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BIOGRAPHY

Christophe Macabiau graduated in 1992 as an electronics engineer at the Ecole Nationale de l'Aviation Civile (ENAC) in Toulouse, France. He is specialized in signal processing and in radionavigation electronics. After working in 1993 for the MLS Project Office in Ottawa, Canada, he became a Ph.D. candidate at the Laboratoire de Traitement du Signal et des Télécommunications of the ENAC in 1994. He is working on the application of precise GPS positioning techniques to aeronautics.

Abdelahad Benhallam obtained his Ph.D. in communications from the Institut National Polytechnique of Toulouse in 1988. His areas of research include satellite communications, radionavigation and nonstationary signal processing. He is currently responsible of the Laboratoire de Traitement du Signal et des Télécommunications (LTST) activities, at the Ecole Nationale de l'Aviation Civile (ENAC).

ABSTRACT

GPS Ambiguity Resolution On-the-Fly (AROF) procedures process DGPS code and carrier phase measurements to deliver in real-time a position estimate with a centimeter accuracy in optimal conditions. They are very attractive to the civil aviation community, but questions still remain unanswered about their reliability. Following a series of papers concerning the principles of a new procedure called MAPAS, its comparison with the standard LSAST, its theoretical performances and its evaluation among three other procedures using simulated data, this paper reports a preliminary evaluation of MAPAS on real measurements. The aim of this article is to estimate the performances of MAPAS from real measurements, and to emphasize problems encountered when processing real measurements with AROF procedures. The major data pre-processing operations applied to the raw data, such as time-matching of reference samples with respect to user samples, atmospheric delays compensation and quality control of measurements, are reviewed. The main findings about MAPAS are recalled. Some results of the application of MAPAS to real measurements collected using a NORTEL GPS signal generator and from real life field measurements are presented. The influence of the data pre-processing methods is stressed. A preliminary evaluation of the integrity and of the availability of the precise position delivered by the procedure is presented.

I. INTRODUCTION

GPS carrier phase observations can be made with a *centimeter* resolution by a receiver, but they are biased by a constant number of phase cycles called the *ambiguity*. Resolution of the carrier phase measurements ambiguities was achieved since early GPS history in static applications, providing *centimeter* level positioning accuracy to users. In the end of the years 1980, several procedures were designed to raise the ambiguities in dynamic applications in real-time, and were called Ambiguity Resolution On-the-Fly (AROF) procedures. Application of these techniques in real-life situations brings centimeter level accuracy in optimal operating conditions, but some failures of the procedures to solve the correct ambiguities in due time are often reported.

The civil aviation community is very interested in the exploitation of carrier phase measurements to provide the required positioning accuracy to airplanes in precision landing phases. However, several questions still remain unanswered regarding the *reliability* of these techniques. In order to contribute to the evaluation of the capabilities of these techniques, the technical services branch of the french Civil Aviation Authority (the STNA) initiated a series of researches on these procedures, together with the LTST and SEXTANT AVIONIQUE, which are reported in (Macabiau, 1997).

The principle of AROF procedures was analyzed, and a new procedure was designed, called the Maximum A Posteriori Ambiguity Search (MAPAS) presented in (Macabiau, 1995). As shown in (Macabiau, 1996), the basic principle of this method is similar to the principle of the Least Squares Ambiguity Search Technique

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(LSAST) presented in (Hatch, 1989) and (Lachapelle et al., 1992). The theoretical performances of MAPAS were analyzed and bounds and asymptotic values of its error probability and time of convergence were reported in (Macabiau and Benhallam, 1996). Then, an analysis of the requirements of AROF procedures was conducted on the basis of the latest operational requirements for GNSS based CAT II/III landing systems issued by AWOP. This analysis enabled a first assessment of the capabilities of four AROF procedures, namely MAPAS, LSAST, DIAS and FASF, to provide CAT II/III guidance. This assessment was made using computer generated data simulating several landing configurations. This analysis was reported in (Macabiau et al., 1997).

The aim of the present paper is to give a first evaluation of the performances of MAPAS on real measurements, with the intention to analyze all the problems encountered when processing real data. The real measurements processed were made using NOVATEL GPSCard receivers in two distinct configurations. A first batch of measurements were made using a NORTEL GPS signal generator executing different scenarios designed to show the impact of the typical problems encountered when processing real data, such as atmospheric perturbations and multipath. Then, a second series of measurements was conducted in real situations on airport ground. All the analyses reported were done in the post-processing mode.

The paper starts with the description of the data pre-processing methods, then the main findings about MAPAS are recalled, the data sets collected are described, the results of the application of MAPAS on these data are presented, and a conclusion is drawn.

