Simulated collision risk of an uncoordinated airborne self separation concept of operation

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***Abstract*—This paper evaluates through Monte Carlo (MC) simulation of a model of an airborne self separation concept which has been developed for use under low en-route traffic conditions such as encountered over the Mediterranean area. In this self separation concept, each aircraft is equipped with an Airborne Separation Assistance System (ASAS) that proposes uncoordinated changes of its own aircraft path in order to resolve a conflict with the nearest other aircraft. For three different encounter scenarios, probabilities for violating minimum separation and for near-mid-air and mid-air events are estimated through rare event MC simulation. The paper presents quantitative risk estimates for several scenarios, and provides an interpretation of these results for the model of the airborne self separation concept considered. This provides novel insight in the efficacy of airborne conflict resolution management, and shows that uncoordinated airborne self separation can be very effective in safely handling low density en route airspace. It also shows that events of multiple conflict clusters may grow in size more rapidly than an uncoordinated airborne self separation may be able to solve. The insight gained shows developers of airborne self separation which issues are key for improvement in order to safely accommodate future high en-route traffic densities.**

***Index Terms*— Sequential Monte Carlo simulation, Petri net modelling, Safety risk assessment, Safety-critical systems, Autonomous Free flight**

I. INTRODUCTION

In [1] it has been proposed that aircrew obtain the freedom to select their trajectory, and the conceptual idea has been called free flight. Airborne self separation changes ATM in such a fundamental way, that one could speak of a paradigm shift: the centralised control becomes a distributed one, responsibilities transfer from ground to air, fixed air traffic routes are removed and appropriate new technologies are brought in. Each individual aircrew has the responsibility to timely detect and solve conflicts, thereby assisted by navigation means, surveillance processing and equipment displaying conflict-solving trajectories. Due to the many aircraft potentially involved, the system is highly distributed. Since the initial free flight concept definition leaves open many challenges in developing adequate procedures, systems and regulations, it has motivated the study of multiple airborne self separation operational concepts, implementation choices and requirements, e.g. [2]-[8].

All these concepts make use of an Airborne Separation Assistance System (ASAS) on board an aircraft. Key differences concern the coordination assumed between the aircraft, and whether all aircraft are equipped or not. [2] and [5] both assume all aircraft to be ASAS equipped. The former assumes full coordination of all aircraft trajectories through some centralized automated system, whereas the latter assumes some implicit form of coordination in tactical conflict resolution only. [8] proposes a self separation concept which incorporates airborne based distributed coordination.

Inherent to the nature of air traffic, the challenge of airborne self separation increases with increasing traffic demand. In [9] the safety of airborne self separation design for core USA and European airspace has been addressed, and this showed that it is crucial to gain an understanding of how to take safety well into account during the design of an airborne self separation operation. This question applies as well to advanced air traffic management concepts that do not use self separation. For example, the Automated Airspace Concept [10]-[11] aims to accommodate much higher traffic demand levels using ground based centralized coordination. For this advanced concept, [12]-[13] address the question whether the possibility of service outages means that automation cannot be permitted to exceed the traffic densities that are safe to handle by manual control. The results of a fault tree analysis suggest that service outages may be tolerable under two significant assumptions. One significant assumption is that the centralized ground system is able to timely manage and communicate separated trajectory plans that are conflict free for an extended period and which remain in effect while the system is re-configured from its fault condition, and traffic is rerouted. The other significant assumption is that simultaneous occurrences of two or more defined faults in the system have no significant impact upon the proper working of the specific design.

In [14] it is well explained that the key difficulty of evaluating advanced operations is to include emergent behavior, i.e. behavior which emerges from the combined dynamic actions and reactions by individual systems and humans within the overall system. This emergent behavior typically cannot be foreseen and evaluated by examining the individual behaviors alone. [14] also explains that multi-agent

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based simulation allows prediction of novel emergent behavior resulting from a change in the air transport design operation.

The aim of this paper is to develop a multi agent model of an airborne self separation operation, including nominal and non-nominal conditions and in an operational environment with imperfections, and then to perform MC simulations with this multi agent model of the operation. [15]-[16] performed such a safety risk study for airborne self separation equipped aircraft that are obliged to fly within a conventional fixed route structure. The main finding is that the largest risk contribution came from communication imperfections and common causes, and also that the safety risk imposed by this was somewhat reduced when the conflict detection and resolution control loop was shortest (i.e. pilot is in this loop, and controller is not). A key limitation of this study is that aircraft are required to fly within a fixed route structure.

The current modelling and MC simulation study considers a concept where airborne self separation equipped aircraft fly without any route structure restriction. The specific concept that we consider is referred to as Autonomous Mediterranean Free Flight (AMFF). AMFF has been developed as one of the potential advanced operational concepts to accommodate air traffic over the Mediterranean area [17].

For this AMFF application, fault trees have been developed and safety requirements have been derived [18] for the enabling technical systems such as ASAS (Airborne Separation Assistance System), ADS-B (Automatic Dependent Surveillance-Broadcast) and GNSS (Global Navigation Satellite System). [18] also concludes that the fault tree approach used has limiting analysis capability, and therefore recommends taking a more advanced safety modelling approach which is able to handle dynamic interactions between the multiple pilots involved.

