on this technique. To do so, it is important to have access to the Melbourne-Wübbena satellite biases b^s_{MW}. These biases are now freely available and released with a week latency by the CNES-CLS IGS center (.wls products) [Loyer, et al., 2010]. Once the satellite biases are removed, the user can determine both the Melbourne-Wübbena receiver bias and the ambiguities by using, for instance, a sliding averaging window.

In the next section, the new algorithm referred to as OBIWAN will be presented. It aims at fixing the widelane ambiguity more efficiently. Fixing the widelane ambiguity correctly leads to a decimeter-level position, which can be sufficient for many applications. It can also pave the way to L1 ambiguity resolution and centimeter-level positioning [Liu, 2003].

4. ALGORITHM PRESENTATION

4.1 OBIWAN ALGORITHM

As explained earlier, one of the disadvantages of the use of code double difference to initialize float solution is that it adds the noise/multipath error of the rover measurements with the noise/multipath error of the reference receiver measurements since these kinds of error are uncorrelated between receivers. Moreover, the double difference increases the correlation between the ambiguities which makes more complex the ambiguity resolution step. The algorithm proposed hereafter offers a solution to both problems.

First, let's form the widelane and the narrowlane combination on the reference receiver and the rover:

$$\begin{aligned}
\phi^{\mathrm{ref}}_{\mathrm{WL}} &= \rho^{ref} + c(dt^{ref} - dT) + T^{ref} + I^{ref} + N^{ref}_{WL}\lambda_{WL} \\
&\quad + b_{r,\phi^{\mathrm{ref}}_{\mathrm{WL}}} - b^s_{\phi_{\mathrm{WL}}} + \varepsilon_{\phi_{\mathrm{WL}}} \qquad (2a) \\
P^{\mathrm{ref}}_{\mathrm{NL}} &= \rho^{ref} + c(dt^{ref} - dT) + T^{ref} + I^{ref} + b_{r,P^{\mathrm{ref}}_{\mathrm{NL}}} - b^s_{P_{\mathrm{NL}}} \\
&\quad + \varepsilon_{P^{\mathrm{ref}}_{\mathrm{NL}}} \qquad (2b)
\end{aligned}$$

$$\begin{aligned}
\phi^{\mathrm{rov}}_{\mathrm{WL}} &= \rho^{rov} + c(dt^{rov} - dT) + T^{rov} + I^{rov} + N^{rov}_{WL}\lambda_{WL} \\
&\quad + b_{r,\phi^{\mathrm{rov}}_{\mathrm{WL}}} - b^s_{\phi_{\mathrm{WL}}} + \varepsilon_{\phi_{\mathrm{WL}}} \qquad (3a) \\
P^{\mathrm{rov}}_{\mathrm{NL}} &= \rho^{rov} + c(dt^{rov} - dT) + T^{rov} + I^{rov} + b_{r,P^{\mathrm{rov}}_{\mathrm{NL}}} - b^s_{P_{\mathrm{NL}}} \\
&\quad + \varepsilon_{P^{\mathrm{rov}}_{\mathrm{NL}}} \qquad (3b)
\end{aligned}$$

where the superscript 'ref' refers to the reference station and the superscript 'rov' refers to the rover.

Comparing equation (1) and equation (2), we can first denote that the Melbourne-Wübbena biases can be expressed as:

$$\begin{cases} b_{r,MW} = b_{r,\phi_{\mathrm{WL}}} - b_{r,P_{NL}} & (4a) \\ b^s_{MW} = b^s_{\phi_{\mathrm{WL}}} - b^s_{P_{\mathrm{NL}}} & (4b) \end{cases}$$

The OBIWAN algorithm is as such:

- **Resolution of the widelane ambiguities on the reference receiver:** The widelane ambiguities N^{ref}_{WL} of the reference receiver are solved by removing satellite biases from Melbourne-Wübbena combination (equation (1)) and averaging over a sliding window in order to reduce measurement noise. The optimal window length depends on satellite elevation and goes from 5 minutes to 30 minutes with 1 Hz data [Laurichesse, et al., 2009]. The float value obtained after the averaging can be decomposed into an integer ambiguity (specific for each satellite) and a hardware receiver bias (common to all satellites). This couple is defined modulo a widelane cycle. The output of this step is then a set of widelane ambiguities and a receiver bias. Once this estimation step is complete, the widelane carrier phase measurements of the reference receiver can be considered as a very precise and unambiguous observation.
  This step should not be a problem as the reference receiver is assumed to be in a friendly environment with a good satellite visibility.
- **Combinations using the unambiguous carrier phase measurements of the reference receiver and the reduced-noise code measurements of the rover**. Two observables are created in this step:
  - The first is a single difference of the widelane carrier phase observables.
  - The second is the Melbourne-Wübbena combination, with the phase of the receiver and the code of the rover

