Analysis of Three Ambiguity Resolution Methods for Real Time Static and Kinematic Positioning of a GPS Receiver

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BIOGRAPHIES

Leandro Baroni obtained his Ph.D. from the National Institute for Space Research (São José dos Campos, Brazil) in Space Engineering and Technology. His research focuses on integer ambiguity resolution and its application to aerospace systems.

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ABSTRACT

The objective of this work is to compare the performance of three methods of ambiguity resolution: LSAST, LAMBDA, and FASF. To do this evaluation, the methods were implemented in software and data were collected using two dual frequency geodetic quality Trimble R8 GPS receivers in static situation and two Ashtech Z12 GPS receivers in kinematic situation. The data were processed using LSAST, LAMBDA, and FASF methods for ambiguity resolution. During the processing, the float solution and ambiguity resolution process was reset once every 5 minutes. The ability of the methods to obtain a fixed solution was then analyzed in terms of time to fix and percentage of correct ambiguity fixes, where truth ambiguities were obtained by processing the entire data set using LAMBDA without any filter resets. As these methods use distinct search space reduction processes, differences in ambiguity resolution time and correct fix percentage were observed.

INTRODUCTION

The Global Positioning System (GPS) is a satellite-based navigation system which allows the user to determine position and time with high precision. The GPS signal is subject to several error sources in the measurements. The combined effects of these errors in the propagation signal cause a degradation in precision of positioning. However, using phase measurements, it is possible to reduce positioning error up to 100 times, if compared with positioning using code measurements (Misra and Enge, 2001). However, this type of measurement contains an inherent difficulty that is the determination of the ambiguity in the number of wavelengths of the corresponding signal. At the beginning of the positioning procedure, this ambiguity must be resolved (determined) in order to obtain an unambiguous phase pseudorange and then determine a position with the highest precision.

Positioning by means of phase measurement is attained in three steps: float solution, ambiguity resolution and fixed solution. The float solution consists of estimating baseline values between the receivers and ambiguities as real values. The ambiguity resolution step consists of an integer estimate of the ambiguities, that is, to determine the value as an integer number. These integer values are used to correct the baseline value and provide the fixed solution. Three ambiguity resolution methods are tested: LAMBDA, FASF and LSAST.

LAMBDA method (Least-squares AMBiguity Decorrelation Adjustment) is a procedure for integer ambiguity estimation in carrier phase measurements. This method executes the integer ambiguity estimation through a *Z*-transform, in which ambiguities are decorrelated before the integer values search process. Then, minimization problem is approached as a discrete search inside an ellipsoidal region defined by decorrelated float ambiguities, which is smaller than original ones. As a result, integer least-squares estimates for the ambiguities are obtained. This method was introduced in Teunissen (1993; 1994). De Jonge and Tiberius (1996) and de Jonge *et al.* (1996) show computational implementation aspects and ambiguity search space reducing.

The FASF method (Fast Ambiguity Search Filter) has reduced both computational effort and required number of observations to resolve the ambiguities. This enables this method to be tested in situations in which ambiguities should be resolved in real time (Chen, 1993; 1994). The search space of each ambiguity is determined recursively and sequentially updating the restrictions. To calculate the search space for an ambiguity, all previous ambiguities are assumed known. The number of potential solutions is used as an index to exit the ambiguity search. An attempt is made to fix the ambiguities if the total number of potential ambiguity sets from the search is less than a certain threshold, 20 candidates is used here. If the number is one, the ambiguity set is regarded as the correct one. Otherwise, the validation *W*-test is carried out on candidates. However, if the *W*-test fails, the ambiguities are estimated as float values. Since the full search of potential ambiguities is avoided with this method, only a relatively small amount of computation time is needed for ambiguity searching.

LSAST method (Least-Squares Ambiguity Solution Technique) was proposed in Hatch (1990). This method involves a modified sequential least-squares technique, in which ambiguity parameters are divided into two groups: primary ambiguities (typically three double difference ambiguities), and the secondary ambiguities. Only the primary ambiguities are fully searched, in ±5 cycles around the corresponding float ambiguity, after rounded to the nearest integer. For each set of the primary ambiguities, there is a unique set of secondary ambiguities. Therefore, the search dimension is smaller and the computation time is significantly shorter than the full search approach. The choice of primary group measurements is based on GDOP value. Satellites with low GDOP will lead to a search with less potential solutions. However, GDOP cannot be very low, in order to avoid the position uncertainty including more than one solution for secondary group measurements. The procedure is to choose primary group of satellites which have a reasonable GDOP.

The *W*-test, described in Wang *et al.* (1998), was used as a criterion for ambiguities to be considered resolved. If the value of *W*-test is greater than a certain threshold, ambiguities are considered resolved. If this threshold is not reached, the real valued ambiguities given by the Kalman filter are used.

Algorithms were implemented for static positioning, in which both receivers (base and user) are kept fixed during the whole test, and kinematic, in which user receiver is moving. Results for the ambiguity resolution presented in both cases (static and kinematic) were obtained from the same estimation process using a Kalman filter, processing code and carrier phase measurements. Ambiguity resolution is achieved epoch by epoch, applying LAMBDA, FASF and LSAST methodologies over real valued estimated ambiguities obtained from the Kalman filter (float solution) to evaluate the ambiguity values and *W*-test behaviors, as data accumulates over time, processed by the filter. The position solution was obtained using an iterated least-squares method, processing carrier phase with ambiguities resolved measurements. This procedure was implemented for real time ambiguity resolution and positioning. However, in a practical situation, once ambiguities are validated and accepted, they are kept constant and the process of resolving ambiguity is not carried out until a signal interruption is found. This is a common procedure in carrier phase positioning.

