AN APPROACH TO ASSESS SAFETY CONSIDERING INTEGRITY OF DATA OF ADS-B BASED AERIAL SYSTEMS

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ABSTRACT

The increasing demand for the densification of the national airspace in various social and economic applications have pressed aviation authorities to reduce aircraft separation, allowing more efficient operations in Air Traffic Management (ATM) in a given air space. However, issues related to the safety of air traffic operations arise when considering the possibility of reducing aircraft separation. Thus, surveillance plays a key role in monitoring and controlling air traffic in new scenarios. The accuracy of positional information provided by the Automatic Dependent Surveillance - Broadcast (ADS-B), originally designed to improve situational awareness for pilots and support controllers in air traffic management, is fundamental in order to avoid exposure to events of loss of separation (AIRPROX) and collisions for new Global ATM paradigm. This paper presents a qualitative approach to assess safety when using ADS-B systems considering its data integrity as a relevant factor for safety in aerial systems in aeronautical operations for different scenarios. A testing platform – the Integrated Platform for Testing Critical Embedded Systems (PlpE-SEC) – is also presented as a possible solution for this safety evaluation.

Keywords: ADS-B, RAIM, Safety, Surveillance, Integrity.
1. INTRODUCTION

According to the forecast of the International Civil Aviation Organization (ICAO, 2007a), between 2005 and 2025, it is expected that the number of passenger-kilometres and the number of passengers carried to increase over 100%. In absolute values, the expected increase in passenger-kilometres for the forecast period is approximately 5.460x10^{12}, which is more than twice the increase through 1985-2005, which was 2.355x10^{12} passenger-kilometres. The absolute increase of the number of passengers carried is thought to be slightly below 2.5 billion in 2025, compared to the 1.13 billion from 1985 to 2005.

This geometric growth is due to the evolution of society, in which globalization and socioeconomic interactions have increased, causing, for instance, an increase in per capita income. These facts combined with price reduction of airline tickets also make that the distances travelled in each trip for each passenger tend to be higher. (PORTAL BRASIL, 2012)

Another factor that reflects the growth in passenger numbers in Brazil is the increase in average income of Brazilian citizens, making air travelling more accessible to a large amount of the population previously unable to use this type of transportation. (SECOM, 2011)

The growth of world air traffic faces a series of safety restrictions determined by air traffic control (ATC), e.g. the separation value applied by ATC that inversely affects the safety characteristics and capacity in air transportation systems. In one hand, the reduction in the values of separation between aircraft promotes a direct increase in the capacity of the air transport system. In the other hand, the reduction in the values of separation also promotes increasing in the risks that contribute for possible collisions between aircraft, directly affecting safety system. Thus, one can conclude that the capacity and safety of the air transport system are conflicting characteristics (VISMARI, 2007). Because of the currently technological limitations, one cannot increase the number of flights simply by decreasing the separation between aircraft.

Considering the needs for a more efficient and yet safe environment for the air traffic management, a new concept so-called Global Air Traffic Management, was created based on new technologies for the tripod Communication, Navigation and Surveillance also known as CNS/ATM paradigm. This new paradigm can be defined as “Communications, Navigation, and Surveillance systems, employing digital technologies, including satellite systems together with various levels of automation, applied in support of a seamless global air traffic management system” (ICAO, 2007b). Figure 1 shows the new technologies that can be used in this new concept of Air Traffic Management.

![Figure 1: CNS/ATM technological evolution](VISMARI; CAMARGO JR, 2009)

The Automatic Dependent Surveillance-Broadcast (ADS-B), a surveillance technology defined in the concept of Global ATM, has been under development and implementation for almost a decade before its recent adoption (DEPARTMENT OF TRANSPORTATION, 2010). Even though this technology was primarily developed for improving situational awareness for manned aircrafts, in the same way, it also has appeared as a potential solution for Unmanned Aerial Systems (UASs) regarding the Sense and Avoid (S&A)
issue which is an inherent characteristic of this system (ICAO, 2012).

