ANALYSIS OF THE IMPORTANCE OF WIND IN CONFLICTS BETWEEN AIRCRAFT IN THE AIRSPACE

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Abstract

This article, on air traffic accelerated simulation, has two main objectives: firstly, to analyze the importance of wind in the conflicts between aircraft in the airspace and, secondly, to analyze an optimized version of a wind model originally developed by a European research group. To achieve these objectives, it was necessary to develop the model of the aircraft controlling system, as well as an airspace scenario, and a methodology to stochastically generate the aircraft both in space and in time. One of the main conclusions of this work is that the optimized wind model has a behavior similar to that of the original model, with the advantage that it has presented a considerable gain on computational efficiency.

Keywords: Safety Analysis, Certification, Air Traffic Control, Risk Assessment, Automation

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1. INTRODUCTION

According to INFRAERO (2007), in 2008, a total of 2,128,824 take offs and landings were observed in Brazilian airports. Comparing to a similar register made in 2004, there was an increase of 19%, observing a permanent upward trend. When analyzing the number of passengers, it is possible to observe a total number of 113,263,537 in 2008, which represents a 37% growth as compared to 2004. Knowing that there are a large number of rules to maintain airspace safety, several problems may be created, such as overloading air traffic controllers and airports. Therefore, the need to improve the methods and technologies used in air traffic management arises.

In order to help solving these problems, computer systems have been used either to help air traffic controllers with their duties, or in simulation of new scenarios for air traffic management. This work presents a contribution for decisions at the realism level to be used in simulations, considering those aiming to measure the probability of conflict in the airspace. The definition of conflict used here is from (Oliveira, 2007), in which airspace conflicts are defined as present or future situations in which two aircraft are hazardously close to each other. The objective of these simulations is to evaluate the safety of air traffic rules and technologies.

Several authors have developed stochastic models to analyze the conflict and collision risks in the airspace (Blom *et al.*, 2001; Oliveira, 2007; Vismari, 2007), where the wind influence is neglected, based on the opinions of air traffic specialists. On the other hand, Glover and Lygeros (2004) present a method to include the wind influence on probabilistic air traffic models. However, so far, this method has only been applied to limited scenarios (Chaloulos; Lygeros, 2007), with a maximum number of two aircraft, and a maximum flight time of 30 minutes, due to its computational complexity. Since more realistic wind models demand both greater memory and smaller simulation time, this work provides information on a variation of the Glover and Lygeros wind model, which allows the simulation of scenarios with a larger number of aircraft and longer duration.

This work is divided as follows. In section 2, the stochastic wind model and its optimization is presented. Section 3 focuses on the aircraft model and on its control system. Section 4 presents the airspace simulation scenarios as well the results of the simulation and the influence of wind on the aircraft conflict in the airspace rate. Finally, Section 5 is dedicated to final comments.

2. THE WIND MODEL

Wind may have a great influence in commercial aircraft flights. This influence is even more markedly observed on long distance routes, where front or rear wind may considerably affect the flight duration, or in landings with cross wind, where a greater control effort is demanded from pilots and flight control systems. Although several wind characteristics may affect a flight, the only wind aspect which is being taken into account is its speed.

A first approximation is made by considering the wind constant. Although its results are better than the ones obtained by a simulation with total absence of wind, they are not realistic, since the wind vectors vary considerably both in space and in time. Based on these facts, a stochastic model is presented, in which the wind is approximated by a sequence of Correlated Gaussian Vectors. The mean of these vectors is the wind conditions forecast of the wind speed of the area under analysis. In Brazil, this information can be found on the REDEMET (2007) web site, which is maintained by the Brazilian Air Force. The model to be presented was initially developed by Glover and Lygeros (2004) and, after this, its optimized version, in subsection 2.2.

2.2. The High Correlation Wind model

The model presented in Glover and Lygeros (2004) considers the instantaneous wind as a tridimensional vector, being represented on the Cartesian canonical base. This way, the wind is going to be described exclusively by its components, (X, Y, Z). The values assumed by this vector are extractions of a Gaussian probabilistic distribution, with a mean equal to the meteorological forecast information. Several assumptions are made in order to obtain a simpler model which would allow simulation. The first assumption is to consider the wind a wide sense stationary stochastic process (a stochastic process in which the mean is constant, and the covariance between two instants t and $t+\tau$ is only a function of τ). The second assumption is to consider the vector isotropic with respect to the X and Y components, which, in this model, represent the Earth's surface. The third assumption is to consider the wind independent in every direction. A fourth assumption considers the absence of high frequency factors, which represents turbulence phenomena, and finally a last assumption considers that the vertical wind is always equal to zero, based on the fact that the vertical correlation of wind decreases rapidly (Chaloulos;Lygeros, 2007).