Test results were obtained using real dual frequency data, and were analyzed in terms of the percentage of resolved ambiguities (PR) and correctly resolved (PRC) and, if static, the error of position of user receiver with respect to the position of the landmark in which this receiver was located. Kinematic positioning algorithms were applied in a data set from an aircraft on a flight test. Results can be compared to a post-processed reference trajectory. The parameters used in result analysis are defined as:

- *Percentage of correctly resolved ambiguities* (PRC): PRC is the percentage of ambiguities which are estimated to the correct integer value. PRC is calculated as the total number of ambiguities that are resolved to correct integer values divided by total number of ambiguities resolved to an integer value.
- *Percentage of resolved ambiguities* (PR): PR is the total number of ambiguities resolved divided by the total number of ambiguities in the whole period.
- *Time to resolve ambiguity* (TR): TR is the time required for the first ambiguity set validated as a solution.

METHODOLOGY

Ambiguity resolution is carried out using double differenced L1 and L2 carrier phase observables, φ_1 and φ_2 (in cycle units). These measurements are re-parametrized in a linear carrier phase widelane combination, given by:

$$\varphi_{wl} = \varphi_1 - \varphi_2 \tag{1}$$

This combination has ambiguity:

$$N_{wl} = N_1 - N_2 \tag{2}$$

and wavelength given by:

$$\lambda_{wl} = \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)^{-1} \tag{3}$$

The wavelength of the widelane phase observable is 86cm. The widelane combination is more resistant to ionospheric effects in cycles than L1 and L2 measurements and is more reliable to resolve ambiguity under adverse ionospheric conditions, due to reduction of ionospheric effects. Another advantage is its decorrelation property (Teunissen, 1997). Because of its large wavelength, widelane combination is more resistant to position errors. Although the combination widelane reduces the impact of the ionospheric error in cycles, it amplifies its effect in meters, for the estimation of the position. The noise is also amplified in the widelane observable compared to the L1 and L2 raw measurements (Liu *et al.*, 2003). Widelane ambiguities converge faster and they can be resolved to integers easily, while more data is needed to resolve the L1 ambiguities.

The observation equation corresponding to one double differenced measurement is:

$$\begin{bmatrix} \rho \\ \Phi_1 \\ \Phi_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & \lambda_1 & 0 \\ 1 & \lambda_2 & -\lambda_2 \end{bmatrix} \begin{bmatrix} D \\ N_1 \\ N_{wl} \end{bmatrix} + \varepsilon \tag{4}$$

where ρ is double differenced code pseudorange, $\Phi_1 = \lambda_1\varphi_1$ and $\Phi_2 = \lambda_2\varphi_2$ are double differenced carrier phase measurements from L1 and L2 frequencies (wavelengths λ_1 and λ_2) in distance units respectively, D is the geometric distance in double difference form, and ε represent unmodeled observation errors. This measurements model is used in a Kalman filter to estimate the float solution for N_1 and N_{wl} ambiguities, and its covariance matrix.

The float solution is used to construct a search window, which is assumed to contain the correct integer ambiguities. For all integer ambiguity resolution method tested, the process of searching all possible integer ambiguity is then performed using a search criterion based on the minimization of the quadratic form of the residuals. Normally, the first two best ambiguity combinations are identified for validation purposes. The validation procedure is based on the ratio of the difference between the minimum and second minimum quadratic forms of the least-squares residuals and its standard deviation (Wang *et al.*, 2000). The W-test is defined as:

$$W = \frac{d}{\sqrt{\mathrm{Var}(d)}} \tag{5}$$

with

$$\begin{aligned} d &= \Omega_s - \Omega_m \\ \mathrm{Var}(d) &= 4\sigma^2 (\breve{a}_s - \breve{a}_m)^T P_a^{-1} (\breve{a}_s - \breve{a}_m) \end{aligned} \tag{6}$$

where Ω_s and Ω_m are the quadratic form of the residuals of second best and best solutions candidates respectively, $\breve{a}_s$ and $\breve{a}_m$ are the second best and best ambiguity candidates, σ^2 is the variance factor, and P_a is covariance matrix of float solution ambiguities. If W-test is larger than a certain critical value, the likelihood of the integer ambiguity combination $\breve{a}_m$ is statistically larger than that of the second-best one, $\breve{a}_s$, and the ambiguity is considered resolved for $\breve{a}_m$. Otherwise, the ambiguities are not considered resolved.

As W-test has a Student's t distribution, the critical value for ambiguities acceptation C_W can be calculated, for a level of significance α (or confidence level 1 - α), by (Wang *et al.*, 1998):

$$\int_{-\infty}^{C_W} t_f(y)\mathrm{d}y = 1 - \alpha \tag{7}$$

where $t_f(y)$ is probability density function of Student's t distribution with f degrees of freedom.

RESULTS

Ambiguity resolution methods use Kalman filter as float solution estimator. The search for ambiguity integer values is based on float ones, which define a search space. Once ambiguities are resolved, one can obtain phase pseudoranges, which are used to calculate the position solution.

