THE IMPACTS OF SURVEILLANCE FAILURE ON AIRBORNE SEPARATION ASSISTANCE SYSTEM BASED CONTINUOUS DESCENT APPROACH

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Abstract

Airborne Separation Assistance System (ASAS) is seen as a promising option for the future Air Traffic Management (ATM). One idea of recent interest in ASAS application is Interval Management (IM), which is expected to support energy saving arrivals, commonly referred as Continuous Descent Approach (CDA). The questions are how the IM application achieves safety and capacity in the CDA environment, and how to identify any potential emergent behavior that should be taken into account in the operation design. The motivation for our study is the need to properly understand the nominal and non-nominal behavior of many aircraft when the ASAS application is applied to the CDA environment.

For this purpose, our study has conducted a preliminary safety assessment of the ASAS speed control for multiple trailing aircraft in CDA operation. This paper focuses on ASAS surveillance failure as one of the critical events during flight. By using Stochastically and Dynamically Colored Petri Net (SDCPN), ASAS core components and their interactions are modeled. Through Monte Carlo simulation via the SDCPN models, we assess the impact of the ASAS surveillance failure on the ASAS-based CDA operation.

1 Introduction

Airborne Separation Assistance System (ASAS) is an integrated air to air, and air to ground system which enables flight crews to maintain airborne separation by visualizing surrounding air traffic information in a cockpit display using Automatic Dependent Surveillance -Broadcast (ADS-B). It allows shifting Air Traffic Controller (ATCo)'s tasks to the crew during flight. One idea of recent interest in ASAS application is Airborne SPAcing application (ASPA) - Interval Management (IM) [1], including the former ASPA-Sequencing and Merging (S&M) [2]. This application asks the crew to achieve and maintain an assigned spacing to the target aircraft at a chosen waypoint. The questions are how safety and capacity depend on the setting of spacing criteria in combination with specific IM design aspects, and how to identify any potential emergent behavior that should be taken into account in the operation design. To clarify these questions, the need is to properly understand the nominal and non-nominal behavior of many aircraft when the IM is applied. The state of the art in scientific research is that non-nominal emergent behavior of advanced designs can be identified through conducting large scale Monte Carlo simulations with a well specified multi-agent based mathematical model of the operation [3]-[5]. In line with this, this research furthers the mathematical modeling and Monte Carlo simulation study to assess separation loss events in time spacing included in the ASPA-IM application.

In an earlier study, we developed an initial mathematical model of time spacing using ASAS speed control [6], which evaluated on safety of a novel ASAS speed controller for time spacing [7]. This novel controller was shown to behave in a robust way to random errors in the aircraft's initial values, e.g. initial position, airspeed, and time error. The effect of multiple aircraft and wind speed was also discussed in [6], and the Monte Carlo simulation results showed that ASAS speed control was one of the possible applications for CDA operation. The separation performance was not deteriorated due to the increase in the number of trailing aircraft under the simulated condition. These initial modeling and simulation did not consider non-nominal conditions. One of the rare events which should be considered is a loss of ADS-B connection, and how to recover from such situation. The aim of the current paper is to conduct a mathematical modeling and simulation study in order to learn understanding the non-nominal property in the ASAS surveillance failure and the corresponding emergency actions.

For the mathematical modeling, the ASAS control loop, which is a complex system in which many stochastically and dynamically components interact with each other, have to be captured in an integrated model. In order to handle the complexity of this modeling challenge well, we make use of the powerful Petri net formalism of Stochastically and Dynamically Colored Petri Nets (SDCPN) [8] [9]. The SDCPN formalism forms a powerful and compositional specification approach that enables a systematic implementation of the complex system in computer programming for rare event analysis and Monte Carlo simulation. For efficient computation, in study [6] use has been made of the Interacting Particle System (IPS) approach [10] which speeds up Monte Carlo simulation several orders in magnitude. For applications where rare failures significantly add to the risk, however, this IPS approach may fail to produce reasonable estimates within acceptable periods of running Monte Carlo simulations. In order to address such situations, Ref. [11] developed some further extension of the IPS approach under the name Hierarchical Hybrid IPS algorithm (HHIPS). Both the IPS approach and this HHIPS approach have for example been used in [5] for the estimation of rare separation loss events within a reasonable amount of simulation time. In the current paper, the necessary Monte Carlo speed up is realized by making use of this HHIPS approach.

