Emergent Behaviour of Trajectory Based Operations Under Very High En-route Traffic Demand

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Abstract—**Effective collaboration between planning controller, tactical controller and pilots in handling various uncertainties and hazards is the result of decades of evolutionary development. The forthcoming paradigm shift to Trajectory Based Operations (TBO) requires a similarly effective collaboration between the TBO layer and a tactical layer. Through agent-based modelling and simulation the authors have recently shown that in a pure airborne self-separation environment these two layers together can yield remarkably positive emergent behaviour in managing uncertainties and hazards, as a result of which very high en-route traffic demands can safely be accommodated. The current paper addresses the question if similarly good emergent behaviour is feasible with a ground based TBO design. The key findings are twofold. A negative finding is that ground-based TBO is not providing the remarkably positive emergent behaviours of pure airborne TBO. Though a positive finding is that ground-based TBO has the potential to safely accommodate high en route traffic demands.**

I. INTRODUCTION

SESAR and NEXTGEN future concepts of operations involve a series of changes relative to conventional Air Traffic Management (ATM) [1-3]. Central to these changes is Trajectory Based Operations (TBO) that stands for the paradigm shift that aircraft should fly according to agreed conflict-free four dimensional (4D) trajectory plans that are made known to all actors involved.

Inherent to the attractiveness of TBO, several TBO concepts have been developed by NASA, ranging from a fully automated ground-based TBO [4] to partially automated ground-based TBO [5] and to airborne self-separation TBO [6]. Each of these future concepts consists of a TBO layer and a tactical layer that generate tactical maneuvers for the aircraft involved if the 4D planning in the TBO layer tends to run out of time. These different TBO concepts have been evaluated through two coordinated pilot and controller in-the-loop simulation experiments [7]; the overall finding is that under most of the evaluated TBO concepts the controllers and pilots are able to manage their task loads under twice as much en-route traffic as today.

A question that remains to be answered is how well the two layers in these TBO concepts collaborate under various kinds of uncertainties and hazards. These include meteorological uncertainties and hazards; data related uncertainties and hazards; technical systems related uncertainties and hazards; and various human related uncertainties and hazards. The latter concerns issues like situation awareness and mode errors, e.g. [8,9].

In conventional ATM, medium-term planning is provided by the planning controller, flight crews and their Flight Management Systems (FMS), whereas the tactical loop is formed by the tactical controller and flight crews. Thanks to decades of evolutionary developments, the collaboration between these two layers has learned to handle various uncertainties and hazards well. For these non-nominal situations a similarly effective collaboration between the TBO layer and the tactical layer is needed. Because the collaboration between these layers involves dynamic interactions between human decision makers, technical support systems, aircraft evolution, weather and other uncertainties, the combined effects result in emergent behaviours that can be understood through conducting agent-based modelling and simulation [10,11].

In a series of studies [12-14], agent-based modelling and rare event simulation have been used to evaluate an advanced airborne self-separation ConOps under very high en route traffic demand. This ConOps, shortly referred to as A3 ConOps, also makes use of a TBO layer and a tactical layer, though both are fully airborne, and are distributed over all aircraft. The key finding is that the TBO and tactical layers in this A3 ConOps work so well together that this leads to remarkably positive emergent behaviours in managing various uncertainties and hazards. The three positive emergent behaviours that have been identified for this A3 ConOps are: 1) Tactical conflict resolution layer is working so well in combination with the TBO layer that the A3 ConOps can

safely accommodate very high en-route traffic demand; 2) To realize this high safety level, there is no need to use a buffer between TBO resolution minimum and separation minimum; and 3) Even under increase of en-route traffic demands to extremely high demand, there are no phase transitions happening. These three emergent properties go beyond the prior expectations of the A3 design team.

A logical follow-up question is if A3's remarkably positive emergent behaviour in managing uncertainties and hazards can also be realized by a ground-based TBO concept [15]. In order to address this question, agent-based modelling and rare-event simulation have been applied to a ground-based version of A3, shortly referred to as A3G. In this A3G ConOps the sub-systems of the TBO and tactical layers in the A3 ConOps have been moved from the air to the ground, and also the tactical and planning controllers have been inserted in the loop. The simulation results obtained for this A3G model clearly showed that A3G performs far less than A3 [16]. Subsequently, an independent design team has used these A3G simulation findings as triggering points for the development of a significantly improved A3G (iA3G) ConOps [17]. The aim of the current paper is to evaluate this iA3G ConOps using agent-based modelling and rare-event simulation.

This paper is organized as follows. Section II reviews the A3 ConOps. Section III describes the iA3G ConOps improvements. Section IV presents the iA3G agent-based model. Section V tunes the iA3G model parameters on an 8 a/c encounter scenario, and derives imposed safety requirements. Section VI presents iA3G safety simulation results for very dense random traffic. Section VII presents controller and pilot activity and flight efficiency simulation results. Section VIII draws conclusions.

Part of the results in this paper have been presented at the 2016 SESAR Inovation Days from the perspective of the SESAR project EMERGIA [18].

II. A3 ConOps

A. A3 overview

NASA's Autonomous Flight Rule (AFR) concept [19,6] has gratefully been used as baseline for the development of an advanced airborne self separation TBO ConOps for en route traffic [20,21]. This so-called A3 ConOps intentionally addresses the hypothetical situation of 100% well-equipped aircraft, and it assumes no support at all from air traffic control on the ground.

In the A3 ConOps each aircraft maintains a 4D trajectory plan that is shared with all other aircraft. Following [1], we refer to these shared 4D trajectory plans as Reference Business Trajectories (RBT's). In order for a pilot to manage safe separation without support from air traffic control on the ground, each aircraft is equipped with an A3 dedicated

Airborne Separation Assistance System (ASAS) which is monitoring the surroundings and helps the flight crew to detect and resolve conflicts. Similar to NASA's AFR concept, A3 uses two layers in the detection and resolution of potential conflicts: the TBO layer and the tactical layer. The TBO layer takes care of making updates of the RBT in case of a medium term conflict, whereas the tactical layer takes care of resolving short term conflicts. A3's ASAS therefore consists of two sub-systems: a Medium Term Conflict (detection and) Resolution (MTCR) system, and a Short Term Conflict (detection and) Resolution (STCR) system.