Consider two extractions of wind vectors, $\{t, [x, y, z]^T\}$ and $\{t', [x', y', z']^T\}$, where t and

t' represent the time of these two extractions. The covariance ρ_{xy} between these two extractions, according to the Glover and Lygeros (2004) model is given by equation (1):

$$\rho_{xy}\left(t,\begin{bmatrix}x & y & z\end{bmatrix}^T, t',\begin{bmatrix}x' & y' & z'\end{bmatrix}^T\right) = \sigma^2 f_t(|t-t'|) f_{xy}\left(\begin{vmatrix}x-x'\\ y-y'\end{vmatrix}\right) f_z(|p(z)-p(z')|) \quad \textbf{(1)}$$

Where σ is the standard deviation of the wind speed which is equal to 7.7m/s. f_t is the correlation function of time, f_{xy} and f_z are the correlation functions on the plane *XY*, and on axis *Z*, respectively, and $p(z)$ is the variation of atmospheric pressure depending on the height. These functions, which were presented by Glover, Lygeros and Maciejowski (2005), are defined as

$$p(z) = 288.08\left(\frac{-0.00649\,z + 288.14}{288.08}\right)^{1/5.256} - 273.1 \quad \textbf{(2)}$$

$$f_t(\chi) = 0.154 + 0.7755 \cdot e^{\frac{-\chi}{118500}} + 0.0705 \cdot \cos\left(2\pi\frac{\chi - 32640}{76500}\right) \quad \textbf{(3)}$$

$$f_{xy}(\chi) = -0.006 + 1.006 \cdot e^{\frac{-\chi}{337000}} \quad \textbf{(4)}$$

$$f_z(\chi) = -0.1 + 1.1 \cdot e^{\frac{-\chi}{213}} \quad \textbf{(5)}$$

With equation (1) to (5), it is possible determine all elements of the covariance matrix of a given set of points, making it possible to calculate a wind realization for each of these points. However, by this method, it is necessary to know exactly the aircraft trajectory in order to perform the wind extractions, which would make the problem infeasible. Nonetheless, all covariance matrices are symmetric and positive semi-definite. Assuming that these matrices are non-singular, it would be possible to calculate their Cholesky??, and this decomposition could be calculated line by line, based only on past wind extractions.

In order to apply this method, it is necessary to assure that the covariance matrix is nonsingular. It has been empirically observed that this is the case for most simulations. However, there is a specific condition that would make this matrix singular, which happens when two different wind extractions are taken for the same point and the same time. This situation is so specific that it can be avoided, either by copying the previous extraction, because two wind extractions for the same point at the same time must be

identical. Thus, as both positive semi-definiteness and nonsingularity can be guaranteed, it is possible to consider the covariance matrix positive definite, and calculate its Cholesky?? decomposition.

This procedure, presented in Glover and Lygeros (2004) to calculate n^{th} extraction, based only on the previous extractions, is presented on equation (6).

$$w_n = \mu_n + \sum_{i=1}^{n} B_{ni} g_i \qquad \textbf{(6)}$$

where μ_n is the wind forecast for the n^{th} position in time and in space; g_i is an extraction of an independent Gaussian vector, with mean equal to zero and variance equal to $[1,1,0]^T$, for $i = 1,...,n-1$, the past extraction (which must have been stored in the memory), and $i = n$ the present extraction. The B_{ni} are the coefficients of the n^{th} row of the Cholesky?? decomposition of matrix $\{\rho_{ij}\}$, generated by the covariance function ρ_{xy}.

2.2. The Optimized Model and its Implementation

The wind model developed by Glover and Lygeros (2004) requires every single coefficient B_{ij} and ρ_{ij} to be stored with all wind values w_i and with all random vectors g_i. In other words, in order to calculate the next extraction, it is necessary to store the complete list of historical values of the simulation in the memory. This implies that the spatial complexity of the algorithm is $O(n^2)$, where n is the total number of wind vectors generated during the simulation. Rewriting the spatial complexity of the algorithm using the number of aircraft N_a and the total number of simulation steps T, it is possible to observe a complexity of $O(T^2 \times N_a^2)$.

Analyzing the structure of the problem, it is possible to observe that as long as matrix $\{\rho_{ij}\}$ grows, the importance of the older lines decreases in the calculation of the newer ones, due to the fact that these lines are distant from the newer ones in time and/or in space, which implies that they have a small correlation. A way to solve the quadratic memory consumption problem consists in truncating the first k lines and columns of the matrix $\{\rho_{ij}\}$, obtaining a new matrix with dimensions $(n-k)\times(n-k)$. This is equivalent to restarting the simulation when it is truncated. It is important to mention that this procedure must not be performed directly in the matrix $\{B_{ij}\}$, because it is possible to observe that the coefficients stored in the first columns are considerably greater that all the other elements in a row. If this column is eliminated, the system may become divergent,

as it was empirically observed. Hence, it is necessary to truncate matrix $\{\rho_{ij}\}$ and recalculate its Cholesky decomposition, matrix $\{B_{ij}\}$. Besides, due to importance of row $\{B_{1j}\}$, it is important to store the value of g_1, obtained before the matrix was truncated, and reuse it as presented in equations (7)-(10). This way, the new formula to obtain a wind extraction, considering the elimination of the rows and columns 1,…,*k* of matrix $\{\rho_{ij}\}$, is:

$$w_n = \mu_n + B'_{k+1}g_1 + \sum_{i=k+2}^{n} B'_{(n)i}g_i \quad \textbf{(7)}$$

Where B'_{ij} is obtained by

$$B'_{n(k+1)} = \frac{\rho_{(k+1)n}}{B'_{(k+1)(k+1)}} \quad \textbf{(8)}$$

$$B'_{ni} = \frac{\rho_{in} - \sum_{j=k+1}^{i-1} B_{ij}B_{nk}}{B_{ii}} \quad \textbf{(9)}$$

$$B_{nn} = \sqrt{\rho_{nn} - \sum_{j=k+1}^{n-1} B_{nj}^2} \quad \textbf{(10)}$$

2.2.1. Comparative Precision Analysis

In order to verify the precision of the optimized model, a simulation was made, in which several wind samples were extracted every 10s for a period of 10,000s, from a fixed point, enabling to observe an average wind intensity of 35 knots and the direction of 35° Northeast. This simulation was made in two steps. Firstly, the simulation was performed with the original (Glover;Lygeros, , 2004) algorithm. At a second moment, the same scenario was simulated with the optimized algorithm, with the first truncation, in which 20 samples would be discarded, being performed after 500 seconds, meaning that the correlation matrix maximum dimension would be of 50 samples. Then, the truncation would happen again every 200 seconds, it means, as long as 20 new samples would be extracted. In figures 1 and 2, it is possible to observe the evolution in time for both the module and the direction of the wind. It is possible to observe through figure 1 that the wind sample average is 29 knots, when it was said that the average would be 35 knots. The reason for that is that the wind intensity is dependent on the first extraction, which has a standard deviation of 7.7 knots (Glover;Lygeros, 2004).