II. DATA PRE-PROCESSING METHODS

A first-order model of the carrier phase measurements made at epoch k by a GPS receiver on the signal transmitted by satellite i is as follows:

$$\varphi^i(k) = -\frac{\rho^i(k)}{\lambda} + f\left(\Delta t^i(k) - \Delta t_U(k)\right) + fI^i(k) \\ -f\tau^i(k) + SA^i(k) - N^i + \varepsilon^i_{mult}(k) + n^i(k) \quad (1)$$

where

- i is the number of the satellite.
- φ^i is the carrier phase measurement of satellite i, expressed in cycles.
- ρ^i is the true geometric distance between the user and the satellite i.
- f is the L1 frequency and λ is the corresponding wavelength.
- Δt^i and Δt_U are respectively the satellite and user clock offsets with respect to GPS time.
- I^i and τ^i are respectively the ionospheric and tropospheric propagation delays in seconds.
- SA^i is the measurement error due to Selective Availability (SA).
- N^i is the carrier phase measurement ambiguity.
- ε^i_{mult} is the measurement error induced by the multipath propagation of the signal.
- n^i is the carrier phase loop tracking error. In the following, we assume n^i is a zero-mean discrete white noise process with variance σ^2 .

To cancel most of the errors affecting the user measurements, like the satellite clock error, the SA, and the atmospheric propagation delays, the observations of a reference station with known position can be subtracted from these measurements. The obtained quantities are called the *single differenced* carrier phase measurements.

The cancellation of these errors can only be achieved if the user and the reference quantities are related to the same GPS time, and if these errors are highly correlated for both receivers. The first condition requires that a special re-synchronization procedure be operated between the user and the reference measurements, as measurements events are not identical for both receivers. The second condition is not verified in practice, as tropospheric and ionospheric propagation delays vary quickly with the electric path followed. Therefore, it is usually required to apply specific correction models that provide some estimates of the atmospheric propagation delays.

A model of the single differenced measurements is deduced from (1) as follows:

$$\begin{aligned}\Delta\varphi^i_{RU}(k) &= \varphi^i_R(k) - \varphi^i_U(k) \quad (2)\\ &= -\tfrac{\Delta\rho^i_{RU}(k)}{\lambda} - f\Delta t_{RU}(k) + f\Delta I^i_{RU}(k)\\ &-f\Delta\tau^i_{RU}(k) - \Delta N^i_{RU} + \Delta\varepsilon^i_{mult_{RU}}(k) + \Delta n^i_{RU}(k)\end{aligned}$$

where

- Δt_{RU} is the difference between the reference station clock offset and the user receiver clock offset.
- ΔI^i_{RU} and $\Delta\tau^i_{RU}$ are the atmospheric propagation delay residuals that remain after single differencing. Further reduction of these residuals can be achieved through the application of the specific propagation models introduced in the previous paragraph.
- ΔN^i_{RU} is the single differenced ambiguity.
- $\Delta\varepsilon^i_{mult_{RU}}$ is the single differenced multipath induced measurement error.
- Δn^i_{RU} is the single differenced carrier phase noise.

In order to eliminate the additive clock offset term Δt_{RU}, the single differenced measurements (2) of a particular satellite, called the reference satellite, are subtracted from the other single differenced measurements. The resulting quantities are called the *double differenced* measurements. A model of these quantities is:

$$\begin{aligned}\nabla\Delta\varphi_{RU}^{ri}(k) &= \Delta\varphi_{RU}^{r}(k) - \Delta\varphi_{RU}^{i}(k) \\ &= -\frac{\nabla\Delta\rho_{RU}^{ri}(k)}{\lambda} + f\nabla\Delta I_{RU}^{ri}(k) - f\nabla\Delta\tau_{RU}^{ri}(k) \\ &\quad +\nabla\Delta\varepsilon_{mult_{RU}}^{ri}(k) - \nabla\Delta N_{RU}^{ri} + \nabla\Delta n_{RU}^{ri}(k) \quad (3)\end{aligned}$$

where exponents r and u are used to distinguish between the reference and the user measurements.

The double differenced carrier phase measurements obtained in equation (3) depend on the unknown user position. They are affected by atmospheric residuals and by the double differenced multipath errors that add up with the measurement noise to distort the data.

Several ambiguity resolution methods use linear identification techniques, such as the least squares resolution method, and therefore require that the quantities (3) be linearized around a position estimate $\hat{X}(k)$. This position estimate is usually provided by the code DGPS positioning module.

Before the measurements are handed to the procedure, it is necessary to apply a procedure designed to perform a quality check of the data. The aim is this quality control procedure is to look for any inconsistent data, and to detect and correct any cycle slip observed on the carrier phase measurements. An example of such a procedure is presented in (Lu and Lachapelle, 1992).

