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Analysis of CHARACTERISTICS of GPS AROF procedures FOR APPLICATION to precision landings

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ABSTRACT

GPS Ambiguity Resolution On-The-Fly (AROF) procedures process DGPS code and carrier phase measurements to deliver in real-time a very accurate position estimate. They are very attractive to the civil aviation community, but questions still remain about their reliability. The aim of this article is to present a state of the art analysis of the characteristics of the GPS AROF procedures through comparison of several methods. It constitutes a contribution to the evaluation of the applicability of these procedures to precision landings. Using requirements proposed for CAT II/III landings, constraints are extracted on four identified sets of parameters, such as performances, processing modes, means of control and working assumptions. Then, these parameters are determined for four particular procedures, namely the LSAST (Least Squares Ambiguity Search Procedure), MAPAS (Maximum A Posteriori Ambiguity Search), DIAS (Direct Integer Ambiguity Search) and FASF (Fast Ambiguity Search Filter) methods, following principles presented in corresponding publications and after an adaptation of algorithms. This determination is done on a theoretical and practical basis in several configurations. Mathematical developments provide an analysis of performances, and simulations of data for L1 measurements, pseudolites and perturbations such as multipath errors are used to assess the values of the parameters.

I. INTRODUCTION

The accurate pseudorange information contained within the GPS carrier phase observations is the basis for centimeter level positioning. However, full access to this information requires the resolution of the intrinsic ambiguities of these phase measurements and the elimination of all the additional errors. In dynamic applications, this can be done in real time through the application of one of the ambiguity resolution on-the-fly procedures, after double differentiation of the observations. Unfortunately, the major problem encountered when using these procedures in demanding applications is their sensitivity to all the measurement noises, which induces their lack of reliability. Thus, many questions arise about their true capacity in providing reliable accurate positioning information in the case of precision landings.

This paper is intended to be a contribution to the analysis of the applicability of these procedures to CAT II/III aircraft landings through comparison of several AROF procedures. The study first begins with a review of the requirements of a GNSS based CAT II/III landing system, then an overview of GPS AROF procedures is presented, afterwards their characteristics are identified and assessed through theoretical and practical evaluations, performed by the LTST and SEXTANT AVIONIQUE, and finally these characteristics are checked against the constraints.

II. OPERATIONAL REQUIREMENTS

The constraints to be applied to a GNSS based CAT II/III landing system have yet to be defined by ICAO. However, successive propositions have been made by its working panels, the latest of which was issued during the Working Groups meeting of the GNSSP in Brisbane, as reported in (ICAO, 1997). The requirements stated are based on constraints imposed on the Required Navigation Performances (RNP) of the aircraft equipment. They are expressed in terms of accuracy, integrity, availability and continuity of service of the whole landing system, thus defining volumes of expected position of the aircraft, also called tunnels, as presented in (ICAO, 1994). The size of the tunnels is defined by the maximum specified Total System Error (TSE). The TSE represents the deviation between the true aircraft position and its desired flight path. This deviation is the composition of the Navigation Sensor Error (NSE) with the Flight Technical Error (FTE), the latter representing the accuracy with which one the aircraft is controlled using the information provided by the navigation sensor. Assuming both errors are independent, we can write $TSE^2 = NSE^2 + FTE^2$. The latest proposition of the GNSSP working groups, derived from AWOP, is presented in table 1.

RNP Type TSE	0.01 Nm/14ft	0.003Nm (CAT

95% (Lat/Vert)	(CAT II)	III)
NSE 95% (Lat/Vert)	6.3m/2.06m	4.95m/0.91m
NSE 99.99999% (Lat/Vert)	19m/6m	14.85m/2.7m
Time-To-Alert	1 sec	1 sec
Continuity	approx. 10^{-6} in any 15 sec	approx. 10^{-6} in any 30 sec
Integrity	approx. 10^{-9} per approach	approx. 10^{-9} per approach
Availability	0.9985	0.9990

Table 1: *Operational requirements on CAT II/III landing equipment, as proposed during Working Groups meeting of GNSSP in Brisbane, 1997.*

Once the characteristics of AROF procedures are identified, the stringent requirements presented in this table provide guidance for elaboration of constraints on AROF procedures.

