Safety of advanced airborne self separation under very high en-route traffic demand

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***Abstract*—Since the “invention” of free flight, an outstanding question is how much traffic demand can safely be accommodated by airborne self separation. In order to answer this question, within the iFly project an advanced airborne self separation concept of operations (ConOps) has been developed. This paper shows the results of an assessment of this ConOps on safety risk under very high en-route traffic demand. The accident risk assessment is conducted using advanced techniques in agent based modelling and rare event Monte Carlo simulation. The results obtained show which en-route traffic demand can safely be accommodated by advanced airborne self separation.**

Keywords-component; Free flight; Monte Carlo; rare events; safety risk assessment; airborne self separation, velocity obstacles

I. INTRODUCTION

Since the “invention” of free flight [38], airborne self separation research has received significant attention. Nevertheless, the current situation is of two schools of research holding different beliefs. One school believes airborne self separation can be safely performed at traffic demands well above current demands. The other school believes airborne self separation cannot be carried out at sufficiently safe in busy airspace. Both schools also agree on two key points:

- At very low traffic demand, safety will be improved by equipping aircraft with an appropriate Airborne Separation Assistance System (ASAS).
- There will be some limit on the air traffic demand that can safely be managed.

From a research perspective this means there is an urgent need to address the question: Up to which traffic demand can safely be accommodated by airborne self separation? The aim of this paper is to address this question.

The paper is organized as follows. Section II introduces the advanced airborne self separation ConOps considered. Section III explains the simulation model developed. Sections IV, V and VI present rare event MC simulation results for two, eight and random traffic scenarios respectively. Section VII draws conclusions.

II. ADVANCED AIRBORNE SELF SEPARATION

A. Free flight background

The free flight “invention” has motivated the study of multiple airborne self separation operational concepts, implementation choices and requirements, e.g. [15,17,20,22,31, 34,35,39]. Although all concepts make use of some ASAS onboard an aircraft, there are large differences, e.g. on the coordination between aircraft.

Both [15] and [20] assume all aircraft to be equipped with an ASAS that supports pilots with conflict resolution using an implicit form of coordination. Using this approach, a full ConOps has been developed for conducting airborne self separation over the Mediterranean area [19,33]. For this ConOps in-depth human in the loop simulations have shown that pilots are very well able to manage high traffic demands [40,41]. Subsequently [10] has shown that this Autonomous Mediterranean Free Flight (AMFF) ConOps falls short in safely accommodating high en-route traffic demands, because in some infrequent cases, it takes too many manoeuvring trials and time to resolve conflicts involving many aircraft [10].

Because AMFF has shown to work very well most of the time, it is expected that a more advanced airborne self separation approach can safely accommodate higher traffic demand. A potential candidate is the [35] proposed airborne self separation ConOps. Here, ASAS conflict resolution is assumed to work intent based, both strategically and tactically, again through an implicit form of coordination. [11] shows through standard Monte Carlo simulations that under nominal conditions, the strategic layer resolves all medium term conflicts well, also under very high en-route traffic demand. In follow-up studies [12,14] the effects of pilot response delays on the performance of the strategic layer have been studied using standard Monte Carlo and human in the loop simulations. [13] evaluates the effect of wind deviations on the strategic layer using standard Monte Carlo simulations. These results show that the strategic layer is not always able to resolve all conflicts. From safety perspective this means there is a need for conducting rare event Monte simulations for the combination of strategic and tactical layers, including coverage of various non-nominal situations [26].

B. iFly's Advanced airborne self separation ConOps

During the first part of the iFly project, the [35] ConOps has been used as starting point for the development of an advanced airborne self separation concept for en-route traffic under the name A^3 ConOps [23]. This A^3 ConOps intentionally addresses the hypothetical situation of 100% well equipped aircraft, and no help from air traffic controllers on the ground. For further details of the A^3 ConOps and A^3 Operational Services and Environmental Description (OSED), see [23] and [30]. Here we give a high level description of the A^3 intended operation only.

Similar to the SESAR2020 ConOps [42], the A^3 ConOps works with Reference Business Trajectories (RBT's). In contrast to SESAR2020, however, A^3 ConOps RBT management is done without help from ATC. Moreover, voice communication between pilots is assumed to be mainly for use under emergency situations. Typically, information exchange between aircraft is assured through ADS-B, which is extended over the horizon through a System Wide Information Management (SWIM) network. Each aircraft broadcasts information about its state and intent (its RBT) to other aircraft. This allows each aircraft to predict the intended trajectories of other aircraft, and to act such that separation criteria are adhered to. Each aircraft is assumed to be equipped with a dedicated ASAS system which is monitoring the surroundings and helps the flight crew to detect and resolve conflicts. This ASAS supports two lines of defense in the resolution of potential conflicts: Medium Term Conflict Resolution (MTCR) and Short Term Conflict Resolution (STCR). Both MTCR and STCR are assumed to use implicit coordination only.