According to (FAA, 2010), ADS-B can be considered one of the most important underlying technologies to transform air traffic control from the current grounded-based system (such as Radar and VOR-DME systems) to a satellite-based system by conferring precision and reliability of satellite-based surveillance (GNSS-based position) to the skies, allowing the safe reduction of the mandatory separation between aircrafts. The complete ADS-B system will allow pilots to see and to avoid weather disturbances, air traffic, and terrain with the most up-to-date flight information, providing an unparalleled level of situational awareness contributing to the improvement of flight safety and flight operations (ICAO, 2012). ADS-B also provides greater coverage, since ADS-B ground stations are much easier to place than Radar systems. As a result, remote areas without Radar coverage are now covered by ADS-B. The Federal Aviation Administration (FAA) anticipates compulsory compliance for ADS-B to be complete by 2020 for the majority of aircraft in the North-American airspace (DEPARTMENT OF TRANSPORTATION, 2010). In this scenario, ADS-B appears as a practical requirement improving airworthiness and reducing separation minima in flight operations. “The improvement in situational awareness for pilots greatly increases safety” (FAA, 2010).

The primary function for ADS-B is to serve as a surveillance system for Air Traffic Control (ATC). Nevertheless, it can also be applied in remote areas where it is not possible to have a Radar equipment. In addition, it can be used as a complementary element in areas served by radar service. So, for a safe substitution of current radar systems aiming a more efficient usage of air space, the integrity of data provided by the new digital technologies must be seriously taken in consideration.

The main goal of this paper is to present a qualitative approach to assess safety when using ADS-B systems considering its data integrity as a relevant factor for safety in aerial systems in aeronautical operations for different scenarios. Similar work was made by Vismari (2007) however it was not considered the ADS-B data integrity.

This paper in section 2 presents the definition of surveillance and how it is inserted in ATC. Moreover, it is briefly described the ADS-B, one of the new technologies of Global ATM (GATM) concept. Section 3 talks about integrity of data regarding ADS-B messages and defines RAIM technique. In section 4 is presented the methodology to be used for assessing safety considering different scenarios for ATM. For last, in section 5, we make the final considerations and present the future work.

2. SURVEILLANCE TECHNOLOGIES

Aeronautical Surveillance System is defined in (ICAO, 2012) as a system that “provides the aircraft position and other related information to ATM and/or airborne users” In general terms, surveillance is responsible for updating flight plans, improving estimates at future waypoints and also removing the workload for pilots reducing voice communication while they are in flight. Several surveillance technologies are suitable for delivering Air Traffic Control (ATC) services to separate aircraft that are currently available, such as radar technology and ADS-B. Figure 2 shows the role that surveillance plays in ATC architecture and how is inserted in it.

![Figure 2: Air Traffic Control architecture](VISMARI; CAMARGO JR, 2009)

Surveillance plays an essential role in Air Traffic Control (ATC). The ability for accurately and reliably determine the location
of aircraft has a direct influence on the separation distances required between aircraft (i.e. separation standards) and, therefore, on how efficiently a given airspace may be utilized. In certain areas where there is no electronic surveillance, ATC relies exclusively on voice communication between pilots and Air Traffic Controllers (ATCo) to report aircraft position. Because of this, the separation distance between two or more aircraft have to be relatively large taking into account the uncertainty in the estimated position of the aircraft and the timeliness of the information. Conversely, ADS-B intends to improve the airspace performance, accommodating a higher density of aircraft when compared, for instance, to voice-based surveillance systems. It also allows aircraft vectoring for efficiency, capacity and safety reasons.

The main usage of surveillance in Air Traffic Management (ATM) is to monitor ATC expectations of aircraft movements based on clearances or instructions issued to pilots, and the actual trajectories of these aircraft indicating to ATC when compared, for instance, to voice-based surveillance systems. It also allows aircraft vectoring for efficiency, capacity and safety reasons.

The demand to increase flexibility to airspace use either by manned or unmanned aircraft by reducing restrictions associated with flying along fixed routes requires improved navigation capability on board the aircraft. Equally, accurate surveillance is required to assist in the detection and resolution of any potential conflicts associated with the flexible use of the airspace, which is likely to result in a more dynamic environment.