A summary of the main pre-processing operations applied on the acquired data is presented in figure 1.

Once formatted as described in figure 1, the data is fed to the AROF procedure that tries to determine the value of the double differenced ambiguities. In the next section, we briefly present the procedure developed by the LTST, SEXTANT AVIONIQUE and the STNA, called the Maximum A Posteriori Ambiguity Search (MAPAS).

III. MAPAS

The Maximum A Posteriori Ambiguity Search (MAPAS) method is a method for ambiguity resolution on-the-fly inspired from the technique presented in (Brown and Hwang, 1984), which is based on the same principles as the Least Squares Ambiguity Search Technique (LSAST). This procedure performs an active search of the value of the double differenced ambiguities of four particular satellites called the *primary satellites*. It is a *multiple hypotheses sequential test* that processes as many carrier phase measurements as necessary to isolate the best candidate in a predetermined set of three-integer combinations. The principle of MAPAS is presented in (Macabiau, 1995).

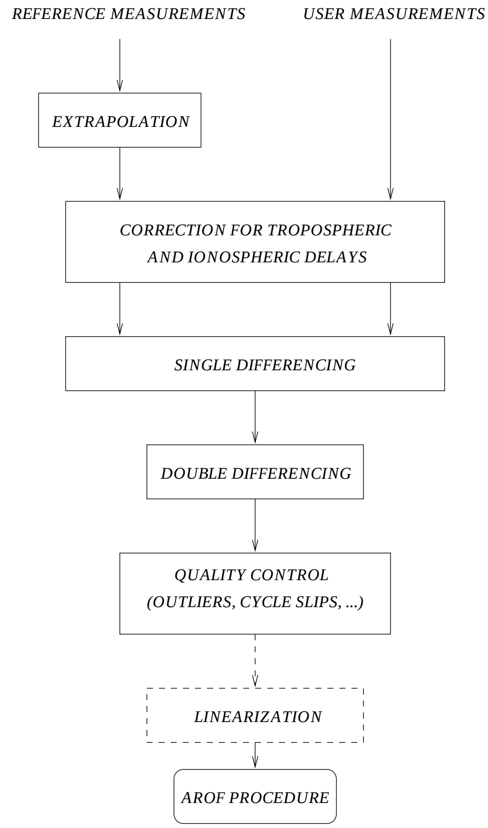

Figure 1: *Main data pre-processing operations applied to received data.*

Once linearized around the position estimate $\hat{X}$ as illustrated in figure 2, the double differenced measurements (3) can be written as:

$$\Phi(k) = -C(k)\delta X(k) - N + B(k) \qquad (4)$$

where

- Φ is the vector of the double differences.
- C is the matrix of the difference between the direction cosines of the reference satellite and the direction cosines of satellite i, scaled by λ.
- δX is the position error: $\delta X = \hat{X} - X$
- N is the vector of the double differenced ambiguities
- B is the noise vector, comprising all the correction and difference residuals as well as the tracking noise.

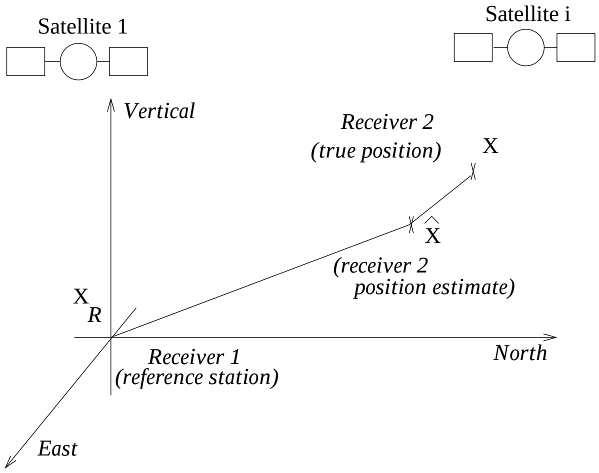

Figure 2: *Illustration of the situation of the receivers in a local coordinate system.*

The determination of the position is conditioned on the resolution of the double differenced ambiguity vector N. This resolution is done by testing thousands of possible values of N. These values are determined as the integer vectors associated with a position contained within a predefined *search volume*. The search volume is centered around the position estimate $\hat{X}(k)$, and its size depends on the uncertainty of that estimate.

The size of the trial set can be reduced if we note that only three of these ambiguities are independent in the noise free model derived from (4). Thus, the procedure looks for the best three-integer combination to be affected to the double differenced ambiguities of four particular satellites.