MTCR aims to identify 4D trajectories which are conflict free (5 Nm/1000 ft distance between centerlines) over a time horizon of at least 15 minutes. Once an identified 4D trajectory is accepted by the crew it is adopted as the aircraft's RBT, and it is broadcasted to the other aircraft. When a Medium Term Conflict with an RBT of another aircraft is detected, then the aircraft having lowest priority has to resolve the medium term conflict. The aircraft with higher priority simply sticks to its RBT. The priority of an aircraft is primary determined by the remaining time to CTA. The lower priority aircraft should adapt its RBT in order to solve the conflict as well as not creating a conflict with any of the other aircraft RBT's.

STCR forms the next line of defense with a time horizon of at least 3 minutes and separation criterion of 3Nm/900 ft. When STCR detects a potential infringement of these separation criteria, then it is obliged to resolve this through a tactical manoeuvre, i.e. the priority rules do not apply anymore.

III. MONTE CARLO SIMULATION MODEL

A. Multi Agent model of A^3 ConOps

In order to perform rare event Monte Carlo simulations for the A^3 ConOps, it is needed to develop a mathematical model of the operation which captures both nominal and non-nominal behaviour. The TOPAZ modelling approach [3,4] has been used to develop such a model. The first step is to develop an agent based model of the A^3 ConOps which allows to be used for rare event Monte Carlo simulation. Powerful rare event Monte Carlo simulation requires that the agent based model satisfies specific mathematical conditions [5,6]. In order to satisfy these conditions, the A^3 model is developed in the framework of Stochastically and Dynamically Coloured Petri Nets (SDCPN) [16]. Further details of this A^3 model development are given in [28].

In the A^3 model the following types of agents are taken into account:

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

It should be noticed that the A^3 model developed is an initial one which does not yet incorporate environment/weather, Airborne Collision Avoidance System (ACAS) and Airline Operations Centre (AOC). Moreover, our current ASAS model is restricted to horizontal conflict detection and resolution, which implies that for the time being only aircraft flying at the same flight level are considered.

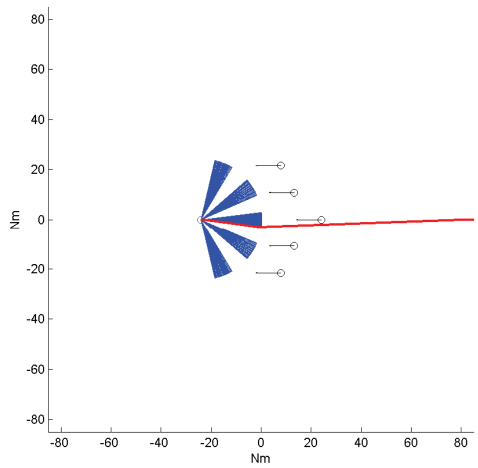

Figure 1. Velocity Obstacles (3 minutes & 3 Nm.) in case of five head on encountering aircraft, together with a conflict free path (red line).

B. Velocity Obstacles in conflict resolution

Because the A^3 ConOps definition [23] leaves details of conflict resolution algorithms open, it was needed to adopt specific approaches for MTCR and STCR. The review in [29] of literature sources and the results in [24] show there are a large variety of conflict resolution approaches available for potential use within the A^3 ConOps. In order to perform a risk assessment using rare event Monte Carlo simulation, one of these approaches had to be selected. Because computational load is a severe issue in rare event Monte Carlo simulation, we have selected Velocity Obstacles based conflict resolution [1,18]. Within the ASAS context, Velocity Obstacles based conflict resolution means that an aircraft stays away from the set of courses and velocities that lead to a predicted conflict with any other aircraft. In airborne self-separation research, this Velocity Obstacles approach has been referred to as Predictive ASAS [20]. Figure 1 shows the 3 minutes Short Term Velocity Obstacle area that applies in case of five head-on aircraft. The red line shows for the ownship aircraft a conflict free path.