Static Test

The first data set was collected by static receivers, which remain stationary at precisely known positions, to verify the quality of the proposed algorithm. The data were collected by two Trimble R8 receivers, and 1Hz of sampling rate. Base receiver was placed on a reference landmark with coordinates N 51° 04' 45.94126'', W 114° 07' 58.29947'' and 1116.617m, in ECEF coordinates of WGS-84 system, and user receiver was placed in another landmark, 2.944m from base. The solution was calculated through a Kalman filter, processing code and carrier phase measurements in L1 and L2 frequencies.

Measurement model used in static test is described in Eq. (4). The standard deviation for code measurement was set to 1.0m, and phase, in both frequencies, 5mm. Initial values of D, N_1 and N_{wl} standard deviations used to initialize the state covariance matrix were 100m, 20 cycles, and 20 cycles respectively in all methods. Process noise covariance corresponding to geometric distance D in the Kalman filter was set to $(10\text{m/s})^2$, and to ambiguities, $(0.001\text{cycles/s})^2$ for LAMBDA and LSAST, and $(0.1\text{cycles/s})^2$ for FASF.

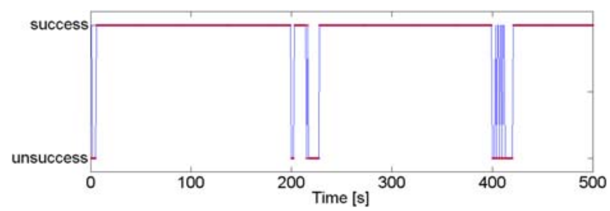
Static test was performed in a data set with 500 epochs, with same 8 visible satellites all the time, leading to 14 ambiguities to resolve (7 in L1 frequency and 7 in widelane combination). Ambiguity parameters and their covariance were reset to initial values each 200 epochs, to evaluate the recovery in ambiguity resolution. This results in three periods in test data, with 200, 200, and 100 epochs respectively. Ambiguity resolution is carried out epoch by epoch, applying LAMBDA, FASF, and LSAST methodologies on float ambiguity values from a Kalman filter, in order to evaluate ambiguities and W-test values behavior as data accumulates in time. However, in a practical situation, once using ambiguities are selected by means of *W*-test value, they remain constant and no further ambiguity resolution is carried out, until a signal interruption is found. This is a common procedure in carrier phase positioning.

W-test mentioned in previous section was used as criterion to consider ambiguities resolved. If *W*-test value is larger than a critical threshold, ambiguities are considered fixed. If this value is not reached, float ambiguities from Kalman filter are used instead. For 90% probability of correct fix and ambiguities from 7 double differences, *W*-test value must be larger than 1.41. Truth ambiguities were obtained by processing the entire data set using LAMBDA method without any filter resets.

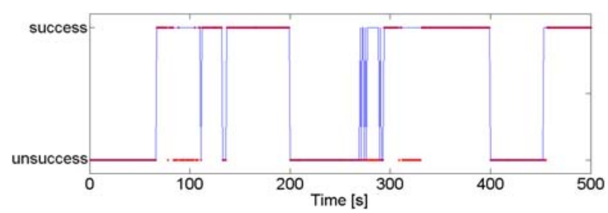
After each reset, the filter needs some time to converge again. With LAMBDA method, although ambiguities are resolved to correct values within a few epochs after each reset, validation test takes 4s, on average, to accept ambiguities as correct. PR values were 98%, 93% and 87% in each period between resets. Using FASF method, it takes 63s, on average, to ambiguities be considered resolved, because either filter convergence or the number of solutions is larger than threshold of 20 candidates. This method had PR values of 64.3%, 61.8%, and 48.0% in each period. LSAST method was able to resolve widelane ambiguities in second and third data periods to the true values, but L1 ones had only a few successful epochs at the end of third period, although L1 ambiguities have passed in validation test most of time, So, PRC is zero in the firsts two periods, and 19.1% in the third one. However, PR values were 73.3%, 84.9% and 89.0% respectively. Analyzing LSAST widelane ambiguity resolution only, the PR values were 75.9%, 92.4%, and 99.0%, and PRC were 29.1%, 100%, and 100%. In first period, ambiguities have passed in validation test, but they were resolved to values within ±1 cycle from correct ones. This gives a position error for LSAST method slightly larger than other methods at the end of first period, and at second and third ones. These results are shown in Table 1. Graphics in Fig. 1 show the epochs when ambiguities are considered resolved by *W*-test, and if they are resolved to the true values during the test.

Position errors, given by calculated user position minus known user landmark position, are shown in graphics of Figs. 2, 3, and 4, for each ambiguity resolution method. While ambiguities were not validated, float values were used, causing the large position errors after the resets. Table 2 shows the position error statistics for each method, considering whole data set.

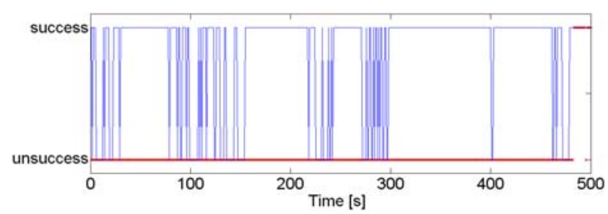
These three methods build search space in different manner. LSAST processing time is considerably longer than other ones. For LSAST method, processing time in each epoch was 516±31ms, whereas LAMBDA method was 14±7ms, and FASF was 2±4ms for resolving 7 L1 and 7 widelane ambiguities. Most of time in this test, FASF reaches the deepest loop just once.