Both A3's MTCR and A3's STCR support systems are using Velocity Obstacle (VO) based conflict resolution [22, 23]. In the A3 ConOps, VO-based conflict resolution is used to generate horizontal course changing maneuvers only, i.e. no changes in height and neither in airspeed. VO-based conflict resolution uses implicit coordination in the sense that an aircraft stays away from the set of courses and velocities that lead to a predicted conflict with a VO of any other aircraft. In the literature, VO-based conflict resolution is commonly applied in a tactical layer only, e.g. [24]. Hence, the application of VO-based conflict resolution not only in the tactical layer but also in the TBO-layer of A3 forms a significant next step.

B. VO approach in A3's MTCR support system

A3's MTCR uses VO's to identify ownship 4D trajectories which are free of planning conflict with the RBT's of higher priority aircraft over a time horizon of at least 15 minutes, such that centerlines stay 5Nm or 1000 ft. apart. 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. An aircraft with a shorter remaining distance to destination has a higher priority, and therefore may stick to its RBT; lower priority aircraft should adapt their RBT in order to resolve the conflict as well as not creating a conflict with an RBT of any of the other aircraft that have higher priorities. A3's MTCR detects planning conflicts (5Nm/1000ft) 10 min. ahead. An aircraft with lower priority has to make its 4D plan free of planning conflicts over a horizon of 15 min (i.e. 5 minutes more than the detection horizon) with all other plans. For each aircraft, the MTCR is doing so by determining an RBT advisory that consists of a sequence of Trajectory Change Points (TCPs) with minimum turning angle (to the left or to the right) within the MTCR horizon. Upon acceptance by the flight crew, the 4D plan is entered into the FMS, and it is broadcasted as the new RBT.

A complementary feature of A3's MTCR is that in the rare case that no feasible conflict free plan has been identified, then rather than doing nothing, MTCR will identify a plan that may have a TCP that creates a minimal undershooting of the 5Nm/1000ft criterion. In case of such undershooting, MTCR will flag then the 4D plan with a handicap flag. This handicap flag means that the priority of the handicapped aircraft is

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increased at the cost of a reduced priority for the other aircraft. Hence upon reception by other aircraft of an RBT with such handicap flag, these other aircraft become aware that they have now a lower priority than the handicapped aircraft, and therefore they become active in resolving conflicts that remain in the rare case of undershooting.

C. VO approach in A3's STCR support system

If a short term conflict is detected its resolution through RBT updating would take too much time. Hence a faster tactical resolution process is necessary, and A3's STCR provides this tactical support. To start with, STCR detects potential infringements of its own aircraft RBT (4D plan) with the RBT's and maneuver info received from all other aircraft. This is done over a time horizon of 3 minutes, using 5 Nm/900 ft separation criteria. In contrast to A3's MTCR, no conflict resolution priority rules apply for A3's STCR, and a tactical conflict resolution is open loop, i.e. it does not include back-to-goal maneuvers. Upon detection of a conflict, an aircraft's STCR determines a course change that is conflict-free with VO's of other aircraft over a period of 4 minutes (i.e. 1 minute more than the detection horizon). The proposed tactical resolution is shown to the Pilot Flying (PF). The PF verifies the proposed resolution, and may reject or accept it. If accepted, the PF will implement the tactical resolution by switching the aircraft from Flight Management System (FMS) mode to manual (tactical Auto Pilot / Flight Director) mode and subsequently implementing the given course change. In parallel, ADS-B broadcasts the tactical course change to the other aircraft.

A3's STCR also has an undershooting option in the rare case that no conflict-free course change has been found. If no such turning angle is possible below a certain value (e.g. 60 degrees) a turning angle that provides the lowest undershooting of the minimum separation criteria is identified. This implies that neighboring aircraft will help in resolving remaining short term conflict(s).

III. A3G AND IMPROVED A3G (IA3G)

A. From A3 to A3G

Whereas under the A3 ConOps the responsibility for managing separation was completely moved to the air, under the A3G ConOps this responsibility is moved back to the ground. Hence under A3G the 4D trajectory plans and tactical resolutions are provided by Air Traffic Control (ATC). Because A3's MTCR and A3's STCR support systems have proven to work so well for A3, both are moved for each aircraft from the air to the ATC center on the ground to get A3G. In A3G, both MTCRs and STCRs form now support systems for ATC rather than for flight crews. In addition to this, in the A3G ConOps the ATC system will maintain a database containing all currently active RBTs.

Upon acceptance of a new MTCR resolution proposal by the controller, it is uplinked to the appropriate aircraft and

evaluated by the flight crew. Upon acceptance by the flight crew a 4D trajectory plan is entered into the FMS and downlinked to the ATC system as the aircraft's new RBT. In the ATC system this downlinked RBT is then stored in the database of currently active RBTs. Similarly, A3's STCR proposes candidate tactical resolution maneuvers to the controller for each of the aircraft involved. The controller selects one of these tactical resolution maneuvers and subsequently instructs the corresponding flight crew to implement this maneuver. This tactical maneuver instruction is then also inserted in the ATC database as a correction to the corresponding RBT.

Agent-based modelling and rare event simulation of this A3G ConOps has been conducted; the simulation results clearly show that A3G performance stays far away from A3 performance [16].

B. Improvements in A3G's TBO layer

An independent design team has used the A3G simulation findings as triggering points for the development of a significantly improved A3G (iA3G) ConOps [17].

Regarding iA3G's TBO layer, the following three improvements of the iA3G ConOps over the A3G ConOps have been proposed:

1. Re-introducing a spacing buffer between the minimum distance between 4D plans and the horizontal separation minimum of 5 Nm;

2. Uplinking of resolution instructions is done according to a time-to-conflict prioritization criterion rather than A3G's First-In-First-Out principle.

3. Prior to involving the air traffic controller (ATCo) and pilots, the ATC system completes the iteration of MTCR's for all aircraft involved;

Improvement 1 means for the MTCR algorithm that planning conflict buffers are added to the corresponding minimum separation values. The right size of these planning conflict buffers will be evaluated through running Monte Carlo simulations with a model of iA3G. Improvement 2 simply means that the most urgent resolution instructions are not delayed by less urgent resolution instructions.

