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iFly

Safety, Complexity and Responsibility based design and

validation of highly automated Air Traffic Management

Specific Targeted Research Projects (STREP)

Thematic Priority 1.3.1.4.g Aeronautics and Space

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Operational Performance Assessment (OPA)

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Contents

1 Introduction

The iFly project aims to develop a design for self separation operations in segregated high density airspace, where only aircraft with self separation capability are allowed to operate in. However, the project goal is not to develop a fully defined airborne system solution, but rather to investigate the theoretical performance and safety boundaries of such an advanced airborne self separation concept, to develop the required algorithms and to provide the preliminary analysis of cost-benefit mechanisms.

The goal of the iFly Work Package WP9 is to develop preliminary Safety and Performance Requirements of the iFly A3 Concept of Operations defined within WP1.3 and described in the deliverable D1.3. The WP9 work started with WP9.1 where the description of the operational environment and the required air traffic services were provided. The outcome of WP9.1 was D9.1: *Operational Services and Environment Description (OSED)* document, which served as the base for Operational Safety Assessment (OSA) that has been performed within WP9.2, and Operational Performance Assessment (OPA) that is described in this document.

The document *Operational Performance Assessment (OPA)* of Airborne Self-Separation (SSEP) operations is the result of WP9.3 and was developed in accordance with the guidelines provided by EUROCAE ED-78A/RTCA DO-264.

1.1 The scope of Operational Performance Assessment

The OPA is one of the key parts of the Safety, Performance and Interoperability Requirements (SPR) development process performed within the standardization committees. This process is an essential step allowing an industrial implementation of new applications. However, there is an essential difference in the approach adopted in iFly: SPR are usually developed later in the application development process, in particular, after an extensive validation of the concept when the application definition is already considered mature and complete. The development process is clearly described in the E-OCVM methodology, which is widely used in the current ATM research and whose main elements are shortly outlined in Appendix A.

On the contrary, the iFly concept of operations (as well as self separation operations in general) is still a research concept which needs to be extensively validated, refined and will be completed based on the results of the subsequent research[1]. These activities will be partially performed within the iFly project

[1] In terms of EOCVM methodology (Appendix A) we are still in the validation phase V1, i.e., setting the Scope of Airborne Self Separation under Very High Traffic Demands.

(e.g., WP7 – Accident risk and flight efficiency of A^3 operations, and WP8 – A^3 ConOps refinement) but they go considerably beyond the scope of this project.

In this context, the OPA presented in this document tries to accomplish two main goals:

- Provide a list (as complete as possible) of high-level performance requirements resulting from A3 Concept of Operations (D1.3).
- Connect these requirements to the existing standards, in particular, considering early Airborne Surveillance Applications (ASA) from ASAS Package 1.

It is considered that the implementation of advanced ASAS applications, such as self separation, is a long term process which will be strongly dependent on the practical experience from the implementation of earlier ASA applications, e.g., ATSA-ITP (In-Trail Procedures), ATSA-AIRB, ATSA-SURF, ASPA-S&M (IM). Thus, all requirements provided in this document should be considered as the initial guess which will be refined based on the concept validation and the practical experience with other ASAS applications. **The aim of the document is therefore primarily to provide a consistent analysis of requirements that would simplify subsequent research and validation activities.** Considering this goal the definition of quantitative performance requirements was omitted and rather the references to related requirements for existing ASA applications are provided whenever possible.

On the other hand, the A3 Concept of Operations envisions the use of enhanced strategic means to increase the performance of own flight. These functions are dependent on the availability of updated information about weather, traffic complexity, restricted areas, etc., and are therefore tightly connected to the definition of ground support services. As the latter are not ASAS specific and their definitions are out of iFly's scope, the presented OPA is restricted to the onboard separation management tasks and the strategic functions are not considered.

1.2 Organization of the Report

The OPA document starts with a short overview of operational assumption (Section 2) based on the OSED (D9.1) and Concept of Operations (D1.3) documents. Subsequently, the communication requirements are elaborated in Sections 3-5: first a high-level system architecture is introduced in Section 3, then a short overview of ADS-B is provided in Section 4, and finally the communication requirements of A3 ConOps are discussed in Section 5. The performance requirement on airborne system and the flight crew (the core part of this document) are analyzed in Section 6. Some high-level performance aspects, in particular considering the communication requirements, are further discussed in Section 7 and the overall summary is provided in Section 8. A lot of supporting material was placed into Appendixes, including E-OCVM overview (Appendix A), selected elements from A3 ConOps (Appendices B and C), a proposed extension of A3 ConOps considering the use of priority rules (Appendix D), etc.