These satellites, called the primary satellites, are chosen according to their degree of visibility and their Position Dilution Of Precision (PDOP) factor. They must stay visible as long as the resolution is not done, and their PDOP must be a compromise between the *computation time* and the *integrity* of the procedure.

The initial search set is built using the primary measurements, and contains all the three-integer combinations that are associated with a position contained within the search volume. At each epoch, for each candidate $[abc]^T$ in the search set, a position is computed. From the knowledge of that position, a set of secondary ambiguities is determined, enabling the procedure to compute a set of predicted secondary measurements $\hat{\Phi}(k)$ associated with the candidate.

Then, the *secondary prediction error* vector $z_{S_{abc}}(k) = \hat{\Phi}(k) - \Phi(k)$ is formed, as the difference between the predicted secondary measurements and the actual secondary measurements. In the next step, the *prior probability* of the prediction errors obtained for that candidate is updated, conditionally on the value of the candidate. Finally, the *posterior probability* of the candidate is computed using Bayes' rule, conditionally on the prediction errors obtained for that candidate.

Therefore, if the a posteriori probability of a candidate is lower than a predefined threshold P_{min}, then it is rejected from the search set and will not be tested for at the next epoch. If this probability is larger than a preset decision threshold P_0, then this candidate is elected as the correct solution, and the current epoch N_a is called the *stopping time*.

A subtile trade off must be achieved when specifying the major tuning parameters of the procedure, which are:

- the rejection threshold P_{min}
- the decision threshold P_0
- the prior noise variance σ^2
- the PDOP of the primary satellites

All of these four parameters individually influence the performance of the algorithm. The key criteria of the performance are the *error probability* and the *time of convergence* of the procedure, which are directly related to its integrity and its continuity of service.

The knowledge of these performance parameters is a critical aspect of the assessment of the procedure for the desired application. These performances can be evaluated from theoretical considerations, or using simulated data, or from extensive experiments in the field.

The first step of the evaluation of MAPAS consisted in the determination of *theoretical expressions* of its error probability and time of convergence. Using results derived from a multiple hypotheses sequential test called the M-ary Sequential Probability Ratio Test (MSPRT) presented in (Baum and Veeravalli, 1994), the theoretical performance parameters of MAPAS were analyzed and reported in (Macabiau and Benhallam, 1996). In particular, expressions of bounds and asymptotic values of the expected stopping time and error probability of MAPAS are determined as functions of the decision threshold P_0, thus providing a means to control the performances.

Several hypotheses have to be made for the MAPAS method to be called an MSPRT:

1. We must assume that the *direction cosines* of the satellites from the moving receiver's point of view are *constant* during the whole resolution process. This is necessary if we want to consider that the secondary prediction errors are identically distributed over time. This hypothesis is a *pessimistic* assumption, as the evolution of the satellite geometry, although slow for vehicles of classical dynamics, enhances the selectivity of the procedure.

2. We must suppose that the phase measurement noise is an *independent sequence* over time. This is a quite strong assumption, as usually the double

differenced noise has slowly varying components which are mainly due to the carrier phase tracking error induced by multipath. This hypothesis *limits the range* of the theoretical developments presented in this work to the applications using measurements unaffected by low-frequency noise.

3. We need to consider that the *rejection process* of the MAPAS method, performed through the comparison of the posterior probabilities with the threshold P_{min}, has *no influence* on the structure of the test. That is, we must consider that the influence of the rejected combinations would have been negligible in the selection process if they had been kept in. Thus, we assume that all the hypotheses are considered at each measurement epoch. This hypothesis is *optimistic* for the *error probability* and *pessimistic* for the *expected stopping time*.

Provided that these assumptions hold, we can determine theoretical expressions of bounds and asymptotic values of error probability and time of convergence.

The bounds are:

- the stopping time of the test is necessarily finite: $N_a \leq \infty$
- the error probability α is bounded by $1 - P_0$:

$$\alpha \leq 1 - P_0 \tag{5}$$

The deduced upper bound of α depends only on the decision parameter P_0.

Furthermore, it can be shown that

$$\alpha \leq \frac{1 - P_0}{P_0} \tag{6}$$

which is equivalent to (5) when P_0 is very close to 1, as it is in our case.

The asymptotic expressions are:

- the expected stopping time is an inverse function of the separability between the true candidate $[abc]^T$ and its best competitor $[ijk]^T$:

$$E_{f_{abc}}[Na] \rightarrow \frac{-\ln(\frac{1-P_0}{P_0})}{\min\limits_{[ijk]\neq[abc]} D(f_{abc}, f_{ijk})} \text{ as } P_0 \rightarrow 1 \tag{7}$$

where

$$D(f_{abc}, f_{ijk}) = E_{f_{abc}}\left[\ln \frac{f_{abc}(Z_{S_{\alpha\beta\gamma}})}{f_{ijk}(Z_{S_{\alpha\beta\gamma}})}\right] \tag{8}$$

is the Kullback-Leibler information between probability density function f_{abc} and f_{ijk}.