The paper is organized as follows. In section 2, the ASAS application in this paper is briefly explained. In section 3, ASAS components and their interactions under a defined CDA operation are captured as SDCPN models. In section 4, HHIPS is applied to Monte Carlo simulation to count separation loss events. ADS-B transmitter/receiver failures and related action delays are stochastically considered. Deviations of aircraft initial attitude, airspeed, and entry time are given in the simulation. The results show the effects of the surveillance failure on the ASAS-based CDA operation. Concluding remarks are given in section V.

2 Brief Description of the ASAS Application

2.1 ASAS speed control in CDA

The ASAS application this paper considers is one of the ASPA-IM applications, which keeps time spacing between a target and follower (own) aircraft by aircraft speed control. In the ASPA-IM time spacing procedure, the aircraft involved are in a terminal maneuvering area (TMA) or in an adjacent sector, due to the assumption that this procedure may start between the Extended-TMA entry point and the Final Approach Fix (FAF), where the procedure should be ended. In this interval of the flight, the flight crew must be aware of the surrounding traffic through ASAS surveillance information displayed on the cockpit display. The ATCo gives an instruction to the flight crew for identifying the target aircraft and for keeping assigned time spacing between the aircraft at a chosen waypoint. This ASPA-IM operation is expected to support energy saving approaches commonly referred to as CDA, while keeping the high capacity in air traffic control.

In support of the ASPA-IM operation, ASAS is assumed to be working in Airborne Spacing mode, including automatic speed controller. The flight crew has then only the task of monitoring the evolution of the spacing, when the follower aircraft is equipped with an ASAS director that inputs automatically its suggested speed to the Autopilot System. In building upon Eurocontrol's CoSpace project [12] [13], a novel ASAS speed control law was developed [7]. The developed controller has been shown to work in a robust way against stochastic behavior of the aircraft and their surrounding environment [6]. In the current ASPA-IM time spacing study, the novel speed control law is considered. If ASAS surveillance information of the leading aircraft or own aircraft is lost, then own aircraft execute an emergency procedure. This emergency procedure is assumed to be executed manually by the flight crew.

In the remainder of this section, we first summarize the functional characteristics of the ASAS related systems in Subsection 2.2. Next the operational goal of ASPA-IM is described in Subsection 2.3. Subsequently the emergency procedure is explained in Subsection 2.4.

2.2 Functional Characteristics

Assumptions on equipment, aircraft performance, and execution procedures are as follows.

- Equipment
  Aircraft are equipped with standard navigation and telecommunication systems, plus ADS-B, and ASAS. A simplified composition of the equipment follows in Table 1.

Equipment	Aircraft
SSR transponder	100%
ADS-B transmitter	100%
ADS-B receiver	100%
ASAS Spacing Director	100%
ASAS airside	100%
FMS (Flight Management System)	100%
Inertial Navigation System	100%
GNSS (Global Navigation Satellite System)	100%

Table 1 Aircraft Equipments

- Ground system
  Ground systems have the standard surveillance systems for TMA, plus the ground counterpart of ASAS.
- Aircraft Performance
  For simplicity, for the modeling and simulation in this paper all aircraft are assumed to be B747-400.

The IM application has the following procedural flow that will be supported by the above equipment to achieve an operational goal [1]. The execution procedure contains the following three phases; initiation phase, execution phase, and termination phase:

Initiation phase: In the case IM application is beneficial, the ATCo identifies a target-follower aircraft pair which has conditions for being involved in an IM procedure. The ATCo instructs aircraft to identify a specific aircraft as target. The flight crew must read back the instruction, acquires the target in the ASAS system, and communicates the results of the target identification. The ATCo passes a spacing instruction message, detailing the specific maneuver to be carried out. This instruction includes the merging waypoint, the time/distance difference and horizontal maneuver instruction to be applied. Once the IM instruction is accepted, the flight crew engages the ASAS Spacing Mode for IM operation (IM equipment).

Execution phase: In this phase, the flight crew starts the execution of the instruction of the former step. If the IM equipment is coupled with autopilot/autothrust (auto throttle), the IM speed may be implemented by the aircraft system. This encompasses the horizontal maneuver, if required, and, when separation is achieved, the speed adjustments for maintaining the separation.