III. ON-THE-FLY AMBIGUITY RESOLUTION

The GPS carrier phase measurements performed by a receiver can be modeled in the following way :

$$\varphi_i(k) = -\frac{\rho_i(k)}{\lambda} + f\left(\Delta t_{S_i}(k) - \Delta t_R(k)\right) + fI_i(k) \\ - f\tau_i(k) - N_i + b_i(k) + \varepsilon_{mult_i}(k) + SA_i(k) \quad (1)$$

where
- $\varphi_i(k)$ is the carrier phase measurement of satellite i at epoch k expressed in cycles
- ρ_i is the geometrical distance between satellite i and the receiver
- f is the nominal carrier frequency and λ the associated wavelength
- Δt_{Si} and Δt_R are respectively the satellite and receiver clock offset with respect to GPS time
- I_i and τ_i are the ionospheric and tropospheric phase delays
- b_i is the carrier phase measurement noise. In the following, it is assumed that b_i is a zero-mean white gaussian noise stochastic process, with standard deviation σ.
- N_i is the integer carrier phase measurement ambiguity
- SA_i is the error due to SA
- ε_{mult} is the carrier phase tracking error due to multipath

Most of the errors affecting this measurement exhibit a high spatial correlation. This is the case of satellite clock offset, SA, and ionospheric and tropospheric delays in a small geographical zone. Thus, by using measurements performed by a reference station located no more than 20 km away from the moving receiver, we can eliminate these errors through

between-station differentiation, provided that both measurements are made available at the roving receiver at the same time.

Then, choosing a base satellite, we can cancel the remaining receiver clock error through inter-satellite differentiation. The resulting quantities are called the double differenced measurements, that can be modeled as :

$$\nabla\Delta\varphi_i(k) = -\frac{\nabla\Delta\rho_i(k)}{\lambda} - \nabla\Delta N_i - \nabla\Delta r_i(k) \quad (2)$$

where $\nabla\Delta r$ denotes the phase residuals.

When n satellites are tracked by both receivers, we can collect all the *(n-1)* double differenced measurements in one vector, and the model becomes :

$$\phi(k) = -\frac{\nabla\Delta\rho(k)}{\lambda} - N + B(k) \quad (3)$$

These double differenced measurements only depend on the unknown position of the moving receiver and the double differenced ambiguities. As the ambiguities are constant over time in the absence of cycle slips, determination of the value of the ambiguities enables the receiver to compute a precise position at each measurement epoch.

As we can see from model (1), the phase residuals *B(k)* include the double differenced multipath errors, atmospheric residuals resulting from spatial decorrelation, and clock offsets residuals due to bad synchronization. However, ambiguity resolution procedures usually assume that these quantities are time-independent, zero-mean gaussian quantities. Thus, the measurement model considered by these procedures is not consistent with the true nature of the measurement model, and this discrepancy induces many failures.

Furthermore, it must be emphasized that the measurement model (3) is only valid when no receiver channel experiences a cycle slip. In the other case, one or several components of the ambiguity vector *N* change abruptly and proper exploitation of the double differenced measurements requires repair of this change. The difficulty in detecting and repairing the cycle slips arises from the fact that the receiver may not be able to determine whether the change in phase that occurred is due to a cycle slip or to its own displacement with respect to the satellite. Thus, the capacity of detection of any cycle slip by the receiver is increased if the ambiguities are already resolved when the cycle slip occurs, as compared to the case where it happens during the ambiguity resolution.

IV. CHARACTERISTICS OF AROF PROCEDURES

The ambiguities can be determined either through decision or estimation theory. Procedures that adopt the decision approach, like the AFM (Remondi, 1991 ; Mader, 1992), LSAST (Hatch, 1991 ; Lachapelle et al.,

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1992), MAPAS (Macabiau, 1995) are multiple hypotheses tests that check thousands of integer combinations to find the most consistent one. On the other hand, estimating procedures, like the Lambda method (Teunissen, 1994), the optimized Cholesky decomposition method (Landau and Euler, 1992), FASF (Chen, 1993), DIAS (Wei and Schwarz, 1995), FARA (Frei and Beutler, 1990) use the measurement model to estimate in two stages the best integer vector. The vector is first estimated as a floating point quantity, then fixed using integer least-squares theory. All of these procedures can be stopped after the first step, providing a good floating estimate of the ambiguities that will enable the receiver to reach decimeter-level positioning after a few seconds.