- the error probability α is related to P_0 as:

$$\alpha \rightarrow \frac{1 - P_0}{P_0}\gamma \text{ when } P_0 \rightarrow 1 \tag{9}$$

where γ is a coefficient such as $0 < \gamma < 1$, calculated following (Woodroofe, 1982) depending on the minimum Kullback-Leibler information introduced previously.

These theoretical expressions were checked against observed values of performances in (Macabiau et al., 1996), and showed a good agreement with the observed values when the number of satellites is larger than 7.

The second step in the assessment of the performances of MAPAS consisted in the execution of numerous simulations in various configurations. These simulations were run in the same configurations for four procedures, namely MAPAS, LSAST, DIAS and FASF, as reported in (Macabiau et al., 1997). The software used for LSAST, DIAS and FASF evaluation were implemented from theoretical principles found in (Hatch, 1991), (Lachapelle et al., 1992), (Wei and Schwarz, 1995) and (Chen, 1993). Although the software used were not written by their original developers, the names of these methods have nevertheless been unchanged, even if only the theoretical principles have been conserved. The procedures were implemented in ADA and run on HP workstations and IBM PC compatible computers by the LTST and by SEXTANT AVIONIQUE.

The GPS phase observations are generated using the visible constellation from the receivers point of view. Thermal noise with preset standard deviation can be added to the measurements, as well as distortions induced by multipath generated from reflection off the Earth's surface. Moreover, observations from one or two *pseudolites* can be added to the measurement vector in order to assess potential benefits from their operation.

The measurements are computed at each epoch from the knowledge of the positions of the satellites and the simulated trajectory of the moving receiver, which corresponds to a certain scenario. In our case, the scenario is the landing phase of an aircraft at the Toulouse-Blagnac airport on a 3^o glideslope, beginning 20 km from the runway. The scenarios are run one after the other for 24h.

The performances are expressed in terms of time of convergence, integrity and availability of the precise position. The *High Accuracy Decision Threshold* (HADT) is introduced to evaluate the contribution of the procedure to the continuity of service of the landing system. The HADT is the lowest point on the approach path at which the ambiguities have to be declared as raised by the procedure. In our simulations, the HADT is set at the CAT I decision threshold (200 ft), although it is anticipated that this point would have to be moved further away from the runway threshold to ensure proper stabilization of the aircraft when switching from the code DGPS to the phase DGPS. It takes 3 minutes and 25 seconds (205 s) to an aircraft flying at 62 m.s^{-1} (120 knots) to go from the 20 km starting point to the

HADT.

This first set of results enables to draw several conclusions about the performances of these methods. First of all, we see that the influence of multipath induced errors is dramatic. This is a direct consequence of the measurement model used by all these procedures, that does not include multipath. Then, we can deduce from these first simulations that compliance to integrity requirements is far from being satisfied. Furthermore, the benefit of adding one or two pseudolite measurements is not significant when the pseudolite carrier phase ranging noise is identical to the satellite carrier phase noise. Finally, according to the simulations performed, MAPAS and FASF seem to have better performances than the other tested procedures, which certainly has to do with the smoothness of their selection process.

The next step for the evaluation of MAPAS is to estimate its performances on real data. The initial results of this evaluation using NORTEL generated signals and preliminary field measurements are presented in sections IV and V.

IV. DESCRIPTION OF DATA SETS

The performances of AROF procedures were evaluated on data collected by real receivers in several configurations. A first set of measurements was collected using a NORTEL GPS signal generator connected to the receivers, and a second set contains measurements in the field. All the data collected were not processed in real time, but post-processed.

On each set of data, the differences with the simulated measurements are analyzed, then the time of convergence and the error rate are assessed on the samples collected.

The NORTEL GPS signal simulator is an electronic device that generates GPS-like RF signals from computer models of the satellite constellation, of the signal models and of the receiver's dynamics. The NORTEL simulator STR 2760 is owned by the STNA and was made available for the study reported here. This simulator is a differential test bench: it can simultaneously generate signals for a reference receiver and for a user receiver, as shown in figure 3.