2.1. Role of ADS-B in ATC

By design, ADS-B can be used in different functional levels of the Air Traffic Management System (ATM). Examples of its application goes from collision prevention on board the aircraft (airborne situational awareness), detection and resolution of conflicts (for both air and ground systems), through the estimation of wind characteristics and other weather conditions (ICAO, 1999). However, the primary function for ADS-B is to serve as a surveillance system for Air Traffic Control (ATC), applied in areas where it is not feasible, both technically and economically, to implement a Radar equipment, or even being used as a complementary element in areas served by radar service.

As a communication element, ADS-B is composed by a transmission element (responsible for generating and transmitting its message), by means of communication (data link) and a receiving element (that receives messages, processes and presents it to the final application). Thus, the ADS-B is part of the process of communication of information in the surveillance system. Sources of information and the end-user application are not part of the ADS-B system (CASA, 2014). Therefore, the “ADS-B out” (transmitting element of ADS-B) should be supplied with the information of the on-board navigation equipment.

For ADS-B to be used as a radar surveillance system (or “Service Radar-like”), it is necessary that the message transmitted by the “ADS-B out” to contain certain data information such as Position, Integrity (of Location), Altitude, Identification, Version Number, SIL (Surveillance Integrity Level) and NACp (Accuracy Navigation Category for position) (CASA, 2014).

For the “ADS-B out” message to contain information mentioned, CASA (2014) specified a minimum set of information sources that should be available to the ADS-B:

1) Position: the Global Navigation Satellite System (GNSS) system is considered sufficient, in both accuracy and integrity, to provide this type of information. The GNSS equipment must adhere to at least the following requirements:
   a) GNSS equipment must be capable of providing position information periodically, with less than or equal to 1 second interval;
b) GNSS equipment must continually provide the ADS-B information from HPL (Horizontal Protection Limit), or notify the pilot in the event of interruptions or loss of availability.

2) Integrity of the position: GNSS equipment must provide, along with position data, HPL (Horizontal Protection Level) integrity data. In the absence of HPL due to operational constraints, it can replaced by HFOM (Horizontal Figure of Merit).

3) Altitude: GNSS equipment can provide it in case of unavailability of barometric altitude. In case of barometric altitude is available, it must be in accordance with the standards established for its use in the Transponder.

4) Identification: must be provided by the Transponder as a way to keep the same value configured in the flight plan.

Figure 3 illustrates the process of generating, transmitting, receiving and visualizing surveillance messages using ADS-B.

![Figure 3: Surveillance Process and ADS-B message structure (VISMARI, 2007)](image)

3. INTEGRITY OF DATA IN ADS-B

Integrity is the measure of the trust that can be placed in the correctness of the information supplied by a navigation system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation (DEPARTMENT OF DEFENSE; DEPARTMENT OF HOMELAND SECURITY; DEPARTMENT OF TRANSPORTATION, 2008).

There is great concern regarding the integrity of data provided to the ADS-B, especially regarding aircraft position. This concern is increased by the amount of GNSS standards in the equipment and related to the health parameters provided as well as posts patterns to be applied to the ADS-B, (Dunstone, 2005).

According to studies by Brooker (2004) the following values of integrity are sufficient to provide surveillance radar service through ADS-B (“Radar-like Services”):

1. **SIL = 2**: a Surveillance Integrity Level (SIL) equal to “2” corresponds to a probability of $10^{-5}$ per flight hour of HPL (Horizontal Protection Level) be exceeded without detection of abnormal behavior. SIL is a static value and it depends on the position of the sensors used.

2. **NACp ≥ 6**: the Navigation Accuracy Category for position (NACp) - a figure based on EPU (Estimated Position Uncertainty) - greater than or equal to 6 corresponds to EPU less than 0.3 NM (i.e., the actual position obtained by GNSS to be on a radius less than or equal to 0.3 NM during 95% of the time). The EPU is also known as HFOM (Horizontal Figure of Merit), and it represents a measure of accuracy considering that all satellites are used for proper operation.

