QUANTITATIVE SAFETY ASSESSMENT OF CNS/ATM-BASED AIR TRAFFIC CONTROL SYSTEM

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Abstract

This paper presents a quantitative assessment of the impact of paradigm CNS/ATM (Communication, Navigation, Surveillance/Air Traffic Management), specifically the concept of Automatic Dependent Surveillance - Broadcasting (ADS-B) on the safety levels of the Air Traffic Control system (ATC). A comparative assessment was made on what levels of exposure to events of loss of separation (AIRPROX) aircraft will be submitted when inserted into two distinct ATC environments: the current environment, which is based on Radar surveillance and navigation by radio-aids, and the environment CNS/ATM, the surveillance of which will be based on ADS-B and satellite navigation. As the main result, it was concluded that the ADS-B, **even making the elements of navigation and surveillance independent**, is a viable application, in terms of safety, for the ATC under the CNS/ATM paradigm.

Keywords: CNS/ATM, ADS-B, Risk Assessment, ATC, AIRPROX.

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1. INTRODUCTION

Over recent decades, the paradigm of safety critical systems has undergone changes so as to adapt itself to the new social demands, such as reducing costs and increasing productivity. In the air traffic system paradigm, changes are being ruled by the so-called CNS/ATM (Communication, Navigation, Surveillance / Air Traffic Management) paradigm. As defined in ICAO (2000), the CNS/ATM is "… *employing digital technologies, including satellite systems together with various levels of automation, applied in support of a seamless global air traffic management system*". The CNS/ATM is aimed at the following improvements for each one of the air traffic system elements (ICAO, 2000):

Communication: increasing coverage, accessibility, capacity, integrity, performance, safety and security for the aeronautical communications systems;

Navigation: increment coverage and operational capacity in any weather conditions and airspace type, including approaches and landings, while maintaining or increasing the levels of integrity, accuracy and performance;

Surveillance: expanding effective surveillance coverage over oceans and remote areas, and the increment of situational awareness for the pilots;

Fig.1 presents the evolutionary plan developed by the International Civil Aviation Organization (ICAO) to achieve those desired improvements for the "C", the "N" and the "S" air traffic system elements.

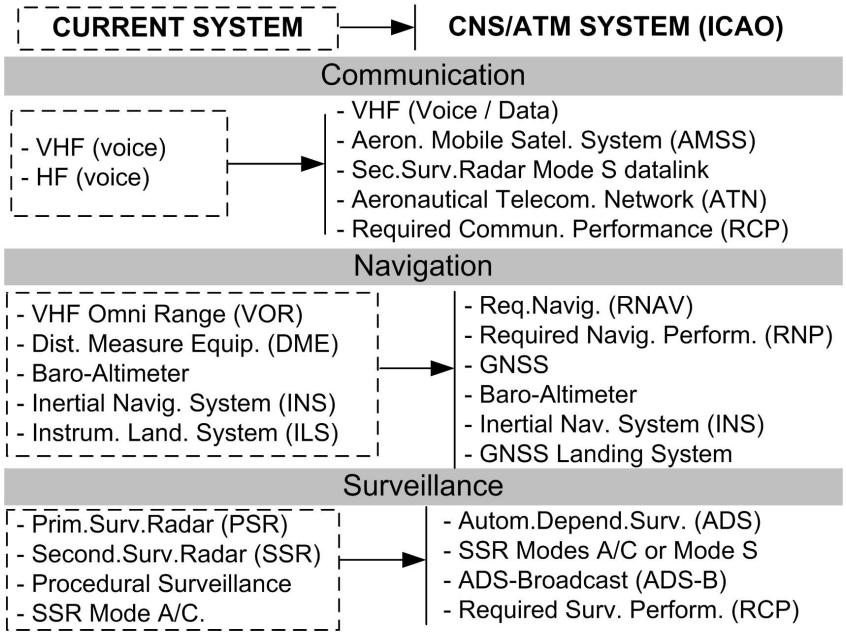


Fig.1 - CNS/ATM technological evolution

In a systematic way, local improvements in the air traffic system elements intend to comply with the CNS/ATM mission, that is, to develop comprehensive and unified Air Traffic Services (ATS) to supply the growth in demand for this type of transport, accompanied by improvements in the air traffic safety, regularity and efficiency levels.