Improvement 3 is most complex of the three. Under the A3G ConOps, each time that the ATC system computes a new medium term conflict resolution for one of the aircraft, this activates ATCo and flight crew, and may cause new medium term conflicts for other aircraft. These new conflicts subsequently trigger the ATC system to compute new 4D plans for each of these other aircraft, followed by activities by additional flight crew. In order to avoid that ATCo and pilots are involved in each step of this iteration, the improvement is to iteratively mimic all these activities within the ground based ATC system before sending any newly proposed 4D plan to an ATCo or a crew. In the iA3G ConOps this mimicking is done by a MTCR internal iteration system (MTCR-IIS). The

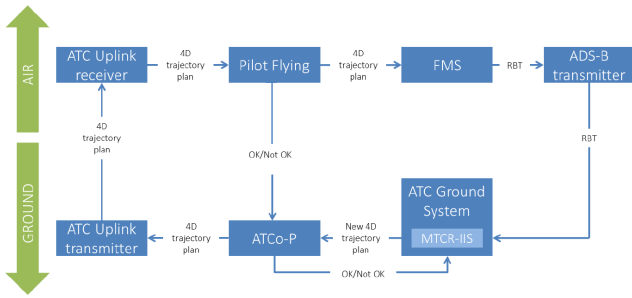resulting information flow in the TBO layer of iA3G is presented in Figure 1.

Figure 1. 4D trajectory plan information flow in TBO layer of iA3G ConOps; MTCR-IIS makes part of the ATC ground system.

The information flow in Figure 1 works as follows. If ATCo-P accepts the MTCR-IIS proposed 4D plan(s), then these 4D plans are sent (uplinked) to the a/c, and they overwrite the current 4D plans in the data base of the ATC ground system. This assures that there is maximal one version of the 4D plan for each aircraft in this data base. Upon receiving the uplinked 4D plan, the crew puts it into the FMS and the a/c downlinks the FMS Intent to ATC. Note that due to various kind of hazards [25] the 4D plan sent by the a/c may differ from the uplinked 4D plan received. Each time the ATC ground system receives an RBT, this RBT is compared with the 4D plan in the data base of the ATC ground system, the latter is overwritten with the received RBT in case of a difference, and MTCR and ATCo are informed about this.

C. Improvement of the Tactical layer

Regarding the tactical layer, there are five improvements of the iA3G ConOps over the A3G ConOps:

1. The tactical ATCo is no longer in the direct loop of approving a tactical resolution proposal, as a result of which a tactical resolution by the ATC system is directly uplinked to the pilot;

2. Preventing that a tactical conflict resolution is opposite to a preceding tactical conflict resolution;

3. Short term conflict resolution algorithm on the ground will anticipate that the implementation of such tactical resolution will happen with a non-deterministic delay;

4. Uplinking of short term resolutions is done with higher priority than medium term resolutions, and according to a time-to-conflict prioritization criterion rather than A3G's First-In-First-Out principle;

5. Prior to uplinking a tactical resolution, the ATC system completes the iteration of STCR's for all aircraft involved.

Improvement 1 means that aircraft crew are the only human that remain directly in the tactical conflict resolution loop, just as it is under A3. Improvements 2-3 mean that the STCR algorithm takes both the previously issued instruction as well as the implementation delays into account. Improvement 4

assures that an urgent tactical resolution gets priority in uplinking over less urgent and 4D plan updates.

Improvement 5 is most complex of the five. Under the A3G ConOps, each time that the ATC system has computed a new short term conflict resolution for one of the aircraft, this activates ATCo and flight crews and may cause new short term conflicts for other aircraft, which subsequently trigger the ATC ground system to compute new tactical resolutions for each of these other aircraft. These new tactical resolutions subsequently may trigger activities by other flight crews, etc. This iterative way of working also applied to the A3 ConOps, though then without any involvement of ATC. In order to get closer to A3, the improvement proposed for iA3G is to mimic all these ATCo and flight crew activities prior to involving any ATCo or pilot in this tactical resolution process. For the iA3G ConOps this implied that the ATC ground system has an STCR internal iteration system (STCR-ISS) that mimics this behaviour. The resulting information flow in the tactical layer of iA3G is presented in Figure 2.
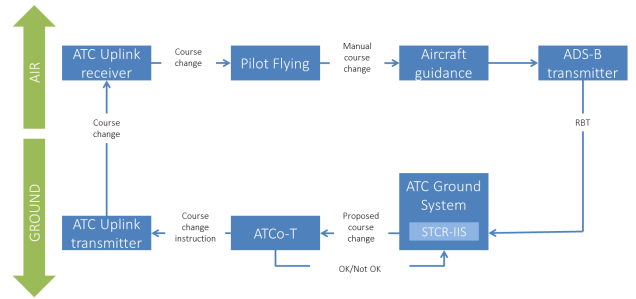

Figure 2. Information flow in the tactical layer of iA3G ConOps; STCR-IIS makes part of the ATC ground system.

The information flow in Figure 2 works as follows. Upon receiving STCR-IIS proposed new aircraft courses, the tactical ATCo (ATCo-T) accepts them all by default. Hence, the proposed courses are sent (uplinked) to the a/c and the 4D plans in the data base of the ATC ground system are overwritten accordingly, to assure that at most one version of the 4D plan exists for each aircraft in this data base. Upon receiving the uplinked course, the crew changes the aircraft course through Manual Mode control. Once this has been done, an RBT is constructed by the FMS and sent to the ground. Each time the ATC system receives a 4D plan, then this is compared with the 4D plan in the data base of the ATC ground system and overwritten if it differs. In the latter case, the ATC ground system notifies MTCR and the ATCo.

IV. AGENT-BASED MODEL OF IA3G

This section provides a high level explanation of the agent-based model of the iA3G ConOps, including the model assumptions adopted and the implementation and verification of the iA3G simulation code. Further details are in [26].

A. iA³G model assumptions

In developing the iA3G model, the following model assumptions have been adopted:

A0. R/T communication between ATCo and pilots is not used.

A1. All aircraft are identical and fly at the same altitude with the same speed.

A2. No emergency situations are modelled.

A3. No Secondary Surveillance Radar (SSR) data is assumed to be available to ATC.

A4. A 4D plan in the ATC system is considered to be unreliable if no timely ADS-B message about the corresponding RBT is received.

A5. No ground based navigation support is available, i.e. navigation is based on Global Navigation Satellite System (GNSS) and Inertial Reference System (IRS) only.

A6. ATCo-P always accepts an MTCR-IIS proposed 4D plan.

A7. The ATCo-T always accepts and does not overrule the STCR-IIS proposed tactical changes..