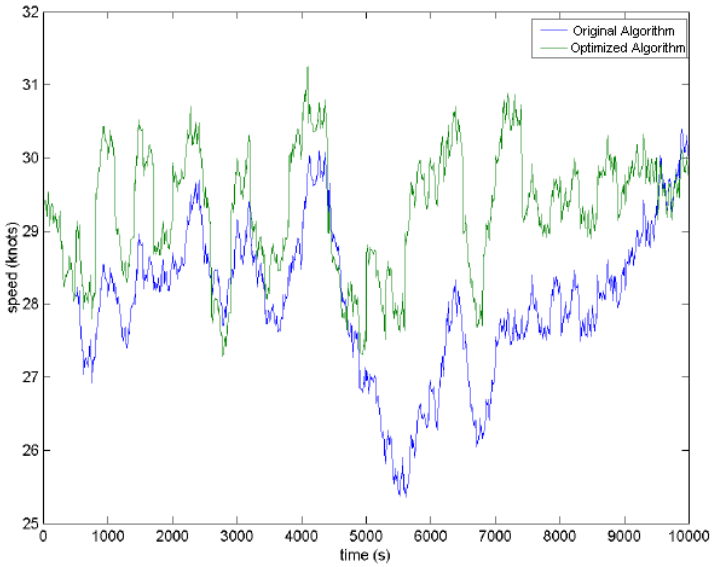


Figure 1 - Comparison Between the Wind Speed for the Original and Optimized Model.

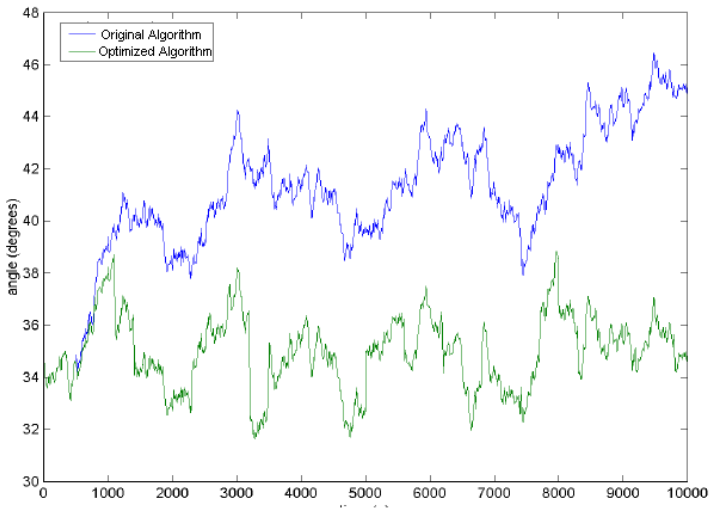


Figure 2 - Comparison Between the Wind Direction for the Original and Optimized Model.

Through these images, it is possible to observe that, even with a high extraction rate, a sample every 10 seconds, the optimized model does not considerably diverge from the original model (There was a larger divergence in the wind direction analysis; however, the original wind model presents a larger final fluctuation, apparently due to cumulative errors). Besides, the optimized model seems to reduce the effect of cumulative errors, due to the fact that matrix $\{B_{ij}\}$ is periodically reset.

2.2.2. Comparative Performance Analysis

The optimized model used at most a 50×50 matrix, whereas the original model matrix

final matrix was 1000 ×1000. This does not certainly represent a problem, not even for personal computers nowadays. However, when Monte Carlo simulations with importance sampling is used (Oliveira, 2007), it is necessary to store thousands of matrixes in the memory.

When matrix $\{\rho_{ij}\}$ truncation is performed, it is necessary to recalculate all coefficients of matrix $\{B_{ij}\}$, which demands an additional time of $O((m-k)^2)$, at every truncation, where m is the maximum size of the matrix $\{\rho_{ij}\}$. Nevertheless, it is necessary to consider that the matrix size is reduced drastically, reducing the total number of operations for a wind extraction, distributing the time necessary for the truncation. For example, when the optimized algorithm is run with m=50 and k=20, every truncation requires a calculation of $O((m-k)^2) \approx (50-20)^2/2 = 450$ coefficients B_{ij} (the ½ factor, comes from the fact that the matrix is triangular), every 20 samples, which can be considered as a surplus of 22.5 calculations at every single extraction. When the 1000th sample is analyzed, it is possible to observe that it is necessary to calculate 50 ρ_{ij} coefficients and 72.5 B_{ij} coefficients for the optimized algorithm, and this number of calculations is this upper bound. On the other hand, with the original algorithm, it is necessary to calculate 1000 ρ_{ij} coefficients and 1000 B_{ij} coefficients, and the total number of calculations, which is unbound, would continue to growth for the following extractions.