(a) LAMBDA



(b) FASF



(c) LSAST

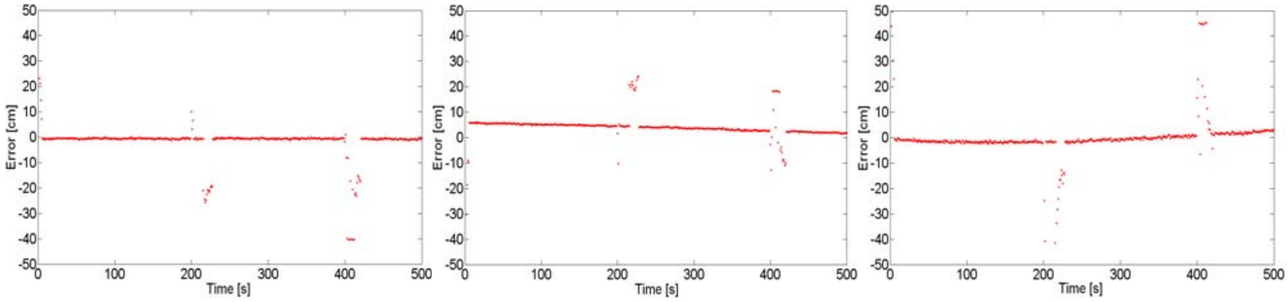
Figure 1: Successful epochs of the ambiguity resolution in static test given by *W*-test (blue line), and epochs in which ambiguities match correct values (red line).

Table 1 – PR, PRC and TR (in seconds) values for each method.

Time	0			200			400		
	PR	PRC	TR	PR	PRC	TR	PR	PRC	TR
LAMBDA	98.0	99.5	6	93.0	100	3	87.0	92.0	3
FASF	64.3	81.2	67	61.8	70.0	70	48.0	93.7	53
LSAST	73.3	0.0	3	84.9	0.0	1	89.0	19.1	3

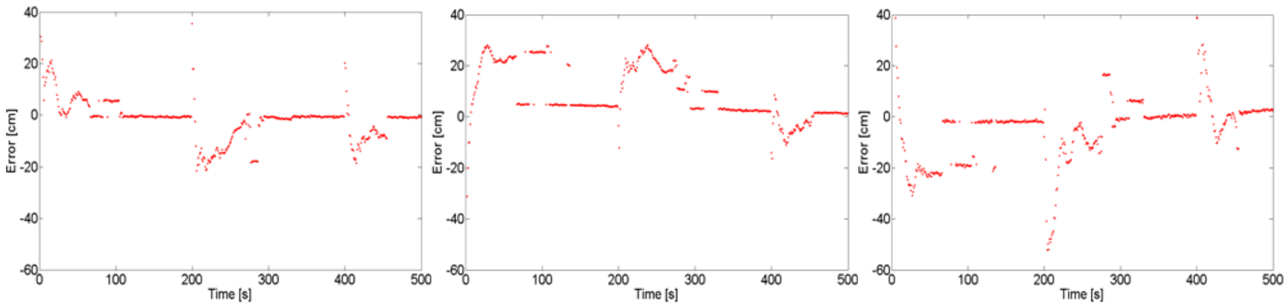
Table 2 – User position error statistics [m].

	Sul	Leste	Vertical
LAMBDA	-0.018±0.070	-0.018±0.080	0.101±0.157
FASF	-0.017±0.082	0.086±0.107	-0.043±0.146
LSAST	0.000±0.101	-0.079±0.162	-0.055±0.147



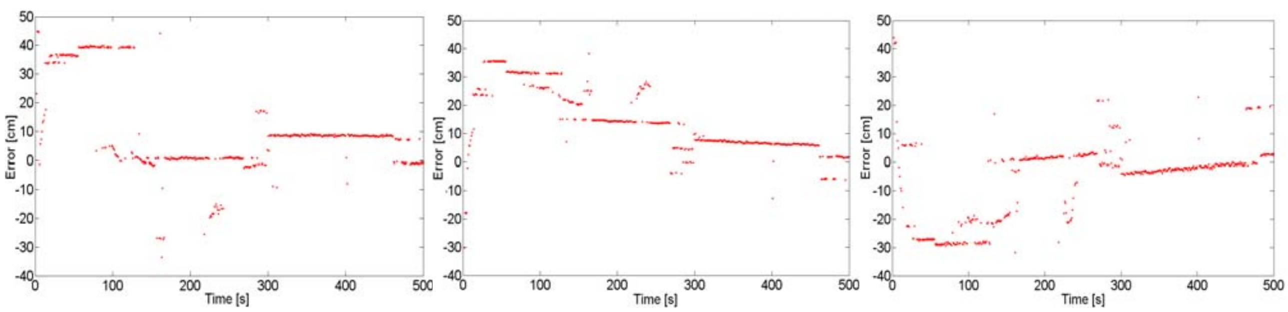
(a) (b) (c)

Figure 2: Position error using LAMBDA method: (a) south; (b) east; (c) vertical.



(a) (b) (c)

Figure 3: Position error using FASF method: (a) south; (b) east; (c) vertical.



