A NEW APPROACH FOR MITIGATING CARRIER PHASE MULTIPATH ERRORS IN MULTI-GNSS REAL-TIME KINEMATIC (RTK) RECEIVERS

M. Sahmoudi, A. Kouki and R. Jr. Landry

Navigation Research Group, LACIME Lab.
Ecole de Technologie Supérieure (ETS), Québec University
Montréal, QC H3C 1K3, Canada

ABSTRACT

In this paper, we introduce a new approach for RTK positioning using triple-frequency combinations of GNSS measurements in presence of carrier phase multipath. The proposed method is based on a modification of the LAMBDA method, where the a-priori information on multipath errors is exploited as a constraint in the optimization and ambiguities search process to mitigate the effect of multipath. Triple-frequency combinations of measurements is used to formulate a new carrier phase multipath index, then incorporate it as additional constraint in the LAMBDA method cost function for multi-frequency ambiguity resolution. Simulations and real experiments shows the effectiveness of the developed scheme.

***Index Terms*—** Triple-frequency GNSS measurements, RTK, integer ambiguity resolution, carrier multipath.

1. INTRODUCTION

The GNSS (global navigation satellite system) technology known as RTK uses carrier phase measurements from two GNSS receivers. The carrier-phase observable is the total number of carrier cycles plus a fractional cycle part between the satellite and the receiver [4]. This unknown number of cycles must be estimated along with the other unknowns of interest that may include the receiver's coordinates and the velocity of the user's movement. The carrier phase measurements are very precise but ambiguous unfortunately. Thus, the relative positioning with carrier phase turns out to be a problem of correct estimation of integer ambiguities. The standard procedure of solving this problem is to first apply an estimation method such a Kalman filter [5] or a standard least-square adjustment [2] so that a real-valued *float* solution is obtained [3]. The second step is to map the real-valued ambiguity estimates to integer values. In the literature of single, dual and triple frequency RTK, there are many ambiguity solutions for single and dual frequency GPS observations [3] including essentially the LAMBDA method [2].

Clearly, carrier phase multipath errors are one of the most limiting factors in accuracy and reliability regarding GNSS-RTK based positioning and navigation [4]. They are very hard to mitigate since there is no multipath indicator available in the literature for each couple of satellite and receiver. The existing methods of carrier phase multipath mitigation are based mainly on previous data processing, multipath modeling or on multiple antennas [7]. The quality of carrier-phase multipath calibration is highly dependent on the ability to separate multipath effects from other errors. For multipath mitigation and ambiguity resolution in RTK positioning, multi-GNSS carrier phase measurements are a promising opportunity [9], because with the upcoming modernized GPS, modernized GLONASS and the new GALILEO, the measurement redundancy will be increased and the satellite geometry will be improved via the composed constellation.

In this paper, we derive a new multipath equality constraint, that is based on the relationship between linear combinations of double differences of three carrier phases and their ambiguities. Then, we incorporate this constraint into the LAMBDA method cost function to mitigate the multipath effect, which helps also to limit the number of searched ambiguities.

2. MULTI-GNSS RTK MEASUREMENTS MODEL

2.1. Triple pseudorange and carrier phase measurements

We consider the measured pseudorange code and carrier phase, as related to the unknown parameters via the following measurements equations for satellite q, given in meters by,

$$P^q_{i,u} = \rho^q_u + c[\delta t_u - \delta t^q] + \frac{f_1^2}{f_i^2} I^q_u + T^q_{u,i} + \varepsilon^q_{u,i} + M_{P^q_{u,i}}, \quad (1)$$

$$\Phi^q_{i,u} = \rho^q_u + c[\delta t_u - \delta t^q] - \frac{f_1^2}{f_i^2} I^q_u + T^q_{u,i} + \lambda_i N^q_{u,i} + \epsilon^q_{u,i} + M_{\Phi^q_{u,i}}, \quad (2)$$

holding for any of the L-band frequency signals, $f_i =$ L1, L2, L5, E1, E5a and E5b. For simplicity of models presentation, we ignore the index time. Each of the above terms is described in Table 1. The double difference (DD) for all combinations of K satellites are computed between data of reference station and the user receivers. The clock errors and possible equipment delays per frequency or measurement type cancel explicitly when double difference of measurements are taken over the two used receivers and pair-wise satellites. A part from noise, the between receiver, between-satellite measurements are composed of DD combination of geometric ranges, differential ionospheric delay terms, and the DD ambiguity, that is known to be an integer, expressed as,