Termination phase: The IM operation is terminated, and the task of speed management reverts to the ATCo.

2.3 Operational goal

The operational goal is to achieve an assigned time spacing τ_s at a waypoint after passing FAF (Final Approach Fix). A first aircraft enters IAF (Initial Approach Fix) at h_e feet by v_e CAS (Calibrated Air Speed) knots, then continuously descends to the FAF by keeping a 2.5 degrees flight path. After reaching the FAF at 2,000ft, the aircraft reduces airspeed to 180 CAS knots and increases the flap angle to 25 degrees proportionally in 100 seconds. The distance between IAF and FAF is 45.0 NM. The other trailing (following) aircraft enters IAF at h_e feet by v_e CAS knots τ_e seconds after the target aircraft, and trails the target aircraft while keeping τ_s seconds separation and descending to the FAF by keeping a 2.5 degrees flight path.

The simulation results for two pairs of target/follower aircraft are shown in Figures 1-4. The dynamics and engine models are given by the AMAAI tool box [13]. The ASAS speed controller developed in Ref. [7] is used for speed control. Here we set $\tau_s = 90$ seconds. The values, h_e, v_e, τ_e , are given by a uniform density f_U and normal density f_N as follows:

$$h_e \leftarrow f_U(x; h_{min}, h_{max}) \qquad (1)$$

$$v_e \leftarrow f_N(x; v_m, \sigma_v) \qquad (2)$$

$$\tau_e \leftarrow f_U(x; \tau_s - \tau_d, \tau_s + \tau_d) \qquad (3)$$

Here $h_{min} = 10{,}000\,ft$, $h_{max} = 11{,}000\,ft$, $v_m = 240\ CAS\ knot$, $\sigma_v = 5\ knot$, $\tau_s = 90$ seconds, $\tau_d = 5\ second$. f_U and f_N are as follows:

$$f_U(x; l_{min}, l_{max}) = \begin{cases} \dfrac{1}{l_{max} - l_{min}} & if\ l_{min} \le x \le l_{max} \\ 0 & else \end{cases} \qquad (4)$$

$$f_N(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \qquad (5)$$

As shown in Figs. 1 and 2, the second aircraft follows the first aircraft, and the third aircraft follows the second aircraft by adjusting airspeed in CDA. As shown in Figs. 3 and 4, the ASAS speed controller keeps certain distance and time separation using estimated time errors.