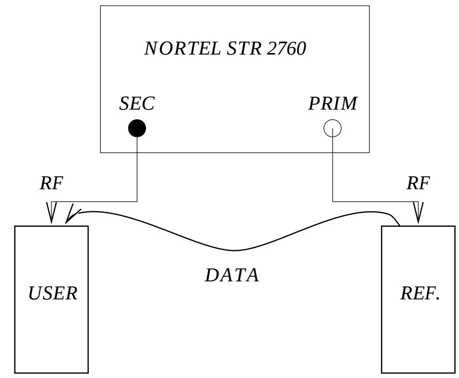

Figure 3: *Set-up of the NORTEL connexions. The primary channel sends signals for the reference station. The secondary channel sends signals to the user receiver.*

Several scenarios were run to evaluate the performance of MAPAS in various configurations. A first batch of scenarios simulates a static user receiver receiver at various points of the 3^o elevation approach path over Toulouse-Blagnac airport. These scenarios were designed to quantify the effect of the distance D and height h of the user receiver with respect to the reference station. A summary of these scenarios is presented in table 1.

Type	#	Position
Static	1	D = 1 m h = 0.5 m
Static	1 b	D = 500 m h = 25 m
Static	2	D = 5 km h = 260 m

Table 1: *Configuration of scenarios run on NORTEL simulator.*

Field measurements used for this analysis were conducted in August and September 1996 at the Toulouse-Blagnac airport, and in February 1997, at the Paris Charles De Gaulle airport using NOVATEL GPSCard receivers. The dynamic measurements were collected using a car driven around the Toulouse-Blagnac airport. The reference position for the dynamic set is the position determined using the GeoTracer software, developed by GEOTRONICS.

A description of the data sets is presented in table 2.

Type	Name	Trajectory
Static	CDG1	Static, 29 m
Dynamic	TLS5-2	Dynamic with car

Table 2: *Description of real data sets.*

V. RESULTS

The ambiguity resolution trials are launched one after the other every 15 s on each file. This is done in order to get significant statistics from the recorded file with the constraint that two consecutive trials should use as different data as possible.

When applied, the tropospheric correction model used is the model presented in (Nato, 1993). The reference measurements are extrapolated using a second order polynamial.

The parameters observed are:

- the convergence rate, which is the ratio of the number of trials for which a solution was found over the total number of trials run.
- the integrity, which is the total number of correct ambiguity resolution trials over the total number of trials for which a solution was found.
- the time of convergence, which is the time to first fix of the ambiguities.
- the unavailability of the precise position, which is the ratio of the total number of trials for which no solution was found before the HADT over the total number of trials run

Results on scenario 1

	5 Hz (σ=0.02)	1 Hz (σ=0.02)	5 Hz (σ=0.01)
Convergence rate	100%	92.86%	100%
Integrity	100%	100%	100%
Time of convergence	μ_T: 26.26 σ_T: 47.58 max: 323.40	μ_T: 59.55 σ_T: 33.16 max: 125	μ_T: 10.53 σ_T: 29.74 max: 308.2
Unavailability	2.27%	7.14%	0.92%

Table 3: *Results of the application of MAPAS to data of scenario 1 (GPS time 176500s to 177670s, week 767). Note that the unavailability of the precise position may be related to continuity risk (see discussion in section 3).*

We can see in table 3 the influence of the data rate and of the prior variance.

The average time of convergence is divided by 2 when going from 1 Hz samples to 5 Hz samples. The gain is not a 5:1 ratio, mainly because of failures of the communication link between the receiver and the computer that induces data lags, and also because the phase noise samples are slightly correlated due to atmospheric residuals.

The average time of convergence presented in this table does not reflect the observed values of this time: all the trials converge in a few tens of seconds, but one single trial in the middle of the file takes a very long time. Its time of convergence corresponds to the maximum time displayed in the table. This occurs because the number of visible satellites is 6 in the beginning of the trial. Otherwise, for all the other trials, the number of visible satellites is 7.

All the trials performed converged towards the good solution: the integrity is 100% in every case. The computation time is well under the time of convergence.

The position error is lower than 1 cm, which is as good as expected using carrier phase measurements.

No cycle slips were found in this file.

Results on scenario 1 b

	5 Hz (σ=0.02)	1 Hz (σ=0.02)	5 Hz (σ=0.01)
Convergence rate	97.44%	92.31%	98.72%
Integrity	100%	100%	100%
Time of convergence	μ_T: 10.57 σ_T: 14.74 max: 50.6	μ_T: 26.76 σ_T: 28.24 max: 107	μ_T: 6.14 σ_T: 9.25 max: 40.80
Unavailability	2.56%	7.69%	1.28%

Table 4: *Results of the application of MAPAS to data of scenario 1 b (GPS time 174870s to 176040s, week 767). Note that the unavailability of the precise position may be related to continuity risk (see discussion in section 3).*

Once again, we can see in table 4 the high influence of the data rate and of the prior variance.

The average time of convergence is divided by 2.5 when going from 1 Hz samples to 5 Hz samples, which still is not a 5:1 ratio.