The AMFF concept of operations has also been assessed on pilot acceptability through conducting real-time simulations of nominal and non-nominal conditions [19]-[21]. In addition, some flight trials have been conducted [22]. The results obtained show that pilots typically experience the AMFF way of operation as being acceptable and comfortable.

MC simulation studies of airborne self separation commonly assess safety in terms of conflict probability, e.g. [4], [23]-[25]. These studies already demonstrate the kind of challenges such studies have to deal with. There is a major additional challenge if one wants to conduct simulations aimed at estimating mid-air collision probability; it is required to further accelerate MC simulation by many orders of magnitude. For self-separation equipped aircraft that are assumed to fly within a conventional fixed route structure, such factors in MC acceleration have been realized by taking advantage of the fixed route structure [26],[16]. Since this acceleration approach does not work for concepts without route structure, another approach in accelerating MC simulations is needed. Such a novel approach has been developed through a sequence of dedicated studies in rare event estimation.

The current paper briefly outlines the novel developments in modeling and MC simulation, and then focuses on explaining the MC simulation results obtained by applying these approaches to demanding scenarios within the AMFF operational concept setting. [27] presents the initial collision risk estimation results that have been obtained following this approach. The current paper further elaborates the results obtained, such as:

- To systematically show what these MC simulation results mean for the conflict resolution phases that pass from medium term conflict through short term conflict to near mid-air;
- To compare the safety of operation under AMFF against a situation where aircraft are assumed to behave and collide like individual molecules within the well known gas model [28];
- To discuss what these simulation results mean for the AMFF operational concept considered and for airborne self separation in general.

The paper is organized as follows. Section II provides a brief overview of the AMFF concept of operation considered. Section III explains the Monte Carlo simulation approach developed for assessing collision risk. Section IV presents results of Monte Carlo simulations performed for three traffic encounter scenarios. Section V provides concluding remarks.

Parts of the research results in this paper have been presented at the AIAA-ATIO Conf. of September 2007 in Belfast, Ireland [29]; and at the Eurocontrol Safety R&D Seminar of October 2007 in Rome, Italy [30].

II. AIRBORNE SELF SEPARATION CONCEPT CONSIDERED

The development of the AMFF operational concept was completed prior to the current research, and falls outside the scope of this paper. For this reason, we provide a high level description of AMFF only; for a complete description of AMFF we refer to [17],[31]. An important guideline in the development of the AMFF concept has been pilot acceptability and comprehensibility of the conflict resolution maneuvers. This guideline, and the attempt to avoid vulnerabilities in the information exchange between aircraft, has led to the adoption of the following simple principles during the development of the AMFF design [17]:

a) In order to avoid dependence of exchange of any trajectory intent information between aircraft, a state-based conflict detection and resolution is adopted, and it is assumed that there is no coordination or negotiation of intent between aircraft;
b) In order to accommodate pilot wishes, conflicts of own aircraft with other aircraft are detected and resolved in a sequential way (priority goes to resolving the nearest conflict), and without taking into account that such a local resolution need not improve the overall conflict situation between all aircraft;
c) Pilot rules and procedures are straightforward, and do not involve decision-making by artificially intelligent support systems;

d) The level of automation is such that the pilot has the decision power to adopt one of the automatically generated conflict resolution advisories and to steer the aircraft away from the corresponding conflict accordingly, i.e. without a direct coupling of the conflict resolution advisories with the guidance and control systems of its own aircraft.

It is remarked that the conflict management approach developed for AMFF has its roots in the modified potential field approach in [5], where simultaneous multiple conflicts are resolved through an implicit coordination via the joint potential field. This implicit coordination part, however, has not been taken over in AMFF by the MFF designers [17] for reasons of improved pilot acceptability and comprehensibility of resolution maneuvers. Therefore all resolution maneuvers are completely uncoordinated between conflicting aircraft, with the exception of priority rules described below. The resulting AMFF design can be summarized as follows:

- Aircraft are equipped with ADS-B, which periodically broadcasts own aircraft state information, and continuously receives state information messages broadcasted by aircraft that fly within broadcasting range.
- Aircraft are equipped with a system referred to as Predictive ASAS (P-ASAS), which indicates which maneuvers should be avoided to maintain a conflict-free trajectory. For example, it verifies if an aircraft can safely return to its flight plan after executing a conflict resolution maneuver.
- Aircraft are equipped with ASAS, including conflict detection and resolution based on linear extrapolation of the current states of the aircraft.
- The vertical separation minimum is 1000 ft and the horizontal separation minimum is 5 NM. A conflict is detected by ASAS if these separation minima will be infringed within a look-ahead time of 6 minutes.
- The conflict resolution process consists of two phases. During the first phase (predicted conflict is 6 to 3 minutes ahead), unambiguous priority rules determine for each crew whether their aircraft should make a resolution maneuver or not. Those priority rules are in favour of respectively aircraft in emergency, aircraft with limited maneuverability, aircraft flying level, et cetera. If this approach does not timely solve the conflict, then during the second phase (predicted conflict is 3 minutes or less ahead), both crews should make a resolution maneuver.
- Two conflict resolution maneuver options are presented: one in the vertical and one in the horizontal direction. The presence of other aircraft than one in nearest conflict is not taken into account in these conflict resolution maneuver options. The crew decide which maneuver option to execute.
- All aircraft use the same resolution algorithm, and all crew apply the same procedures.
- ASAS-related and surveillance information is presented to the crew through a Cockpit Display of Traffic Information (CDTI).