P_i^q	i-th frequency code measurement of satellite q (m)
ρ_u^q	distance between satellite q and the receiver u (m)
c	is the speed of light $\approx 2.99792458 \times 10^8$ m/s
δt_u	receiver clock bias (s)
δt^q	clock bias of satellite q (s)
I_i^q	ionospheric delay (m)
T_i^q	tropospheric delay (m)
ε_i^q	noise of the i-th frequency code observation (m)
Φ_i^q	i-th carrier phase measurement (m)
$\lambda_i = \frac{c}{f_i}$	i-th carrier wavelength (m)
N_i^q	integer ambiguity of the i-th carrier phase (cycles)
ϵ_i^q	noise of the i-th carrier phase measurement (m)
$M_{P_i^q}$	multipath error on the code measurement
$M_{\Phi_i^q}$	multipath error on the carrier phase measurement.

Table 1. Mathematical notation.

$$\begin{aligned}\nabla\triangle P_{i,ur}^{ql} &\stackrel{\text{def}}{=} \{P_{i,u}^q - P_{i,r}^q\} - \{P_{i,u}^l - P_{i,r}^l\}\\ &= \nabla\triangle\rho_{ur}^{ql} + \frac{f_1^2}{f_i^2}\nabla\triangle I_{ur}^{ql} + \nabla\triangle\varepsilon_{i,ur}^{ql}, \quad (3)\\ \nabla\triangle\Phi_{i,ur}^{ql} &\stackrel{\text{def}}{=} \{\Phi_{i,u}^q - \Phi_{i,r}^q\} - \{\Phi_{i,u}^l - \Phi_{i,r}^l\} \quad (4)\\ &= \nabla\triangle\rho_{ur}^{ql} - \frac{f_1^2}{f_i^2}\nabla\triangle I_{ur}^{ql} + \lambda_i\nabla\triangle N_{i,ur}^{ql} + \nabla\triangle\epsilon_{i,ur}^{ql},\end{aligned}$$

where

$$\begin{aligned}\nabla\triangle I_{ur}^{ql} &\stackrel{\text{def}}{=} (I_u^q - I_r^q) - (I_u^l - I_r^l) \stackrel{\text{def}}{=} \triangle I_{ur}^q - \triangle I_{ur}^l,\\ \nabla\triangle N_{i,ur}^{ql} &\stackrel{\text{def}}{=} (N_{i,u}^q - N_{i,r}^q) - (N_{i,u}^l - N_{i,r}^l) = \triangle N_{i,ur}^q - \triangle N_{i,ur}^l.\end{aligned}$$

and the same definition applies for the noise term.

2.2. System Model

We mitigate the ionospheric delay by considering the single differences between ionospheric delays at the reference and rover receivers as variables in the state vector. Without loss of generality, we assume that the first satellite (i.e. $q = 1$) is the reference satellite and we form the DD pseudo-measurements vectors at each update interval time of the receiver as,

$$\begin{aligned}\nabla\triangle P_{i,ur} &\stackrel{\text{def}}{=} [\nabla\triangle P_{i,ur}^{12}, \nabla\triangle P_{i,ur}^{13}, \cdots, \nabla\triangle P_{i,ur}^{1K}]^T, \quad (5)\\ \nabla\triangle\Phi_{i,ur} &\stackrel{\text{def}}{=} [\nabla\triangle\Phi_{i,ur}^{12}, \nabla\triangle\Phi_{i,ur}^{13}, \cdots, \nabla\triangle\Phi_{i,ur}^{1K}]^T. \quad (6)\end{aligned}$$