However, estimating AROF procedures can be viewed as decision-making techniques, considering that any estimating procedure comes with a final validation stage that has the structure of a multi-hypothesis sequential test, as the best candidates are sorted and tested for consistency for several epochs before the election of the best one.

Any AROF procedure, designed according to any of the two approaches presented in the previous paragraph, is mainly characterized by its performances and working assumptions. Performances are the accuracy and time of convergence. Working assumptions are the nature and the mathematical model of the measurements used. As the determination of the performance parameters is usually very difficult, it is important to have knowledge of the internal characteristics of the procedure in order to predict its potentials or limitations. Thus, the processing method, which induces the nature and the quantity of information extracted from the observations, as well as the computation burden, is an important feature of the procedure. Finally, as presented by Hatch and Euler in (Hatch and Euler, 1994), it is desirable that the procedure provides a means of control of the solution proposed under the form of a quantified criterion. Thus, the performances, working assumptions, processing method and means of control consitute four sets of parameters that we can use to characterize each AROF procedure and evaluate its adequacy to the desired application.

V. CONSTRAINTS ON PARAMETERS

Using the requirements presented in section II of this paper, we can elaborate some constraints on the characteristics of the AROF procedures if we intend to use them for guidance of aircraft during precision approaches.

The position accuracy requirement can be directly translated into the ambiguity accuracy requirement, as a one cycle error on the output ambiguities can induce up to 30cm positioning error, as we can see from figures 1 and 2. Thus, to fulfil the CAT II requirement,

ambiguities have to be solved within ±7 cycles on each channel. For CAT III requirement, ambiguities have to be solved within ±3 cycles. However, great care must be taken when implementing this requirement for particular procedures like LSAST and MAPAS, where the ambiguity search is performed on a basic set of four satellites called the primary satellites. Indeed, a one cycle error on one of the primary ambiguities may induce large secondary ambiguity errors, and cause a positioning error of up to 1m, as we can see from figure 3.

Figure 1

Figure 2

Position error induced by a 1 cycle error on 1 primary ambiguity
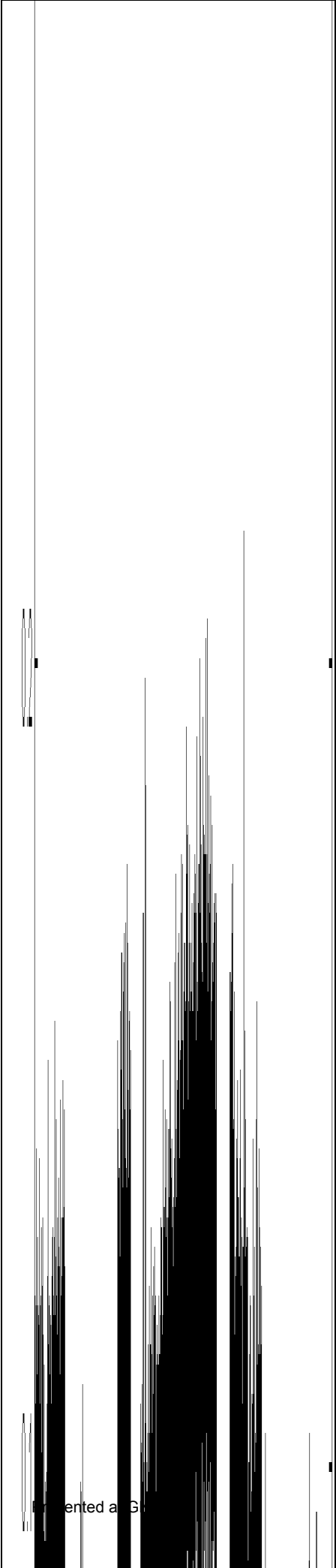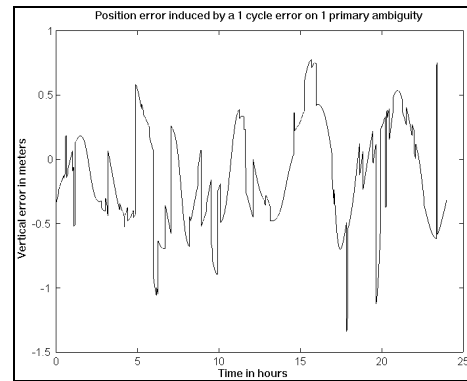
Figure 3

Thus, if selection is performed on a subset of primary satellites, for CAT II/III landings, it is mandatory for the AROF procedure to raise the correct ambiguity integer combination, in order to prevent geometrical effects to degrade the position accuracy.