2 Operational Assumptions

The self separation operations and the environment defined in D1.3 (A3 ConOps) are described in detail in D9.1 (OSED), and therefore only a short overview is provided here. The goal of the iFly Concept of Operations is to enable a safe and efficient autonomous flight through an en-route airspace where all aircraft are self separation capable. The en-route phase of flight is ended by a flight constraint (3D point with a time interval) at the entry point of the destination TMA representing an ATM strategic flow constraint.

The self separation operations are defined in terms of Autonomous Flight Rules (AFR) which are binding for all autonomous aircraft (see Appendix B). In addition, in the OSED (D9.1) a set of operational assumptions/requirements was formulated based on A3 Concept of Operations (D1.3). The latter are listed in the Appendix C.

The considered onboard separation management is based on a two-level Conflict Resolution (CR) process according to the estimated time to predicted Loss of Separation (LoS)[2]. When the time for maneuvering is shorter than a predefined threshold, all conflicting aircraft must maneuver and the applied maneuvers shall be coordinated through so-called implicit coordination. The implicit coordination is based on the use of compatible algorithms that generate complementary maneuvers for conflicting aircraft. Conflicts detected in advance (with respect to the time threshold) are solved using the priority rules principle.

ASSUMP-OPA.1: According AFR it is assumed that there are two operational types of conflicts:

- Mid-term conflicts for which the maneuvering of conflicting aircraft is driven by priority rules.
- Short-term conflicts where an implicit coordination among conflicting aircraft is used.

The conflicts are classified according to the expected time (relative to the predicted Loss of Separation) when the resolution maneuver will be initialized. The value of the corresponding threshold (referred as Short-term Time Threshold (STT) in the following) will be determined during the validation of the concept.

ASSUMP-OPA.2: There are two envisioned onboard operational procedures to modify the own flight path in order to avoid a detected threat:

- The first procedure is based on the generation of a new trajectory and on the updating of trajectory information in the navigation system (e.g., FMS). In this case the full intent

[2] Collision avoidance is assumed independent of ASAS functions and is provided in the same way as in the ATC-managed airspace.

information starts to be broadcast (shared) at the moment the new trajectory is initiated by the flight crew. This procedure is referred to as **Trajectory Modification** in the following.

- The second procedure is based on the generation of a CR maneuver(s) without updating the full flight trajectory. In this case only the reduced intent information related to the current flight segment (target state) is broadcast at the moment of initiation of the maneuver. This procedure is referred to as **Tactical Maneuvering** in the following.

The key enabler of onboard separation management is an effective information sharing process providing each aircraft with information about its surrounding traffic. This is primarily achieved by a periodic broadcast of state and intent[3] information by all autonomous aircraft through Automatic Dependent Surveillance – Broadcast (ADS-B). In addition and in line with both the European SESAR and the US NextGen ATM Concepts of Operations it is assumed that 4D (i.e., position and time) trajectories (the term Reference Business Trajectory (RBT)[4] is used thereafter) are dynamically shared through the System Wide Information Management (SWIM) system, which will incorporate ground infrastructure and air-ground data links network. This information will be used for strategic purposes, conformance monitoring, and to complement and back-up the ADS-B communication means.

It is anticipated that different types of airspace, different environmental conditions, and different requirements on the performance of the overall ATM system may result in definition of airspaces with different level of information sharing support. Namely, three Service Levels are considered in the OSED:

- **Service Level 1 (SL1)** – all autonomous aircraft are broadcasting the state information.

- **Service Level 2 (SL2)** – all autonomous aircraft conform to SL1 and in addition they broadcast intent information. In such a way, each aircraft is able to predict the trajectory planned by surrounding aircraft up to the horizon of the broadcast intent, referred as the Mid-Term Time Horizon (MTTH) in this document. The initial estimation of MTTH is 10 minutes based on NASA research.