C. MTCR and STCR implementation principles

In addition to the choice of Velocity Obstacle based conflict resolution, various implementation principles have been adopted for MTCR and STCR respectively. The specific MTCR implementation principles adopted are:

- MTCR detects planning conflicts (5Nm/1000ft) 10 min. ahead, and resolves 15 min. ahead.
- Aircraft nearest to destination has priority over other.
- Aircraft with lowest priority has to make its 4D plan conflict free (15 min ahead) with all other plans.
- Undershooting of 5Nm/1000ft is allowed if there is no feasible conflict free plan and it does not create a short term conflict (this way everyone keeps on moving).
- Upon approval by the crew, the aircraft broadcasts a non-conflict-free 4D plan together with a message of being "Handicapped" (which is priority increasing).

Using the above principles, the MTCR part of ASAS computes an RBT advisory by determining a sequence o Trajectory Change Points (TCP's) with minimum turning angles (to the left or to the right) such that there are no predicted conflicts remaining with any aircraft which has higher priority than ownship aircraft and which is within the MTCR horizon. If there is no minimum turning angle possible below a certain value $\varphi_{M,\max}$, then the turning angle below $\varphi_{M,\max}$ is identified which does not create a short term conflict and provides the lowest undershooting of the minimum spacing criteria of 5Nm and 1000 ft between the RBT's. In that case the ownship aircraft names itself handycapped. As soon as the advised MTCR advisories and the corresponding advisories have been implemented in the Airborne GNC agent of the ownship aircraft, then these are broadcasted together with a handycap message.

The specific STCR implementation principles adopted are:

- STCR detects conflicts (3Nm/900ft) 3 min. ahead and resolves 5 min. ahead through course changes.
- When an aircraft detects a short term conflict it is obliged to resolve the conflict without awaiting any of the other aircraft
- Undershooting of the 3Nm/900ft values is allowed if there is no feasible alternative (this way everyone keeps on moving)
- Upon approval of the crew, the aircraft broadcasts its new course

Using the above principles the STCR part of ASAS determines a resolution course as the minimum turning angle (to the left or to the right) such that there are no predicted conflicts remaining with any aircraft and which is within the short term horizon. If there is no minimum turning angle possible below a certain value $\varphi_{S,\max}$, then the turning angle below $\varphi_{S,\max}$ is identified which provides the lowest undershooting of the minimum separation criteria.

IV. TWO AND EIGHT AIRCRAFT ENCOUNTERS

A. Two aircraft scenarios

In these encounter scenarios, two aircraft start at the same flight level, some 320 km (173 Nm) away from each other, and fly on opposite direction flight plans head-on with a ground speed of approximately 250 m/s. The initial 3-dimensional position has standard deviations of 20m along the RBT centerline, 0.5Nm in the lateral direction (RNP1) and 20m in height. For this two aircraft encounter scenario several A^3 model parameter settings are considered.

For each of the 164 parameters of the A^3 model a baseline value has been identified [28]. Moreover, in order to evaluate the sensitivity of the assessed safety risk level to changes in parameter value(s), the following six (groups of) parameters are formed:

- Crew response delay parameters
- ASAS dependability parameters (see Table I)
- Actual Navigation Performance (ANP) parameter
- MTCR horizontal separation parameter (see Table II)
- STCR horizontal separation parameter (see Table II)
- Groundspeed parameter

TABLE I. BASELINE VALUES OF KEY DEPENDABILITY PARAMETERS OF A^3 ENABLING TECHNICAL SYSTEMS

Model parameters of A^3 enabling technical systems	Baseline dependability
Probability of GNSS down	1.0×10^{-5}
Probability of Global ADS-B down[1]	1.0×10^{-6}
Probability of Aircraft ADS-B Receiver down	5.0×10^{-5}
Probability of Aircraft ADS-B Transmitter down	5.0×10^{-5}
Probability of Aircraft ASAS performance corrupted	5.0×10^{-5}
Probability of Aircraft ASAS System down	5.0×10^{-5}

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

TABLE II. BASELINE VALUES OF A^3 CONOPS MODEL BASED MTCR AND STCR PARAMETERS

	Look ahead time	Horizontal separation	Vertical separation	Info used	Max turn angle $\varphi_{M,\,max}$
STCR	3 min + 10 sec	3Nm	900ft	State & Intent	$\varphi_{S,\,max} = 60^0$
MTCR	15 min	5Nm	1000ft	Intent	$\varphi_{M,\,max} = 60^0$

TABLE III. PARAMETER VALUES IDENTIFIED FOR SENSITIVITY ANALYSIS OF A^3 CONOPS MODEL

Id	Model parameter(s)	Specific setting(s)
0	Baseline	See Appendix B in [iFLY D7.4]
1	Crew response delay	All crew response times are divided by 2
2	ASAS dependability	10x and 100x better than values in Table 5
3	ANP	ANP0.5 and ANP2 versus baseline ANP1
4	MTCR	Horizontal separation 6Nm instead of 5Nm
5	STCR	Horizontal separation 5Nm instead of 3Nm
6	Groundspeed	300m/s instead of baseline 250m/s