We consider in this work a triple frequency RTK system design. For ambiguity resolution and ionospheric errors correction, we propose to estimate the following state vector,

$$\begin{aligned}\mathbf{x}_k &\stackrel{\text{def}}{=} [X^T(k), \triangle I^T(k), \mathbf{N}^T(k)]^T; \quad (7)\\ X(k) &\stackrel{\text{def}}{=} [x_u, y_u, z_u]^T,\\ \triangle I(k) &\stackrel{\text{def}}{=} [\triangle I_{ur}^1, \triangle I_{ur}^2, \cdots, \triangle I_{ur}^K],\\ \mathbf{N}(k) &\stackrel{\text{def}}{=} [\mathbf{N}_1^T, \mathbf{N}_2^T, \mathbf{N}_3^T]^T,\\ \mathbf{N}_i &\stackrel{\text{def}}{=} [\nabla\triangle N_{i,ur}^{12}, \cdots, \nabla\triangle N_{i,ur}^{1K}]^T,\end{aligned}$$

where i is the frequency index. The sate vector $\mathbf{x}_k$ is of $3 + K + 3(K-1) = 4K$ components. The single differences of the ionospheric delays are modeled as a first order Markov process according to the state equation, $\triangle I(k+1) = \triangle I(k) + \omega_I(k)$. Applying a dynamic model for the moving receiver, we can express the state equation as,

$$\mathbf{x}_{k+1} = F_k\mathbf{x}_k + B_k\omega_k, \quad (8)$$

where k is the index of the receiver update time interval, ω_k is the process noise, B_k is a known appropriate weighting matrix for covariance of the process noise. Using the double difference equations of two pseudorange and three carrier phase measurements, we can formulate the observation equation as,

$$\begin{aligned}\mathbf{y}_k &\stackrel{\text{def}}{=} (\nabla\triangle\Phi_{1,ur}, \nabla\triangle\Phi_{2,ur}, \nabla\triangle\Phi_{3,ur}, \nabla\triangle P_{1,ur}, \nabla\triangle P_{2,ur})^T\\ &= \tilde{h}(X(k)) + \tilde{\Pi}\triangle I(k) + \Lambda\mathbf{N}(k) + \mathbf{v}_k\\ &\stackrel{\text{def}}{=} \mathbf{H}_k([X^T(k), \triangle I^T(k), \mathbf{N}^T(k)]^T) + \mathbf{v}_k\end{aligned}$$

where,

$$\Pi \stackrel{\text{def}}{=} [\mathbb{1}_{K-1}, \text{diag}(-1, \cdots, -1)_{K-1}]; \quad \mathbb{1}_{K-1} = [1, \ldots, 1]^T.$$

$$\tilde{h}(X(k)) = [h(X(k)), h(X(k)), h(X(k)), h(X(k)), h(X(k))]^T,$$

$$\tilde{\Pi} = \left[\Pi, \frac{f_1^2}{f_2^2}\Pi, \frac{f_1^2}{f_3^2}\Pi, -\Pi, -\frac{f_1^2}{f_2^2}\Pi\right]^T, \Lambda\mathbf{N} = [\lambda_1\mathbf{N}_1, \lambda_2\mathbf{N}_2, \lambda_3\mathbf{N}_3, 0, 0]^T.$$

$$\Lambda \stackrel{\text{def}}{=} \text{diag}(\lambda_1, \lambda_2, \lambda_3)_{5\times3}, \quad \mathbf{v}_k = \left[\mathbf{v}_1^T, \mathbf{v}_2^T, \mathbf{v}_3^T, \mathbf{v}_{P2}^T, \mathbf{v}_{P1}^T\right]^T,$$

The noise terms $\mathbf{v}_1^T, \mathbf{v}_2^T, \mathbf{v}_3^T, \mathbf{v}_{P2}^T$ and $\mathbf{v}_{P1}^T$ are assumed to be independents and $h_{q-1}(X) = (\rho_r^1 - \rho_u^1) - (\rho_r^q - \rho_u^q)$; $q = 2 : K$. Accordingly, the observation equation is given as,

$$\mathbf{y}_k = \mathbf{H}_k(\mathbf{x}_k) + \mathbf{v}_k. \quad (9)$$

The noise covariance $\mathbf{R}_k$ is given by the block diagonal matrix of elements $\mathbf{R}_1, \mathbf{R}_2, \mathbf{R}_3, \mathbf{R}_{P_1}, \mathbf{R}_{P_2}$, which are the corresponding noise covariances of the first, second, third carrier phase, first and second code measurements, respectively. To estimate the state vector $\mathbf{x}_k$, we use the robust particle filter algorithm that were developed in [8]. The obtained solution of ambiguities is called *float* ambiguity solution.