(a) (b) (c)

Figure 4: Position error using LSAST method: (a) south; (b) east; (c) vertical.

Kinematic Test

The second data set was collected by an aircraft during a flight test. These data were collected by a receiver installed on an aircraft and a fixed receiver as base. The base position coordinate are given by S 23° 13' 42.9859'', W 45° 51' 23.4615'' and 686.227m, in ECEF coordinates of WGS-84 system, and sample rate was 2Hz. Graphics in Fig. 5 show the aircraft horizontal and vertical trajectories during the test. The results were compared to a trajectory obtained post processing the data with proprietary PNAV software from Ashtech, whose accuracy is in the same level as commercial softwares.

The measurement model for this test is given in Eq. (4), but with two more states added: geometric distance variation $\dot{D}$ (m/s), and ionospheric refraction on L1 frequency I_1 (m). As baseline reaches up to 25km, it is introduced a pseudo-observation of ionospheric error I_0, whose value is zero and variance $(0.2\text{m})^2$ in each epoch. (Liu *et al.*, 2003). Thus, the model becomes:

$$\begin{bmatrix} \rho \\ \Phi_1 \\ \Phi_2 \\ I_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & -1 & \lambda_1 & 0 \\ 1 & 0 & -\beta & \lambda_2 & -\lambda_2 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} D \\ \dot{D} \\ I_1 \\ N_1 \\ N_{wl} \end{bmatrix} + \varepsilon \qquad (8)$$

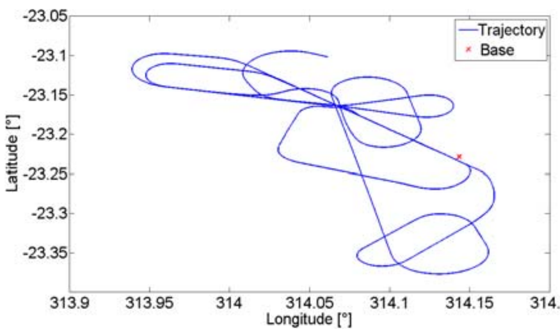
where $\beta = (\lambda_2 / \lambda_1)^2 = (77 / 60)^2$. The state transition matrix is given by:

$$\mathbf{T} = \begin{bmatrix} 1 & dt & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (9)$$

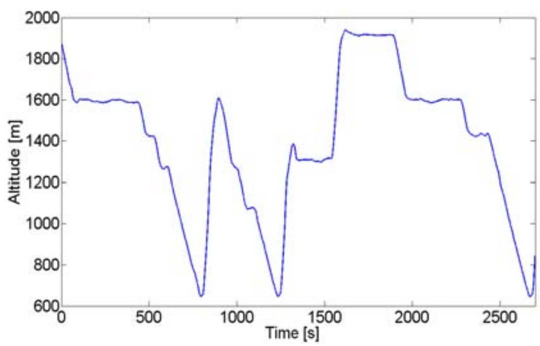
where dt = 0.5s. In this test, the standard deviation for code measurement was set to 1.0m, and phase, in both frequencies, 3mm. Using LAMBDA method, process noise covariance was set to a matrix whose diagonal is given by:

$$Q = \mathrm{diag}\begin{bmatrix}0 & 10^2 & 0.005^2 & 0.001^2 & 0.001^2\end{bmatrix} \qquad (10)$$

For FASF, the values corresponding to ambiguities was set to $(0.1\text{cycle/s})^2$, and for LSAST, $(0.01\text{cycle/s})^2$.



(a) horizontal



(b) vertical

Figure 5: Aircraft trajectory during the flight.

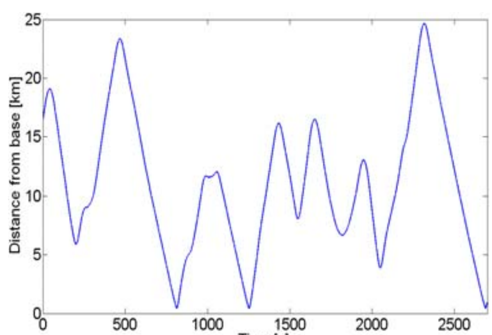
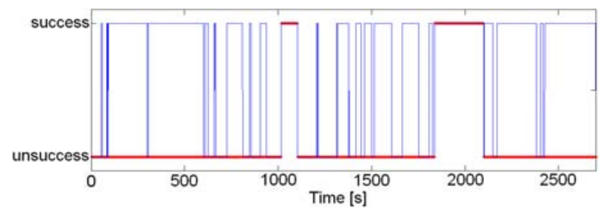


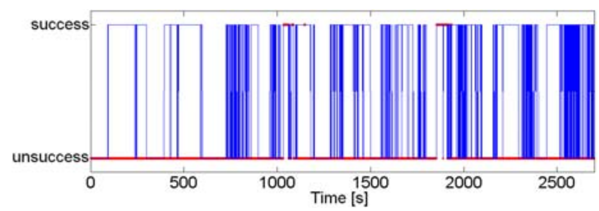
Figure 6: Aircraft distance from base.

This test had duration of 5400 epochs, or 2700s because 2Hz sample rate. The same 7 satellites were kept in view, and free from cycle slips. Ambiguities were reset every 5 minutes, i.e., every 600 epochs. In this kinematic test, *W*-test value was chosen to be larger than 1.15, for 90% probability of correct fix.