TABLE IV. DEFINITION OF SAFETY RELATED EVENTS USED IN COLLECTING STATISTICS FROM THE RARE EVENT MC SIMULATION

Event	MSI	LOS	NMAC	MAC
Horizontal distance (Nm)	3.0	2.0	1.0	0.054
Vertical distance (ft)	900	600	400	131

For the two-aircraft encounter scenario, rare event Monte Carlo simulations are repeated one-by-one for the baseline and each of the six (groups of) parameter changes in Table III. For each of these seven cases, probabilities for the following safety related events have been assessed:

- Minimum Separation Infringement (MSI)
- Loss Of Separation (LOS) = ⅔rd of MSI
- Near Mid Air Collision (NMAC)
- Mid Air Collision (MAC)

These safety related events are defined through horizontal and vertical distance criteria in Table IV.

B. Two aircraft simulation results

The parameter value scenarios considered are those specified in Table III. The full results are given in [28]. Because of space limitation we only show the results for parameter value scenarios 0 (Baseline) and 2 (ASAS dependability); see Figure 2. In this Figure, the horizontal axis is linear and typically runs from 6.0 Nm to 0.0 Nm miss distance (from left to right the miss distance reduces, which means that time runs from left to right also). The MAC point is only some 100 m away from the 0.0 Nm point. The vertical axis is logarithmic and covers 10 orders of magnitude in frequency of events (either per encounter or per flight hour).

The A^3 baseline results in Figure 2 show that in the A^3 model, conflict detection and resolution works quite effectively in avoiding MSI; only about one in 5000 (= 1.0 / 2.0E-4) head-on encounters leads to an MSI. Moreover, under baseline dependability, about one in 800 (= 2.0E-4 / 2.5E-7) of such MSI's leads to a LOS. This means that the A^3 model is very effective in preventing LOS for a head-on encounter between two aircraft. The results also show that A^3 performs its work before reaching LOS. This means that A^3 seems to avoid competition with TCAS, although formally this remains to be verified by including TCAS model in the MC simulations.

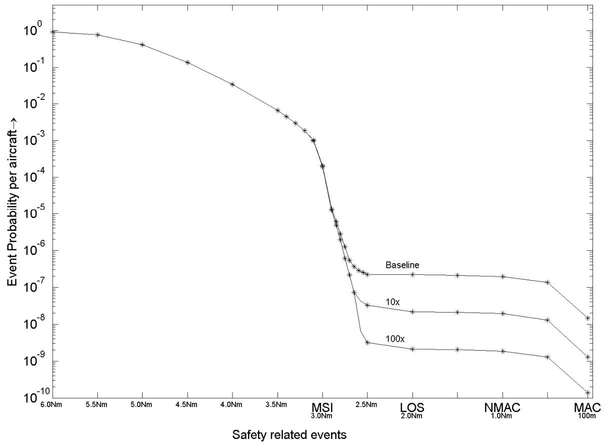

Figure 2. Effect on rare event probabilities of improving ASAS dependability by factors 10x and 100x respectively.

The curves in Figure 2 also show that for the two aircraft head-on encounter, the 10- and 100-fold improvements in the dependability of A^3 enabling technical systems lead to 10-fold and 100-fold improvements respectively in the estimated LOS, NMAC and MAC probabilities, whereas the estimated MSI probabilities remain unchanged. This is in line with the finding that the cause for collision risk in this scenario lies in the dependability of A^3 enabling technical systems. Moreover, the results show that for a two aircraft encounter the A^3 model reduces the probabilities for LOS, NMAC and MAC by improving the dependability of the A^3 enabling technical systems.

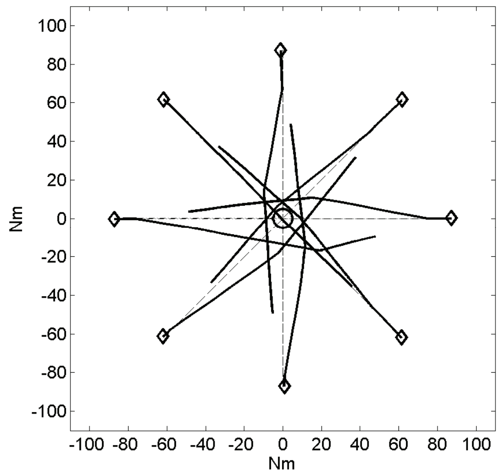

Figure 3. A^3 generated conflict resolutions example for eight aircraft encounter scenario; ◊ = starting points. Circle in centre has a 10Nm diameter.