3. MULTI-FREQUENCY AMBIGUITY RESOLUTION IN MULTIPATH ENVIRONMENTS

3.1. Carrier phase multipath indicators

Contrary to the code measurements, there is no available metric to compute carrier phase multipath errors. The existing analysis methods provide only measure of mixed residuals that may include multipath errors. With triple-frequency measurements, we derived in [8] an interesting carrier multipath variation indicator and even for each single receiver. First, we showed the following relationship,

$$\begin{aligned}&\nabla\triangle\phi_1(\lambda_3^2 - \lambda_2^2) + \nabla\triangle\phi_2(\lambda_1^2 - \lambda_3^2) + \nabla\triangle\phi_3(\lambda_2^2 - \lambda_1^2) - \nabla\triangle M_\phi\\ &= \lambda_1\nabla\triangle N_1(\lambda_3^2 - \lambda_2^2) + \lambda_2\nabla\triangle N_2(\lambda_1^2 - \lambda_3^2) + \lambda_3\nabla\triangle N_3(\lambda_2^2 - \lambda_1^2).\end{aligned}$$

Then, we obtain $\nabla\triangle M_\phi$ as a multipath indicator using double difference observations because the constant ambiguities terms vanish when we differentiate in time.

3.2. Multipath constraint for ambiguity resolution

In some non-ideal environments such as urban canyons, where most of the data will be contaminated by multipath errors, one needs to obtain a precise RTK solution from these contaminated measurements. Instead of cleaning the data by using only multipath-free measurements, we will enforce the ambiguity resolution scheme to mitigate the effect of multipath. We develop a new multipath-constrained ambiguity resolution technique by incorporating the following constraint,

$$\begin{aligned}&\nabla\triangle\phi_1(\lambda_3^2-\lambda_2^2)+\nabla\triangle\phi_2(\lambda_1^2-\lambda_3^2)+\nabla\triangle\phi_3(\lambda_2^2-\lambda_1^2)\\&=\lambda_1\nabla\triangle N_1(\lambda_3^2-\lambda_2^2)+\lambda_2\nabla\triangle N_2(\lambda_1^2-\lambda_3^2)+\lambda_3\nabla\triangle N_3(\lambda_2^2-\lambda_1^2).\end{aligned} \tag{10}$$

This constraint aims to minimize the multipath error, given by the difference between the right and left sides of (10). More compactly, we can write (10) as,

$$\mathbf{N}^T\mathbf{h}=m; \tag{11}$$

$$\mathbf{N}\overset{\text{def}}{=}(\nabla\triangle N_1\quad\nabla\triangle N_2\quad\nabla\triangle N_3)^T,$$

$$\mathbf{h}=(\lambda_1(\lambda_3^2-\lambda_2^2)\quad\lambda_2(\lambda_1^2-\lambda_3^2)\quad\lambda_3(\lambda_2^2-\lambda_1^2))^T,$$

$$m=\nabla\triangle\phi_1(\lambda_3^2-\lambda_2^2)+\nabla\triangle\phi_2(\lambda_1^2-\lambda_3^2)+\nabla\triangle\phi_3(\lambda_2^2-\lambda_1^2).$$

Using this constraint is two-fold ; i) utilize (11) as an additional constraint on carriers and ambiguities to mitigate the impact of multipath on the carrier phase, which improves the performance of the ambiguity resolution scheme ; and ii) exploit it as relationship between ambiguities which lead to simplification since we will need to resolve only two ambiguities and deduce the third one from (11) using $\lambda_3\nabla\triangle N_3(\lambda_2^2-\lambda_1^2)=m-\lambda_1\nabla\triangle N_1(\lambda_3^2-\lambda_2^2)+\lambda_2\nabla\triangle N_2(\lambda_1^2-\lambda_3^2)$. To improve the float solution, we include the multipath constraint (11) in the optimization problem of ambiguities estimation and derive a multipath-constrained LAMBDA method. Similarly to LAMBDA method, we use an orthogonal decomposition of the least-square cost function to separate the optimization problem of ambiguities estimation from the other parameters (baseline and ionospheric errors in our model). Then, the fixed ambiguity solution becomes equivalent to the following constrained least-square optimization solution,