The unsolved trials are due to unexplained incorrect code measurements made by the receiver during 1.2 second at a particular point in the middle of the scenario, between 175106.4s and 175107.6 s included. These outliers cause the program to be unable to determine its differential position using code measurements. As these measurements are not deleted from the file, the longer the trials last, the more trials are affected. Therefore, we see that when the prior variance is set to a low value (σ=0.01 cycle) at a high data rate (5 Hz), the number of unsolved trials in the set is reduced to 1 as opposed to 6 in the worst case presented.

As a consequence, the unavailability of the precise position is highly influenced by the presence of this corrupted sequence in the file, going from 7.7 % in the worst case to 1.28 % in the best case.

The vertical positioning error obtained is lower than 1 cm in successful cases.

The number of satellites for this set ranges from 6 in the beginning to 9 at the end.

One cycle slip was found in this file on satellite 1 at epoch 175749.40.

It is essential to report that when this file is processed without any tropospheric correction model, MAPAS is unable to raise the correct ambiguities.

Results on scenario 2

	5 Hz (σ=0.04)	5 Hz (σ=0.02)	5 Hz (σ=0.01)
Convergence rate	86.36%	86.36%	86.36%
Integrity	91.23%	68.42%	63.16%
Time of convergence	μ_T: 27.31 σ_T: 18.24 max: 61.6	μ_T: 12.65 σ_T: 10.73 max: 42.00	μ_T: 4.89 σ_T: 4.35 max: 20.40
Unavailability	13.64%	13.64%	13.64%

Table 5: *Results of the application of MAPAS to data of scenario 2 (GPS time 174746 s to 175748 s, week 767). Note that the unavailability of the precise position may be related to continuity risk (see discussion in section 3).*

The average time of convergence is divided by 2.5 when going from a prior variance σ=0.04 to σ=0.01 with 5 Hz samples. However, in the same time, the integrity drops from 90 % to 60 %. We see here that a trade-off must be done using the best value of σ.

The unsolved trials are due to unexplained incorrect code measurements made by the receiver during a total 1.2 second at a particular point in the beginning of the scenario, between 174876.6 s and 174877.8 s included. These outliers cause the program to be unable to determine its differential position using code measurements. As the trials are very slow in the beginning of the file because there are only 5 satellites visible, all of them get resetted whenever they reach that point.

All the 9 first trials are aborted due to this problem. As a consequence, the unavailability of the precise position is highly influenced by the presence of this corrupted sequence in the file, leading to an unavailability of 13.6 %.

If this corrupted segment had been removed, the availability would have been significantly increased. This problem is attributed to a failure of the quality control module that needs to be corrected.

The vertical positioning error obtained is lower than 1 cm in successful cases. However, when the procedures makes errors, the vertical position error reaches 1 m in the worst case observed.

The number of satellites for this set ranges from 5 to 8.

No cycle slips were found in this file.

Results on data set CDG1

	1 Hz (σ=0.1)	1 Hz (σ=0.07)	1 Hz (σ=0.05)
Convergence rate	73.64%	79.22%	85.63%
Integrity	80.25%	76.43%	77.97%
Time of convergence	μ_T: 160.70 σ_T: 93.12 max: 497	μ_T: 121.04 σ_T: 69.59 max: 327	μ_T: 91.02 σ_T: 53.73 max: 227
Unavailability	33.39%	28.61%	16.47%

Table 6: *Results of the application of MAPAS to data set CDG1 (GPS time 391010 s to 396070 s, week 893). Note that the unavailability of the precise position may be related to continuity risk (see discussion in section 3).*

As we can see in table 6, the integrity has dropped with respect to the results observed on the NORTEL data. The integrity remains around 80 %, and a large increase of the availability of the precise position is observed when decreasing the prior variance of the noise.

The position error in the successful cases is larger than with the NORTEL data, but still remains under 1 cm. Similarly, the position error induced by wrong ambiguities is around 2 m, which is twice as much as observed on NORTEL data.

The number of visible satellites in this set ranges from 7 to 9, with a large majority to 8.

No cycle slips were found in this file.

Results on data set TLS5-2

The trajectory of the vehicle is shown in figure 4.

The ambiguities are properly raised at the very beginning in 158 s, and the procedure is able to keep track of the movement of the vehicle during the whole file. The standard deviation of the 3D position error is 4mm. Figures 5, 6 and 7 show the evolution of the position error over time. As we can see, all three of them exhibit a peak rising up to a few centimeters between epochs 397740 and 397750. During this interval the car is stopped on a service road, and the position estimate is affected by a small unexplained variation, that may be attributed to multipath. No cycle slips were found in this file.