Continuity of service of the precise position delivery system is dependent on continuity of the code DGPS sub-system, and of the phase DGPS sub-system coupled with the cycle slip detection and repair module. In particular, delivery of the precise position can be stopped if this module detects a cycle slip that it is unable to repair. Thus, the continuity requirement does not have a direct implication on the AROF procedure itself.

Availability of the precise position is dependent on the availability of the correct ambiguity estimate and of the code and phase DGPS sub-systems equipped with cycle slip detection and repair. The ambiguity estimate is delivered after several processing epochs, starting from the entrance of the aircraft in the coverage zone. The coverage zone has an approximate radius of 15km from the runway. The lowest point of the approach path at which one the precise position has to be available must be located before the decision point of the approach phase, in order to ensure proper stabilization of the aircraft when crossing the CAT II or CAT III decision thresholds. In the following, without specific guidance material, this point has been taken as the CAT I decision threshold. However, it is probable that this point would have to be moved further away from the runway threshold to ensure safe stabilization of the aircraft when switching from code DGPS to phase DGPS. Thus, the AROF procedure must deliver its ambiguity estimate during this time interval, related to the coverage area and the location of the high accuracy decision threshold.

Integrity risk of the AROF procedure is directly related to its error probability, which is the probability that the procedure raises out of bounds ambiguities. Thus, the integrity risk of the AROF procedure has to be at least lower than the integrity specified for the CAT II/III landing system as a whole. The time-to-alarm constraint applies on the precise positioning module once the ambiguities have been delivered by the

procedure. It requires the implementation of a quality control procedure that checks continuously the consistency of the ambiguity solved, and monitors measurements for detection of cycle slips and abnormal observations as presented for example in (Lu and Lachapelle, 1992). This module has to be extremely efficient, and provide alarms in less than 1s after occurrence of event.

VI. THEORETICAL PERFORMANCES OF AROF PROCEDURES

It is very difficult to compute the expected theoretical performances of an AROF procedure. This derives from the complex nature of such algorithms, that all behave like multihypothesis sequential tests, as we already saw in section III. Sequential tests are characterized by the variable number of samples required to satisfy a decision condition. Thus, a compromise must be struck between the number of samples before decision and the accuracy of the decision. This compromise is performed through the setting of the decision thresholds of the procedure, and drives the Average Sample Number (ASN), as well as the error probability of the test. Further details can be found in (Macabiau, 1995) and (Macabiau and Benhallam, 1996).

To our knowledge, theoretical performances of AROF procedures have been published only for MAPAS (Macabiau and Benhallam, 1996). The analysis found in this reference relies on the analogy between MAPAS and the MSPRT, and is based on the works presented in (Baum and Veeravalli, 1994) and (Baum and Veeravalli, 1995). The paper provides theoretical expressions of bounds and asymptotic values of ASN and error probability. Expressions of bounds are very useful and enable the designer to set the decision thresholds in accordance with the desired performances of the procedure. Denoting N_a as the stopping time of the test and *[abc]* any three-integer vector combination, we have:

$$P\left[N_a > n \middle| H_{abc}\ true\right] \xrightarrow[n\to\infty]{} 0 \quad (4)$$

and the error probability α is bounded by:

$$\alpha < \frac{A}{1+A} \quad (5)$$

where A is such that the decision threshold of MAPAS is $P_0 = \frac{1}{1+A}$.

Furthermore, if we note $D(H_{abc}, H_{ijk})$ the Kullback-Leibler distance between hypotheses H_{abc} and H_{ijk}, we have:

$$E\left[N_a \middle| H_{abc}\right] \xrightarrow[A\to 0]{} \frac{-\ln A}{\min_{ijk} D(H_{abc}, H_{ijk})} \quad (6)$$

and

$$\alpha \xrightarrow[A\to 0]{} \gamma A \quad (7)$$

where γ is such that $0<\gamma<1$.

These predicted asymptotic performances (4) to (7) lack of accuracy when the number of satellites is lower than eight, mainly because of the assumptions that have to be made for MAPAS to be considered as an MSPRT. The study emphazises the role of the number of visible satellites and the importance of their geometry.