V. EIGHT AIRCRAFT ENCOUNTERS

A. Eight-aircraft scenarios

Next we consider an encounter scenario between eight aircraft. Each aircraft starts at the same flight level and from a circle of about 320km (173 Nm) in diameter. The initial 3-dimensional position has standard deviations of 20m along the RBT centerline, 0.5Nm in the lateral direction (RNP1) and 20m in the height. Each aircraft has a ground speed of 250 m/s and is heading to the opposite point on the circle. Figure 3 shows a top view of an example of trajectories that are generated for the eight-aircraft encounter scenario under the A^3 concept of operation. For this scenario the A^3 model resolutions are very sensitive to small changes in the initial conditions. Because of random initial conditions and random disturbances, each MC simulated eight aircraft encounter generates trajectories that differ from those generated before.

B. Simulation results

The parameter value scenarios considered are those specified in Table III. The rare event MC simulation results for parameter value scenarios 3 (ANP), 4 (MTCR) and 6 (Groundspeed) show little effect on safety. The results for scenarios 0 (Baseline), 1 (Crew response), 2 (Dependability) and 5 (STCR) are shown in Figures 4 through 7.

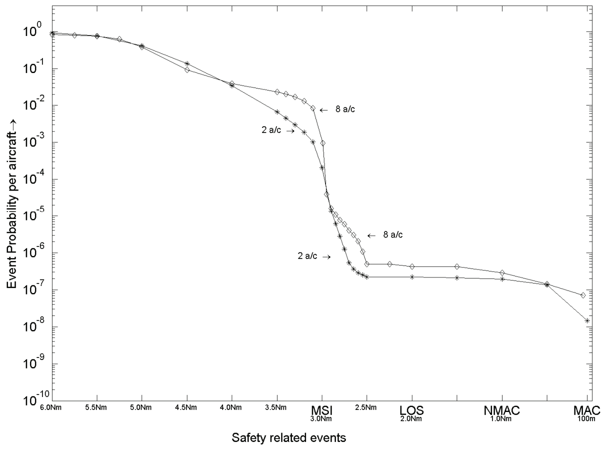

Figure 4. Estimated probabilities of safety related events per aircraft in two-aircraft head-on encounter(*) vs. eight-aircraft encounter (◊).

Figure 4 presents the event probability results for the eight-aircraft encounter Baseline parameter scenario in comparison to the probabilities obtained for two-aircraft head-on encounter scenario, both under baseline parameter values. The MSI probability for the eight-aircraft encounter is a factor 5 (= 1.0E-3 / 2.0E-4) times higher than for the two-aircraft encounter, while there are 7 times more aircraft to collide with. From an MSI probability perspective, the results obtained for the eight-aircraft encounter show that A^3 is performing remarkably well. The LOS and NMAC probabilities for the eight-aircraft encounter are of the same magnitude as for the two-aircraft encounter. Thus also for these events A^3 is doing very well.

Figure 5 shows the sensitivity of the A^3 results for crew response. When crew response values are a factor 2 lower than baseline values then the footing in the curve for values between 3 and 2.5 Nm disappears. This means that crew response is a factor that should not be ignored.

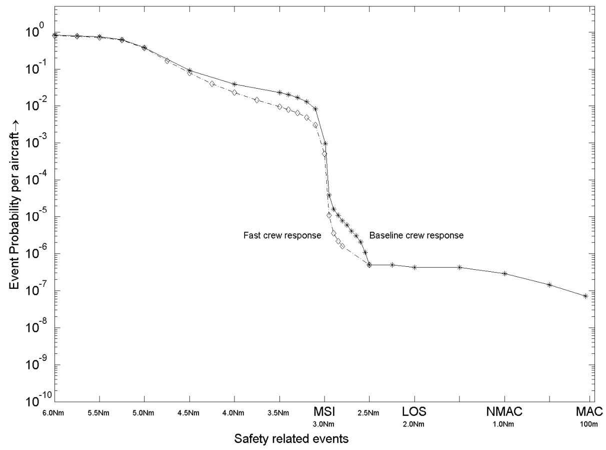

Figure 5. Effect on event probabilities of crew response values. * = Baseline crew response parameter values, ◊ = Fast crew response parameter values.