3. **NIC ≥ 6**: the Navigation Integrity Category (NIC) - a figure based on HPL - greater than or equal to 6 corresponds to an HPL less than 0.6 NM (a $10^{-7}$ probability of the actual position value to be in the region outside 0.6 NM radius of the obtained position per flight hour).

Based on the American experience of the use of ADS-B as “Radar-like Service” in the Alaskan region (Project Capstone11), ADS-B requires a value of NUCp ≥ 4 to be used in air traffic control applying minimum separation of 5 NM. The NUCp (Navigation Uncertainty Category for position) is based on
3.1. The RAIM Technique

The Receiver Autonomous Integrity Monitoring (RAIM) is a technique used in a GPS receiver/processor to determine the integrity of its navigation signals, using only GPS signals or GPS signals enhanced with barometric altitude data. This determination is achieved by a consistency check between redundant pseudo-range measurements. At least one additional available satellite is required with respect to the number of satellites that are needed for the navigation solution (ICAO, 2010).

RAIM algorithms basically make use of measurements redundancy to verify the relative consistency among them (by means of the residuals) and in case of detection, the most likely “failed” satellite is determined. A key assumption usually made in RAIM algorithms for civil aviation is that only one satellite may be faulty, i.e. the probability of multiple satellite failures is negligible. Another key issue related to RAIM algorithms is that one of their goals is to find measurement errors derived from non-nominal situations. Many RAIM algorithms follow these main steps (ESA, 2011):

1) Compute the navigation solution,
2) Fault detection mechanism,
3) Isolation of “faulty” satellites,
4) Protection levels computation (optional).

Taking into account that the user needs to solve four unknown parameters (3D position and clock) from the satellites, it follows that:
- 4 visible satellites are not enough to provide integrity,
- 5 visible satellites: if an anomaly is detected, the measurement from that specific satellite is discarded and therefore only 4 satellites are left. With only four satellites, the receiver does not have redundancy to compute the solution with different measurements and confirm that the solution is indeed correct. Therefore the receiver is able to issue a warning but not to provide integrity,
- 6 or more satellites: the receiver is able to detect and perform the exclusion.

The more satellites in view, the more combinations of subsets of 4 satellites are available to detect potentially faulty satellites and the better the geometric observability.

4. SAFETY ASSESSMENT METHODOLOGY

A collision between aircraft is the most important factor affecting the perceived aeronautic safety (RICHARD PROFIT, 1996) for causing great social impact. Thus, guaranteeing the safety levels for air traffic services is related to the minimization of risks concerning the interaction of aircrafts, especially over factors that could affect their separation procedures. System parameters directly affecting the risk of collision are compiled in (ICAO, 1998), such as: exposure time to aircraft separation losses; navigation systems performance of aircraft fleet; surveillance and navigation systems performance available for air traffic controllers (ATCo) and for aircraft fleet.

Hence, flying an aircraft in any airspace requires approval from the appropriate authorities, which tend to evaluate airworthiness and operational approvals according to current regulations for aircraft in general. Each of these approvals depends on a safety case, which must demonstrate that any foreseeable hazards would be controlled within an acceptable frequency (ANGELOV, 2012).

It can be noticed that separation standards and safety are interdependent characteristics in air traffic systems, both depending on the parameters influencing the levels of collision risks. Consequently, the current safety/risk assessment methods are, overall, applied to processes that determine the standard values of minima separation (VISMARI; CAMARGO JUNIOR, 2011).
A critical step toward developing performance requirements will be performing safety assessment of this new technology. This will involve the determination of operational hazards – an example would be a midair collision— that could arise from the failure or incorrect performance of each function or data flow. Examples of failure events arising from the surveillance system could include:

1) **Aircraft not detected by surveillance system.**
2) **Aircraft detected late by surveillance system.**
3) **Aircraft detected with incorrect position or velocity.**

The second and the third examples involve deeper analysis, since a ‘late’ or ‘incorrect’ detection may not cause a hazardous outcome with certainty, but would increase its likelihood. The relationship between the cause and the effect might depend on the design or technology involved. The analysis should consider not only failures in resolving collisions, but also incorrect maneuvers that ‘induce’ a collision where none would have otherwise occurred. This is a very real hazard, which could arise from various causes, including measurement error, human decision, limitations in the algorithm, or even the communications link to the aircraft (ANGELOV, 2012).