With this result, it is possible to observe that the computation time would drastically be reduced. This difference was observed in a simulation where 100 scenarios, with 2000 extractions each, were executed. The total time for this simulation with the original method was of 4045s, and the total simulation time with the optimized method was of 42s.

2.2.3. Comments on the wind model

In Section 4, it is analyzed if a realistic wind model plays an important role in air traffic simulations for safety analysis. Considering that it is important to use a realistic wind model, it is necessary to take in account that, in Monte Carlo simulations, it is necessary to perform millions of simulations, with thousands of wind extractions each. With this, it can be said that the optimized model is quite realistic, with a considerably low consumption of RAM memory, and a much smaller simulation time than that necessary for the original model (Glover;Lygeros,, 2004).

3. AIRCRAFT DYNAMICS

In order to perform the simulations, besides having a realistic wind model, it is also

necessary to have a model of the aircraft dynamics, considering an automatic closed-loop control algorithm, which is used in modern commercial aircraft. This control-loop is composed by systems that react to the measured wind disturbances, in order to maintain the aircraft on its route, offering an acceptable comfort level to the passengers. The model describing the aircraft dynamics is presented in figure 3.

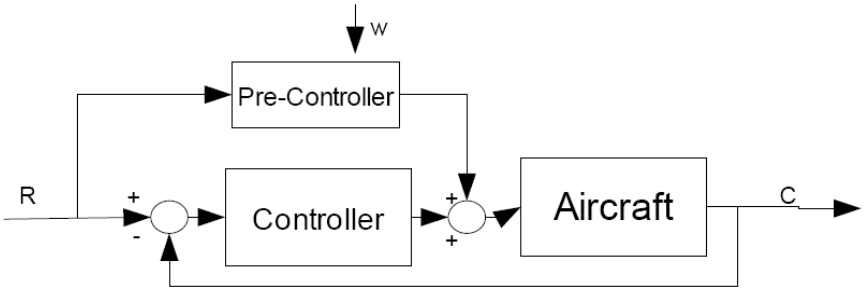


Figure 3 - Aircraft Control-Loop

It is assumed here that all aircraft fly at a constant height of 30,000 feet, at cruise speed, with a constant velocity, compared to the surrounding air mass. The maximum flown distance is of 300 nautical miles, which makes the fuel consumption considerably low, and validates the constant aircraft mass approximation. Let x_1 be the aircraft position in the West-East direction, x_2 be the aircraft position in the South-North direction and x_3 the heading angle. Let u, which is the aircraft roll angle, be the control input, and $X = [x_1, x_2, x_3]^T$ the system state. The system dynamics can be defined by:

$$\dot{X} = \left[v\cos(x_3) + w_1 \quad , \quad v\sin(x_3) + w_2 \quad , \quad \frac{g}{v}\tan(u) \right]^T \qquad \textbf{(11)}$$

Good simulation results were obtained using the fourth order Runge-Kutta method, which has an error of $o(X^5)$, for a time step of 1 second, in order to solve this system. Although the initial position is arbitrary, it is necessary to fix the initial heading angle x_3 in order to avoid the initial transitory dynamics, which may make the model unstable. However, the solution for this stability problem is shown in next section.

An important remark about this model is that the system has 3 outputs, which are the system states, and only one input. It may be thus possible to infer that there are not enough degrees of freedom in this system, which would indicate that the system is not reachable (Astrom; Wittenmark,, 1984). This would mean that it is not sure whether the aircraft will be able to achieve a given state. However, since it is important for the model to fly through given paths, which would create

a link between x_1 and x_2, and also considering that x_3, despite being an output, is not controlled; it is possible to observe that the problem concerning the number of degrees of freedom is solved. Another problem is that the variable being manipulated is an angle, which is intrinsically bounded; this would limit the operation range. In order to solve this problem, we limit the applicability of this model to systems where the wind speed is much smaller than the aircraft speed.

3.1. FEED-FORWARD CONTROL LOOP

The feed-forward segment, which is represented by the "pre-controller" block in figure 3, is used only during the aircraft start-up, in order to correct the heading angle. From the initial and final positions of the flight plan, it is possible to determine the desired heading angle; however, due to the wind presence, it is necessary to correct this angle in order to attain the goal. The initial angle is determined by the expression:

$$x_3^0 = \Psi - \arcsin\left(\frac{\| \vec{w} \|}{v} \sin\left(\langle \vec{w} \rangle - \Psi\right)\right) \qquad \textbf{(12)}$$

Where Ψ is the desired heading angle, $\vec{w}$ is the wind vector, and $\langle \vec{w} \rangle$ is the wind angle.

The idea behind this feed-forward loop comes from the fact that if the aircraft initial state is set with a heading angle equal to the desired value, due to the presence of the wind, the controller will force a sudden change in the roll angle, in order to correct this value. Hence, this control loop sets the aircraft to its cruise direction.

3.2. THE FEED-BACK CONTROL LOOP

Since the wind model is stochastic, it is necessary to implement a feed-back control loop in order to make the aircraft follow the desired path. In figure 3, this controller is represented by the "controller" block. As long as the system is modeled by a group of non-linear equations, a way to stabilize the system would be to find a Lyapunov function for this system. However, since this solution would demand great experience and mathematical intuition, this analysis methodology was discarded. For this reason, the choice was to work with a variant of the heuristic solution, presented by Glover and Lygeros, (2004), a proportional controller that limits the roll angle to $\pm 35°$ and the variation on the heading angle of $\pm 60°$.