Largely due to the adoption of the simple design principles, the resulting AMFF concept may perform less well than what might be feasible with a coordinated airborne self separation concept design. In spite of AMFF's design choice to avoid any coordination, human factors research and piloted real-time simulations have shown that an AMFF operation is perceived by pilots to be comfortable both under Mediterranean traffic demands [22] as well as under high continental en-route traffic demands [20],[32]. The aim of the current study is to formally assess if a model of the AMFF concept can safely accommodate high en-route air traffic demands or what are the reason(s) when this cannot.

An AMFF model has been developed of the AMFF operation, and subsequently this AMFF model is used to perform MC simulations. By definition, the AMFF model forms an approximation of the true AMFF operation. Moreover, within this AMFF model some aspects of the AMFF operation are intentionally not covered, and therefore these have not been mentioned earlier in this section. These intended differences between AMFF operation and AMFF model are:

- In the AMFF concept there is a Flight Level Orientation Scheme (FLOS), and aircraft flying according to it get priority over aircraft that do not. In the AMFF model there is no FLOS.
- In the AMFF operation there are adjacent airspaces and therefore transitions to or from Managed Airspace. In the AMFF model there is no adjacent airspace at all.
- In the AMFF concept there are flight planning and air traffic flow management. In particular, a ground ATM network has means to monitor traffic density and mechanisms to prevent aircraft entering the airspace if the traffic density is considered too high. Moreover, the Air Traffic Controller has the task to provide precautionary information if specific local areas are predicted to become too congested. In the AMFF model there is none of this.

III. AMFF MODEL AND MC SIMULATION

A. *Agents in AMFF model*

In the AMFF model developed [33] the following types of agents are taken into account:

- Aircraft state
- Pilot-Flying (PF)
- Pilot-Not-Flying (PNF)
- Airborne GNC (Guidance, Navigation and Control)
- Airborne Separation Assistance System (ASAS)
- Communication / Navigation / Surveillance systems

It should be noticed that this AMFF model is an initial one which does not (yet) incorporate environment/weather, Airborne Collision Avoidance System (ACAS) or Airline Operations Centre (AOC). For each agent, particular local Petri Nets (PNs) have been developed, and subsequently the interactions between these local PNs have been specified. A listing of agents and local PNs (per agent) is given in Table 1.

TABLE I. AGENTS AND LOCAL PN'S IN THE AMFF MODEL

- Aircraft state local PNs:
    - Type
    - Evolution mode
    - Systems mode
    - Emergency mode
- Pilot-Flying (PF) local PNs:
    - State Situation Awareness
    - Intent Situation Awareness
    - Goal memory
    - Current goal
    - Task performance
    - Cognitive mode
- Pilot-Not-Flying (PNF) local PNs:
    - Current goal
    - Task performance
- Airborne GNC local PNs:
    - Indicators failure mode for PF
    - Engine failure mode for PF
    - Navigation failure indicator for PF
    - ASAS failure indicator for PF
    - ADS-B receiver failure indicator for PF
    - ADS-B transmitter failure indicator for PF
    - Indicator failure mode for PNF
    - Guidance mode
    - Horizontal guidance configuration mode
    - Vertical guidance configuration mode
    - FMS flightplan
    - Airborne GPS receiver
    - Airborne Inertial Reference System (IRS)
    - Altimeter
    - Horizontal position processing
    - Vertical position processing
    - ADS-B transmission
    - ADS-B receiver
- ASAS local PNs:
    - Processing
    - Alerting
    - Audio alerting
    - Surveillance
    - System mode
    - Priority switch mode
    - Anti-priority switch mode
    - Predictive alerting (of other aircraft)
- Communication / Navigation / Surveillance systems PNs:
    - Global Navigation Satellite System (GNSS)
    - Global ADS-B ether frequency
    - SSR Mode-S frequency

The resulting AMFF model comprises 41 different local PN's. With exception of the last three local PN's above, each local PN is copied for each aircraft in the AMFF model. Hence, for N aircraft, there are 38N+3 local PNs in the AMFF model.

B. *From AMFF model to MC simulation model*

Once the AMFF model has been specified in terms of Petri nets, then the next phase consists of a systematic development of a corresponding Monte Carlo simulation model. This is done through the following sequence of steps:

- Identification of the scenarios that have to be evaluated through MC simulations, and identification of the safety relevant events that have to be counted during these MC simulations.
- Software coding: The SDCPN specification language of the Petri net model is transferred to any preferred computer coding language. For the AMFF model computer coding we used Borland's Delphi 2006 Professional coding language. Since SDCPN specification forms a detailed model, the transfer to Delphi code is rather straightforward;
- Software testing. This is done through conducting the following sequence of tests: random number generation, statistical distributions, common functions, each LPN implementation, each agent implementation, interactions between all agents, full MC simulation;
- Numerical approximation testing. This is needed to identify the maximum numerical integration step allowable, and the minimum number of particular MC simulations required for reaching statistically significant results;
- Development of suitable methods for the acceleration of the MC simulations for each of the identified scenarios, and implementation of these methods in the form of a software shell around the MC simulation model software.
- Graphical user interface testing. This is to verify that the input and output of data works well;
- Parameterization. This is done through a search of literature and statistical sources, and complemented by conducting expert interviews. The fusion of these different pieces of information is accomplished following a Bayesian approach.