The difficulty in deriving theoretical performances of AROF procedures induces the high amount of practical experiments that have to be performed on such procedures. Testings aim at estimating the performances of the methods, and include evaluation on simulated data, on data collected from GPS signals simulators, and trials in real configurations.

VII. PERFORMANCES ON SIMULATED DATA

The performances of MAPAS, LSAST, DIAS and FASF are estimated from the average performances observed during 12h to 24h, using simulated data in several configurations. The procedures are first run on data generated according to the assumed measurement model, with several noise levels. Then they are run on data augmented with one or two pseudolite signals. Finally, they are run on data corrupted by multipath signals reflected off the Earth's surface.

The LSAST and MAPAS procedures were implemented in ADA and run on HP workstations and PC compatible computers at the LTST. The DIAS and FASF procedures were implemented in ADA and run on PC compatible computers by SEXTANT AVIONIQUE. The softwares used for LSAST, DIAS and FASF evaluation were implemented from theoretical principles published in corresponding publications. The names of these methods has nevertheless been unchanged, even if only the theoretical principles have been conserved. Algorithms have been modified and adapted to CAT II/III application and to simulations which were done. 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 perturbation 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 preset scenario. In our case, the scenario is the landing phase of an aircraft at the Toulouse-Blagnac airport, beginning between 10 km and 20 km from the runway. The scenarios are run one after the other for 12h or 24h.

The performances are expressed in terms of time of convergence, integrity and availability of the precise position. The time of convergence is the acquisition time required by the procedure to deliver its ambiguity

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estimate. The integrity estimate is the ratio of the number of correct ambiguity resolutions to the total number of trials where the ambiguity was declared as solved by the procedure. The availability is the percentage of trials that are declared as solved by the procedure when the simulated aircraft crosses the high accuracy decision threshold, with respect to the total number of trials performed. In our case, as explained in section V, if the ambiguities have not been properly delivered by the procedure at the CAT I decision threshold, the accurate position from the AROF procedure is said to be unavailable for the pilot.

Degradations on the measurement include thermal noise and multipath. Thermal noise is digital random white gaussian noise, with a preset standard deviation of 1mm, 2mm or 4mm. Multipath induced error is computed using an electromagnetic model for the Earth's surface, a model for the receiving antenna, and a simple model for the phase and code tracking loops, as exposed in (Macabiau, 1996).

The results presented can only be interpreted as comparisons between methods in the same category, following the classification presented in section IV of this paper. As LSAST and MAPAS were implemented and compared by the LTST and DIAS and FASF were implemented and compared by SEXTANT AVIONIQUE, differences in software design and simulation parameters prevent a systematic comparison of performances of decision making and estimating methods. The differences in software design only concern thresholds settings, that were adjusted by two different teams, both performing trade-offs between the error probability and the time of convergence. The differences between the simulation parameters are presented in table 2.

Methods	LSAST, MAPAS	DIAS, FASF
Noise level	4 mm	1mm, 2mm or 4mm as indicated
Starting point of flight path	20 km	10 km or 20 km as indicated
Multipath	All visible satellites	Highest visible satellite
Pseudolites	700m radius bubbles @ 3km from runway threshold	Coverage extended to all the approach path