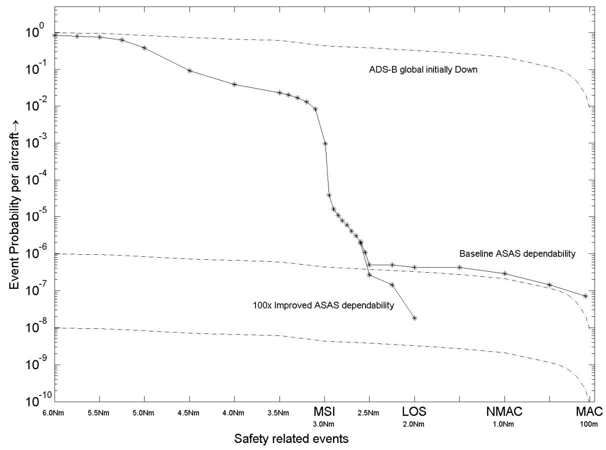

Figure 6. Effect on event probabilities of improving the dependability values for GNSS, ADS-B and ASAS systems by a factor 100x. The dashed curve at the top of the Figure is obtained by running standard MC simulations for the case that ADS-B is initially Down. The other two dashed curves copy the top level curve down at factors 10^{-6} and 10^{-8} respectively.

Figure 6 shows the effect of improving the dependability of ASAS technical support systems by a factor 100. This demonstrates a healthy improvement of the rare event frequencies in case the dependability value of ASAS technical support systems is improved by a factor 100. Because the MC simulation results for a 100x improved dependability of ASAS related systems did not deliver (reliable) probability values for LOS, NMAC and MAC, in Figure 6 dashed curves have been inserted to show the expected behavior of A^3 model for LOS, NMAC and MAC values. First the dashed curve at the top has been obtained by running standard MC simulations with the A^3

ConOps model under the initial condition that ADS-B global is down. Next this curve has been copied at factors 10^{-6} and 10^{-8} down respectively. These factors represent baseline and 100x better values for the probability values adopted for Global ADS-B being down (second item in Table II). Figure 7 shows that an increase of STCR separation value from 3 Nm to 5 Nm has a large impact on the curves. The sharp reduction that worked around 3 Nm is now already working around 5 Nm.

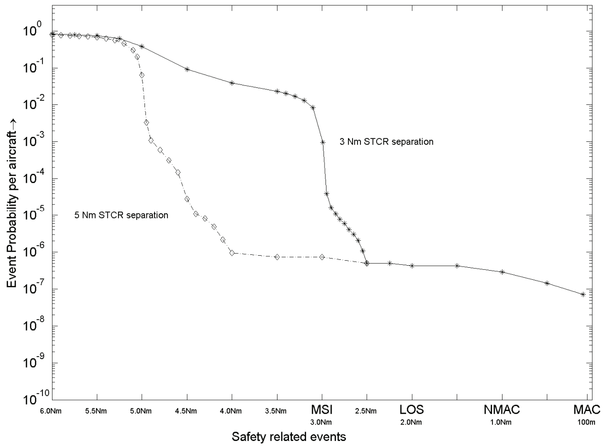

Figure 7. Effect on event probabilities of varying STCR separation values. * = 3 Nm (baseline), ◊ = 5 Nm.

VI. DENSE RANDOM TRAFFIC

A. *Dense random traffic encounter scenario*

The third encounter scenario artificially simulates A^3 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 250 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, and for aircraft that pass the boundary of a container we apply the Periodic Boundary Condition (PBC) approach, e.g. [37]. 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 neighboring 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 neighboring container, the size of a container should not become too small.

The baseline traffic density value is selected to be 4 times the level of one of the busiest en-route sectors in Europe in 1999. This is about 3 times the busiest traffic density in 2005. 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 aircraft per Nm^3. Multiplied by 4 yields our baseline traffic density of 0.0128 aircraft per Nm^3. The latter is 12.8 times the highest traffic density that has been considered in the example of [2] and 1.6 times the highest traffic density considered for AMFF [10].

For the MC simulation of baseline traffic density, i.e. 0.0128 aircraft per Nm^3, we assume for the MC simulations that all 8 aircraft fly on the same flight level (FL) within the container. For the baseline traffic density, this yields 8 aircraft per 62Nm×62Nm×1000ft. Hence, in the MC simulations, we use a 62Nm×62Nm horizontal container size. Because the initial conditions of seven of the eight aircraft are random, there will be serious short term as well as medium term conflicts in the beginning. Hence for each initial condition, we give the A^3 ConOps a time period of 10 minutes to organize the given traffic situation in line with its concept of operation. Only after this 10 minutes convergence time, we start to measure safety related events, during a period of 10 minutes..