- **Service Level 3 (SL3)** – all autonomous aircraft conform to SL2 and in addition there is a ground information sharing (SWIM) support. This level corresponds to the full ATM system described in the A3 ConOps (iFly: D1.3).

The Service Level of the operating airspace affects the performance requirements for both communications and onboard processing. However, in this document only the communication requirements are explicitly split out according the service level of operations, while the other airborne

[3] Intent is a part of the intended trajectory used for tactical ATM tasks. Its accuracy is usually higher than the accuracy of the whole planned trajectory (which is used mainly for strategic tasks). The considered look-ahead time horizon is typically about 10-20 minutes.

[4] This term originates from SESAR where it is used for trajectory information shared during the flight.

requirements are already considered for SL3, as this is a service level primarily addressed in the A3 ConOps.

As already stated in Introduction, the scope of the iFly project lies in the V1 phase of the E-OCVM framework (Appendix A) and therefore, the goal of A3 concept of operations is not to provide a complete definition of self separation procedures – further refinement and extensive validation is expected during the subsequent E-OCVM phases. For instance, one of the open issues is the detailed operational definition of the use of priority rules and the coordination of trajectory changes among multiple maneuvering aircraft (either in the case of a multi-aircraft conflict or for aircraft that are close to each other but they aim to maneuver simultaneously for independent reasons). Within the work on this OPA, the authors proposed a possible extension of the A3 ConOps in order to cover also these aspects. This approach is presented in Appendix D.

3 High-Level Airborne System Architecture

For the definition of communication requirements it is possible to build on the published standards related to the Airborne Surveillance Applications. For this purpose, the high-level system architecture is adopted from the recent ATSA-AIRB SPR (DO-319) is used in this document (Figure 1).