A8. The Pilots always accept the proposed 4D plans and tactical changes.

A9. The Pilot always enters the received 4D plans and tactical changes correctly in the FMS

A10. Datalink information exchange (ADS-B and ATC-uplinking) happens without corruption.

The consequences of these iA3G model assumptions will later be taken into account when arguing about the meaning of the iA3G model simulation results obtained.

B. Agent-based iA³G model

The agents in the iA3G model are:

- Aircraft-*i*, one for each aircraft i.
- Pilot-Flying-i,
- Pilot-Not-Flying-*i*,
- a/c-*i*'s Guidance, Navigation and Control (GNC),
- ATC ground system,
- MTCR-IIS within ATC ground system
- STCR-IIS within ATC ground system
- Air Traffic Controller (ATCo),
- Global Communication, Navigation & Surveillance.

An important activity in the model development of each of these agents is the agent-based modelling of various hazards in the future ATM ConOps considered. To do so the most important agent-based hazard models [27] have been used for the development of the agent-based model, including human information processing [28], basic human error types [29], and a multi-agent extension of Endsley's situation awareness [30].

For the specification of each agent and their interactions the formalism of Stochastically and Dynamically Coloured Petri Net (SDCPN) is used [31]. This formalism supports a compositional specification approach, which means that for each agent local Petri nets (LPN's) can be developed, using specific expert knowledge, without the need to bother about the connections between agents. Once the LPN's have been specified, the interactions between these LPN's are being developed; first for LPN's within an agent, and then between different agents. Further iA3G model details are in [26].

The resulting iA3G model comprises 63 different LPN's. With the exception of 12 LPNs in the ATC Ground system, 2 LPNs for the ATCo's, and 3 LPNs in the Global CNS, each LPN is copied for each aircraft in the model. Hence, for N aircraft, the iA3G model comprises 46N+17 LPNs.

C. Implementation and verification of the iA³G code

The iA3G model has subsequently been implemented in Delphi XE3, i.e. the same language as used for the A3 and A3G model implementations. This allowed developing the iA3G model code in a stepwise way from the A3G code. After each of these steps, dedicated verification tests have been conducted to compare the new results with those obtained by the A3 model:

Step 1: Replace MTCR entities by MTCR-IIS agent

Step 1 has been realized by a systematic implementation, replacement and testing of the MTCR-IIS agent. This addresses TBO layer improvements 1 and 2.

Step 2: Replace STCR entities by STCR-IIS agent

Step 2 has been realized by a systematic implementation, replacement and testing of the STCR-IIS agent. This addresses tactical layer improvements 1-3 and 5.

Step 3: Implement a prioritization of uplink instructions

In step 3, the first-in-first-out uplinking principle is replaced by a prioritization based on time remaining to resolve the conflict. This addresses TBO layer improvement 3 and tactical layer improvement 4.

Step 4: Rare event verification of iA3G code

The verification tests conducted in steps 1-3 run a limited number of simulations of the implemented code. Hence, positive outcomes of these tests do neither catch code errors that have rare event impact only, nor differences in rare emergent behaviour of the iA3G model. In order to get hold on both, rare event MC simulations have been conducted for 8 a/c encounters (see next section). Identified code errors have been corrected, and emergent differences have been mitigated through tuning iA3G model parameter values.

V. TUNING OF IA3G MODEL PARAMETERS

This section addresses rare event simulation based tuning of iA3G model parameters, and what this means in terms of iA3G imposed safety requirements, taking into account model assumptions.

A. iA3G model parameter tuning on 8 a/c encounter scenario

The iA3G simulation model has a total of 164 scalar parameters, the tuning of which has been done in [26] by conducting rare event Monte Carlo (MC) simulations of an 8 a/c encounter scenario. Initially, all iA3G model parameters were set at reference values such that the iA3G model performed better or equal than the A3 model under A3 baseline values. Subsequently the iA3G parameters have systematically been tested on the possibility to relax their values. Each such test required conducting another rare event MC simulation of the iA3G model on the 8 a/c scenario. This resulted into the set of iA3G parameter baseline values, of which the main ones (P0-P9) are listed in Table 1. The simulation results of the 8 a/c encounter scenario for iA3G with these baseline values are shown in Figure 3, together with the A3 curve under A3 baseline values on the same scenario.

TABLE I. iA3G MODEL PARAMETER BASELINE VALUES

| P#	Key model parameter	Baseline
P0	ANP / Separation / Resolution *minima*	1/5/6 Nm
P1	GNSS receiver *failure prob.*	1.0E-7
P2	ADS-B transmitter *failure prob.*	1.0E-8
P3	ATC Ground system *failure prob.*	1.0E-7
P4	ADS-B ground receiver *failure prob.*	1.0E-7
P5	Uplink or ADS-B *frequencies occupied*	1.0E-7
P6	ATCo-T maximum *response time*	1 s
P7	ATCo-P maximum *response time*	30 s
P8	ATC uplink transmitter *sending duration*	1 s
P9	Pilot mean *response time*	5.7 s
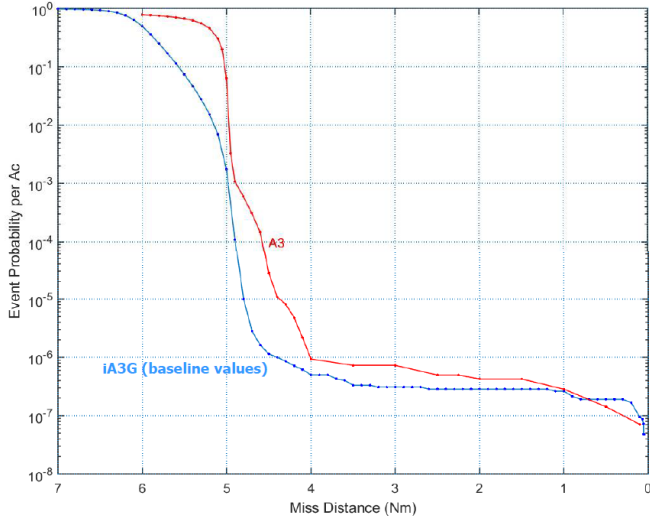
Figure 3. Estimated miss event probability per aircraft in the 8-a/c encounter scenario, as function of horizontal miss distance for the iA3G model vs. the A3 model (source [Blom and Bakker, JAIS2015]).