The Air Traffic Control (ATC) is one of the air traffic services most impacted by the CNS/ATM concept, since the elements of communication, navigation and surveillance of air traffic system are used by Air Traffic Controllers (ATCo) to accomplish the ATC mission, which is to prevent collisions, both between aircraft and between aircraft and obstacles in the area of operations, and to accelerate and to maintain the orderly air traffic flow (ICAO, 1998a). Fig.2 is a simplified architecture of the ATC system, illustrating the information flow among its elements (C, N, S and users - "ATCo" and "Pilot").

The separation values practiced by ATC are both related to the quality of information available to pilot and ATCo (communication and surveillance performances) and the accuracy with which the pilot adheres to its trajectory (navigation performance) (ICAO, 1998a). Regarding communication and surveillance elements, their inaccuracies and limitations introduce uncertainty about the real situation of the controlled environment (the aircraft positions), affecting the process of conflict detection and resolution executed by ATCo. Regarding the navigation element, its inaccuracies and limitations lead to the increase in potential conflicts, because the pilot tends to wrongly occupy larger regions of airspace. All of those inaccuracies and limitations impact the effective separation values applied between aircrafts by ATCo, which limits the flow capacity of the whole air traffic system.

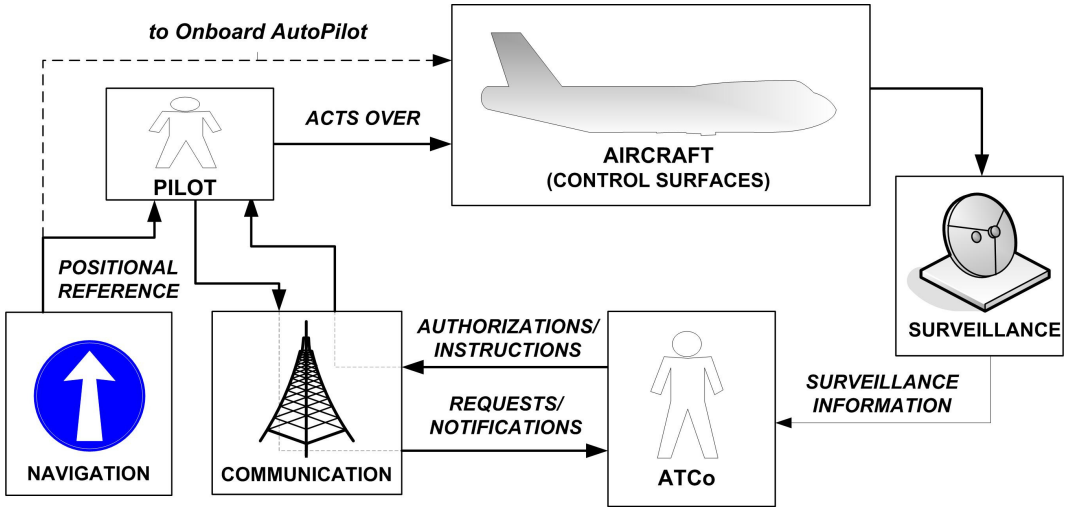


Fig.2 - Air Traffic Control architecture

Based on these facts, it can be concluded that the CNS/ATM paradigm is the solution to minimize the constraints to the air traffic system capacity, because technological developments on the CNS elements directly affect the characteristics of the ATC and, consequently, their ability to manage the separation distance between aircraft, beyond the possibility of improvements in conflict detection and resolution process due to newer levels of automation.

Thus, the CNS/ATM introduces a new concept in the air traffic system. As occurs in any safety critical system, it is necessary to assess if this new paradigm will be able to meet the desired safety levels before its effective implementation. In this way, the authors have developed an extensive work focused on identifying the methodological needs to quantitatively assess the safety of this new air traffic system paradigm. The main work results were a quantitative risk assessment methodology – the details of which can be found in Vismari (2007) (complete work in Portuguese) or in Vismari and Camargo Junior (2005, 2008) – and its application over a real CNS/ATM-based ATC system. In this experience report, our aim is to present the steps of this safety assessment work, highlighting the main real parameters involved and to discuss some of the results obtained.

2. THE "CNS/ATM-BASED ATC SYSTEM": A QUANTITATIVE SAFETY ASSESSMENT

2.1. The Methodology

As described before, the authors have developed a work focused on identifying the methodological needs to quantitatively assess the safety of the CNS/ATM paradigm. One major requirement was to adopt methods and techniques fully known and applied to the air

traffic community. In this way, the work resulted in a quantitative risk assessment methodology. For details, see Vismari (2007) (complete work in Portuguese) or Vismari and Camargo Junior (2005, 2008).