$$\hat{\mathbf{N}}=\arg\min_{\mathbf{N}\in\mathbb{Z}^{3(K-1)}}(\mathbf{N}-\check{\mathbf{N}})^T\Sigma_N(\mathbf{N}-\check{\mathbf{N}})\quad s.t.\quad\mathbf{N}^T\mathbf{h}=m, \tag{12}$$

where K is the number of available satellites, $\check{\mathbf{N}}$ is the float solution obtained from the previous step of particle filtering and Σ_N is the weighting covariance matrix corresponding to the ambiguities. Thus, the multipath constrained ambiguity resolution requires the solution of a linearly constrained least square optimization problem given by (12). By neglecting the integer nature of ambiguities, this final minimization can be solved using the Lagrange multiplier, finding $\min_{\mathbf{N}}\mathcal{L}(\mathbf{N},\mu)$,

$$\mathcal{L}(\mathbf{N},\mu)=(\mathbf{N}-\check{\mathbf{N}})^T\Sigma_N(\mathbf{N}-\check{\mathbf{N}})+\mu(\mathbf{N}^T\mathbf{h}-m) \tag{13}$$

After differentiating with respect to $\mathbf{N}$ and μ, and setting the derivatives equal to zero we obtain the *improved float* ambiguity solution,

$$\hat{\mathbf{N}}=-\mu\Sigma_N^{-1}\mathbf{h}-2\check{\mathbf{N}}\quad\text{where}\quad\mu=-\frac{2\mathbf{h}^T\check{\mathbf{N}}+m}{\mathbf{h}^T\Sigma_N^{-1}\mathbf{h}}. \tag{14}$$

The resulting multipath-free float ambiguities solution $\hat{\mathbf{N}}$ is called the *improved float solution* and is then passed to the *integer ambiguity search* step using LAMBDA method. The integer results are validated then using a *ratio test* . In (12), $\mathbf{N}$ may be defined to contain only two carrier ambiguities and deduce the ambiguities on any third frequency through the linear relationship (10) once the ambiguities on the two frequencies are computed. Regarding the multipath mitigation, we need three frequencies to formulate the proposed constraint. In ionosphere-free GNSS, the geometry- free combination would be constant and the relationship between ambiguities on the two frequencies becomes,

$$\nabla\triangle\phi_1-\nabla\triangle\phi_2=(\lambda_1\nabla\triangle N_1-\lambda_2\nabla\triangle N_2). \tag{15}$$

As we estimate the ionospheric error in the previous step of nonlinear filtering, the software is managed to use the multipath constraint in the above form (15). The benefit from the third frequency is that we do not need to ignore or estimate the ionospheric delay in order to apply the multipath constraint, because it does not depend on the ionospheric term. In other words, the introduced constraint is geometric-free.

4. SIMULATIONS AND PERFORMANCE RESULTS

We generate three carrier phase measurements, L1, L2 (GPS signals) and E1 (Galileo signal), using the multi-GNSS software simulator developed in the HRnav project by the navigation Group at ETS University. For the GNSS constellation, we use the Matlab Navigation Toolbox commercialized by GPSoft Corp. We added a multipath component to each signal using the same static scenario with random phase and direct signal to multipath ratio (SMR) of 6 dB.

• Ambiguity resolution : comparison of float -based solution with the improved float -based solution. We consider the ambiguity resolution success rate defined as the sum of all ambiguities that were correctly resolved divided by the total number of ambiguities. We consider the above multipath scenario with variable baseline length and normal noise levels : here we use some typical values such as carrier phase noise of 4 mm and code noise of 50 cm. Three strategies of float ambiguity resolution are combined with the LAMBDA method for the integer fixed solution computation, then the overall ambiguity solutions are compared : a Kalman filter with widelane linear combination of L1 and L2, while in the second and third methods we use (respectively), the RobPKF float solution and the RobPKF combined with the multipath constrained least-square (CLS) technique, referred as RobKPF-CLS. According to Figure 1, we can see clearly the improvement of the RobPKF-CLS scheme with respect to the RobPKF, emphasizing the advantage of the third carrier phase observations and the benefit of the new multipath mitigation step.