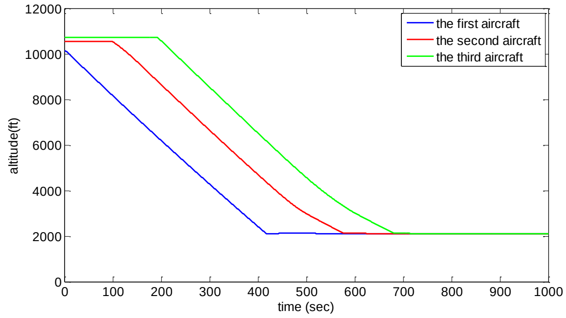

Figure 1 Altitude of two pairs of target/follower aircraft

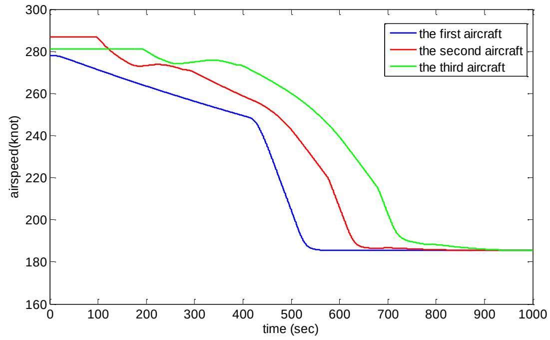

Figure 2 Airspeed of two pairs of target/follower aircraft

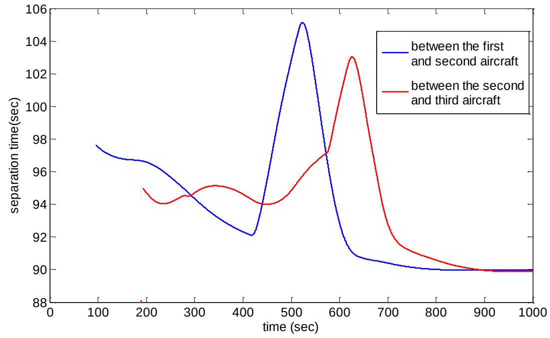

Figure 3 Separation distance between target and follower aircraft

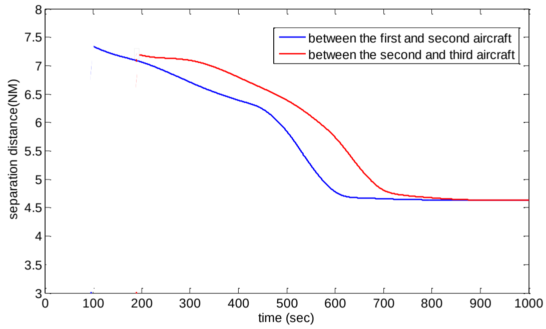

Figure 4 Estimated time separation between target and follower aircraft

2.4 Emergency Action

It is possible that the IM procedure is abnormally finished due to an equipment failure or to some unsafe situation detected by ATCo or by the flight crew. In this case some emergency actions may need to be executed. Since this paper focuses on ASAS surveillance failure, the following emergency actions are employed:

- In the case the ADS-B receiver and/or transmitter of the own (follower) aircraft is not working, the own aircraft leaves the queue of CDA aircraft while keeping the same attitude, airspeed, and heading angle.
- If the own aircraft loses the target aircraft in ASAS surveillance, the own aircraft follows an IM procedure for the first aircraft in the queue of CDA aircraft.

As a basis for modeling the above emergency actions, the following conditions are included:

- If the ADS-B receiver of the own aircraft and/or transmitter of the other aircraft fails, an $\alpha\beta$ tracker estimates surveillance information for 10 seconds after the detected failure. After 10 seconds estimation, the old information is dropped.
- When the aircraft executes the emergency procedure, there are action delays of flight crews/ATCo in their communication/cognition.

Modeling details are briefly described in section 3.

Figures 5 and 6 show one of the simulation results when the first two aircraft execute an emergency action. The ADS-B transmitter of the first aircraft was failed at 200 seconds. Then, the first aircraft left the queue of CDA aircraft while keeping the same attitude and airspeed. The second aircraft stopped trailing the first aircraft and followed the CDA procedure for the first aircraft. The third aircraft kept following the second aircraft by ASAS speed control.

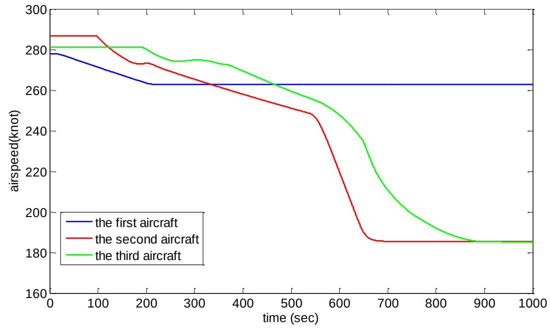

Figure 5 Altitude of two pairs of target/follower aircraft in emergency action

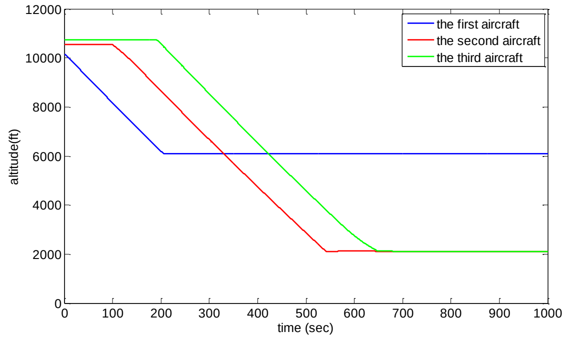

Figure 6 Airspeed of two pairs of target/follower aircraft in emergency action

3 Mathematical Modeling

3.1 Agent-level Petri Nets

In order to handle the complexity of the real system in the modeling, we employ the hierarchical way of working to develop a model. Firstly, at the top level, agents are defined, and secondly, interactions between these agents are pictured. Thirdly, each agent is modeled in further detail in several local models and their interactions.