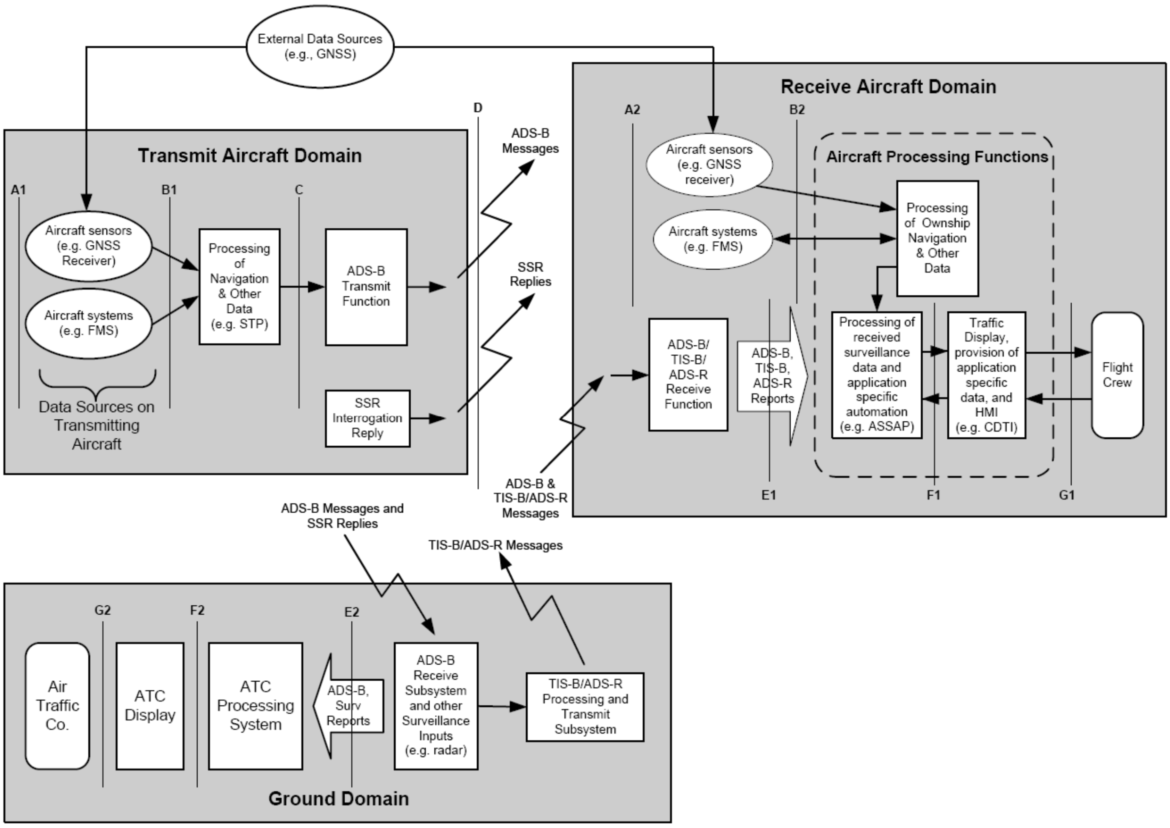


Figure 1: High-level airborne system architecture for ATSA-AIRB (taken form RTCA DO-319).

In the existing ASA standards (e.g., DO-312, DO-317, DO-319) the transmit aircraft domain typically refers to the surrounding aircraft while the receive aircraft domain is associated with own aircraft with an ASA capability. The operational assessment then results in the definition of separate requirements for surrounding and ASA-equipped aircraft: interoperability and performance requirements, respectively. However, A3 ConOps assumes that all aircraft are self separation capable, i.e., each aircraft has to meet the requirements for both the transmission and reception of information. Based on the OSED functional framework, the transmit aircraft domain falls under Navigation Functional Block (FB), while the receive aircraft domain lies in Surveillance FB. This approach is also adopted in Section 6.

4 ADS-B Overview

ADS-B is the key enabler of all currently envisioned ASAS applications. The Minimum Aviation System Performance Standards (MASPS) for ADS-B are defined in RTCA DO-242A. In addition the Minimum Operational Performance Standards (MOPS) for 1090 Extended Squitter implementation of ADS-B are specified in RTCA DO-260B.

From the operational point of view the key information that is required to be shared with surrounding aircraft is:

- Position information and the quality of this information
- Velocity vector information (including vertical rate) and the quality of this information
- Aircraft status/mode information (priority, emergency, etc.)
- Intent information (SL2 and SL3) and the quality of this information

For the aircraft processing function (Figure 1) it is essential to have the information about quality of received data. This is particularly important for information that is used to predict the trajectory of surrounding aircraft, such as position, velocity, intent. The quality of the data is usually described in terms of accuracy (expressed in terms of 95% uncertainty boundary) and the integrity. The latter represents the level of trust in the method and sensors used to determine the reported data (for GPS it may depend e.g., on the number and configuration of available satellites, etc). This reporting is already quite well implemented for the position information (for systems certified according to DO-260A/B) where both accuracy and integrity is reported through tabularized quantities (categories): Navigation Accuracy Category (NAC) defines the uncertainty boundary around the reported value where the true value lies with 95% probability; Surveillance Integrity Level (SIL) defines the probability that there could be an undetected measurement error beyond the containment specified through Navigation Integrity Category (NIC). The numeric values used in the definition of these parameters in DO-260B are provided in Appendix E.

Considering the transmission aspects, DO-242A defines 5 types of ADS-B reports. We adopted the definition of reports but only the elements mentioned in this section are explicitly required in the following (the other details may differ from the current version of DO-242A). Independently, it is assumed that all reports contain the participant's address and Time Of Applicability. Further details are available in the current version of DO-242A document. The 5 types of reports are:

- **State Vector (SV)** report includes the position (latitude, longitude), horizontal velocity vector (North, East), pressure altitude, and Navigation Integrity Category (NIC).

- **Mode Status (MS)** report includes the aircraft Capability Code (e.g., installed and operating TCAS, CDTI capability, etc.), Operational Mode (e.g., TCAS Resolution Advisory action, receiving ATC services, etc.), parameters describing quality of SV (in particular, Navigation Accuracy Category for Position (NACp), Navigation Accuracy Category for Velocity (NACv), Surveillance Integrity Level (SIL), Barometric Altitude Quality), and emergency/priority status.

- **Air Referenced Velocity (ARV)** report includes primarily airspeed and heading information.

- **Target State (TS)** report provides information (targets) considering active flight segment. It includes in particular target heading or track angle and target altitude.