In addition to the above, initial model validation has been performed in three ways:

- By comparing MC simulation results of the uncontrolled model with analytical results obtained through the gas model [28],[34];
- By discussion and interpretation with AMFF experts of the MC simulation results of the AMFF model; and
- By running specific additional MC simulations upon requests by AMFF experts, and subsequent discussion of the results obtained with their expectations.

C. *Parameter values*

The AMFF model has a set of 108 scalar parameters. For each of these parameters a baseline value has been identified. In addition to these baseline values, for the parameters of AMFF enabling technical systems and for the parameters of the pilot flying response, non-baseline sets of values have also been identified.

The set of values used for the main safety critical parameters of the AMFF enabling technical systems (GNSS, ADS-B and ASAS) are given in Table II. Three sets of values are identified; a set of baseline dependability, and two sets of 10x and 100x improved dependability respectively. The baseline dependability values are based on [35] and [36]. In the 10x and 100x improved dependability sets, each individual dependability value is respectively 10x and 100x improved over its baseline value.

TABLE II. Parameter values of AMFF enabling technical systems

Model parameters of AMFF enabling technical systems	**Baseline Dependability**	**10x Baseline Dependability**	**100x Baseline Dependability**
Probability of Global GPS down	1.0×10^{-5}	1.0×10^{-6}	1.0×10^{-7}
Probability of Global ADS-B down[1]	1.0×10^{-6}	1.0×10^{-7}	1.0×10^{-8}
Probability of Aircraft ADS-B Receiver down	5.0×10^{-5}	5.0×10^{-6}	5.0×10^{-7}
Probability of Aircraft ADS-B Transmitter down	5.0×10^{-5}	5.0×10^{-6}	5.0×10^{-7}
Probability of Aircraft ASAS System mode corrupted (see LPN 6 in Fig. 1)	5.0×10^{-5}	5.0×10^{-6}	5.0×10^{-7}
Probability of Aircraft ASAS System mode failure (see LPN 6 in Fig. 1)	5.0×10^{-5}	5.0×10^{-6}	5.0×10^{-7}

For the Pilot Flying activities, two sets of parameter values are used, a baseline set and a “fast response” set. The baseline set of values are best estimates based upon experience gained during real-time piloted simulations. All “fast” PF response values are hypothetically low, but useful for the sake of understanding the impact on reduction of collision risk as a function of improving PF response.

D. Air traffic scenarios and safety related events

For the AMFF model, MC simulations are conducted for the following encounter scenarios:

- Two-aircraft head-on encounter scenario
- Eight-aircraft encounter scenario
- Random traffic scenarios for various traffic densities

The specifics of each of these encounter scenarios and the resulting MC simulation results are presented in Section IV, for the following sets of parameter values:

- AMFF model with baseline parameter settings;
- AMFF model with 10x and 100x improved dependability of technical systems (see Table I) and baseline PF response setting;
- AMFF model with baseline dependability parameter settings and hypothetical “Fast PF response” parameter settings.

For each scenario, probabilities for the following safety related events are estimated:

- Medium Term Conflict (MTC)
- Short Term Conflict (STC)
- Minimum Separation Infringement (MSI)
- Near Mid Air Collision (NMAC)
- Mid Air Collision (MAC)

These safety related events are defined through three parameters: a prediction time, a horizontal distance criterion, and a vertical distance criterion. The specific values adopted for MTC, STC, MSI, NMAC and MAC are given in Table III.

TABLE III. Definition of safety related events used in collecting statistics from the MC simulations. The values typically are some 10% lower than the values that are used within the AMFF design for separation minima. For MTC and STC, the MSI test is applied to the predicted aircraft states (respectively 8 and 2.5 minutes predicted ahead).

Event	MTC	STC	MSI	NMAC	MAC
Prediction time (minutes)	8	2.5	0	0	0
Horizontal distance (Nm)	4.5	4.5	4.5	1.25	0.054
Vertical distance (ft)	900	900	900	500	131

For each encounter scenario simulation results are also given for the uncontrolled condition, i.e. in the AMFF model, the conflict detection and resolution is switched off. Under these uncontrolled condition, the safety related event probabilities in the various encounter scenarios have also been calculated using the gas model [28]; these calculated values agreed with the estimated values obtained through MC simulation.

E. Acceleration of MC simulation

The basic idea of assessing collision risk is to perform many Monte Carlo (MC) simulations with the AMFF model for each of the scenarios identified, and to estimate the collision risk by counting the number of collisions and dividing this by the number of simulated flight hours. Though this idea is simple, in order to make it work in practice, we need an effective way of speeding up the MC simulation. This section describes the basic idea of how this works.