Figure 7 shows the agents and their interactions in the ASAS control loop. Each aircraft contains Aircraft evolution, Guidance systems, Own positioning systems, Communication systems, Action delay, and ASAS agents. Own positioning systems take satellite-based information from GNSS agent. Each aircraft transmits/receives the other aircraft information via Communication systems. Weather influences the Guidance systems.

In order to focus on the effect of ASAS surveillance failure in the CDA operation, this paper gives the following assumptions in the above agents: 1) Own positioning and GNSS systems work without any failure, corruption or degradation. 2) Position/airspeed errors in Own positioning systems are assumed to be zero. 3) Action delays of ATCo and flight crews are simplified by Action delays agent. The above agents consist of detailed local models as follows.

Aircraft evolution agent:

- Aircraft evolution model: this shows the evolution of the aircraft that executes ASAS spacing.

Guidance systems agent:

- FMS flight plan model: this describes the nominal flight plan of the aircraft.
- Aircraft guidance behavior model: this model includes the dynamics of the aircraft including FMS, autopilot, and control systems. Initial values of aircraft speed and altitude are given by probability distributions.

Own positioning systems agent:

- Aircraft GPS receiver model: this includes a probability distribution which describes the time intervals in which the aircraft's GPS receiver is working/not working.
- Aircraft air sensor model: this includes a probability distribution which describes the time interval in which the estimation of vertical aircraft position and speed is working correctly/degraded.
- Aircraft horizontal POS-PROC model: this describes the estimation error of two dimensional horizontal positions and speed of aircraft in GPS/IRS estimates. Probability distributions and dynamics are given for position/airspeed errors.
- Aircraft air data PROC model: this describes the estimation errors of vertical position and speed, as well as the airspeed of the aircraft. The estimation of True Air Speed (TAS) uses altitude estimated by altimeter and pitot tube measurement. Probability distributions and dynamics are given to estimate position/airspeed errors.

Communication systems agent

- ADS-B transmitter model: this includes a probability distribution which describes the time interval in which the aircraft's ADS-B transmitter is working/not working.
- ADS-B receiver model: this includes a probability distribution which describes the time interval in which the aircraft's ADS-B receiver is working/not working.

ASAS agent

- ASAS spacing model: dynamics of ASAS speed controller, which automatically guide aircraft to keep certain time separation with a target aircraft, is given by ASAS space keeping criteria [6] [7].
- ASAS surveillance model: this describes ADS-B information of all other aircraft in the ADS-B range, which the own aircraft updates every 1second.

Action delay agent

- Delay ASAS model: this describes action delay of flight crew/ATCo until switching off ASAS spacing mode not to follow the target aircraft in emergency procedure.
- Delay AGB model: this describes action delay of flight crew/ATCo until taking emergency procedure when the ADS-B transmitter/receiver of the own aircraft does not work.

GNSS agent

- GPS system model: this describes the time interval in which GPS is working/degraded/corrupted/down using a probability distribution.

Weather agent

- Wind model: this describes wind dynamics in 3 directions (x, y, z on the earth axis).

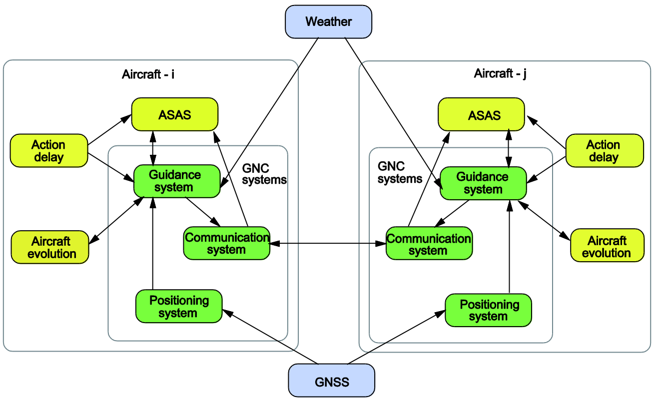

Figure 7 Multiple agents and their interaction

3.2 SDCPN model

General explanation

For the mathematical modeling of the above local models (described in section 3.1) and their interactions, we make use of a suitable Petri net formalism, Stochastically and Dynamically Colored Petri Net (SDCPN) [8] [9]. The SDCPN is a Petri net extension which allows representing a complex system including stochastic behaviors and dynamic processes. A Petri net is a graph of circles (named places), rectangles (named transitions) and arrows (named arcs). The places represent possible discrete modes or conditions, the transitions represent possible actions. The arcs exist between places and transition or vice versa. A condition is current if a token (represented by a dot) is residing in the corresponding place. One of the powerful advantages of Petri nets includes their graphical representation to model a complex system in all of its components and their interactions. In an SDCPN model, each token is associated with a differential equation which represents the dynamics process in the applied system. Figure 8 shows one example of our SDCPN models and their interaction.