- **Trajectory Change** reporting is a series of reports (TC**+n**) describing the consecutive flight segments bounded by so-call Trajectory Change Points (TCP). The latter is defined as a point where an anticipated change in the aircraft's velocity vector will cause an intended change in trajectory (e.g., turns, speed changes). The structure and content of these reports is still a subject of research but typically includes the position of TCP, information about type of corresponding flight segment (e.g., track to fix, direct to fix, etc.) with its sequence number, and the relevant parameters of the flight segment (turn radius, track, etc.).

Target State report and Trajectory Change reports provide information about the **intent** of own aircraft. The definition and format of the communicated intent information is still subject of ongoing research. While TS provides only information about the actual flight segment and therefore only the basic level of intent, TCs allow, at least in principle, to share the information about the whole flight plan.

ADS-B MASPS defines several categories of ADS-B equipment. The basic classification of interactive (ADS-B In + Out) systems is provided in Table 1.

Table 1: Categories of ADS-B equipment according the DO-242A (ADS-B MASPS).

Equipage Class	Required Range (NM)	Required Data – Transmission	Required Data – Reception
A0 (minimum)	10	SV, MS	SV, MS
A1 (basic)	20	SV, MS, ARV	SV, MS, ARV
A2 (enhanced)	40 (50 desired)	SV, MS, ARV, TS, TC+0	SV, MS, ARV, TS, TC+0
A3 (extended)	90 (120 desired)	SV, MS, ARV, TS, TC+n	SV, MS, ARV, TS, TC+n

Considering the different types of the ADS-B reports, the SV report is updated most frequently. The SV required update rate for the A3 class ADS-B equipment is according the distance between aircraft:

Table 2: Update rate of SV report according the DO-242A.

Range (NM)	R < 10	10 < R < 20	20 < R < 40	40 < R < 90
Nominal Update Interval (95%)	5s	7s	12s	12s
99^{th} percentile update period	10s	14s	24s	24s

Considering the other types of report, the update rates are still a subject of active research. In fact, the corresponding requirements shall be determined based on concrete applications and the latter are not widely implemented yet.

5 Communications Requirements

PR.1 : The self separation capable aircraft shall be equipped with ADS-B equipment of the level A3 according the DO-242A.

Note: According the analysis in Section 8, the desired range value (120 NM) may be required for A3 operations.

5.1 For airspace with Service Level 1:

PR.2: Self separating aircraft flying through the airspace with SL1 shall broadcast through ADS-B the SV and MS reports. In addition, the broadcast of ARV report is recommended (may be changed to required based on the operational validation).

Note: It may be considered that the level A2 of ADS-B equipment would be sufficient for this type of airspace.

5.2 For airspace with Service Level 2:

PR.3: Self separating aircraft flying through the airspace with SL2 shall meet all requirements for SL1 and in addition, broadcast through ADS-B the ARV, TS, and TC+n reports.

Note: The update rates for these reports still have to be determined during the validation activities of ASAS applications.

5.3 For airspace with Service Level 3:

PR.4: Self separating aircraft flying through the airspace with SL3 shall meet all requirements for SL2. In addition, the actual RBT of the aircraft shall be available in SWIM.

ASSUMP-OPA.3: Each self separating aircraft shall be periodically (update rate $T_{traffic}$ – initial estimate 2 minutes) provided with the list of aircraft within its pre-defined awareness zone (the exact definition to be determined based on validation results).

Note:

It is envisioned that this service will be provided by an automated ground application based on RBTs information available from SWIM and transmitted through data link.

Note:

Initially it can be considered that the list (awareness zone) should contain all aircraft being at or entering (according the known RBTs) own aircraft's ADS-B range within the next 2 minutes ($T_{traffic}$ – the time until the next list update).

ASSUMP-OPA.4: (Conformance monitoring) There is expected an automated ground application providing conformance monitoring through a continuous comparison of the actual received state data about each self separating aircraft with its known RBT. In the case of unexpected deviations all surrounding aircraft having the deviated aircraft in their awareness zone should be informed.

The overall communication scheme and the role of SWIM are for illustration depicted in Figure 2.