Rather than MC simulation of run after run, we exploit a sequential MC simulation approach, i.e. one which consists of a series of MC simulation cycles, where each cycle uses the output of the previous cycle as input to its own cycle. This way it is possible per cycle to zoom further into the behaviour of AMFF model simulated trajectories. During the first simulation round we are interested in counting events that happen quite regularly, i.e. say once in about 10 to 100 MC simulation runs. Each next cycle we are interested in events that happen an order of magnitude less frequent. In order to make this cyclic approach work, the MC simulation results that have been obtained by one cycle are going to be used to partly generate the seeds for the next MC simulation cycle. In [37],[38] a precise mathematical framework and algorithm has been developed for conducting such a sequential MC simulation well. It also has been proven that the estimated event probabilities converge to the true probabilities under

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[1] Global ADS-B down refers to frequency congestion/overload of the data transfer technology used for ADS-B.

some technical conditions. The main conditions are that the process to be assessed needs to satisfy semi-martingale and strong Markov properties. In [39]-[42] it has been shown that the specific PN specification approach that has been used for the AMFF model, assure that the technical conditions are satisfied.

This general sequential MC simulation approach has been further developed towards the evaluation of the specific AMFF scenarios. This has led to several extensions. One important extension is to insert extra conflict levels in between the safety related events of Table III [27],[33]. Another important extension [43],[44] improves the effectiveness in handling the many discrete mode combinations within the AMFF model, when only some of them are dominating the collision risk.

IV. MONTE CARLO SIMULATION RESUTLS

A. *Two-aircraft head-on encounter scenario*

In this encounter scenario, two aircraft start at the same flight level, some 250 km away from each other, and fly on opposite direction flight plans head-on with a ground speed of approximately 240 m/s. We present MC simulation results for the baseline parameters and also those for 10x and 100x improved dependability.

For the assessment of each scenario for one set of parameter values, we ran 10 times a sequential MC simulation as developed in [29],[44]. Running the sequential MC simulation 10 times allows us to estimate both the event probabilities as well as the precision (e.g. variance) of this estimate. Each of such 10 MC simulations used 80 thousand particles (i.e. 80 thousand randomly and sequentially simulated two-aircraft encounters) and required 8 minutes on one Dell Precision 390, and a computer memory load of about 2.0 Gigabyte.

The lowest probability that has been estimated this way is 1.8E-9. In order to estimate this value similarly well through straightforward MC simulation, this would make one Dell Precision 390 run for 2 years. This means that the novel MC simulation accomplished an acceleration factor in MC simulation of 100 thousand times.

For the two-aircraft head-on encounter, Figure 1 presents the estimated probabilities for the safety related events defined in Table III for the uncontrolled situation and for AMFF controlled with three sets of dependability parameter values. For all three AMFF controlled cases, the MAC probability is dominated by non-nominal global ADS-B.

Figure 1 show that without any control, the probabilities of NMAC and MAC are 1.0 and 0.85 respectively. Thus for the two-aircraft scenario considered, without control, there is a 100% chance that an NMAC happens and subsequently there is 85% chance that the two aircraft collide. The AMFF controlled results in Figure 1 show that in the AMFF model, conflict detection and resolution works quite effectively in avoiding STC; only about one in 2200 (1.0 / 4.5E-4) head-on encounters leads to an STC. Moreover, under baseline dependability, about one in 180 (= 4.5E-4 / 2.5E-6) of such STC's leads to an MSI. Together this means that the AMFF model is very effective in preventing MSI for a head-on encounter between two aircraft.

The results in Figure 1 clearly show that for the two aircraft head-on encounter, the 10- and 100-fold improvements in the dependability of AMFF enabling technical systems lead to 10- and 100-fold improvements respectively in the estimated MSI, NMAC and MAC probabilities, whereas the estimated MTC and STC probabilities remain unchanged. This is in line with the finding that the cause for collision risk in this scenario lies in the dependability of AMFF enabling technical systems. Moreover, the results show that for a two aircraft encounter the AMFF concept as modelled can reduce the probabilities for MSI, NMAC and MAC by improving the dependability of the AMFF enabling technical systems.

Finally, the two aircraft encounter scenario has also been MC simulated for two encountering aircraft that cross each other at angles between 20 and 180 degrees. All MC simulation estimated event probabilities appeared to be equal for any angle of 30 degrees and higher, and with an increase of about 25% in probability value for an angle of 20 degrees.

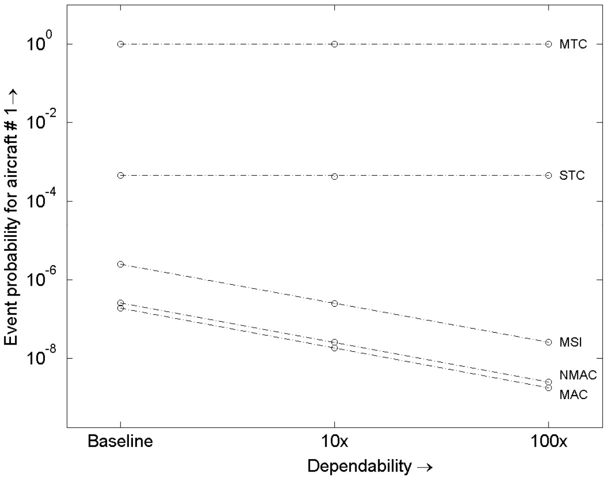

Figure 1. Estimated event probability for two-aircraft head-on encounter under AMFF model, as a function of dependability on GNSS, ADS-B and ASAS systems

B. *Eight-aircraft encounter scenario*

In this Section we consider the eight-aircraft encounter scenario pictured in Figure 2. Each aircraft starts at the same flight level at a circle of about 250 km in diameter. Each aircraft has a ground speed of 240 m/s and is heading to the opposite point on the circle.