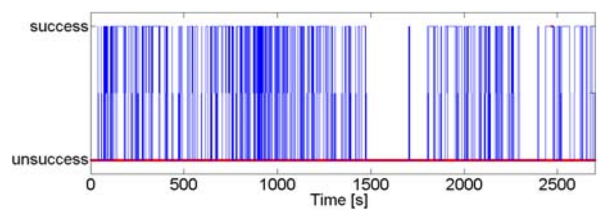
Baseline length reaches up to 25km (Fig. 6), and these resets occur at different distances, so they can show the behavior of ambiguity recovery in different baseline distances. Table 3 shows the distance from base (in km), PR, PRC, and time needed to resolve the ambiguities (TR, in seconds) after each filter reset. Graphics in Fig. 7 show the epochs in which ambiguity resolution was successful. LAMBDA method showed higher PR in most data periods, and the behavior was more stable among tested methods. FASF method needed more time to resolve the ambiguities. In this test, it took 75s on average to deliver the first solution. After obtaining a solution, FASF method also is more unstable due to the difficulty of validating L1 ambiguities. PR of FASF method is generally lower than LAMBDA due to TR is longer and more unstable in the validation of the L1 ambiguities.



(a) LAMBDA



(b) FASF



(c) LSAST

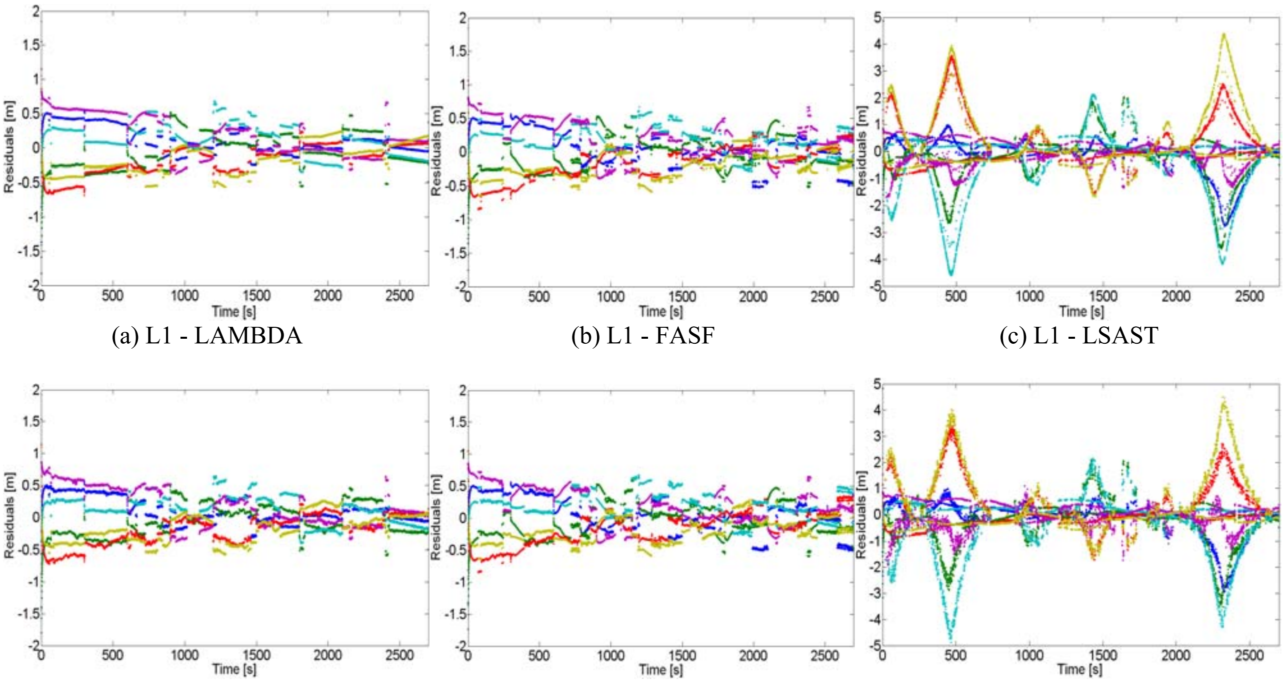
Figure 7: Successful epochs of the ambiguity resolution in static test given by *W*-test (blue line), and epochs in which ambiguities match correct values (red line).

Graphics in Fig. 8 show the behavior of the double differenced phase residuals in L1 frequency and widelane combination. For methods and LAMBDA FASF, residuals have standard deviations smaller than 30cm. This value shows the accuracy of position solution which can be obtained using these methods.

Table 3: Distance from base (in km), PR, PRC and TR (in seconds) for each method.