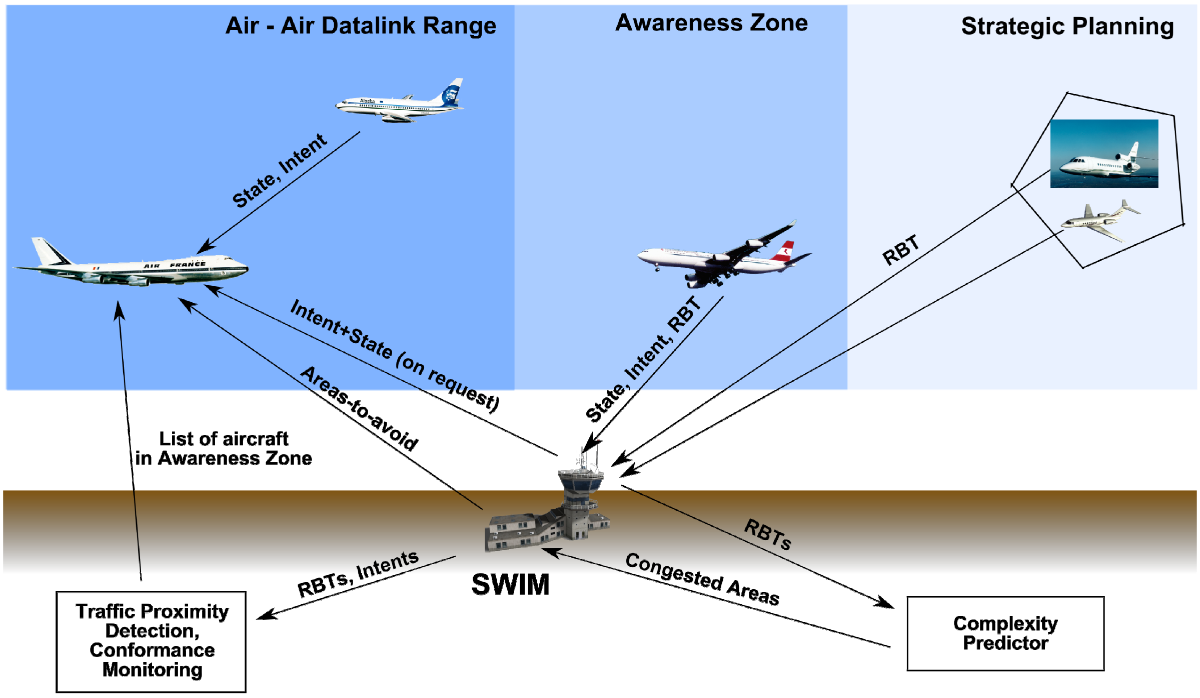


Figure 2: Overview of the communication scheme considered in A3 ConOps.

Note:

As already mentioned in Chapter 2, the application of priority rules for self separation operations may require a refinement of the A3 ConOps. The latter can lead to additional communication and functional requirements. An example of such potential refinement of the operational definition (directly affecting the communication among maneuvering aircraft) is provided in Appendix D.

6 Airborne Requirements

Onboard system and separation management procedures are very complex and there are therefore multiple ways how the performance requirements can be sorted out. In this document the approach defined in OSED (D9.1) is adopted. The procedural requirements and performance parameterization follows the scheme shown in Figure 3, while the requirements on the airborne system are structured according the five functional blocks defined in OSED.