In summary, this quantitative assessment methodology consists in applying the "absolute" assessment method recommended by ICAO (1998b) both in system under evaluation (named "Proposed System") and in a legacy system, named "Reference System". From those independent processes, common safety metrics are obtained, which are compared to determine if the proposed system is safe. In both systems (reference and proposed), it is necessary to adopt the same functional elements and the same safety metrics. The differences between systems are represented in the system parameters, as can be observed herein. The formalism applied to modeling both systems is the Fluid and Stochastic Petri nets (FSPN), and metrics are obtained by Discrete Event Simulation (DES).

2.2. Defining systems under assessment

For this assessment work, the CNS/ATM characteristics that have the most significant impacts over the current ATC paradigm were chosen. It can thus be noticed that the CNS/ATM key elements are based mostly on the existence of two main concepts:

1. A Global Navigation Satellite System (GNSS), which provides both the navigation functionality to aircrafts and the surveillance functionality to Air Traffic Controller (ATCo);
2. An Aeronautical Telecommunications Network (ATN) that will safely and efficiently handle all the aeronautical information between different systems users.

One of the main concepts belonging to the ATN is the Automatic Dependent Surveillance - Broadcast (ADS-B), defined by ICAO as a component of the ATN Application Layer (a 7th ISO/OSI model layer) (ICAO, 1999), responsible for creating and exchanging "ADS reports" (containing position and other information reports required for aircraft flight management) between networks end users (e.g. controllers, pilots) and in a broadcast manner (ICAO, 1999). The ADS-B is considered by the ICAO "*... an Enabler of the Global ATM operational concept bringing substantial safety and capacity benefits ...*" (ICAO, 2006), and represents the fusion between communication (the ATN) and navigation (the GNSS) technologies.

The existence of the ADS-B significantly changes the concepts of navigation and surveillance as we know them. Besides, the

ADS-B itself represents a significant drop in paradigm due to the merger between the communication and navigation fields; it also introduces a strong interdependence between the navigation and surveillance areas. In the current air traffic system, there is a clear decoupling between these areas, because the technology used for surveillance (e.g. Primary and Secondary Surveillance Radars (PSR/SSR)) and navigation (NavAids, such as VHF Omnidirectional Range (VOR) and Distance Measuring Equipment (DME)) are independent of each other. In the case of CNS/ATM, the surveillance is going to be based on ADS-B, which is fully dependent on the technologies used in the navigation field, such as GNSS.

Besides the interdependence between navigation and surveillance, created by ADS-B, other systemic parameters have significant conceptual changes. For example, the current surveillance systems (PSR and SSR) take aircraft positions in a synchronous and deterministic way. ADS-B introduces randomness and asynchronism components, typical in digital communications networks (in this case, the ATN).

Another challenge in CNS/ATM will be dealing with the requirements of aeronautical systems. For example, being the ADS-B part of surveillance, the aeronautical authorities should be concerned both about the requirements for surveillance (range, time of update, accuracy, among others) and the requirements of communication (such as manipulation of messages, priority of messages and quality of service).

Following the methodology developed for this scenario, this safety assessment work has used two ATC systems concepts: the current (the reference) and a CNS/ATM-based (the proposed); both containing the functional elements illustrated in Fig.2 “plus” the Airspace characteristics (route structure, flight plans and so on). The differences between the proposed system adopted (CNS/ATM-based) and Reference System (current ATC) were the Navigation and the Surveillance elements: in the Reference System, the Surveillance was based on Radar (SSR) and Navigation on VOR/DME; in the Proposed system (CNS/ATM), the Surveillance was based on ADS-B and on Global Navigation Satellite System (GNSS). In each of the systems, the elements airspace, aircraft, communication systems and ATCO have the same parameters concerning test comparison.

2.3. Defining the system functional parameters

The following parameters were defined for the elements in both systems:

Airspace: we considered pairs of aircraft, A_1 and A_2, flying in routes A and B, respectively, in 45º convergent on a point of notification Oz, at the same altitude and at the same speed (280kts). In these flights, the minimum separations between aircraft are planned to occur when aircraft A_1 reaches Oz.