In Figure 3, the iA3G curve is slightly better than the A3 curve. Firstly, the iA3G curve starts diving slightly earlier but less steep due to larger resolution distance (6 Nm vs. 5 Nm). Secondly, just beyond the 5 Nm miss distance, the iA3G curve makes a steeper dive than the A3 curve does; this reflects that iA3G's does not actively involve any pilot in iterations needed for identifying joint tactical resolutions. Thirdly, the levelling off by the iA3G and A3 curves are largely defined by the baseline values used for P1-P5 in their simulations.

B. Derivation of iA3G imposed Safety Requirements

Although the curves for A3 and for iA3G in Figure 3 level-off at similar values, there are significant differences in the way this is realized. Under A3, there still are ground systems, such as ground-based navigation and communication support, but no ATC system. This is reflected in the requirements to be posed on the iA3G parameter baseline values identified. The P0 parameter values affect the behaviour in the top of the curves in Figure 3 only. The P1 value (airborne GNSS receiver failure) is high due to model assumption A5 (no other navigation means than GNSS). However, in reality this P1 requirement in Table 2 can be realized through a combination of navigation means (both under A3 and iA3G). P2-P5 requirements are challenging; this is explained below. P6

requirement is satisfied because the ATCo-T is assumed not to be in the direct loop under iA3G. P7 is a typical requirement. The P8 requirement is similar to the requirement under A3 regarding the delay in transferring similar information through System Wide Information Management (SWIM). The P9 requirement is the same in A3.

Under iA3G, the baseline values for P2-P5 are much more demanding than they are for related parameters under A3. This is due to the distributed nature of conflict resolution of A3. If under A3, the airborne ADS-B transmitter (P2) of aircraft-i fails than other aircraft-k are unable to receive state and intent information about aircraft-i. Without state and intent information from aircraft i, aircraft-k can neither detect nor resolve a conflict with aircraft i and thus does nothing. Because in the A3 model aircraft-i still receives state and intent information of aircraft-k, aircraft-i can and will resolve this conflict. In the iA3G model, however, separation is controlled from the ground. If the ADS-B transmitter of aircraft-i fails, then ATC ground system doesn't receive the state and intent information of aircraft-i. Hence no resolution with aircraft-k is possible. Similar reasoning applies to parameters of type P3-P5. So thanks to the A3's distributed nature of conflict detection and resolution, the safety requirement to be posed on parameters of type P2-P5 are orders of magnitude higher under iA3G than it is under A3.

VI. SAFETY UNDER VERY DENSE RANDOM TRAFFIC

In this section, rare event MC simulations of the iA3G model are conducted for very dense random en-route traffic scenarios at a single flight level.

A. Very dense random traffic scenario

The random traffic scenario simulates aircraft flying randomly through a virtually unlimited airspace. In order to accomplish this, the airspace is packed with rectangular boxes. Within each box a fixed number of eight aircraft (i = 1,2, .. ,8) fly at arbitrary position and in arbitrary direction at a ground speed of 250 m/s. Per box, the aircraft within it behave the same, and for aircraft that pass the boundary of a box a Periodic Boundary Condition (PBC) applies, e.g. [32]. This means that we have to simulate all aircraft in one box only, though apply the conflict prediction and resolution processes also relative to aircraft copies in neighbouring boxes. By changing the box size we can vary traffic density. In order to avoid that an aircraft experiences a conflict with its own copy in a neighbouring box, a box should not become too small. Similarly as was done for the evaluation of the A3 model [14], all aircraft are assumed to remain at a fixed flight level. This means we can work with a PBC box of 1000ft high. In order to simulate an aircraft density which is about 3 times the traffic density in one of the busiest en route sectors over Europe in 2005, we set the horizontal size of the PBC box to 62 Nm by 62 Nm, and simulate 8 aircraft per container. This comes down to an aircraft density of 20.8 aircraft per flight level and per square area of 100Nm by 100Nm, which is 12.8x the aircraft density in the example of [33], and similar to the maximum density considered in [34].

While the accuracy of wind forecasts has improved in recent years, it is known that occasional large errors can occur, which are known to significantly affect the performance of trajectory prediction tools [35]; which requires a testing of a ConOps on short term systematic wind prediction errors up to 60 knots or 30 m/s [34]. In the very dense random traffic scenario this is accomplished by simulation of systematic wind prediction errors of 0 m/s, 10 m/s, 20 m/s and 30 m/s respectively.

B. A3 dense random traffic simulation results

Figure 4 presents the risk curves obtained by running rare event MC simulations with the A3 model on the very busy random traffic scenario described above, under systematic wind prediction errors of 10 m/s, 20 m/s and 30 m/s. Even for a systematic wind prediction error of 30 m/s (60 knots) the curve remains well away from the reference bracket that indicates underscoring of 66% of the minimum separation value of 5Nm in current ATM. A systematic wind prediction error of 60 knots eats away about 1Nm separation buffer at the 10^{-5} event probability level. This is much less than the 3Nm reported in [34] for the strategic conflict resolution layer only. Moreover, Figure 4 shows that this 1Nm loss stays very well within the current bracket (I) at 66% of minimum separation. This means that A3 is able to safely resolve the significant wind induced deviations from 4D trajectory intents (RBT's).
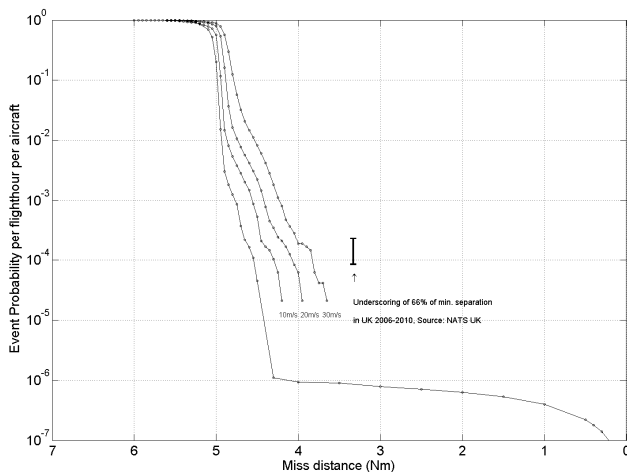

Figure 4. A3 model effect of systematic wind field prediction errors of 0, 10, 20 and 30 m/s. Figure 4 shows that even for a systematic wind field prediction error of 30 m/s the A3 model curve remains well away from the reference bracket I that indicates underscoring of 66% of the minimum separation value of 5Nm in current ATM. Source [14].