However, since this controller was based on a proportional controller, it was possible to observe a steady-state offset, which is represented by the fact that the plane would fly through a path that is parallel to the desired one. In order to eliminate this offset, which was considered undesirable, an integral

factor was introduced to the controller, obtaining the expression

$$u(t) = k_1 d(t) + k_2 \theta(t) + k_3 \int_0^t d(\tau) d\tau \qquad \textbf{(13)}$$

The controller presented in equation (12), in the classical control theory is called a PI (Proportional and Integral) controller, where for the k_i constants adjusted empirically, t is the present time, $d(\cdot)$ is the distance between the aircraft and the desired path (the flight plan), and $\theta(\cdot)$ is the difference between the current heading angle and the theoretical one, obtained from the flight plan. After several experiments, the gains of this controller have been fixed to

$$k_1 = 1.0 \times 10^{-4}; k_2 = 1.0; k_3 = 1.4 \times 10^{-6} \qquad \textbf{(14)}$$

Samples of this controller response may be observed In figures 4 and 5.

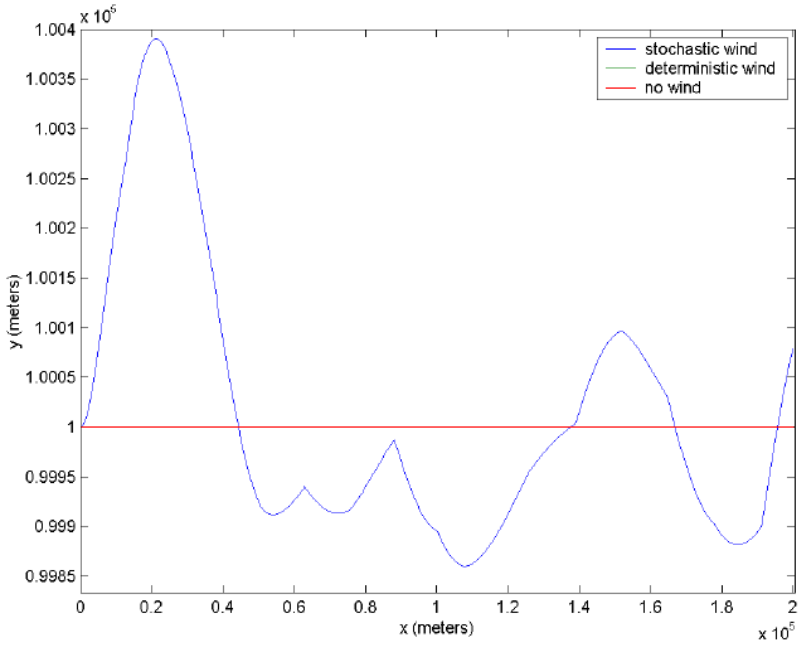


Figure 4 - Aircraft Trajectory for Along Path Wind.

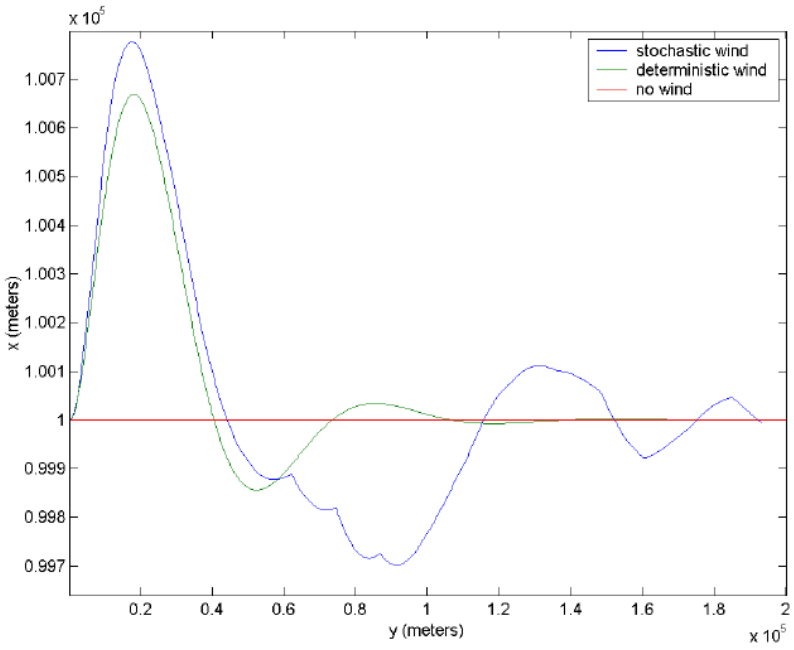


Figure 5 -Aircraft Trajectory for Cross Path Wind.

It is important to mention that in figure 4, paths followed by the scenario with no wind and the scenario with deterministic wind are identical, since the influence of the wind happens only in the direction of the path, affecting only the aircraft speed. On the other hand, due to the fact that the stochastic wind presents components on the cross path direction, even though its mean is on the along path direction, its trajectory is different from the others.

The response of the PI controller takes longer to pass the transient state; however, it eliminates the steady state error.

4. THE AIRSPACE SIMULATOR

This section describes an airspace simulation software that was implemented and used to compare the influence of different wind models in the conflict rate of aircraft flying on assigned routes. Firstly, the simulator and some implementation details are going to be described, then the results of the comparison between the different wind models will be presented.