This provides;

$$\begin{cases} (2a) - (3a) \\ (2a) - (3b) \end{cases}$$

i.e.:

$$\begin{aligned}
\phi^{\mathrm{ref}}_{\mathrm{WL}} - \phi^{\mathrm{rov}}_{\mathrm{WL}} &= \rho^{ref} - \rho^{rov} + cdt + N^{ref-rov}_{WL}\lambda_{WL} + b_{r,\phi^{\mathrm{ref}}_{\mathrm{WL}}} \\
&\quad - b_{r,\phi^{\mathrm{rov}}_{\mathrm{WL}}} \\
&\quad + \varepsilon_{\Delta\phi_{\mathrm{WL}}} \qquad (5a) \\
\phi^{\mathrm{ref}}_{\mathrm{WL}} - P^{\mathrm{rov}}_{\mathrm{NL}} &= \rho^{ref} - \rho^{rov} + cdt + N^{ref}_{WL}\lambda_{WL} + b_{r,\phi^{\mathrm{ref}}_{\mathrm{WL}}} \\
&\quad - b^s_{\phi_{\mathrm{WL}}} - (b_{r,P^{\mathrm{rov}}_{\mathrm{NL}}} \\
&\quad - b^s_{P_{\mathrm{NL}}}) + \varepsilon_{P^{\mathrm{rov}}_{\mathrm{NL}}} \qquad (5b)
\end{aligned}$$

where it was assumed that the stations are close enough so that the tropospheric delays and ionospheric

delays are cancelling out and where $dt = (dt^{ref} - dt^{rov})$ is the difference of the 2 receiver clocks.
It can be seen that equation (5b) contains the known Melbourne-Wübbena satellite bias of equation (4b). This is logical as from a satellite bias point of view, forming a combination of observables from the same receiver or from different receiver is similar.

- **Removing known reference receiver ambiguities and satellite biases:** In this step, the user removes the known satellite biases and the estimated widelane ambiguity of the reference receiver (obtained from step 1) which gives:

$$\phi_{WL}^{ref} - \phi_{WL}^{rov} = \rho^{ref} - \rho^{rov} + cdt' + N_{WL}^{ref-rov}\lambda_{WL} + \varepsilon_{\Delta\phi_{WL}} \quad (6a)$$

$$\phi_{WL}^{ref} - P_{NL}^{rov} + b_{MW}^{s} - N_{WL}^{ref}\lambda_{WL} = \rho^{ref} - \rho^{rov} + cdt' - b_{r,P_{NL}^{rov}} + b_{r,\phi_{WL}^{rov}} + \varepsilon_{P_{NL}^{rov}} \quad (6b)$$

where $dt' = dt + b_{r,\phi_{WL}^{ref}} - b_{r,\phi_{WL}^{rov}}$ represents a new clock term that includes the hardware bias term of equation (5a)
Denoting that $b_{rov,MW} = b_{r,\phi_{WL}^{rov}} - b_{r,P_{NL}^{rov}}$, then the final measurement model is:

$$\begin{cases} \phi_{WL}^{ref} - \phi_{WL}^{rov} - N_{WL}^{ref}\lambda_{WL} = \rho^{ref} - \rho^{rov} + cdt' + N_{WL}^{rov}\lambda_{WL} + \varepsilon_{\Delta\phi_{WL}} & (7a) \\ \phi_{WL}^{ref} - P_{NL}^{rov} - \mathrm{corr} = \rho^{ref} - \rho^{rov} + cdt' + b_{rov,MW} + \varepsilon_{P_{NL}^{rov}} & (7b) \end{cases}$$

with $corr = -b_{MW}^{s} + N_{WL}^{ref}\lambda_{WL}$ the correction.

To summarize, two new observables have been created that are:

- An ambiguous precise observable that is the single-differenced widelane carrier phase.
- An associated unambiguous measurement that is the Melbourne-Wübbena combination, formed with the widelane phase of the reference receiver and the narrowlane code of the rover. This observable is corrected with the satellite widelane biases and the estimated widelane ambiguities of the reference receiver.