Aircraft: three main parameters were considered for each aircraft i: position (P_i), speed (V_i) and heading (ψ_i). Then, the status of an aircraft i (A_i) at a given time t is defined as $A_i(t) = (P_i(t),V_i(t),\psi_i(t))$. The aircraft were responsible for following their own flight plans, controlling $\psi_i(t)$ using the onboard navigation systems and obeying the ATCo instructions .

Air Traffic Controller (ATCo): its availability to detect conflicts was considered, as well as the time spent to take a decision and to communicate it to pilots. The process of conflict resolution starts after ATCo sees a successive number of pairs of aircraft on his monitoring screen with separation smaller than the minimum adopted (5NM). The process is concluded with ATCo instructing Pilots to proceed with a flight resolution maneuver (resolution heading).

The parameters of Navigation and Surveillance elements for the current ATC system (Reference) were:

Navigation: characteristics of a real VOR/DME (mainly its radial axis accuracy) were used; its transmitter was installed at the notification point Oz.

Surveillance: the aircrafts positions provided to ATCo were obtained from a Secondary Surveillance Radar (SSR) installed at 200NM from Oz. The parameters considered for the SSR were their accuracy position (range and azimuth), the scan rate and acquisition latency. The parameter values used were based on a real SSR Mode S (ICAO, 2004).

The parameters of Navigation and Surveillance elements for the CNS/ATM-based ATC system (proposed) were:

Navigation: the navigation positioning was obtained by means of onboard GNSS receivers. The parameter considered was the accuracy of the GNSS position, the values of which are defined at Brooker et al. (2004).

Surveillance: the aircrafts positions provided to ATCo were obtained from their own onboard navigation system (GNSS) and sent through the ATN system (ADS-B). The parameters considered for ADS-B were its scan rate and the latency between the positional acquisition and submission to ATCo. The parameters used were based on Brooker *et al.* (2004). Unlike the reference system, the parameters of which “scan rate” and latency are deterministic, these

parameters were considered stochastic in ADS-B.

In addition to assessing the CNS/ATM in its normal operating conditions (parameters within the specifications), it was planned to be evaluated in degraded situations, aiming to determine the operational situations in which the proposed system could maintain the same safety levels observed in the reference system.

As an example, the normal operating conditions used in this assessment process were:

On the Navigation element:

- VOR: radial accuracy (at receiver) = 1.4°@95%.
- GNSS: accuracy of position (two-dimensional) = 107.94m@95%.

On the Surveillance element:

- SSR: azimuth accuracy = 0.15°; range accuracy = 250m; Scan Rate = 12s (deterministic) and Latency = 0.5s (deterministic).
- ADS-B: scan rate = 14.0@95% and Latency = 1.2@95% s

The degraded parameters applied were:

Accuracy of position obtained from GNSS: [50; 4000] meters, considering the other parameters in normal operation;

ADS-B Scan Rate: [2.0; 34.0] s, considering the two other parameters both in normal operation and considering the accuracy of highly degraded GNSS position (1.5NM@95%).

2.4. Defining the Evaluation Criteria

For the scope of this work, the use collision risk metrics to evaluate the safety of the proposed system was desirable, since collision risk is supported by the ICAO, which accepts the perspective of the risk of accidents in the system safety analysis (Bloom *et al*., 1998). However, the assessment methodology proposed here uses simulation and, according to Campos and Marques (2002), it is "virtually impossible" to obtain collision risk metrics with an acceptable level of significance using this technique. This is explained by the low expected frequency for the occurrence of such an event.

In order to increase the significance of the results, Campos and Marques (2002) proposes the use of alternative metrics related to the event "risk of collision between aircraft" and with higher frequency of occurrence. Thus, the systems models were simulated in order to estimate metrics related to "aircraft proximity" (AIRPROX), which, depending on the separation standard applied, are events of loss of minimum separation between aircraft.

It is worth noting that the two simulation environments considered (reference and proposed) have considered the capacity of the air traffic system to maintain and detect

separation losses based on their own elements, especially in surveillance and navigation. Each environment has 2 processes: the real (real aircraft states) and the monitored process (observed aircraft state by means of supervision and control system). The AIRPROX events were observed over the real process, verifying the situations in which these events may occur due to the inefficiency of the ATC elements (regarding inaccuracies of the ATC parameters values introduced in the real state process).