The very good results obtained under systematic wind prediction errors, mean that A3's STCR layer is very effective in resolving tactical conflicts. Hence the question is whether this power of A3's STCR in the tactical layer is so good that there even might be no need for MTCR in the TBO layer. Rare event simulation results obtained for a crippled A3 version, where the broadcasting of 4D intents is simply blocked, shows that about once in each 10 flight hours the sharp edge in

Figure 4 changes into a very heavy tailed curve [14]. This means that without the TBO layer, VO-based STCR in the tactical layer alone is not able to safely handle very high traffic demand. A similar finding regarding the shortcomings of a VO-based STCR in the tactical layer alone has recently be shown by [24].

C. Initial iA3G random traffic simulation results

The initial iA3G model rare-event simulation results on the random traffic scenario suffered from two problems that were not seen in random traffic simulations of the A3 model. The first problem originated from the way how initial aircraft positions were generated in the random traffic scenario. This has been resolved by adding the following test in the generation of random traffic situations: if an initial aircraft position is closer than 5 NM to any of the neighbouring aircraft positions, then another random initial aircraft position is generated.

The second problem has been traced back to a too high sensitivity of ground-based conformance monitoring of an observed aircraft path versus its 4D plan. This was resolved by adopting the following changes in the conformance monitoring in the MTCR-IIS of the iA3G model:
- Decoupling of position and speed conformance monitoring buffers into along and transversal directions;
- Increasing the conformance monitoring buffers for position and speed by a factor 3 in along direction only;
- Increasing the conformance monitoring buffers for speed deviations by an extra factor 1.5.

With these relative simple improvements, rare-event simulations of the initial iA3G model yields the curves in Figure 5.
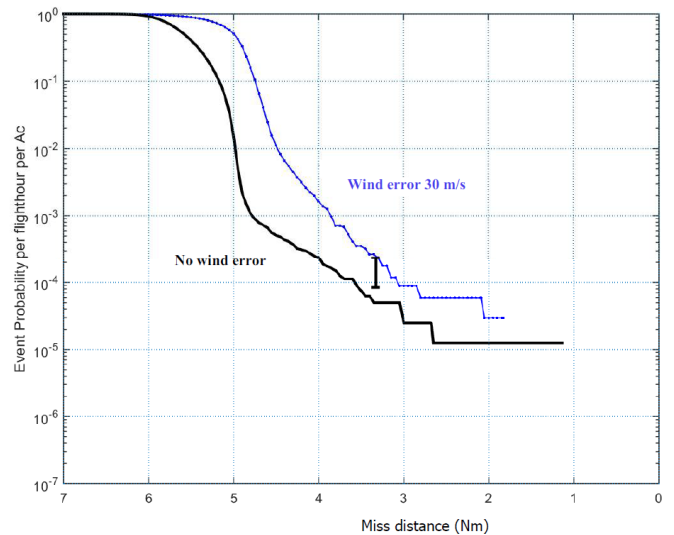

Figure 5: Initial iA3G risk curves on random traffic of 3x 2005 dense busy traffic. The 0 m/s and 30 m/s curves overlap with the reference bracket (I).

Neither the curve for 0m/s wind prediction error nor the curve for 30 m/s wind prediction error is as good as those obtained for the A3 model (see Figure 4). Only the initial parts of both curves are similar as those for the A3 model. However, below

the level 10-3, the 0 m/s curve has a tail which is unknown for the A3 model. The 30 m/s curve has a similar tail below the level 10-2. Investigation of cases in the tail has revealed that these tails are typically caused by rare cases where the pilot delay happens to be much larger than the mean value of 5.7 s.

D. Final iA3G dense random traffic simulation results

In order to give the PF some more space and time for the implementation of tactical instructions, the following additional parameter value changes have been adopted:
- The value of the MTCR used horizontal separation minimum is increased from 5Nm to 6 Nm;
- The waiting time until a repeat of short term conflict detection is shortened from 15 s to 5 s;
- The maximal turn of an aircraft is reduced from 90 degrees to 30 degrees; and
- Time slacks in the ATC ground system are increased.

The resulting rare-event MC simulation results for the very dense random traffic scenario under iA3G are in Figure 6. Both the 0 m/s and the 30 m/s curves are significantly better than those in Figure 5, though not as good as those for A3 (Figure 4). Nevertheless, the 30 m/s curve stays now beyond the reference bracket (I). The main difference between iA3G results in Figure 6 and A3 results in Figure 4 is that below the 2.10^{-5} level the iA3G curves tend to level off earlier than the A3 curves do. Because MC simulation of the iA3G model requires far more computational power than MC simulation of the A3 model, there also is a difference in the statistical significance of the tails of the curves; those in Figure 6 are less reliable than those in Figure 4. In order to improve this, there is need for an order in magnitude extra acceleration in iA3G rare event MC simulation.
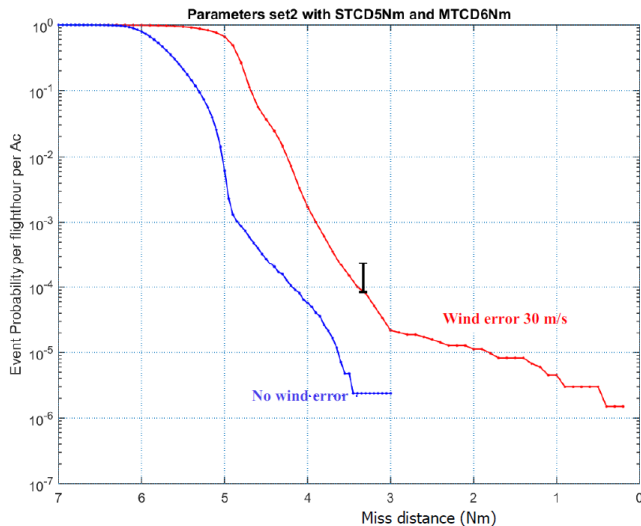

Figure 6: iA3G curves for 0 and 30 m/s wind prediction error.

VII. TASK ACTIVITY FREQUENCY AND FLIGHT EFFICIENCY

The simulation results for the very dense traffic scenarios can also be used to assess pilot and air traffic controller activity frequencies and flight efficiency.