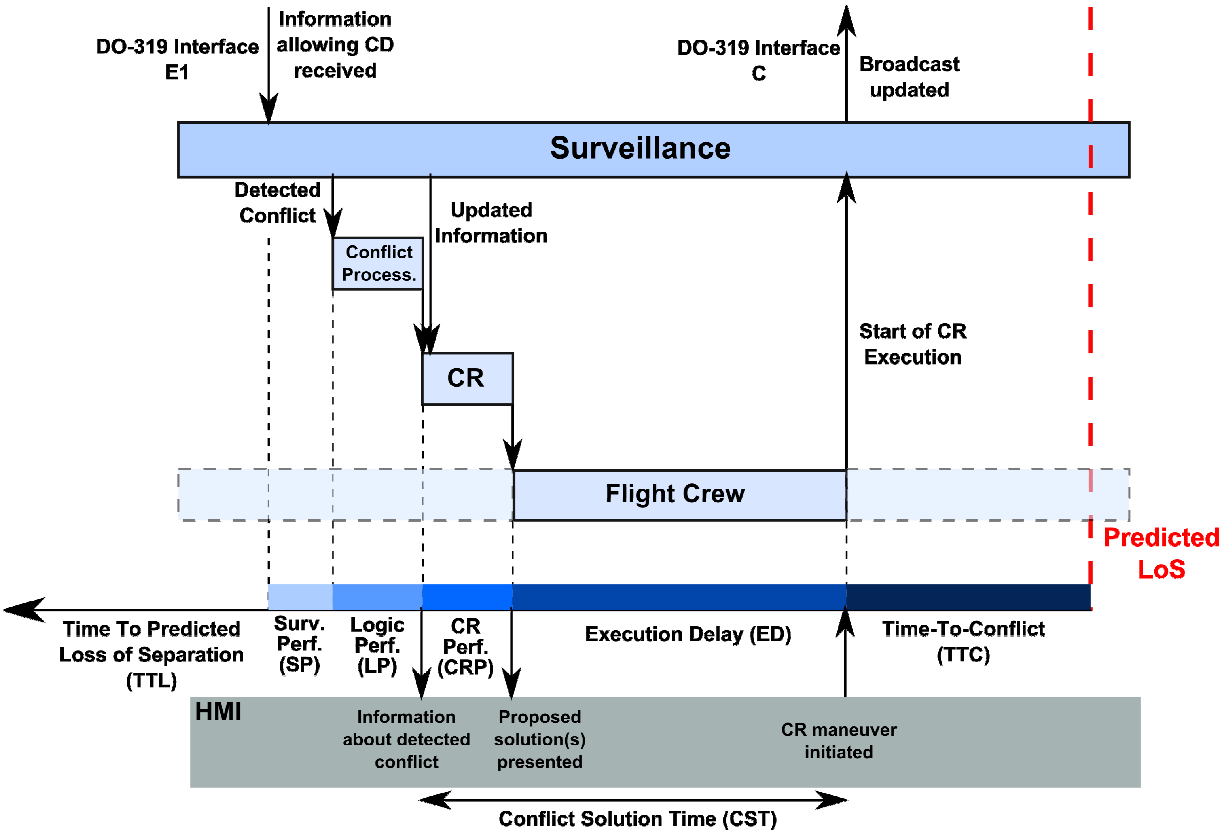


Figure 3: Schematic overview of onboard separation management process.

6.1 Navigation Functional Block

Navigation FB covers primarily the functions related to the navigation of own aircraft along the planned trajectory and to the "transmit aircraft domain" according to the system architecture in Figure 1.

Corresponding performance requirements are therefore focused on the quality of the shared (broadcast) state and intent information.

There is an inherent interconnection between the available (and therefore transmittable) intent information and how the navigation of aircraft is performed. Beyond the fully manual control of aircraft there are two fundamental modes of navigation. First, pilot can use the Mode Control Panel (MCP) to instruct the autopilot to hold a specific altitude, to change altitudes at a specific rate, to hold a specific heading, to turn to a new heading. Second, he/she can engage the Flight Management System (FMS) to navigate aircraft along the inserted active flight plan. While the information broadcast in the TS report is available for both navigation modes, the information about full intent contained in TC+n reports is meaningful (taking into account the needs for the quantifiable conformance to the shared planned flight path) only in the FMS managed mode.

6.1.1 Quality of State Information

PR.5: Self separation capable aircraft shall have horizontal position accuracy NACp=TBD or better (ATSA-AIRB considers NACp > 5, i.e., 95% accuracy 0.5 NM or better).

PR.6: Self separation capable aircraft shall have horizontal position integrity NIC=TBD or better (ATSA-AIRB considers 1.0 NM or better).

PR.7: Onboard uncompensated latency of the self separation capable aircraft for the state information from the time of applicability (B1) to the time of broadcast should be less than T_{RBT}.

PR.8: Self separation capable aircraft shall provide horizontal velocity accuracy NACv =TBD or better (ATSA-AIRB considers NACv=1, i.e., 95% accuracy at least 19.4 kts).

Note: The parameters describing the integrity of the reported velocity are not defined so far neither in GPS nor in ADS-B standards. In reality the different velocity data quality assurance methods are recommended in order to increase the reliability of received velocity information (e.g., by additional processing of the available position data [DO-319, Appendix B.2]).