Table 2

The estimated performances of LSAST and MAPAS are presented respectively in figure 4 and figure 5.
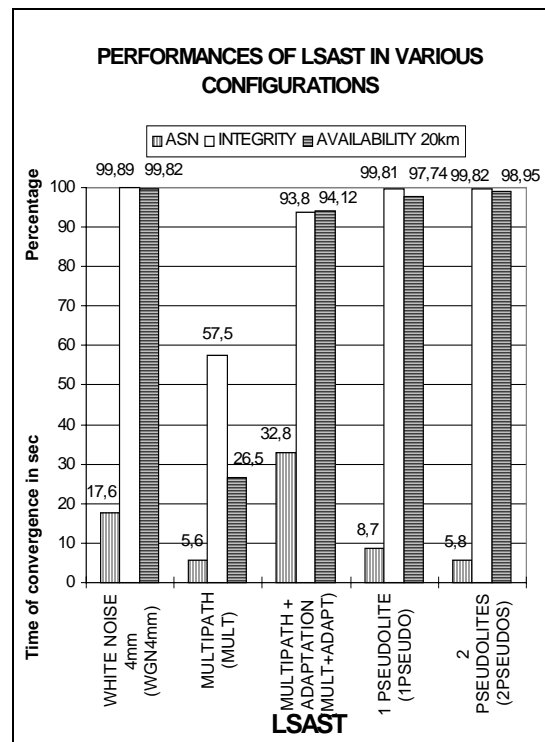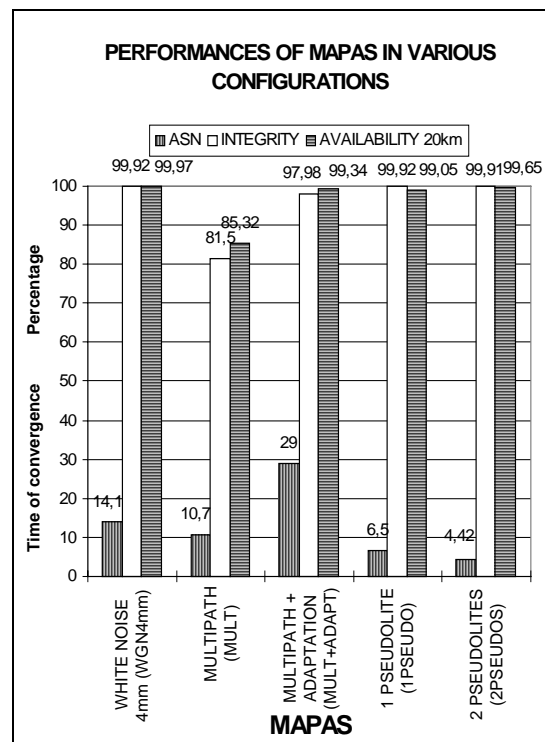

Figure 4

Figure 5

We can deduce from the observation of these graphs that the estimated performances of these two methods are quite identical when no additional perturbation is added to the measurements (see bar plot WGN4mm on figures 4 and 5). But the influence of multipath is dramatic (MULT), as the reliability of both methods drops significantly, although it can be improved by

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setting a highest a priori noise level than the inserted one (MULT+ADAPT). However, we can see that MAPAS seems to show a better resistance to multipath than LSAST, probably because of the smoothness of its rejection mechanisn which is directly performed on probability criteria and not on χ^2 thresholds. This difference is presented in detail in (Macabiau, 1996). The benefit of the addition of bubble pseudolite signals is visible as well, mainly on the estimated time of convergence (1PSEUDO, 2PSEUDOS). However, we see that the impact of this addition on the integrity and availability of the procedures is not significant, not even when adding one extra pseudolite. Note that we can expect a higher benefit when using pseudolites radiating signals having a larger coverage than a 700m radius bubble, as it was done for DIAS and FASF testing.

The estimated performances of DIAS and FASF are presented respectively in figures 6 and 7.

As we can see from the first results presented in figures 6 and 7, FASF seems to have better integrity and availability than DIAS when only white noise is affecting the measurements (WGN1mm, WGN2mm, WGN4mm). As reported earlier about LSAST and MAPAS, multipath induced errors seriously affect the performances of the procedures, with an advantage to FASF, that seems to have a better resistance to that type of unmodeled errors (MULT). Similarly, the influence of the addition of a pseudolite measurement is not very high, improving only the availability of the methods (1PSEUDO), even when multipath is added (1PSEUDO+MULT).