These two new measurements can be used to solve for the widelane ambiguity of the rover based on a precise, single-differenced unambiguous measurement.

Simplifying notations, we have obtained a single-differenced integer widelane model that is such that:

$$\begin{cases} \phi = \rho + c \cdot dt + N \cdot \lambda_{WL} + \varepsilon_{\phi_{WL}} \\ P = \rho + c \cdot dt + b_r + \varepsilon_{P_{NL}} \end{cases} \quad (8)$$

With ρ a geometric term defining the vector from the reference receiver to the rover, dt a clock term common to every satellite, N an integer ambiguity and b_r being exactly the Melbourne-Wübbena receiver bias of the rover.

A scheme of the algorithm can be found on Figure 2.

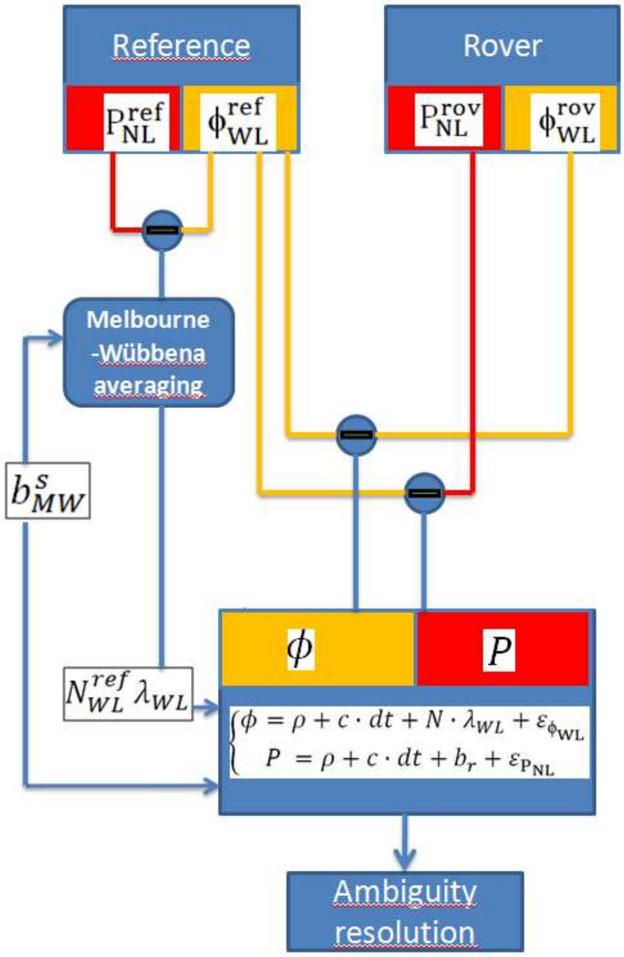

Figure 2 Diagram of the OBIWAN algorithm. The code of the reference receiver is no longer used in the positioning filter while the widelane ambiguity is kept as an integer.

A first remark is that the unambiguous measurements (7b), I a very accurate positioning pseudorange as all the biases have been removed by the single difference and the noise introduced by the reference receiver carrier phase is negligible. This precise pseudorange should provide far better positioning accuracy than double differenced code measurements. Moreover, it is interesting to denote that an increase of the number of reference station would directly result in a higher accuracy as the noise in the solution most entirely comes from the rover.

Secondly, the integer ambiguity in equation (7a) is exactly the integer ambiguity obtained with Melbourne-Wübbena combination on the rover receiver. This property really simplifies combined geometry-free and geometry-based ambiguity resolution. For instance, widelane ambiguities of the rover can be estimated both with the previous algorithm, i.e. estimating the position/clock and all ambiguities altogether, and by averaging Melbourne-Wübbena combination of each satellite individually.

Thirdly, this technique is based on differences between stations to eliminate spatially correlated biases. In term of ionospheric delay, the residual bias is the same for equation (7a) and (7b). It is 1.28 times more important than the residual in meters obtained by differencing L1-only measurements between the 2 stations. However, it is smaller in units of cycles, as the wavelength of the widelane is larger than the wavelength on L1. This should allow successful ambiguity resolution with baselines from a few kilometers to a few tenths of kilometers, depending on ionospheric activity.