First we compare the MC simulation results obtained for this scenario with those obtained for the two-aircraft encounter scenario. Next, we show the effect of "Fast response" by PF upon the probabilities of safety related events.

For the assessment of each scenario for one set of parameter values, we ran 30 times a sequential MC simulation as developed in [45],[33]. This way we estimated the safety related event probabilities 30 times, and this allowed to estimate both mean and variance. For each of such 30 MC simulations we used 25 thousand particles (i.e. 20 thousand randomly and sequentially MC simulated eight-aircraft encounters) and this required about 30 minutes on one Dell Precision 390, and a computer memory load of about 2.0 GB.

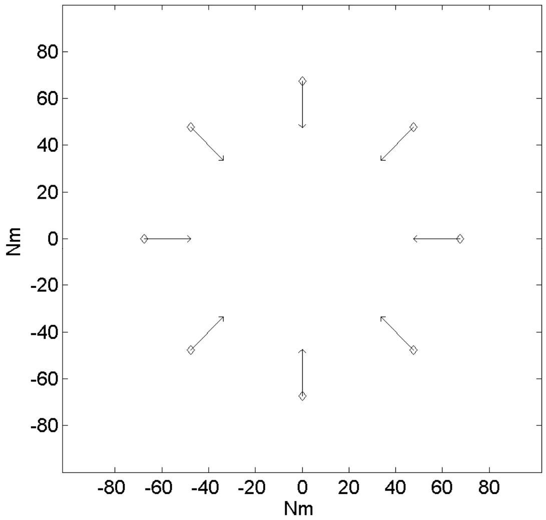

Figure 2. Eight aircraft encounter scenario

Without conflict detection and resolution, the probability of MTC, STC, MSI, NMAC and MAC for an individual aircraft are all equal to 1.0. With AMFF modelled conflict detection and resolution, the estimated probability for one aircraft to collide with at least one of the other seven aircraft equals 1.6E-06. We verified that this risk value was not sensitive at all to the dependability of the AMFF enabling technical systems. In Figure 3, the outcomes of MC simulations of AMFF for the eight-aircraft encounter scenario are compared to the probabilities obtained for two-aircraft head-on encounter scenario, both under baseline dependability.

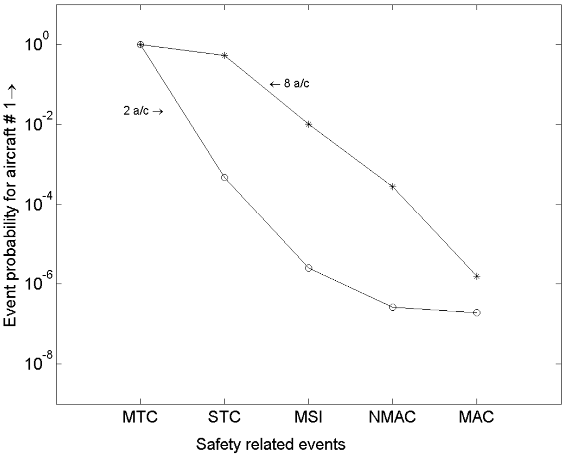

Figure 3. Estimated probabilities of safety related events for a/c #1 in two-aircraft head-on encounter vs. eight-aircraft encounter.

The MAC probability is increased by a factor 8.4 for the eight aircraft encounter, which is almost equal to the 7 times more aircraft that are in the scenario to collide with. Thus on first sight, from a MAC probability perspective only, the results obtained for the eight-aircraft encounter seem to be pretty good. However, there are two types of behavior of the AMFF model on the eight-aircraft encounter scenario which indicate that the results are less good.

The first indication is that, in contrast to two-aircraft encounter, for the eight aircraft encounter the MAC probability does not improve if the dependability of the AMFF enabling technical systems is improved. The second indication is that the AMFF model starts becoming effective in solving conflicts much later for the eight-aircraft encounter than it does for the two-aircraft encounter. This can be seen by comparing (in Figure 3) the factors of improvement when going from MTC to STC, from STC to MSI, from MSI to NMAC and from NMAC to MAC. This shows that the conflict detection and resolution of the AMFF model starts to become effective after an STC instant has been passed. This implies that for the eight-aircraft encounter the conflict resolution in the AMFF model continues resolving conflicts effectively in the time period that is currently reserved for the ACAS safety net. This kind of behavior is quite different from the behavior seen for the two-aircraft encounter scenario, where the AMFF model typically solves a conflict before ACAS could become active.

A more detailed evaluation of simulation results for the eight aircraft encounter scenario (by tracing back what happened prior to a simulated MAC event) has shown that a MAC is typically caused by the following effect. A crew starts to solve a multiple conflict sequentially by executing a certain maneuver that resolves a conflict with one other aircraft. This maneuver may have three possible outcomes, or any combination of these three outcomes:

- It solves the conflict aimed for;
- It solves other conflicts by coincidence;
- It induces new conflicts.