### 4.1. Methodology

The “**Airspace Planning Methodology for the Determination of Separation Minima**”, used by the International Civil Aviation Administration (ICAO) (ICAO, 1998), describes procedures and parameters to be considered in the airspace planning process, mainly for reducing separation values. It is composed of the following steps:

1) **“Identify the needs for change” in the current system;**
2) **“Describe the current system”;**
3) **“Determine the proposed system meeting the required needs”;**
4) **“Identify the Safety/Risk Assessment Method to be applied to the proposed system”;**
5) **“Evaluate Risk to the proposed system” (applying the Safety/Risk Assessment Method ahead chosen);**
6) **“Verify if the proposed system satisfies the safety criteria.”**

Thus, any proposed system shall only be released to commercial operation if its safety levels are assessed (in phase 6), comply with its acceptable safety criteria (the Target Level of Safety to the system), set to the proposed system.

In (VISMARI; CAMARGO JUNIOR, 2011), the safety of the ATC system was assessed considering two different scenarios in which the functional elements, that must be considered to the model for assessing its risks, are:

1) **Airspace (route configurations, airspace structure, aircraft flight plans and so on),**
2) **Aircrafts (flight dynamics algorithms and aircraft performance characteristics),**
3) **Navigation (characteristics of positional data provided to the aircraft),**
4) **Communication (between controllers and pilots),**
5) **Surveillance (estimative of aircraft positions provided to controllers),**
6) **Air Traffic Controller (ATCo) (responsible for managing the safety separation values between aircrafts),**
7) **The aircraft pilot.**

In both systems (the reference and the proposed ones), Airspace, Aircrafts, Pilots, Communication and ATCo models were the same. The differences adopted by the systems lay in the Surveillance and in the Navigation elements (systems related to the ADS-B): i. **In the Proposed System, navigation was based on the Global Navigation Satellite System (GNSS) and surveillance, on the ADS-B;** ii. **In the Reference System, navigation was based on the current VHF Omnidirectional Range / Distance Measure Equipment (VOR/DME)**
equipment and surveillance, on the radar system.

Society’s risk perception makes much stricter demands on new digital air traffic control technologies than currently applied ones, mainly for posing risks to the structure already established (GIL et al., 2010). This makes it necessary to methodically cope with factors related to the interaction of these new systems with air traffic environment, be it for civilian or military applications. In this sense, the existence of methodologies and tools applied to the development, evaluation and validation of concepts and technologies used in this new concept is vital, especially those that may have disastrous impact on the environment in which they operate.

In this context, one of the tools suitable for such studies is the testing platform, called “Integrated Platform for Testing Critical Embedded Systems” (PIpE-SEC1), in Airspace which allows testing different models within the proposed scenarios. It also can be tested the aspects of design stage of these new ATC technologies and aspects related to its operation within a social context (e.g. interaction of this unmanned aircraft with the environment). Consequently, this platform will assess and validate design concepts (requirements, algorithms, embedded technologies, etc.), operational procedures, tools and many other aspects that should be applied over these systems life cycle.

4.2. The PIpE-SEC

The Integrated Platform for Testing Critical Embedded Systems (PIpE-SEC) is a test tool, which is currently being developed by the Safety Analysis Group at the School of Engineering of the University of São Paulo (Poli-USP). It that allows modeling and simulating air traffic operations, in real time, of the actual structural and behavior characteristics of the Air Traffic Control System (ATC), including the interaction between air traffic controllers (ATCos) and aircrafts, be they manned or computer-piloted vehicles. In this real-time simulated environment, through controlled tests, it is possible to evaluate and to validate the concepts intrinsic to the project of both manned and unmanned vehicles (especially the ones that are autonomous). Also, their interaction with the operational environment in which they are inserted, pondering the characteristics related to the technologies and to the procedures applied can be investigated. (GIL et al., 2010)