A. Pilot Activity Frequencies

For the iA3G model, activity frequencies have been measured under random traffic demands. The results obtained are shown and compared to those for A3 and A3G in Table 2.

Table 2. Mean frequency of STCR and MTCR activities per aircraft under 0 m/s wind prediction error

Activities	A3	A3G	iA3G
MTCR	0.11 /min	0.11 /min	0.18 /min
STCR	0.08 /min	0.08 /min	0.018 /min
Total	0.19 /min	0.19 /min	0.20 /min

In comparison to A3 and A3G, under iA3G the MTCR frequency has gone up as much as the STCR frequency has gone down. The explanation for the STCR frequency decrease is that the STCR iteration happens on the ground before pilots are involved. The explanation for the MTCR frequency increase is the increase of the MTCR separation value from 5 NM to 6 NM. Reasonable expectation is that for iA3G this MTCR activity frequency can be reduced to the 0.11 per minute value of A3 and A3G by a further tuning of MTCR parameters. In doing so, care should be taken that this additional tuning should not affect the tails of the curves in Figure 6.

Activity frequencies have also been measured for the simulations for the case of 30 m/s wind prediction error. The results of these measurements are shown in Table 3. In comparison with A3 and A3G, the MTCR frequency has gone up by 40%, and the STCR frequency has gone down by 40%, while the sum of MTCR and STCR frequencies has gone down by 20%. Also under the 30 m/s wind prediction error it is expected that by proper tuning of the MTCR parameters, the MTCR activity frequency for iA3G can be reduced to the 0.15 per minute level of A3 and A3G.

Table 3. Mean frequency of STCR and MTCR activities per aircraft under 30 m/s wind prediction error

Activities	A3	A3G	iA3G
MTCR	0.15 /min	0.15 /min	0.21 /min
STCR	0.40 /min	0.40 /min	0.25 /min
Total	0.55 /min	0.55 / min	0.46 / min

Compared to the activity frequencies in Table 4 (0 m/s wind prediction error), under iA3G the total frequency of STCR and MTCR activities increases from one per 5 minutes (0.20 per min) to one per 2.2 minutes (0.46 per min) due to 30 m/s wind prediction error. By far the largest increase concerns STCR frequency, i.e. from 0.018 per min. to 0.25 per min.

B. ATCo Activity Frequencies

The iA3G activity frequency results allow predicting the MTCR activity loads for the ATCo by multiplying the iA3G measured MTCR frequencies by the number of aircraft for which the ATCo is responsible. The results of such predictions are shown in Figure 7. According to the solid curve in Figure 7, if the ATCo is responsible for 17 aircraft, under the A3G ConOps the ATCo has to perform 3 MTCR activities per

minute under 3x high 2005 traffic demand and no wind prediction error. This may be a demanding task level, though is expected to be manageable by a well-equipped and well-trained ATCo. Under wind prediction errors of 30 m/s, the MTCR activity frequency goes up to 3.6 MTCR activities per minute. Because this higher load will continue for a short period only, this also seems to be manageable. If the MTCR parameters are further tuned, then it is expected that the cap of 17 aircraft per ATCo may significantly increase.
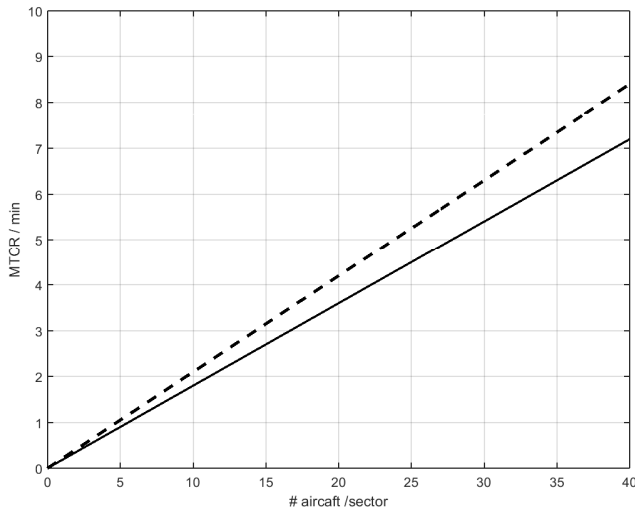

Figure 7. Predicted MTCR activity frequency of an ATCo as a function of the number of aircraft in the sector. Solid curve: 3x 2005 high, no wind error; dashed curve: 3x 2005 high, 30 m/s wind prediction error.
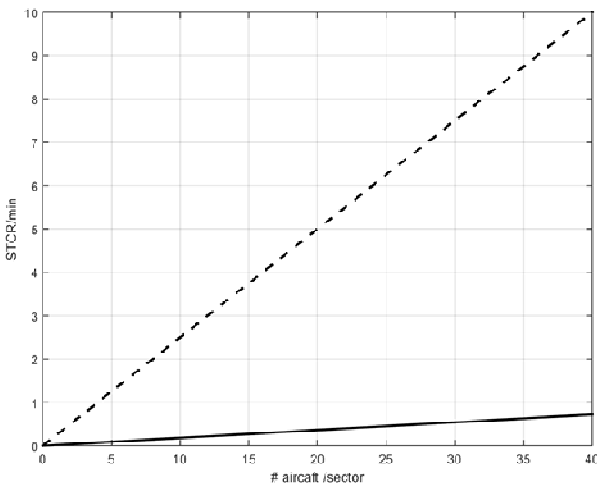

Figure 8. Predicted STCR activity frequency of an ATCo in the direct loop as a function of the number of aircraft in the sector. Solid curve: 3x 2005 high, no wind error; dashed curve: 3x 2005 high, 30 m/s wind prediction error.

For the iA3G ConOps it is assumed that the ATCo-T is not directly in the loop of informing pilots about STCR. However it is relevant to know what would happen if the ATCo-T would be kept in the loop. Then the iA3G STCR activity frequency results allow predicting the STCR activity loads for the ATCo-T by multiplying the iA3G measured STCR frequencies by the number of aircraft for which the ATCo-T is responsible. The results of such predictions are shown in Figure 8. According to the solid curve in Figure 8, under the A3G ConOps, if the ATCo is responsible for 17 aircraft, then the ATCo has to perform 0.3 STCR activities per minute under 3x high 2005 traffic demand and no wind prediction error. Under wind prediction errors of 30 m/s, the STCR activity frequency goes up to 4 STCR activities per minute. Because this higher load will continue for a short period only, this also seems to be manageable. The above means that from a task load perspective it might be an option to keep the ATCo-T in the direct loop.