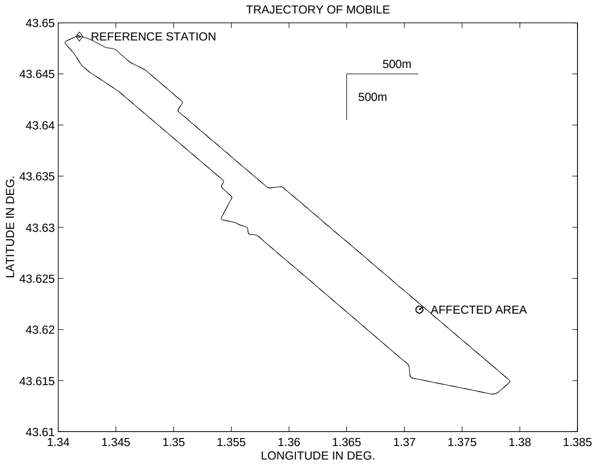

Figure 4: *Trajectory of mobile: the car is driven around the runway of the Toulouse-Blagnac airport.*

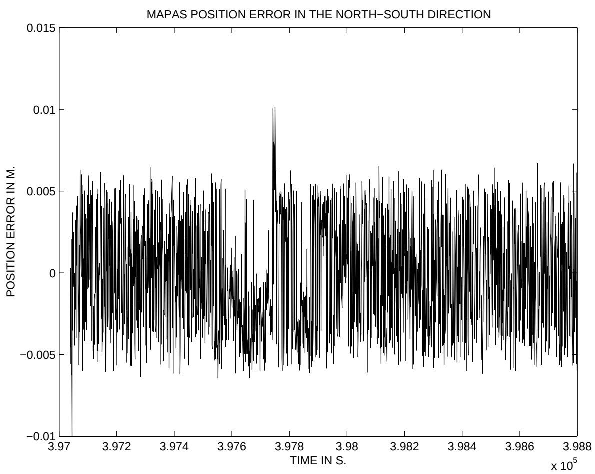

Figure 5: *Position error of MAPAS in the North-South direction (σ_{NS}=4mm).*

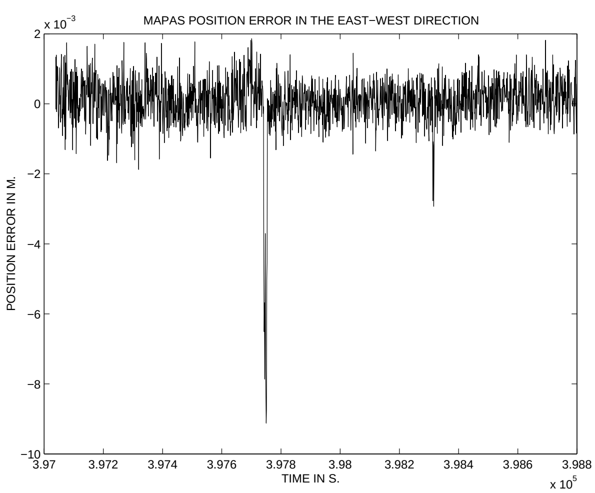

Figure 6: *Position error of MAPAS in the East-West direction (σ_{EW}=1mm).*

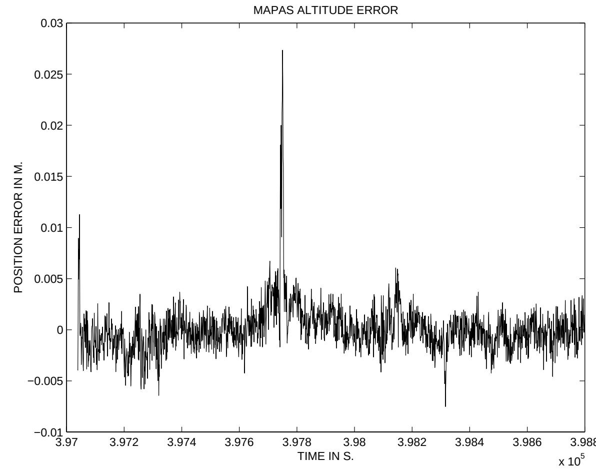

Figure 7: *Altitude error of MAPAS (σ_H=2mm).*

VI. CONCLUSION

As we can see from the first evaluation reported in this paper, the performances of MAPAS are encouraging, although the integrity and the availability of the precise position remain far from the operational requirements for precision landings.

Nevertheless, many improvements could be gained through an adapatation of the processing software, and particularly the quality control module, to offer better resistance to outliers and cycle slips.

Furthermore, the evaluation of the capabilities of MAPAS is to be completed by real-time trials, scheduled to take place in 1998.

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