4.1. THE SIMULATOR DESCRIPTION

The airspace simulator is a computer software which takes a group of *n* routes as input, randomly generates the aircraft and lets them fly along these routes. At the end of the simulation, it generates a report with all the conflicts occurred between the aircraft. In this software, a route is theoretically defined as a straight line between its start point and its end point, with a fix height of 30,000 feet.

4.1.1. The aircraft generation

The aircraft generation is one of the main tasks of the software. Firstly, it introduces an aircraft on at a random time and at a random point near the beginning of the route. Secondly, it removes the aircraft from the simulation, either because it was out of the simulation space, or because a certain amount of time has elapsed, which has been stochastically generated for each aircraft has passed, representing that the aircraft is passing into another flight level (different height), being therefore in another conflict zone.

The time to insert and remove aircraft into and from the route is given by two Poisson processes, with a mean equal to the necessary time for an aircraft to entirely fly this route. In other words, this airspace model can be classified as an ensemble of *n independent* M/M/1 queues (Robert,, 2003). According to the queues theory, this queue would be stable, because the entrance probability is equal to the exit probability, always having an average number of aircraft equal to 1. However, since the objective of the analysis is to analyze the number of conflicts between aircraft, it is important to have a higher number of aircraft in the studied airspace, so the insertion rate is multiplied by a constant k_n>1, and the removal rate is multiplied by another constant $0< k_t < 1$.

The multiplication by the two constants makes all M/M/1 models divergent, making the average of aircraft on one route unbound. This problem is solved by the fact that the analyzed airspace is limited; the aircraft are removed when they get out of the analyzed space, even if it is not its removal time. Another point is that there is a minimum time before another aircraft is generated. This minimum time was created in order to avoid conflict between two aircraft on the same route. Due to the presence of these two constraints, the queue stability problem is solved. On the other hand, the system can no longer be classified as an M/M/1 queue, as it is difficult to classify its behavior in the standard queuing theory.

4.1.2. Conflict detection

Besides introducing and removing aircraft from its route, another function of the simulator is to detect conflict between the aircraft, and to register it for further analysis.

On an airspace that is not near any terminal zone, and that is covered by modern radar systems, a distance of 5 nautical miles (NM) is an appropriate reference, but it is also interesting to have more accurate information on the intensity of the conflicts. For this reason, 4 different conflict stages were created, which can be imagined as 4 concentric circles, having an aircraft in its center. A first level conflict takes place when

the distance of two aircraft is smaller then 5NM. When this distance becomes smaller than 3NM, it turns into a level two conflict. A level three conflict takes place when the distance between the two aircraft becomes smaller than 1NM. Finally, when the distance is smaller than 50m, the last conflict level is achieved, representing the collision between the two aircraft. Two aircraft that enter into conflict are only going to leave it after a minimum time of 1 minute. This rule was introduced due to the fact that the number of conflicts between to parallel routes can increase abruptly, due to oscillations of the aircraft along the path.

4.1.3. The Influence of Wind on the Conflict Rate

An important issue in this study is to analyze if the presence of wind in the simulation increases, reduces or doesn't affect the conflict rate. However, the configurations of the different routes, if they are parallel, or the angle of their crossing, may considerably affect the results (Chaloulos; Lygeros, , 2007), and in order to perform the analysis of the wind importance, a configuration with a wide variety of cases was chosen, as shown in the figure below.

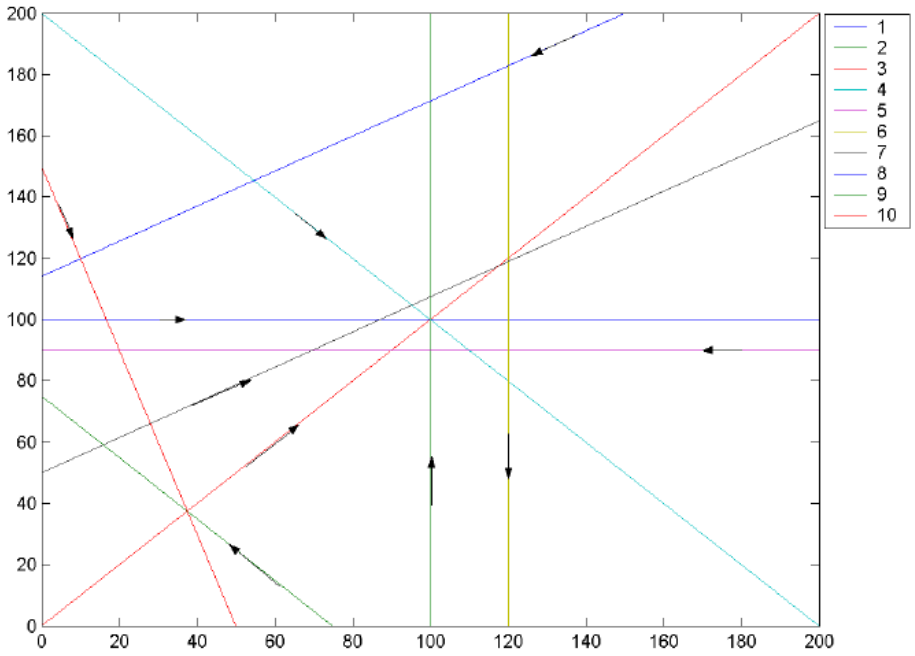


Figure 6 - Simulated Air Space Scenario.