C. Flight efficiency

The simulation results obtained can also be used to assess flight efficiency in terms of mean loss in effective distance travelled, and the mean lateral deviation at the end point of the Monte Carlo simulation period of 20 minutes. As is depicted in Figure 9, the effective distance travelled eliminates any detours made to reach this end point, while the absolute value of the lateral deviation at this end point provides a measure of the net effect of these detours in terms of the lateral displacement at this end point.
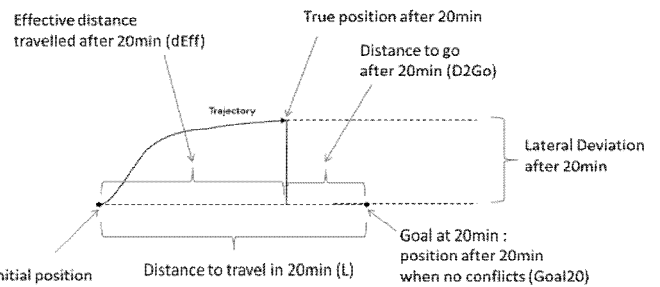

Figure 9. Flight efficiency measures.

In Table 4 and Table 5 the results of flight efficiency evaluations on random traffic scenarios are shown for 0 m/s and 30 m/s wind prediction errors respectively.

Table 4. Flight efficiency of A3 and iA3G under 0 m/s wind prediction error

	A3	iA3G
Effective distance travelled (mean loss)	3.3 %	2.5 %
Lateral deviation (mean absolute value)	15.0 NM	16.3 NM

Table 5. Flight efficiency of A3 and iA3G under 30 m/s wind prediction error

	A3	iA3G
Effective distance travelled (mean loss)	3.0 %	6.7 %
Lateral deviation (mean absolute value)	19.6 NM	26.7 NM

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The results in Table 4 and Table 5 show that the mean loss in effective distance travelled is around 2.5% under 0 m/s wind prediction error, and more than twice as high under 30 m/s wind prediction error. In comparison to A3, the iA3G figures are significantly better under 0 m/s, and significantly worse under 30 m/s wind prediction errors.

VIII. CONCLUSIONS

A. Main findings

This paper has conducted agent-based modelling and rare-event simulation to answer the question whether A3's powerful emergent behaviours in managing uncertainties and hazards can be maintained by ground-based TBO. The findings show that the answer to this question is negative. This is due to various extra air-ground communication activities that cannot be avoided when adopting a centralized ground-based TBO ConOps instead of the distributed A3 ConOps. However, prior expectation was that the burden from these extra air-ground communication activities would be compensated in some way by an advantage of making use of a centralized joint conflict resolution capability. The results obtained show that the latter advantage does not simply outweigh A3's advantage of distributed decision-making.

In addition to the disappointing emergent behaviour findings, iA3G also imposes higher safety requirements on various technical systems. In particular, very high iA3G requirements apply to ATC ground system, to ADS-B ground receiver, to Airborne uplink receiver failures, and to simultaneous failures of airborne ADS-B transmitter and SSR transmitter; very low probabilities of frequency occupancy of ATC-uplink and ADS-B; and short ATC Uplink transmitter sending duration.

In spite of these less positive findings for ground-based TBO, the results obtained also show that in the large design space of future ATM, an advanced ground-based TBO ConOps, referred to as iA3G, has the potential to safely accommodate much higher en-route traffic demands than current ATM.

B. Follow-up research of TBO concepts

Although the emergent behaviours of the iA3G model are not as positive as those of the A3 model, for very high en route traffic demands iA3G does not perform bad at all in safely managing various uncertainties and hazards. Therefore the iA3G model can be used as a valuable reference point for the further research and development of the TBO concepts for SESAR and NEXTGEN. Relevant issues to be addressed are differences between iA3G and other TBO concepts, regarding aspects such as traffic demand, aircraft equipage percentage; time horizons of TBO and tactical layers; conflict resolution support to ATCo; conflict management architecture; closed-loop versus open-loop in tactical conflict resolution; and roles of ATCo's and pilots.

With the current iA3G model it is possible to investigate many of these differences by simply changing the model parameter values (e.g. traffic demand, time horizons). For some other differences (e.g. aircraft equipage percentage) it

will be needed to also change the iA3G simulation model. Complementary to this, the further development of the iA3G model itself also is relevant, e.g. to incorporate climbing and descending traffic in the agent-based modelling and rare event simulation. Another valuable research direction is to conduct bias and uncertainty analysis; this requires the development of a significant extra factor in acceleration of the rare event MC simulations. A third direction of research is to evaluate operational concepts that are mixtures of ground-based and airborne self separation TBO.

IX. ACKNOWLEDGEMENT AND DISCLAIMER

X. REFERENCES

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ABREVIATIONS

4D = Four dimensional

A3 = Advanced airborne self-separation

A3G = Ground-based version of A3

a/c = aircraft

ADS-B = Airborne Derived Surveillance – Broadcast

ANP = Actual Navigation Performance

ASAS = Airborne Separation Assistance System

ATC = Air Traffic Control

ATCo = Air Traffic Controller

ATCo-P = ATCo-Planning

ATCo-T = ATCo-Tactical

ATM = Air Traffic Management

ConOps = Concept of Operations

FMS = Flight Management System

ft = foot

GNC = Guidance Navigation and Control

GNSS = Global Navigation Satellite System

iA3G = improved version of A3G

IRS = Inertial Reference System

LPN = Local Petri Net

MC = Monte Carlo

MTCR = Medium Term Conflict (detection and) Resolution

MTCR-IIS = MTCR Internal Iteration System

Nm = Nautical mile

OSED = Operational Services and Environmental Description

PBC = Periodic Boundary Condition

PF = Pilot Flying

RBT = Reference Business Trajectory

SDCPN = Stochastically and Dynamically Coloured Petri Net

SSR = Secondary Surveillance Radar

STCR = Short Term Conflict (detection and) Resolution

STCR-IIS = STCR Internal Iteration System

SWIM = System Wide Information Management

TBO = Trajectory Based Operations

TCP = Trajectory Change Point

VO = Velocity Obstacle