2.5. Results Obtained

After the simulations of proposed and reference systems, an estimation was obtained for the metrics adopted (related to AIRPROX). Among the various metrics obtained in this assessment process (which can be observed in Vismari (2007)), the key metric was the exposure time to situations of loss of real separation between pairs of aircraft (AIRPROX) for distances below 3.5NM (named "TLmin"). Some results for "TLmin" are illustrated in Figs 3, 4 and 5.

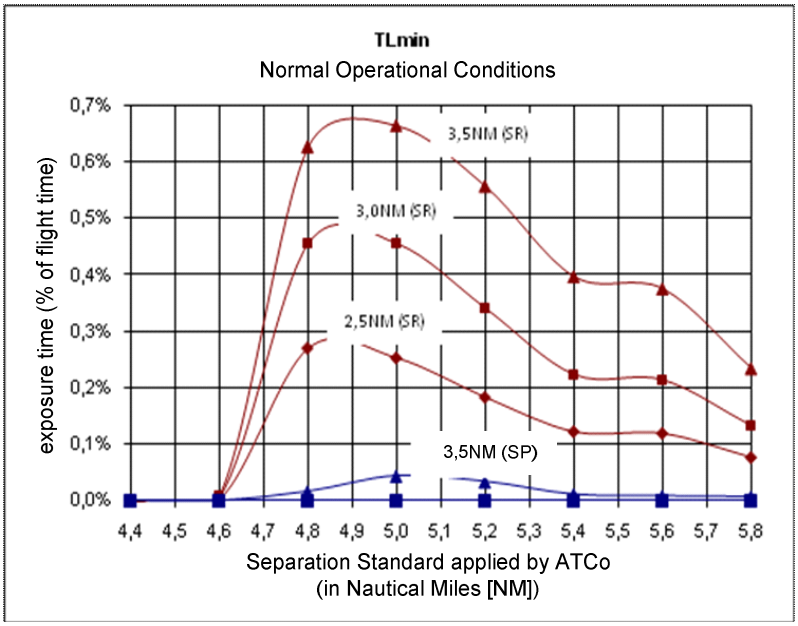


Fig.3 - TLmin @ (normal operation conditions)

Fig.3 shows the results for TLmin in normal operation. A sensitivity analysis was conducted on the separation standard applied by ATCo. The "SR" curves are for the Reference System and the "SP" curves are for the proposed system. Each curve shows the percentage of time in which pairs of aircraft were exposed to real separations lower than that indicated on the curves (3.5NM, 3.0NM to 2.5NM). It may be noted that there was no exposure to real separation losses in the proposed system (SP) lower than or equal to 3.0NM.

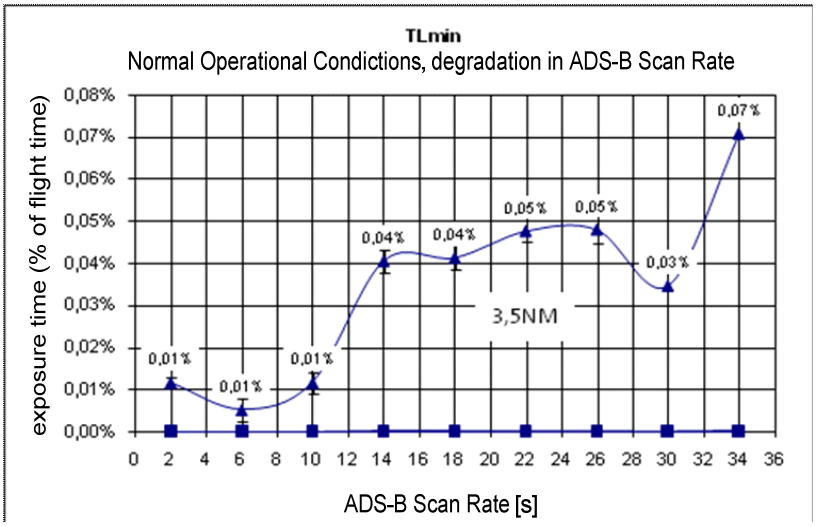


Fig.4 - TLmin @ (degraded ADS-B Scan Rate, normal GNSS position accuracy)

Considering the SP, Fig.4 shows the results for TLmin when the ADS-B scan rate has its value degraded (with GNSS position accuracy maintained in normal operational conditions. Fig.5 shows the results for TLmin when both ADS-B scan rate and the accuracy of GNSS position were degraded (in the SP).