4.2 LIMITATIONS OF OBIWAN FOR SINGLE-FREQUENCY USERS

The concept of using the unambiguous carrier phase of the reference receiver instead of the code seems new and no reference to it was found in the literature by the author. OBIWAN uses the specific property of the widelane carrier phase and the narrowlane code observations.
It is difficult to extend this technique to single-frequency users for different reasons:

- **The ambiguity is very hard to isolate on the reference receiver**. In the code minus phase observable, an ionospheric term remains. For instance, with L1 data:

$$P_1 - \phi_1 = 2 \cdot I_1 - N_1 \cdot \lambda_1 + b_{r,P_1-\phi_1} - b^s_{P_1-\phi_1} + \varepsilon_{P_1} + \varepsilon_{\phi_1}$$

  The advantage of the MW combination is that the ionospheric term is removed. Moreover, the code observable P_1 is noisier than the narrowlane observable. The code-phase receiver bias would also be very difficult to estimate for the same reason.
- **In a monofrequency observable, the phase wind-up would affect the single differenced carrier phase observable**. This effect is both due to a rotation of the satellite antenna and the receiver antenna, since GPS signal is polarized. In the case of between station observables, the receiver rotation contribution would remain. Any full clockwise rotation of the receiver antenna around the vertical axis would result in an apparent increase of 1 cycle in the carrier phase observable [Banville, et al., 2010]. As the receiver rotation is very difficult to model without any external attitude information, a monofrequency version of the algorithm described in the first part couldn't be applied.
  Since the widelane observable is not affected by the phase wind-up ([Banville, et al., 2009]), no external information on receiver antenna rotation is required in our case.

5 TEST ON REAL DATA

5.1 POSITIONING ACCURACY PERFORMANCE

OBIWAN was tested on 3 IGS stations [Dow, et al., 2009] situated in Washington, USN0, USN3 and NRL1 with data from May 1st, 2010. USN0 was considered as the reference station. The baseline USN0-USN3 is approximately 0.3km long and the baseline USN0-NRL1 is approximately 11km long. Observation sampling rate was 1/30 Hz. Data from the 3 stations were synchronized and will be considered simultaneous in the following results. The signals tracked were GPS L1 P and GPS L2 P. Note that the technique could be applied to GPS L1/L5 receivers or GALILEO E1/E5a receivers, but available satellite Melbourne-Wübbena biases are currently only for GPS P1 and P2 code measurements. It is difficult to know if code measurements are carrier-smoothed, but it is highly probable that they are.

Cycle slips were first detected and repaired on the reference station and the widelane ambiguity was determined from the Melbourne-Wübbena combination. Then, the narrowlane code is formed on the rover, combined with the widelane phase of the reference receiver. If the reference receiver and the rover have similar level of noise and multipath, this unambiguous measurement is expected to reduce noise by a factor of 2 compared to double difference with P1 only, from noise propagation laws. Results from Table 1 confirm this theory.

	PRN double difference 1	PRN double difference 2	PRN double difference 3	PRN double difference 4
Std of Double Difference P1 (m)	0.56	0.64	0.56	0.49
Std of Double Difference P2 (m)	0.54	0.59	0.48	0.44
Std of equation (7b) differenced between 2 satellites (m)	**0.27**	**0.31**	**0.25**	**0.21**

Table 1 Noise+multipath statistics of code double differences and the observable of equation (7b), for different double differences. Double-differenced carrier phase on L1 is subtracted to all observables to remove the geometric part. Standard deviation is then computed. Baseline length was 0.3km.

To compare similar quantities, equation (7b) is differenced between 2 satellites to eliminate the clock term. The accuracy on each pseudorange is approximately increased by a factor of 2. However, it is not totally fair to directly compare the level of noise/multipath. Indeed, the new method provides 2 times less observables to the position filter than double differences on both L1 and L2, as only the narrowlane combination on the rover can be used. Considering the observables P1 and P2, a baseline vector solution was then estimated with a least-square on a single-epoch basis. Results can be found on Table 2.

	X	Y	Z
Std of the position from code double difference P1 and P2	0.31	0.56	0.53
Std of the position from equation (7b) (m)	**0.24**	**0.37**	**0.34**

Table 2 Estimated coordinates error statistics for a baseline of 0.3km

Error standard deviation is approximately divided by $\sqrt{2}$, as expected from noise propagation laws. Indeed, the pseudoranges from equation (7b) are 2 times more accurate but there are 2 times less observables compared to a filter including P1 and P2.