The SDCPN models which take important roles in ASAS speed control, Aircraft guidance behavior and ASAS spacing model are introduced in Appendix in Ref. [6]. We further the following development in the SDCPN models.

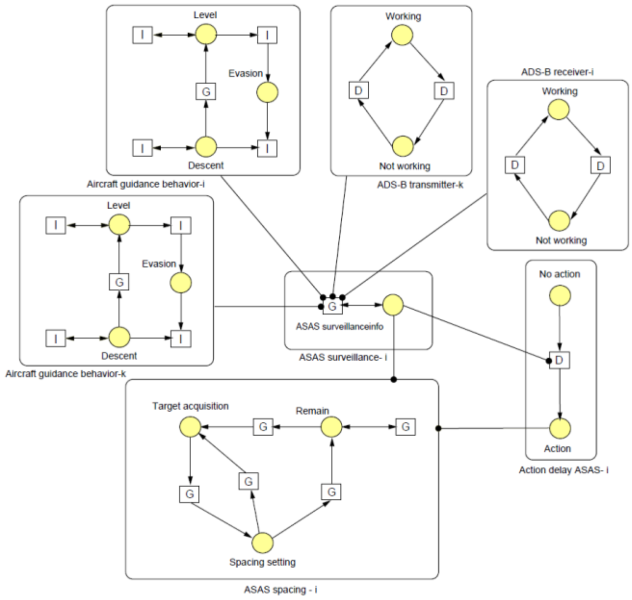

Figure 8 ASAS related part of SDCPN model

Further development of SDCPN models

This paper newly includes the following developments:

<u>Aircraft guidance behavior model</u>

- The model is developed to include the emergency procedure described in section 2.4.

<u>ASAS spacing model</u>

- As described in section 2.4, the model is developed in order not to follow the target aircraft in emergency situation.

<u>ASAS surveillance model</u>

- As described in section 2.4, an $\alpha\beta$ tracker estimates surveillance information for 10 seconds after the ADS-B receiver/transmitter failure. After 10 seconds estimation, the old information is dropped.

<u>ADS-B transmitter/receiver model</u>

- For the time interval of state transition between ADS-B transmitter/receiver working and failure, exponential distributions are given as follows:

From working to failure:

$$\tau_{wf} \leftarrow f_E\left(x;\ \mu_{ADS}^{down}\left(1 - p_{ADS}^{down}\right)/p_{ADS}^{down}\right) \quad (6)$$

From failure to working:

$$\tau_{fw} \leftarrow f_E(x;\ \mu_{ADS}^{down}) \qquad (7)$$

Here τ_{wf} and τ_{fw} are time intervals of the state change from working to failure, and from failure to working, respectively. μ_{ADS}^{down} is the mean duration of the state change from failure to working. p_{ADS}^{down} is the probability of failure. The values of μ_{ADS}^{down} and p_{ADS}^{down} are given in section 4. The exponential distribution f_E is defined in Eq. (8):

$$f_E(x;\ \mu) = \frac{1}{\mu} exp\left(\frac{-x}{\mu}\right),\ \ x \geq 0 \qquad (8)$$

Delay ASAS/ AGB model

- The time interval until taking emergency action τ_{AC} , follows a Rayleigh distribution:

$$\tau_{AC} \leftarrow f_R(x;\ \mu_{AC}) \qquad (9)$$

μ_{AC} is the mean duration of the state change to emergency action. The value of μ_{AC} is given in section 4. The Rayleigh distribution f_R is defined in Eq. (10):

$$f_R(x;\ \mu) = 2\rho x\ exp(-\rho x^2),$$
$$\rho = \frac{\pi}{4\mu^2}, x \geq 0 \qquad (10)$$

4 Results of Monte Carlo Simulation

4.1 Monte Carlo speed-up

Firstly we explain the specific approach used for running Monte Carlo simulations.