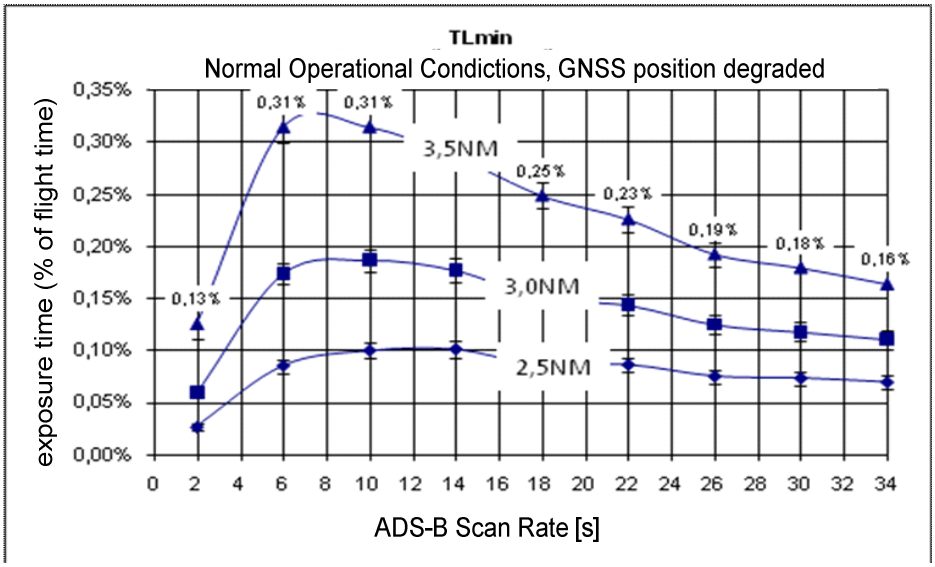


Fig.5 - TLmin @ (degraded ADS-B Scan Rate, highly degraded GNSS position accuracy)

3. DISCUSSION

Observing Fig.3, it can be noticed that aircraft pairs in CNS/ATM-based ATC system (proposed system – curves "SP") were less exposed to AIRPROX events than aircraft pairs in the current ATC system (reference system – "SR" curves) when considering normal operational conditions. In the proposed system, there were no AIRPROX events with aircraft separation smaller than or

equal to 3.0NM, and there was only a small portion of time (less than 0.04% of total flight time, equivalent to 1.2s of exposure) in which separations were between 3.0NM and 3.5NM, considering separation standards between 4.8NM and 5.4NM (whereas the lowest planned separation was 5.0NM). Considering the Reference System, there was a significant number of AIRPROXes (0.25% of the total flight time, equivalent to 8s of exposure) for separation distances smaller than 2.5 NM, and about 18.5s of exposure to separation distances smaller than 3.5NM.

In the case of ADS-B scan rate degraded conditions for both normal and degraded GNSS position accuracy (Fig.4 and Fig.5, respectively), the exposure time to AIRPROXes in the proposed system are smaller than the 0.25% of total time obtained from the Reference System in normal conditions and using 5.0NM separation standard (the Target Level of Safety (TLS) considered in this safety assessment process). Because all results for the SP in degraded conditions were smaller than those obtained for the SR in normal conditions, the worst result obtained to SP in normal conditions such as the TLS (0.04%) was applied to assess SP in degraded conditions. As a result, it was observed that it was enough to obtain the same level of exposure obtained in the proposed system in normal operation (TLS = 0.04%) to keep either the ADS-B scan rate lower than 20s (when the GNSS accuracy is considered normal) or the ADS-B scan rate lower than 2s (when the accuracy of GNSS is considered highly degraded (1.5NM@95%)). Thus, for the conditions presented, the proposed system can be considered safe, because the scan rate specified to ADS-B datalink using 1090ES protocol (ICAO, 2003) is 1s, in addition to the expected levels of degradation for GNSS position accuracy being smaller than 600m. Another important conclusion is that the minimum value of accuracy obtained in this study to maintain the proposed system safe agrees with the value of NACp $\geq$ 6 (Navigation Accuracy Category for position) (Brooker *et al.*, 2004), which correspond to a "GNSS position accuracy" smaller than 0.3NM (556 meters) for using ADS-B surveillance service in ATC. Hence, our study reaffirms that a GNSS position accuracy smaller than 0.3 NM is necessary for using ADS-B in Air Traffic Control.