5.2 SINGLE-EPOCH AMBIGUITY RESOLUTION PERFORMANCE

The improvement in the initial position estimation brought by the use of the unambiguous widelane phase of the reference receiver instead of classic code measurements has been shown to be significant. The aim of this part is now to quantify the impact of the new model in term of single-epoch ambiguity success rate. As stated before, the advantage of the new model for ambiguity resolution is twofold. First the initial position and float ambiguities will be more precise than when using code double difference, as the noise/multipath contribution of the widelane carrier phase on the reference receiver is very small. Secondly, as we do not perform double difference, the ambiguities are less correlated than with the double difference model. As the decorrelation step of the LAMBDA method is responsible of biases amplification, reducing the correlation should also reduce bias amplification.

The LAMBDA method was implemented directly as provided in the Matlab version of Delft University. A least-square filter was first used to estimate the coordinates, the clock term and float ambiguities. LAMBDA algorithm was then used, with float ambiguities and their associated covariance matrix as input. The comparison in terms of ambiguities resolution success rate was performed on 2 baselines. The first was between USN0 and USN3, which is approximately 0.3km and the second was between USN0 and NRL1 which is approximately 11km. Tropospheric delay and ionospheric delay were voluntarily not corrected on the last baseline, to see the impact of biases on the time to fix ambiguities. To separate the impact of the decorrelation and the improved accuracy of the float solution on the success rate, we have computed the percentage of correct first fix with classic double difference, with the method exposed before and the method exposed before differenced between satellites. Differencing between satellites equation (7a) and (7b) avoids estimating the clock term and the receiver bias, but correlates ambiguities. The impact of ambiguities correlation can then be deduced. Indeed, if the bias is estimated correctly, the difference between single difference and double difference of the new algorithm observables should only come from the correlation of the ambiguities in the double difference, as they have the exact same accuracy in the initial float solution. Results can be found on Table 3. The hardware bias of the rover was obtained by averaging over a whole day and by taking a unique value. However, more refined estimation on shorter time windows has to be performed for stations with less stable bias than USN0, USN3 and NRL1.

Baseline length	Single-epoch ambiguity resolution success rate	
0.1km	Double difference	92.30%
	OBIWAN	98.45%
	OBIWAN differenced between satellites	98.30%
11km	Double difference	85.45%
	OBIWAN	93.65%
	OBIWAN differenced between satellites	93.15%

Table 3 Single-epoch ambiguity resolution success rate with different baseline, mask angle=20°, for an entire day.

Note that these values are below the values we can find in the literature (usually close to 100% fix rate). This might be due to the fact that we have not performed any validation of the ambiguities. Higher fix rate would have been obtained if we had rejected ambiguities that didn't pass the validation test. However, it seemed more relevant to compare raw fix rate before validation to see the impact of improved accuracy on ambiguity resolution.

We can see that the biggest contribution to the success rate is the improved accuracy of the float solution in the ambiguity resolution process. However, the fact that the ambiguities ave not been correlated further with a double difference brings a little improvement of up to 0.5% in the case of longer baseline, which is more affected by biases. The reason why this improvement is only marginal might be the difficult step of accurately estimating the rover hardware bias. In any case, the new model improves single-epoch ambiguity resolution even if observables are between-satellite differenced, which avoids the bias estimation.

6 CONCLUSION AND FUTURE WORK

The OBIWAN algorithm presented in this paper reduces the contribution of the reference receiver to the initial float solution in terms of noise and multipath, as it uses only the unambiguous widelane carrier phase instead of code measurements. Moreover, integer ambiguity resolution becomes possible with a single-difference model using code and phase of the rover, which avoids further correlation of the ambiguities and greatly simplifies the work of the RTK program designer. It has been shown that the level of noise and multipath was approximately divided by $\sqrt{2}$ in the position domain compared to a double difference of code on L1 and L2, if the noise and multipath level are similar on the 2 stations. The less correlated ambiguities also bring a modest improvement when carrier phase measurements are biased.

However, the method has not been tested with a rover receiver that is in a difficult environment which will make the estimation of the Melbourne-Wübbena receiver hardware bias more difficult. In this paper, a single value was taken for a day, but average over shorter periods showed variations. However, it is difficult to determine from where those variations come from. It can be either:

- Multipath residuals that bias the average processing
- Actual hardware bias variation

If the estimation of this bias is too complicated due to the environment, the new method should be used with differences between satellites, to eliminate the issue of hardware bias estimation.

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