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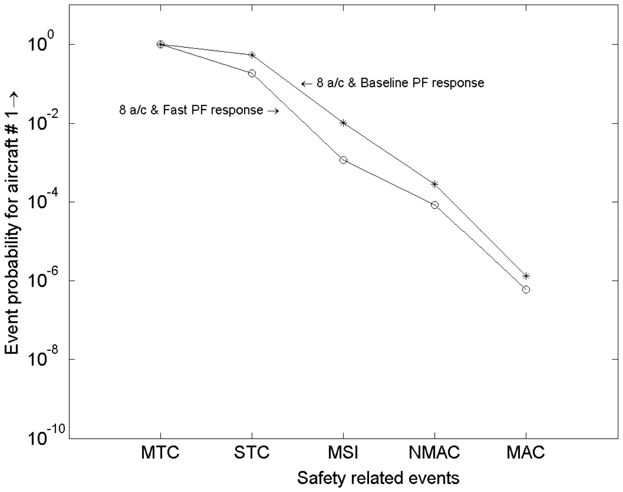

Figure 4. Estimated event probabilities for a/c #1 in an eight-aircraft encounter scenario under AMFF; baseline PF response vs. fast PF response.

All together, this means that the coincidental, uncoordinated way of working by the AMFF model on resolutions may delay the implementation of a joint conflict resolution.

The results above raised the question whether a faster response of the PF might be of help in improving the results for the eight-aircraft encounter. In order to find this out, additional MC simulations have been performed with the mean task durations of pilots reduced to 2s only. The MC simulation results are shown in Figure 4. The faster response of PF leads to about a factor 10 reduction in MSI probability, but of this reduction a factor 2.7 only remains for the MAC probability. This means that a faster response by the PF does not really help to reduce the risk

C. *Dense random traffic scenario*

The third encounter scenario artificially simulates AMFF equipped aircraft flying randomly through a virtually unlimited airspace. In order to accomplish this, the virtually unlimited airspace is filled up with packed containers. Within each container a fixed number of seven aircraft (i = 2, .., 8) fly at arbitrary position and in arbitrary direction at a ground speed of 240 m/s. One additional aircraft (i = 1) aims to fly straight through a sequence of connected containers, at the same speed, and the aim is to estimate its probability of collision with any of the other aircraft per unit time of flying. Per container, the aircraft within it behave the same. This means that we have to simulate each aircraft in one container only, as long as we apply the ASAS conflict prediction and resolution also to aircraft copies in the neighbouring containers. By changing container size we can vary traffic density. In order to avoid that an aircraft experiences a conflict with its own copy in a neighbouring container, the size of a container should not become too small.

With SESAR capacity targets for 2020 in mind, our baseline traffic density value is defined to be 2.5 times the level of one of the busiest en-route sectors in Europe in 1999. Based on a data set of European air traffic that has been collected for a busy day in July 1999, the highest aircraft density reference point is a number of 17 aircraft counted at 23rd July 1999 in an en-route area near Frankfurt of size 1 degree x 1 degree x FL290-FL420. This comes down to 0.0032 a/c per Nm^3, and multiplied by 2.5 yields our baseline traffic density of 0.008 a/c per Nm^3. The latter is eight times the traffic density that has been considered in the example of [12],[13].

For the MC simulation of baseline traffic density, i.e. 0.008 a/c per Nm^3, we chose containers having a length of 40 Nm, a width of 40 Nm and a height of 4000 feet, and with 8 aircraft flying in such container. For this baseline scenario we ran the sequential MC simulation algorithm of [45],[33] ten times (plus one extra sequential MC simulation run later on) over 10 minutes. Prior to this we ran the MC simulation during 5 minutes in order to assure convergence. The number of particles per sequential MC simulation run is 10,000. One sequential MC simulation run took about 24 hours on one Dell Precision 390, and the computer memory load was 0.7 GB.

The MTC, STC, MSI, NMAC and MAC probabilities in the baseline random traffic scenario have been assessed under three control conditions: one without any control in terms of conflict detection and resolution, one under AMFF model with baseline PF response, and one under AMFF model with “fast PF response”. The MC simulation results for the uncontrolled and the AMFF model controlled conditions are given in Figure 5. This shows that under baseline traffic density, AMFF yields a factor 220 reduction in MAC probability relative to the uncontrolled case.

For the baseline random traffic scenario, the estimated mean probabilities have been obtained from 10 minutes sequential MC simulation of random traffic. For the scaling of the event probabilities per 10 minutes to event probabilities per hour, the following equation is used: $p = 1-(1-p_{SMC})^{\frac{T}{T_{SMC}}}$ with T = 60 minutes, T_{SMC} the time period used in the sequential MC simulation (convergence period is not included) and with p_{SMC} the estimated probability per T_{SMC}. For small p_{SMC} values, this yields $p \approx \frac{T}{T_{SMC}} \cdot p_{SMC}$.