The analyzed airspace was represented by a square with 200NM in side, with 10 routes in which the aircraft fly only in one direction. Due to the large number of crossings, the

insertion and removal processes have been adjusted so as to allow all aircraft to fly the longest distance possible on the route. The aircraft was stochastically inserted in the first 0.1% segment of the route. Besides that, in order to maximize the number of airplanes that completed the route, parameter k_t=0.001, so that almost all aircraft are removed only because they have reached the end of the flying space. The maximum number of simultaneous aircraft flying was 20, and the average was 13, which was obtained by setting parameter k_n=2. The TAS (True Air Speed, which is the velocity in relation to the surrounding air mass) was set to 200 meters per second, which is approximately the speed of air jets, such as Boeing 737-300. The calculation step for both the differential equation and the control loop was of 1s, while the wind was updated every minute. The wind speed average was a 35-knot wind in the west-east direction. Finally, the maximum size of the covariance matrix was set to be equal to 500, and whenever the truncation was made, the first 300 columns and rows were discarded.

Three different wind scenarios were performed in order to analyze its influence: the optimized stochastic wind, presented in section 2; a constant wind scenario and finally a scenario with no wind at all. A total time of 5 years was simulated for each of the scenarios (being performed for approximately 20 hours in desktop PC), totalizing a total number of flight hours for each route presented in the table below.

Route	Stochastic Wind		Deterministic Wind		Absence of Wind	
	Aircraft	Flight	Aircraft	Flight	Aircraft	Flight hours
1	151,062	66,443	151,546	66,634	150,989	71,995
2	151,488	72,652	151,239	72,485	151,275	72,135
3	108,693	68,007	109,119	68,223	108,764	71,876
4	108,861	68,076	108,675	67,869	108,446	71,661
5	151,321	79,072	150,887	78,610	151,568	72,284
6	151,391	72,555	151,580	72,562	151,384	72,088
7	132,725	67,666	132,474	67,395	132,020	72,039
8	173,621	78,116	174,049	78,226	174,160	72,332
9	272,622	76,101	272,999	76,064	272,192	71,038
10	188,425	70,359	189,389	70,655	188,195	71,780

The number of conflicts for each of the scenarios is presented in the figures below.

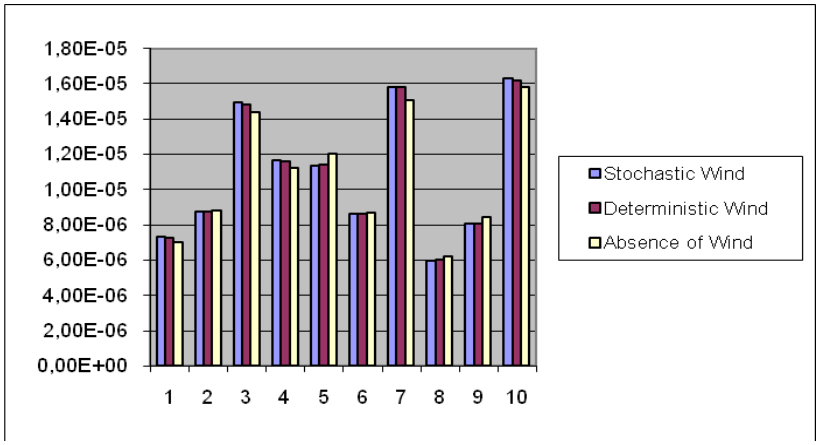


Figure 7 - Number of 5NM Conflicts per Route per Aircraft.

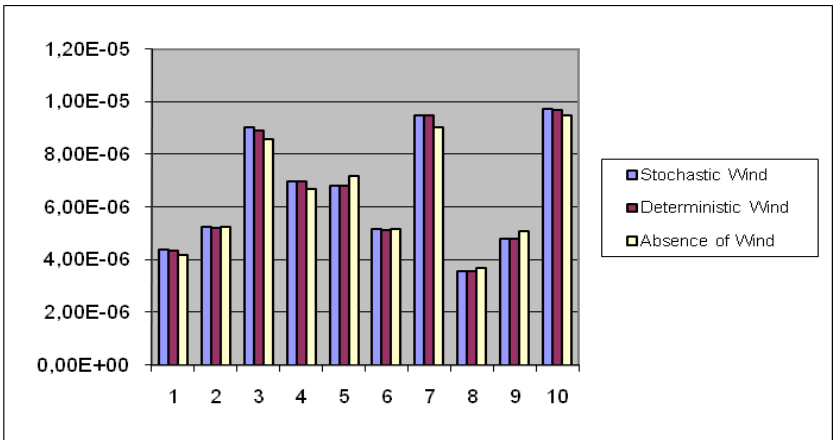


Figure 8 - Number of 3NM Conflicts per Route per Aircraft.

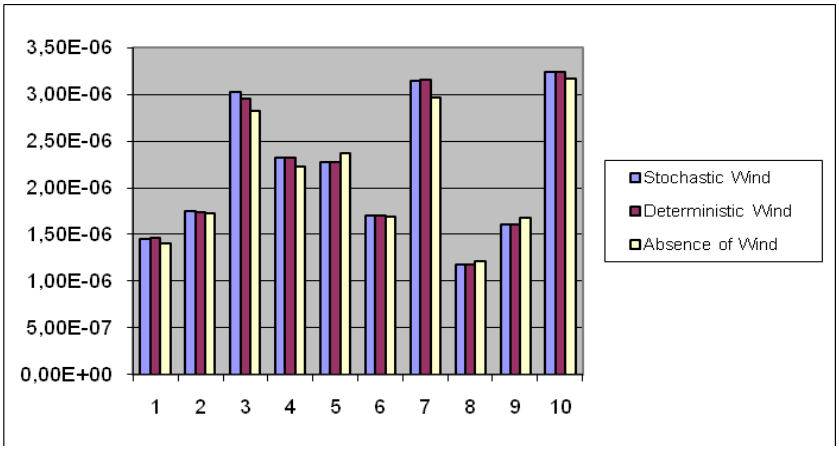


Figure 9 - Number of 1NM Conflicts per Route per Aircraft.