The main reason for adopting this platform is the possibility of testing the new GATM concept in different scenarios either through their computational models or through their actual physical prototypes (in which the variables read or provided by the actual physical equipment are considered in the computationally modeled and simulated environment), using the “Hardware In the Loop” (HIL) concept as shown in Figure 4. As well as the HIL, the possibility of human action in the analysis process (known as the concept of “Human in the Loop”), makes PIpE-SEC essential for developing processes of critical embedded systems. In this context, PIpE-SEC is being adopted in order to seek validation of the proposed models and new scenarios when dealing with a qualitative approach. Models which were properly validated by the tool are now ready for accelerated simulation seeking a quantitative approach of safety analysis as presented in (VISMARI; CAMARGO JR, 2009).

![Figure 4: Detailing of “Aircraft” (Ai) module under the HIL concept. (GIL et al., 2010)](image)

PIpE-SEC is composed of an Experiment Management Kernel (for controlling the execution of tests and data collection),

1 Acronym in Portuguese for Plataforma Integrada para Ensaios de Sistemas Embarcados Críticos.
through an Airspace Modeling and Simulation kernel and through Models of the involved Agents, that could be directly implemented in the software (computational models) or in the hardware (by the “Hardware in the Loop” concept). More details about this specific tool can be found in (GIL et al., 2010).

5. FINAL CONSIDERATIONS AND FUTURE WORK

The International Civil Aviation Organization (ICAO) defines safety in (ICAO, 2006) as

“the state in which the risk of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and risk management”.

Based on this definition and in the global aviation context, the term safety is the feature of a particular system of not causing unacceptable risks of accidents or incidents involving aircraft.

Market demands for the densification of the national airspace are pushing the aeronautical authorities in order to expedite the process of implementing the new Global ATM concept for achieving this goal. However, the perception of risk in our society makes its safety requirements to be even higher than current technology so that there is not an increase of the number of accidents. Thus, regarding the adoption of new technologies in airspace, a very careful assessment of their automated systems for navigation, communication and surveillance is needed. Besides the models in the system itself, it is necessary to evaluate their interaction, since, even though each individual part of these presents correct operation, the interaction between them can lead to potentially unsafe situations (LEVESON, 2011).

Regarding the surveillance system adopted by the new Global ATM concept, the Automatic Dependent Surveillance – Broadcast (ADS-B), there are several possible architectures for its interaction with different types of implementation in an aircraft, for instance, if we consider an Unmanned Aerial System (UAS) and its integration on a non-segregated airspace (STARK; STEVENSON; CHEN, 2013). Each has more or less advantageous characteristics depending on the aircraft model used and also on their respective degree of autonomy.

There are several possible scenarios for interaction between ADS-B considering parameters of integrity of data. In previous work, such as in (VISMARI; CAMARGO JUNIOR, 2011), the impact of ADS-B on air traffic safety was evaluated and compared to systems whose surveillance was primarily based on radar technology. Thus, new parameters available in the ADS-B technology can be considered for evaluating the safety levels of air traffic control, such as the ‘projected-profile’, a field of ADS-B data package, which was not considered in previous analysis.

In order to maintain uniformity of analysis and to establish a reliable comparison with previous work, the method to be used for the safety evaluation system will be the same proposed and used in (VISMARI; CAMARGO JUNIOR, 2011). This methodology combines ‘absolute’ and ‘relative’ methods proposed in (ICAO, 1998) in which both quantitative and qualitative analyses are performed in a given system. It assesses whether the safety level is above an acceptable threshold value and also compares the system with another reference system, which is usually a legacy system already tested or in current operation.

The validation and safety assessment (in a qualitative approach) of each model as well as its interactions with the airspace makes it imperative to simulate those in a computer-based virtual environment. In such an environment, it is possible to assess how a particular model of the aviation system (be it used for navigation, communication or surveillance) interacts with other systems in a virtual computationally controlled airspace. This context makes the Integrated Platform for Testing Critical Embedded Systems (PIpE-SEC) play an import role in this evaluation, since it is a tool under development by the Safety Analysis Group at
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