ICAO's Target Level of Safety (TLS) defines a target of at most 5×10^{-9} collisions per flight hour in each of the three possible directions. In the case we count 10^{-9} order collision risk, the number of simulated samples necessary for the Monte Carlo returning valid results would be expected to be of order 10^{11}. In order to avoid the huge computing time, appropriate techniques have to be used to speed up Monte Carlo simulations.

Level of separation loss events	Horizontal separation distance (NM)	Vertical separation distance (ft)	Separation loss event
1	6.0	3000	No specific name
2	4.5	900	No specific name
3	3.0	700	Minimum Separation Infringement (MSI) in TMA
4	1.25	500	Near Mid-Air Collision (NMAC)
5	0.3	52.5	Mid-Air Collision (MAC)

Table 2 Separation loss event

The technique we used for the speed up in Ref. [6] was the Interacting Particle System (IPS) approach [10]. The IPS takes benefit of the fact that the probabilities of sequence events on aircraft separation loss constitute realizations of a strong Markov process: the probability that an aircraft loses separation in the future time interval is higher for aircraft that already have smaller separation distance at present time. Although in theory the IPS approach is applicable virtually to any strong Markov process, in practice the straightforward application of this approach to stochastic hybrid processes may fail to produce reasonable estimates within a reasonable amount of simulation time [11]. First, there may be few or no particles in modes with small probabilities (e.g. ADS-B transmitter/receiver failure). Second, if the switching rate is small then it is highly unlikely to observe even one switching during a simulation run. For example, since the probability of switching the state (e.g. ADS-B transmitter/receiver is working to failure) is small, it is often difficult to realize such switching within the simulation time. Therefore, another extension was developed, namely, the hierarchical hybrid IPS algorithm (HHIPS). The HHIPS incorporates sampling with modes to cope with large differences in mode weights, and importance switching to cope with rare mode switching [11].

We applied the HHIPS algorithm to assess the probability of aircraft separation loss events during ASPA-IM application. Table 2 specifies the sequence of separation loss events that have been used in the HHIPS based Monte Carlo simulations. HHIPS runs 10,000 particles for 10 times per each parameter setting in this paper.

The simulation results are shown in section 4.2. The separation loss events happened to the second aircraft are counted in all Monte Carlo simulations.

4 .2 Simulation results

Initial deviation

Based on the Monte Carlo simulation results, here we discuss the effects of initial deviation of attitude and airspeed on separation loss events. A spacing time 80 seconds is given to τ_s in Eq. (3). The other parameters in Eqs. (1)-(3) are given in Table 3. Parameters in ADS-B transmitter/receiver and Delay ASAS/AGB models in Eqs. (6)-(10) are in Table 4. The given action delay 6.5 seconds is from Ref. [14], which is assumed to be the delay of flight crew's action after detecting TCAS (Traffic Alert and Collision Avoidance System) alert.

Parameters	h_{min} (ft)	h_{max} (ft)	v_m (kt)	σ_v (kt)	τ_d (sec)
Case1	10000	11000	240	5	5
Case2	10000	11000	240	10	10
Case3	10000	11000	240	15	15

Table 3 Initial deviation

Parameters	μ_{ADS}^{down} in ADS-B transmitter/ receiver (sec)	p_{ADS}^{down} in ADS-B transmitter/ receiver	μ_{AC} in Delay ASAS (sec)	μ_{AC} in Delay AGB (sec)
For Case 1, 2, and 3	1800	5.0×10^{-5}	6.5	6.5

Table 4 Parameter settings in ADS-B transmitter/receiver and Delay ASAS/AGB model for Cases 1-3