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 considered by all these procedures, that does not include multipath. Then, we can deduce from these first estimations that compliance to integrity requirements is far from being satisfied. Furthermore, the benefit of adding one or two pseudolite measurements is not significant. 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.
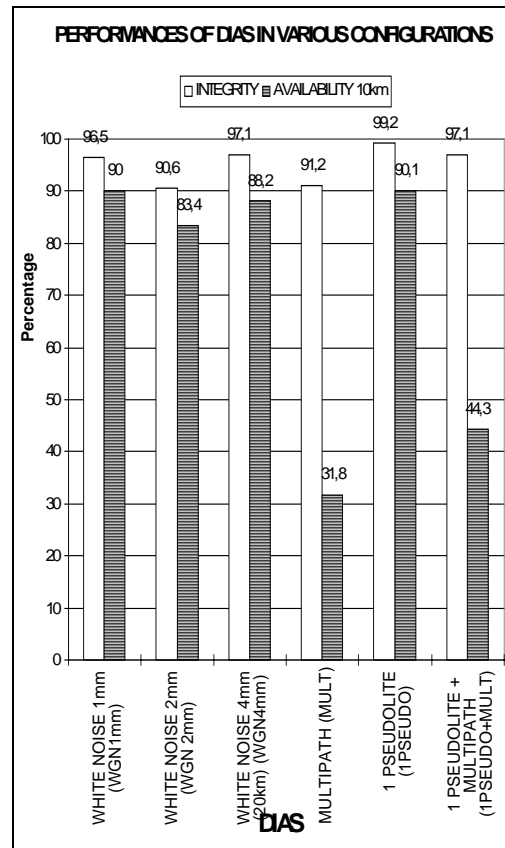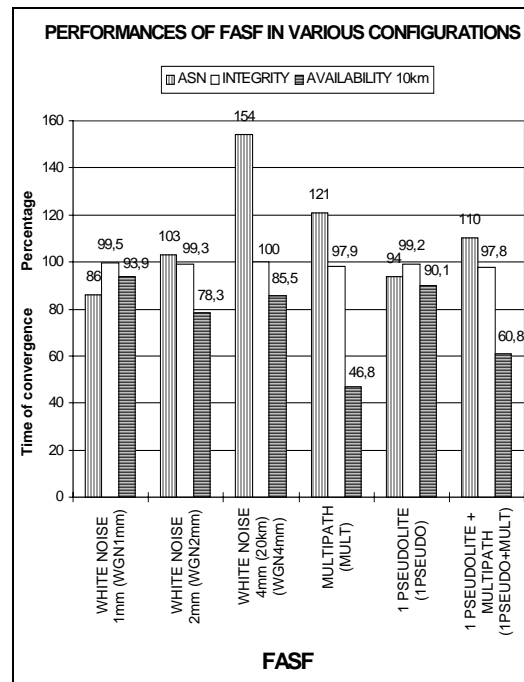

Figure 6

Figure 7

VIII. ADDITIONAL CONSTRAINTS FOR REAL DATA PROCESSING

Exploitation of these techniques using real measurements requires that great care be taken when handling the data. Critical points are receivers synchronization, tropospheric delay compensation, satellites position computation and multipath induced errors. Proper exploitation of the double differenced model (3) usually requires that noise $B(k)$ be considered as a zero-mean, time-independent white gaussian noise. However, this can only be true if all the errors presented in model (1) are cancelled during the double-differencing process. Elimination of SA, satellite clock offset and atmospheric delays through single-differencing requires the measurements to be exactly synchronous and the receivers to be very close. As this can not be done in reality, measurements from one of the receivers have to be extrapolated to determine their value at the GPS time of the other receiver, and atmospheric delays must be estimated from models for compensation before single-differencing. Computation of the position of the satellites can be performed using the broadcast ephemeris data, with extra precaution when determining the GPS time of transmission of the signal processed at the tag time of measurement. Multipath errors can be limited through proper antenna siting and use of choke ring antennas for the reference receiver.

IX. CONCLUSION

The characteristics of four AROF procedures were evaluated and compared with the operational requirements, and a summary of results can be found in table 3.

It appears that AROF procedures are susceptible to measurement errors such as multipath, atmospheric decorrelation and cycle slips.

From these simulations, it appears that availability of the AROF procedures is insufficient, and new integrity techniques have to be developped for AROF procedures. Continuity of service is threatened by the capacity of detection of cycle slips.

Further results will be given concerning this evaluation with real measurements.

Method	LSAST[*]	MAPAS	DIAS[**]	FASF[**]
Processing mode	Decision		Estimation	
Working assumptions	Primary satellites always available		No discrimination	

Means of control	Ratio of residuals	Posterior Probabil.	between sats	
			Ratio of residuals	Uncert-ainty range
Ambiguity Accuracy requirement	Exact ambiguity		±7 cy.(CAT II) ±3 cy.(CAT III)	
CAT II/III Integrity Bound	approx. 10^{-9}			
Error rate	1×10^{-3} (Integrity)	1×10^{-3} (Integrity)	3.5×10^{-2} (Error probabi.)	5×10^{-3} (Error probabi.)
Availability requirement (CAT II)	0.9985			
Availability requirement (CAT II)	0.9990			
Availability	0.998 (20km)	0.9997 (20km)	0.90 (10km)	0.939 (10km)
Theoretical performances	N/A	See section VI	N/A	N/A
Computation time	+	-	-	+

Table 3

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