B. *Simulation results for dense random traffic*

The simulation results obtained are shown in Figure 8. In addition to 3x high 2005 traffic demand, also 6x high 2005 traffic demand has been simulated. This has been accomplished by reducing the size of the PBC by a factor $\sqrt{2}$ in each horizontal direction.

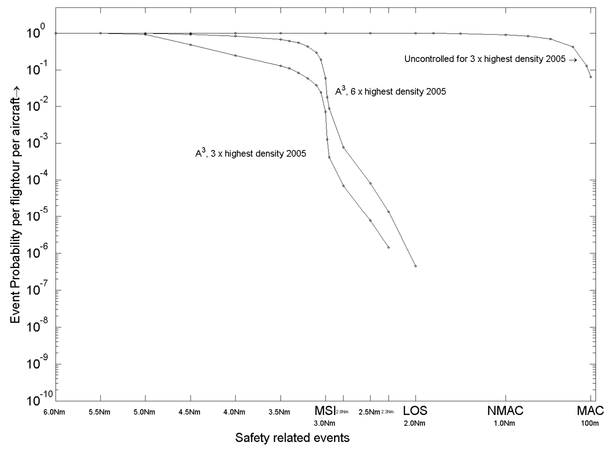

Figure 8. Estimated event probability per aircraft per flighthour for random traffic under A^3 model control and uncontrolled. Traffic densities are 3x and 6x high en-route traffic density in 2005.

The results in Figure 8 show that for the baseline random traffic scenario, the effectiveness of the A^3 model follows the RNP1 kind of behaviour until it reaches MSI level. Subsequently, the A^3 model produces a factor 10^5 or more improvement between MSI and LOS. It is remarkable that in none of the rare event simulations a single event has been counted in which the miss distance was lower than 2.0 Nm. The 2.0 Nm value has been counted only once, and this was for the 6x high 2005 scenario.

C. STCR separation from 3 NM back to 5 NM

Figure 9 shows that setting STCR separation value back from 3 Nm to current value of 5 Nm has a large impact on the curves. The sharp reduction that worked around 3 Nm is now already working around 5 Nm. Although a similar behavior has been seen for the eight aircraft encounter, it is remarkable to see that this also works for very high random traffic.

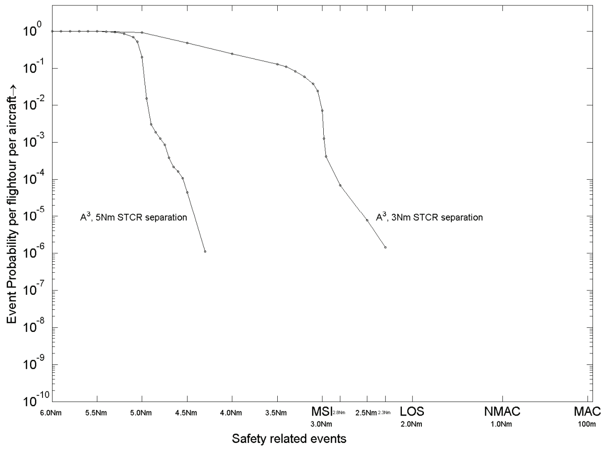

Figure 9. Estimated event probability per aircraft per flighthour for random traffic under A^3 model control at 3x high 2005 en-route traffic demand. Left curve shows effect of 5 Nm STCR separation.

In view of the very good results obtained for the A^3 ConOps with 5 Nm STCR separation, Figure 10 combines this result with an estimated curve for the effect of baseline dependability of ASAS related systems. First the new curve is obtained by running MC simulations with initial condition that ADS-B global is down. Subsequently this curve is copied at a factor 10^{-6} lower values to complete the A3 ConOps curve.

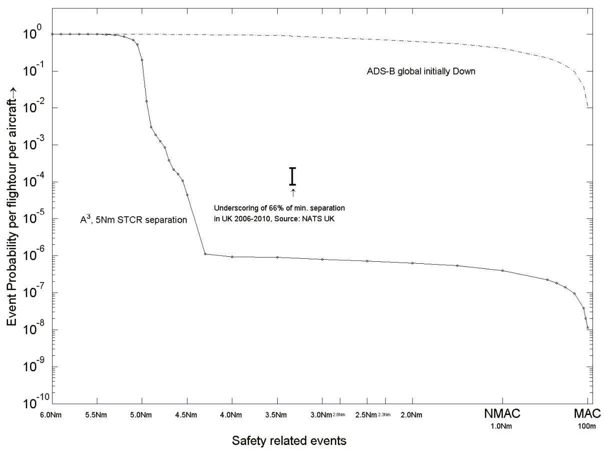

Figure 10. Estimated event probability per aircraft per flighthour for random traffic under A^3 model control at traffic demand of 3x high en-route traffic demand in 2005. The dashed curve at the top is obtained through running standard MC simulations for the A^3 ConOps model under the initial condition that ADS-B Global is Down. nd uncontrolled. This curve has been used to construct a completion of the line curve for miss distance values below 4Nm.