4. CONCLUSIONS

The concepts introduced by the CNS/ATM paradigm, such as satellite navigation and the digital communication technologies, intend to provide a significant improvement in the quality of information available to users of air traffic systems, with consequent increment of

situational awareness by system operators (Air Traffic Controllers and Pilots). These improvements tend to allow the reduction in separation standards applied by controllers and, consequently, to increase the efficiency in airspace use and to increase traffic volume as a whole. However, due to safety being one of the primary requirements to be met by the air traffic system, the reduction in the values of separation between aircraft act against efforts to increase its capacity, because, as an adverse effect, the reduction in values applied for separation of aircraft increases the exposure to possible collisions.

Thus, efforts should be applied to guarantee that the CNS/ATM attains the objective of increasing the air traffic systems capacity, while ensuring (or even improving) their levels of safety. According to the Brazilian Program for CNS/ATM systems (DECEA, 2003), it is necessary to determine the "... *impact of new concepts on the various air traffic services provided …"* through activities focused on the "...*determination of parameters associated with the model used to determine the risk of collision in airspace where it is planned to reduce the separation standards*...", on "...*determining the risk of collision associated with operations in the airspace*..." and on the "...*implementation of risk comparisons obtained with the limits of acceptable risks*...", among other activities.

Therefore, this work assessed what impact the Automatic Dependent Surveillance by Broadcasting (ADS-B) concept causes on the Air Traffic Control System safety levels. The study focused on the relationship between the current surveillance paradigm (based on Radar, with strong characteristics of independence, determinism and synchronism), its "future" paradigm (based on ADS-B, with strong characteristics of interdependence, randomness and asynchronism) and the level of exposure of aircraft to events of loss of separation (AIRPROX). So as to perform this evaluation, the methodology proposed in Vismari (2007), and Vismari and Camargo Junior (2008) was used, which is a conceptual development of methods for "Absolute" and "Relative" risk assessment recommended by the International Civil Aviation Organization (ICAO, 1998b).

It is important to notice that this safety assessment carried out for the CNS/ATM has considered for the proposed system model (CNS/ATM based ATC environment), in its normal operation values, the worst values specified for the ADS-B in the literature, such as “Accuracy of navigation satellites (GPS)” of 86.44m@95% by dimension of the airspace; “Scan Rate of ADS-B messages” of

14s@95%, and "Latency in the reception of ADS-B messages" of 1.2s@95%.

Considering these values for the CNS/ATM-based ATC system, the exposure of the pairs of aircraft to separations smaller than 3.5 nautical miles (NM) – when the applied separation standard was 5NM – was found to be reduced by approximately 93% as compared to the Reference System (current ATC system). The improvement in aircraft adherence to flight plans and the quality of surveillance information provided to the ATCo significantly reduced the exposure of aircraft to incidents of loss of separation (AIRPROXes).

Therefore, using the results obtained for the scenario considered in this assessment, it can be concluded that the main concepts of CNS/ATM paradigm, such as ADS-B, are a viable application, in terms of safety, to be applied in the Air Traffic Control System (ATC), even if the navigation and surveillance elements of the ATC system have become interdependent and can influence the surveillance data acquisition processes in an asynchronous and stochastic way. Moreover, the interdependence between the surveillance and navigation could be beneficial. It was observed that it is possible to compensate the presence of degradation in GNSS position accuracy caused by, for example, atmospheric phenomena, with the increment in the surveillance scan rate (in this case, the ADS-B).

As a general comment on the practical implementation of CNS/ATM, mainly regarding ADS-B, we have observed that several countries, especially Australia and the United States, have advanced development and implementation programs to ADS-B system and other CNS/ATM concepts. Saving features of similarity in relation to continental territorial dimensions, the non-homogeneity of the population distribution, and the latitudes in which its territory is contained (with similar influences on the accuracy and integrity of GNSS signals), it is fully recommended that Brazil follows the Australian example regarding the use of ADS-B in its territory. The lower ADS-B implementation costs in comparison to a Radar implementation (SSR: AU$ 6M, against AU$380K for a ADS-B in route surveillance system (Dunstone *et al.,* 2007), associated with the good coverage of existing communication towers in Brazil and the current state of standardization of digital communication links (such as the 1090ES datalink) allow Brazil and other Latin-American countries to move towards the full implementation of the CNS/ATM paradigm.

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