• Performance of ambiguity resolution. Three baseline locations were simulated with length of 20, 50 and 100 Km. We evaluate the average of number of epochs required to resolve all the ambiguities for all the repeated trials, called the mean time to fix (MTTF). As expected Figure 2 shows that the Kalman filter float ambiguity solution makes the final solution about 40% faster than the particle filter approach for short and medium baselines. However, for long baseline the

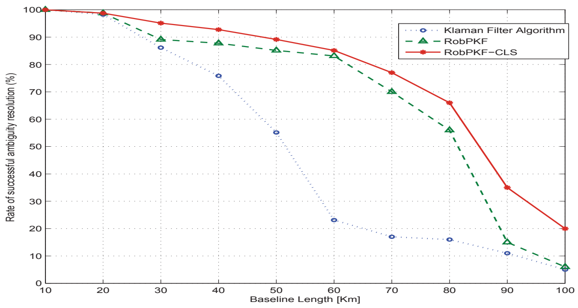

Fig. 1. Ambiguity resolution success rate versus the baseline length. SNR = -20 dB and SMR = 6dB.

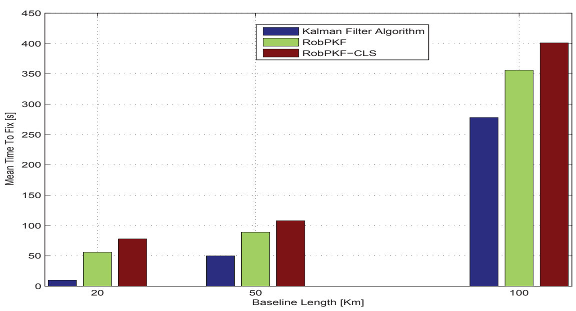

Fig. 2. Mean time to fix ambiguities for short (20 Km), medium (50 Km) and long baseline (100 Km).

difference is only about 20%. This is not a surprising drawback since particle filtering (PF) requires more computations in comparison to the Kalman filter. We remark that one has to wait more 10% of time to obtain a solution free from multipath errors, which is a reasonable cost of computation.

• Performance of the multi-GNSS RTK using real data in a dynamic and long baseline scenario. We present here a high dynamic test made with our industrial partner GEDEX Corp. in October 2004 in the region of Toronto, Canada. The data are coming from two commercial Novatel DL4-plus receivers, one located in an airplane, flying at high dynamic and one base located at the airport. The data were recorded at 20 Hz. The trajectory time length was more than 2 hours (i.e. 15000 epochs). The test is considered as a long baseline trajectory since the airplane goes as far as 100 km away from the base station. In this experiment, we added artificially multipath errors to the code measurements, with the same context as experiment 1. As the new GNSS civil signals (L5, L2C and Galileo) are in the preliminary broadcast periods, it is impossible for us to test the multi-GNSS in real-time with three carrier-phase measurements. Therefore, we consider a dual-frequency L1/L2 RTK configuration of the RobPKF-CLS scheme. The positioning performance are plotted in Figure 3, so we can see the good results due to multipath mitigation, ionospheric corrections and highly precise

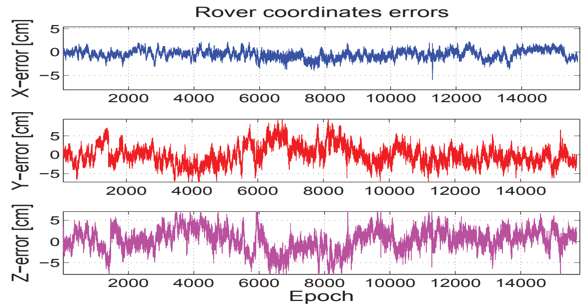

Fig. 3. Performance of the proposed multi-GNSS RobPKF-CLS RTK using dual-frequency L1/L2 measurements with multipath mitigation and ionospheric errors estimation.

tracking PF algorithm, all integrated in the developed advanced RTK system.

5. CONCLUSION

In the proposed multi-GNSS RTK system, float ambiguity estimation is improved by the introduced multipath constraint to mitigate the effect of the carrier multipath errors. The multipath-free float ambiguities are then fed to the integer ambiguity search step using LAMBDA method. We show that the efficient integration of multi-carriers provides more redundancy in the measurements and better observability for multipath and ionospheric errors estimation. Simulations and real-time experiments proved the overall superiority of the developed RTK software with respect to existing techniques.

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