Figure 10 also shows a current reference point in the form of probability values per flighthour that in controlled UK airspace the miss distance between aircraft underscores 66% of the applicable minimum separation criteria [36]. For the 3× highest denstiy in 2005, the A3 ConOps with a 5 Nm STCR separation minimum, is doing much better than the [36] values for the current operation

D. Comparison against future TLS

In [25] a Target Level of Safety (TLS) value has been derived for an advanced airborne self separation operation that has to accommodate X times more traffic demand than was applicable in the year 2000. Using the TLS value specified in [22] as starting point, [25] derives a TLS of $3\times5\times10^{-9}/X$ fatal accidents per aircraft flight hour, where X = 5 when ACAS is not taken nto account. Moreover, ACAS should at least yield a factor 3.5 extra reduction in fatal accident risk.

Our 3x high 2005 traffic demand corresponds to 4x high 1999 traffic demand. In neglecting the one year difference, we assume X=4. This means that the TLS to be adopted is $3\times5\times10^{-9}/4 = 3.75\times10^{-9}$ fatal accidents per aircraft flight hour, and this should apply without taking ACAS into account. The derived TLS value incorporates all three collision types (i.e. 2x horizontal + 1x vertical). Because the simulated scenario in Figure 10 covers only two of these three directions, the applicable TLS value is 2.5×10^{-9}. This means that the estimated curve in Figure 10 points to a factor 5 more safety risk than the derived TLS value. This means that the safety risk remains to be improved by an extra factor 5. One way to realize such a factor 5 lower TLS value is to require the probability of Global ADS-B down to be a factor 5 lower than the 10^{-6} adopted so far. An alternative way to realize such an extra factor 5, is to demonstrate that future ACAS provides this factor 5 extra improvement, i.e. future ACAS should provide a safety improvement factor of 5x3.5 = 17.5.

VII. CONCLUDING REMARKS

In [23] an advanced airborne self separation operation for en-route airspace has been developed under the name A^3 ConOps (Concept of Operations). The key question posed by the iFly project is how much en-route traffic demand can this A^3 ConOps safely accommodate? In order to address this question, a multi-agent model of the A^3 ConOps has been developed, which includes human and technical agents, their interactions and both the nominal and non-nominal aspects of the operation. Subsequently this model has been used to run rare event Monte Carlo simulations for two and eight aircraft encounters, as well as random traffic scenarios

The MC simulation results obtained for these scenarios show that the A^3 ConOps model works very well for all scenarios considered. More specifically, the results show that the A^3 ConOps model may safely accommodate 3x to 6x the traffic demand of high 2005 en-route traffic demand.

Parameter sensitivity analysis shows that the results are pretty insensitive to RNP level, Crew response time, Medium

Term separation minimum and Groundspeed. Significant sensitivity has been identified regarding ASAS dependability level and the tactical separation minimum. For the ASAS dependability this means that it should be 10x more dependable than what was needed for using the AMFF ConOps over the Mediterranean. For the Tactical separation minimum there appears no need to reduce the current value of 5 NM minimum tactical separation to the 3 NM proposed in [23].

Hence the answer to the fundamental question is: an advanced Airborne Self Separation model safely accommodates 3x high 2005 traffic demand, under the following conditions:

- The dependability of ASAS support systems has to be of a high level. From the rare event MC simulation results safety objectives for the dependability parameters of the various sub-systems have been identified.
- The most demanding safety objective concerns the probability of ADS-B Global being down: it must be 5 times better than what has been identified as being needed for the Autonomous Mediterranean Free Flight. If the safety objectives for the ASAS system dependability cannot be realized in practice, then an alternative is to improve future TCAS such that this provides a 5 times higher factor in safety improvement than current TCAS does.

Because this paper covers the safety evaluation of the early development phase of an advanced airborne self separation ConOps, it is recommended that these findings receive follow-up research in the next A^3 ConOps development and validation phase. Follow-up research should also cover weather influences, incorporation of vertical movements, and further validation of the A^3 model results.

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