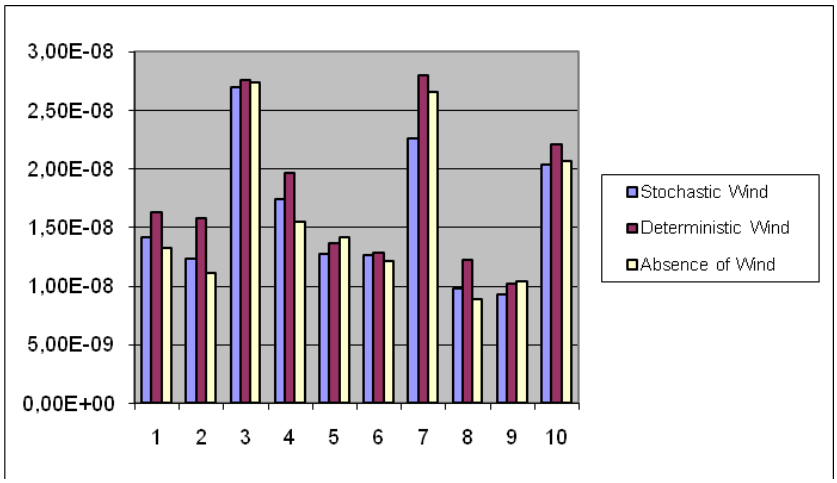


Figure 10 - Number of Collisions per Route per Aircraft.

From these results, although it is possible to observe several differences in the number of conflicts among the different wind models, there are no general tendencies for augmentation or reduction in the conflict rate for any of the models. Depending on the route, every model presented different results, and in several cases, the results were extremely similar. This similarity may be attributed to the aircraft controller precision, which presented a maximum transversal deviation equal to 800m. However, this controller still respects the real requirements of modern navigation systems.

A deeper analysis on the simulation results, which was carried out for the 5NM conflict rate, per aircraft per route, showed the following facts:

- The scenario with absence of wind presented a larger conflict rate on 60% of the routes, while a larger conflict rate was observed only on 20% of the cases for the constant wind scenario, and another 20% for the stochastic wind scenario
- The scenario with deterministic wind presented the smallest conflict rate on 50% of routes, while this happened only on 10% of the routes in the stochastic wind scenario and 40% in the scenario with absence of wind.
- The mean square difference between the conflict rates of the scenarios with stochastic wind and absence of wind was 2.26%, with a tendency of a higher rate in the scenario with no wind.
- The mean square difference between the conflict rates of the scenarios with deterministic wind and absence of wind was 2.36%, with a tendency of a

higher rate in the scenario with no wind.

- The mean square difference between the conflict rates of the scenarios where there was wind was 0.41%, with a tendency of a higher rate in the scenario with stochastic wind.

- There are no conflicts between parallel routes (since there are no extreme deviation cases), showing that a 10NM separation between routes can be considered safe under the hypothesis used in these scenarios.

Besides that, figure 11 allows observing large differences in the collision rates for the different scenarios. This happens due to the fact that collision is a rare event, even in scenarios developed to have a high conflict rate, with a simulated time of approximately 700 thousand flight hours for each scenario. Therefore, the number of collisions becomes an inaccurate indicator.

It is important to emphasize that the chosen airspace configuration was chosen so that the number of conflicts is much higher than real-life numbers. This choice was made because the objective of the study was to analyze the sensitivity of the conflict rate indicator for different wind models, and the variance in the results should be reduced.

5. FINAL COMMENTS

The stochastic model presented in Section 0, which was used in subsequent simulations, provided a performance gain of approximately 100 times when compared to the original Glover and Lygeros model (2004).

The results obtained indicate that the presence of wind in the simulations creates a reduction of about 2.3% in the number of 5NM conflicts, showing that the scenarios with absence of wind are slightly pessimistic. In 40% of the routes, the scenario with absence of wind presented the smallest rate of conflicts. The results indicate that the wind creates a pessimistic or optimistic tendency depending specifically on the crossing geometry. Any more general conclusion is hard to draw, unless one analyzes the behavior of the specific crossing geometries concerning the wind models, and tries to deduce classification rules, which will demand a larger number of simulations.

It has also been observed that the difference between the conflict rates of the scenarios with stochastic and deterministic wind was only about 0.4%, with a slightly optimistic tendency to the deterministic scenario. Besides, due to the fact that the deterministic wind model is less expensive computationally, it can be used instead of the stochastic model for conflict analysis, unless

the precision requirements are extremely strict. However, it is not possible to draw a similar conclusion about the number of collisions, since a sufficient number of results for this were not obtained.

In order to further develop this research work, the following lines could be followed:

- To create a new version of the simulator with non-null vertical wind, together with the improvement of the aircraft control loop to perform the vertical trajectory control;
- To perform a greater number of simulations, aiming at categorizing the trends increase and decrease in the conflict index, according to the route crossing type. This could allow unbiasing in simulations which do not use the wind model;
- To develop a wake vortex model and its integration to the present wind model, for the elaboration of terminal airspace scenarios, close to the airports.

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