Time	0			300			600			900			1200		
Distance	16.4			9.8			14.2			5.3			3.4		
	PR	PRC	TR	PR	PRC	TR	PR	PRC	TR	PR	PRC	TR	PR	PRC	TR
LAMBDA	72.4	0	54	98.7	0	4.5	37.9	0	10	40.4	72.3	4	44.5	0	5.5
FASF	67.1	0	95.5	66.6	0	94.5	34.4	0	127.5	52.4	28.3	61	65.8	0	84
LSAST	46.4	0	20.5	59.4	0	8	19.8	0	4.5	42.7	0	2.5	58.4	0.5	18

Time	1500			1800			2100			2400		
Distance	11.7			6.9			7.5			19.0		
	PR	PRC	TR	PR	PRC	TR	PR	PRC	TR	PR	PRC	TR
LAMBDA	61.2	0	13.5	94.4	92.9	6.5	86.0	0	2.5	96.0	0	3.5
FASF	45.4	0	55	60.9	36.4	53	59.2	0	58.5	65.9	0	45.5
LSAST	24.5	0	4	41.9	0	4	54.2	0	1.5	46.5	0	2.5



(a) L1 - LAMBDA (b) L1 - FASF (c) L1 - LSAST

(d) widelane - LAMBDA (e) widelane - FASF (f) widelane - LSAST

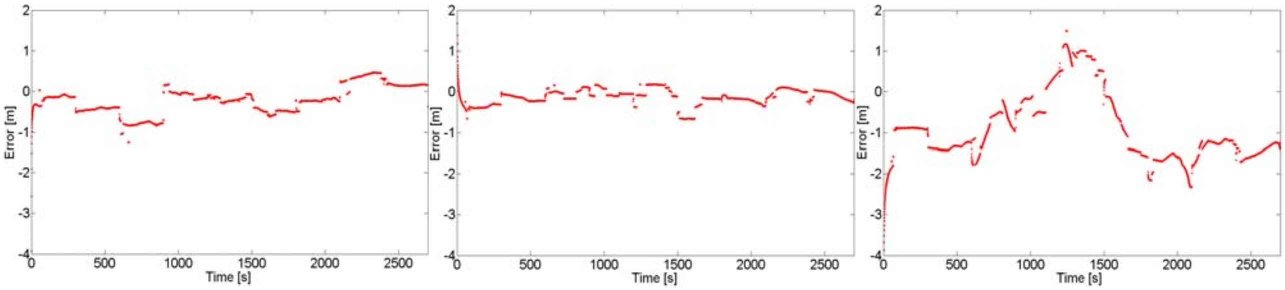
Figure 8: Phase double difference residuals in L1 and widelane for each method.

Graphics of residuals for LSAST method (Figs. 8c and 8f) show significant deviations when the aircraft is found at distances greater than 10km from base. These deviations have 4m in magnitude for a 25km distance. However, the best solution values are validated when compared with second best solution and it has a high level of significance, i.e., the solutions are statistically different between themselves. As LSAST method presents results affected by the aircraft distance from base, position solution has worse quality, with standard deviation of about 1m. Aircraft position error with related to reference trajectory components in south, east and vertical directions are shown in the graphics of Figs. 9, 10, and 11 for each method. The position error statistics are shown in Table 4. From 1837 to 2100s, ambiguities are resolved by LAMBDA method to the values considered correct. Between these epochs, measurements residuals standard deviations are about 2cm in L1 and 3cm in widelane combination.

Table 4 – Aircraft position error statistics [m].

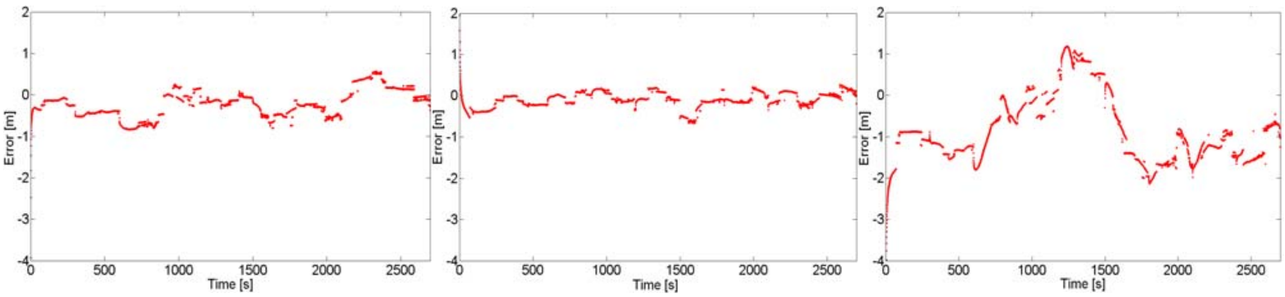
	LAMBDA	FASF	LSAST
South	-0.213±0.344	-0.226±0.327	-0.262±0.463
East	-0.129±0.247	-0.099±0.240	0.038±0.436
Vertical	-0.935±0.857	-0.874±0.843	-0.958±1.156

The processing time of ambiguity resolution step using LAMBDA method, when successful resolution was 6±6ms, by FASF method was 2±1ms, and LSAST method was 310±200ms to resolve 6 ambiguities in frequency L1 and 6 in widelane combination.