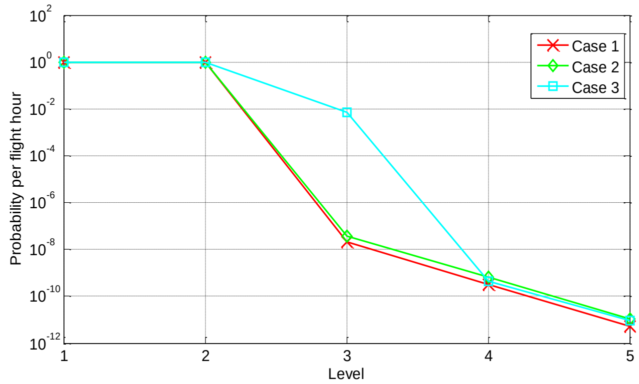

Figure 9 Probability of separation loss events in Cases 1-3

Figure 9 shows the probability of separation loss events per flight hour in Cases 1-3. As shown in Fig. 9, for all initial deviations the probability of collision risk is smaller than the order of 10^{-11} ,which satisfies ICAO's TLS (5.0×10^{-9}). These show that the designed ASAS speed controller in Refs. [6] [7] and emergency action work well. Although probabilities of the collision risk in the all cases keep the same order of magnitude, the smaller initial deviation Cases 1 and 2 have far less MSI events than Case 3 has.

Performance of ASAS surveillance

This section discuss the effects of ASAS surveillance performance and failure probability of ADS-B transmitter and receiver, on separation loss events. The spacing time of 80 seconds is given to τ_s in Eq. (3). For the initial deviation in Eqs. (1)-(3), Case 1 in Table 3 is selected. Parameters in ADS-B transmitter/receiver and Delay ASAS/AGB models in Eqs. (6)-(10) are shown in Table 5.

Paramet ers	μ_{ADS}^{down} in ADS-B transmitter / receiver (sec)	p_{ADS}^{down} in ADS-B transmitter/ receiver	μ_{AC} in Delay ASA S (sec)	μ_{AC} in Dela y AGB (sec)
Case 4	1800	5.0×10^{-7}	6.5	6.5
Case 5	1800	5.0×10^{-5}	6.5	6.5
Case 6	1800	5.0×10^{-3}	6.5	6.5

Table 5 Parameter settings in ADS-B transmitter/receiver and Delay ASAS/AGB model for Cases 4-6

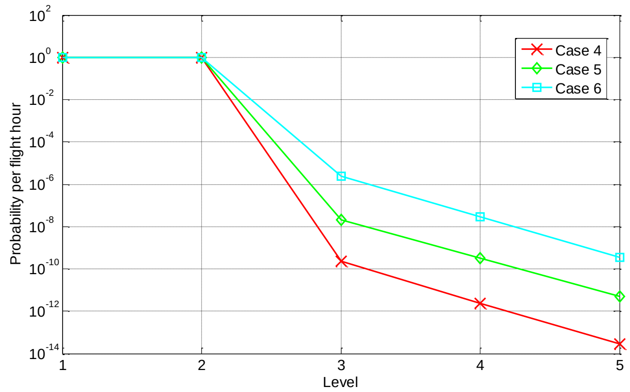

Figure 10 Probability of separation loss events in Cases 4-6

Figure 10 shows the probability of separation loss events corresponding to Cases 4-6. In comparing the results for these three cases, it appears that the probabilities of separation loss events increase linearly with the increase in the failure probabilities. These results showed that the performance of the surveillance determined the number of separation loss events significantly.

5 Concluding Remarks

This paper assessed the impact on surveillance failure in ASAS speed control applied for CDA operation. The mathematical models developed included the failure probabilities of ADS-B transmitter and receiver. HHIPS algorithm was applied to Monte Carlo simulation, and separation loss events were counted within a reasonable amount of simulation time. Considering the initial deviation of aircraft altitude, airspeed, spacing time error, and probability distribution related to ASAS surveillance and emergency action, the simulation results showed the following findings:

- Three combination of initial deviation were used in the simulation for 80 seconds time spacing. When the designed ASAS speed controller and emergency action were working well, all collision risks were less than the order of 10^{-11} under the assumptions in the simulation.
- The performance of ASAS surveillance determined the probabilities of separation loss events. If the probability of surveillance failure increases, then the number of separation loss events also increases linearly.

One of the key issues that determine the initial deviation is how much accuracy the ground control achieves in time management. The ASAS application and the ground system need to collaboratively create a more safe and effective future ATM. Since the performance of surveillance has an effect on the frequency of separation loss events, the requirement of hardware design should be decided to realize the desired safety in operation. Not only speed control but also vectoring may contribute to reducing the separation loss events. Our approach will be further developed for the evaluation of the future ASAS IM application.

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