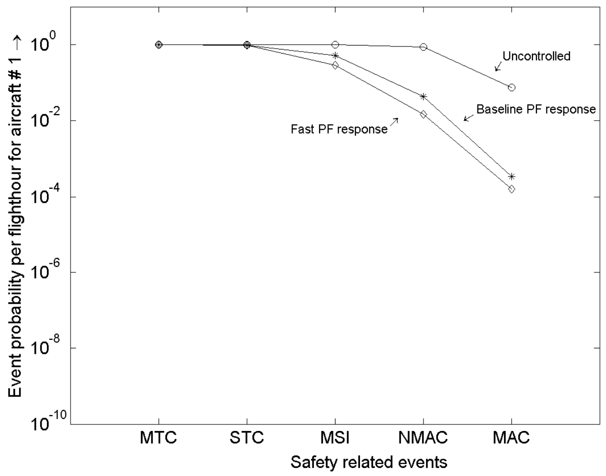

Figure 5. Estimated event probability per flighthour for a/c #1 under baseline random traffic density; uncontrolled vs. AMFF controlled (Baseline and “Fast” PF responses)

Figure 5 shows the impact of “fast response” of PF in comparison with the baseline response values. This “fast response” leads to an improvement of about a factor two between first STC instant and first MSI instant. This factor two remains about the same up to MAC instant. The relatively small reduction in MAC probability seems to show that some multi-aircraft conflicts are so difficult to be resolved through an uncoordinated conflict resolution approach that it does not help a lot if the PF responds faster.

It can also be noticed that for the baseline random traffic scenario, the effectiveness of AMFF model is rather weak prior to the first MSI instant. After this, the AMFF model really starts working, both from MSI instant to first NMAC instant and from this until MAC. This late start of AMFF model becoming effective in resolving conflicts has also been seen with the eight-aircraft encounter scenario. We also verified for the eight aircraft encounter scenario, the estimated event probabilities do not reduce at all when the dependability of the AMFF enabling technical systems is improved.

In order to better understand what causes the late start of AMFF working effectively and the relatively high collision risk, we performed an extra sequential MC simulation run, and memorized in static memory for each particle the ancestor history for each sequential MC simulation of the safety related events. This allowed us to trace back what happened for the particles that reached the MAC event. For this extra sequential MC simulation run with 10,000 particles, we counted five different MAC events. Evaluation of these MAC events showed that all five happened under nominal safety critical conditions. More specifically, four of the five MACs were due to a growing number of multiple conflicts that could not be timely solved by the AMFF concept as modelled. The fifth MAC was of another type: at quite a late moment a conflict of aircraft #1 with another aircraft was solved through a fast climb by aircraft #1 and this created a MAC with a copy of that other aircraft in a neighbouring upper container.

The results in this section indicate that the potential of multiple clogging conflicts are a key factor in the late start of effective AMFF and a subsequent increased risk of collision with random traffic, under baseline traffic density, which is far higher than what the AMFF operational concept was designed for. In the rare occasion that such clogging happens, it is not always possible to timely solve a sufficiently high fraction of those multiple conflicts. This potential clogging of conflicts (i.e. that simultaneous conflict situations occur and then such a cluster of conflicts tends to grow faster in size than the conflict resolution can handle) seems to be due to the AMFF design approach in solving multiple conflicts in an uncoordinated sequential way. Because this clogging of conflicts happens less than once in thousand dense random traffic simulations of 10 minutes, this is an emergent behavior that is difficult to observe and analyse with established approaches.

V. CONCLUDING REMARKS

The safety analysis of advanced operational concepts like airborne self separation has been recognized as a problem that needs to be solved in order to enable a serious consideration of airborne self separation to be valid and feasible for application in busy en-route airspace. In order to improve this situation, the paper has evaluated several demanding airborne self separation scenarios on safety though estimating probabilities of rare events which range from Short Term Conflict (STC) through Minimum Separation Infringement (MSI) to Near mid-air collision (NMAC) and Mid-air collision (MAC). This evaluation has become feasible due to a preceding series of theoretical studies and developments in the area of MC simulation model development and MC speed up techniques in rare event estimation.

In the Autonomous Mediterranean Free Flight (AMFF) airborne self separation concept considered, each pilot solves conflicts sequentially and uncoordinated. This AMFF concept has been very well developed for en-route airspace of low traffic demand, and it has been shown through real-time flight simulation studies that pilots experience flying under the AMFF concept as being comfortable. The MC simulation results obtained for an initial AMFF model provide novel insight in safety related behaviour of an uncoordinated airborne self separation concept, and the analysis of this behaviour is not within scope of the traditional approaches towards safety analysis.

The MC simulation results for a two-aircraft head-on encounter show that an uncoordinated conflict resolution can be very effective, and that collision risk can be lowered to a desired value by improving the dependability of AMFF enabling technical systems. This allows reducing the probabilities for MSI, NMAC and MAC in case of two aircraft encounters by improving the dependability of these systems.

More generally, the MC simulation results obtained show that this AMFF model works sufficiently safe for en-route airspace having sufficiently low air traffic demand. For a busy en-route sector, however, some form of coordination in conflict resolution seems needed to prevent the potential clogging of multiple conflicts.

As follow up of the current research, the following valuable research questions have been identified:

- Up to which en-route traffic demand can safely be accommodated by airborne self separation when effective use is made of airborne based distributed coordination, e.g. [8],[46],[47]?
- What are the potential benefits of using traffic flow management to assure that airborne self separation aircraft are not caught in dense local traffic?
- How should aircraft with such advanced ASAS equipment on board, fit best within SESAR and NEXTGEN?

Within the iFly project (http://iFly.nlr.nl), stochastic control experts, cognitive psychologists and ATM concept development experts from eleven universities and seven industry partners are collaborating to address these research questions.

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