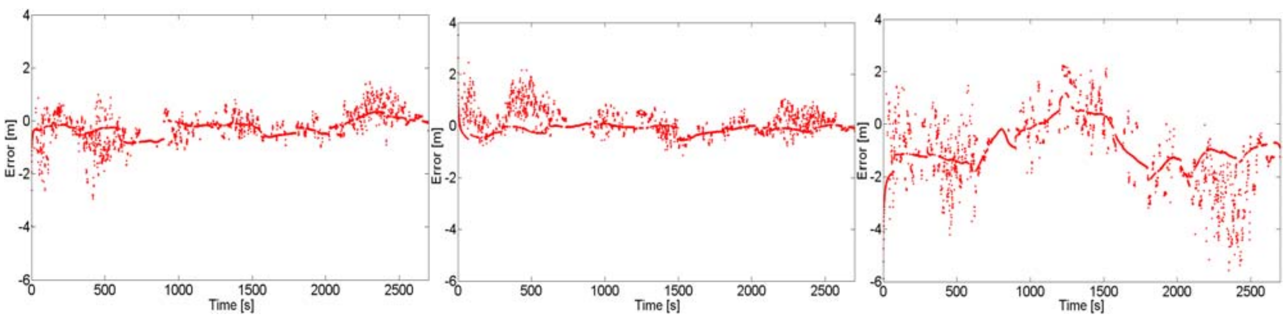
(a) (b) (c)

Figure 9: Position error using LAMBDA method: (a) south; (b) east; (c) vertical.



(a) (b) (c)

Figure 10: Position error using FASF method: (a) south; (b) east; (c) vertical.



(a) (b) (c)

Figure 11: Position error using LSAST method: (a) south; (b) east; (c) vertical.

CONCLUSIONS

Carrier phase measurements can only be obtained after acquiring the signal, the initial integer number of cycles between the satellite and receiver remains unknown. This ambiguity must be determined before using phase measurements in positioning. Thus, ambiguity determination is a fundamental issue in carrier phase positioning. Therefore, three methods for ambiguity resolution were examined: LAMBDA, FASF and LSAST.

The first case to test the algorithms LAMBDA, FASF and LSAST for ambiguity resolution was a static test, in which both receivers were placed in landmarks with known positions. The Kalman filter was reset each 200s. Using measurements in two frequencies to resolve L1 and widelane ambiguities, any residual ionospheric effect could be eliminated and the accuracy of results was less than 10cm with LAMBDA and FASF methods. The LSAST method was able to resolve widelane ambiguities to the correct values, but the L1 ambiguities were shifted ±1 cycle from correct values.

The kinematic test was carried out using a receiver mounted on an aircraft during a flight test. The tests were performed using two frequency measurements and Kalman filter, which estimates the real valued ambiguities, was reset each 5min. The ambiguities were resolved to values which generate residual standard deviations, and thus position ones, less than 30cm with LAMBDA and FASF methods taking into account whole test data. The reason to this value is ambiguities were resolved to values deviating from 1 to 3 cycles from ambiguities considered correct, usually from low elevation satellites. Once the ambiguities are not resolved, the float solution from the Kalman filter is used. This increases the value of standard deviation of position error. However, the analysis of a period when the ambiguities are resolved to correct values shows that the standard deviation of position error reaches about 10cm, when there is no influence of unresolved ambiguities. FASF method presented in general PR (Percent of ambiguities Determined) smaller than LAMBDA method because of the longer time required for FASF can validate the first solution. LSAST method had errors of about 5m, generated by ambiguities that shifted several cycles of values considered correct, when the user was at distances of over 10km of the base, as well the processing time was about 100 times larger than other methods.

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REFERENCES

Chen, D. *Fast Ambiguity Search Filter (FASF): A novel concept for GPS ambiguity resolution*. Proceedings of ION-GPS 1993, Salt Lake City, 1993. pp. 781-787.

Chen, D. *Development of a Fast Ambiguity Search Filtering (FASF) method for GPS carrier phase ambiguity resolution.* 127p. Ph.D. Thesis - University of Calgary, Canada, 1994.

Hatch, R. R. *Instantaneous ambiguity resolution*. Proceedings of KIS'90, Banff, Canada. Springer-Verlag, 1990. pp. 299-308.

de Jonge, P. J.; Tiberius, C. C. J. M. *The LAMBDA method for integer ambiguity estimation: implementation aspects*. Delft University of Technology, 1996. 59p. (LGR-Series, n. 12).

de Jonge, P. J.; Tiberius, C. C. J. M.; Teunissen, P. J. G. *Computational aspects of the LAMBDA method for GPS ambiguity resolution*. Proceedings of ION-GPS 1996, Kansas City, 1996. pp. 935-944.

Liu, J.; Cannon, M. E.; Alves, P.; Petovello, M. G.; Lachapelle, G.; MacGougan, G.; deGroot, L. A performance comparison of single and dual frequency GPS ambiguity resolution strategies. *GPS Solutions*, v. 7, n. 2, pp. 87-100, 2003.

Misra, P. and Enge, P. *Global positioning system: Signals, measurements and performance*, Lincoln MA: Ganga-Jamuna Press, 2001, 408p.

Teunissen, P. J. G. *Least-squares estimation of the integer GPS ambiguities*. Proceedings of IAG General Meeting, Beijing, China, 1993.

Teunissen, P. J. G. *A new method for fast carrier phase ambiguity estimation*. Proceedings of IEEE PLANS 1994, Las Vegas, 1994. pp. 562-573.

Teunissen, P. J. G. On the GPS widelane and its decorrelating property. *Journal of Geodesy*, v. 71, n. 9, pp. 577-587, 1997.

Wang, J.; Stewart, M. P.; Tsakiri, M. A discrimination test procedure for ambiguity resolution on-the-fly. *Journal of Geodesy*, v. 72, pp. 644-653, 1998.

Wang, J.; Stewart, M. P.; Tsakiri, M. A comparative study of the integer ambiguity validation procedures. *Earth Planets Space*, v. 52, pp. 813-817, 2000.