PR.9: Self separation capable aircraft shall report the directional information with accuracy TBD or better (ATSA-AIRB considers 95% accuracy +/-25 degrees, however, better accuracy will be probably required for CD&R functions).

Note: The velocity vector data quality indicators are critical for CD&R functions and therefore the exact requirements should be determined through the validation experiments with true CD&R algorithms.

ASSUMP-OPA.5: It is assumed that the reported altitude performance meet the currently used requirements of ICAO Annex 10 Volume IV, Section 3.1.1.7.12.2.4 (accuracy within +/-38.1 m (125 ft) on a 95% probability).

Note: The assumption is adopted from the RTCA DO-319 (ATSA-AIRB), however, the referred requirement is used for the airspace with applied flight level structure. As the latter is not binding in self separation airspace, it is probable that this requirement will need to be refined in order to cope with flexible vertical profiles of self separating aircraft.

6.1.2 Quality of Intent Information

While for the state information the parameters describing the accuracy, reliability and availability are already defined and included in the reports (see DO-260B), considering the intent information the operational definition is much less mature. It is anticipated that this subject will be further developed within the definition and implementation of 4D trajectory concepts in SESAR and NextGen.

The surveillance functions (in particular, conflict detection) will require the information about the quality of received intent. This information can be either included in the communicated intent data or it may be defined through operational rules (e.g., each self separating aircraft should navigate along the reported trajectory at least according the pre-defined horizontal and vertical RNP).

As the intent information is currently managed by the FMS, the intent reporting in ADS-B Minimum Aviation System Performance Standard (DO-242A) is tightly connected to the ARINC 702A-3 (Flight Management System) where the required FMS output of related information is defined.

PR.10: Self separation capable aircraft flying in the airspace shall report the intent information as well as the quality indicator which will allow the reconstruction of its intended 4D (position + time) path at least for the time horizon specified by Mid Term Time Horizon (MTTH) parameter with the given accuracy boundary (95% of time within the specified limits). When this information is not available (e.g., in the case of tactical maneuvering), the TS report providing the current target state shall be broadcast.

Note: The initial estimation of the MTTH is 10 minutes based on the previous NASA research.

PR.11: Self separation capable aircraft shall have and use the appropriate navigation and flight control means (e.g., FMS managed mode) to meet the reported accuracy of the shared intent information except the cases when it could infringe the safety of own aircraft.

PR.12: Self separation capable aircraft shall report any change of its RBT beyond the predefined boundaries[5] to the SWIM at the latest T_{SWIM} from the initiation of the change. The format and required quality indicators for RBT will be defined in the corresponding operational rules and are out of the scope of this document.

[5] It is assumed that this topic will be further elaborated in the frame of Trajectory-Based Operations in SESAR and NextGen, as it is not ASAS-specific.

6.2 Surveillance Functional Block

Surveillance FB primarily covers the processing of the received traffic information (Receive Aircraft Domain according Figure 1) and the Conflict Detection (CD) process.

6.2.1 State Information

PR.13: Self separation capable aircraft shall have the Cockpit Display of Traffic Information (CDTI) to present the traffic situation to the flight crew.

PR.14: Self separation capable aircraft flying through the airspace with SL3 shall continuously check the received list of aircraft in its awareness zone with the traffic information received through ADS-B. In the case of a missing info about some aircraft, the state and intent information shall be requested from SWIM or potentially from the corresponding aircraft via direct data link (air-air alternative of ADS-C).

PR.15: Onboard uncompensated latency of the self separation capable aircraft for the state information from the interface (see D in Figure 1) to the time of observation by the flight crew shall be less than T_{lat} time (2.5s (95%) used for ATSA-AIRB).

PR.16: When there is not an update of state information about surrounding aircraft for T_{upd} (initial estimation 25 s, based on the A3 category of ADS-B), the aircraft shall be displayed as "degraded" and the information should be requested from SWIM or potentially from the corresponding aircraft via direct data link (air-air alternative of ADS-C). If the information is not received from SWIM/aircraft for another 25s (TBD) the flight crew shall be informed.

Note: This issue of ASA applications is the subject of long discussions in community. For instance, for ATSA-AIRB the aircraft with only degraded information available should be removed from display. However, this is not possible for ASAS application where flight crew is responsible for separation. The alerting logic shall be designed for these cases and extensively validated in Human-in-the-loop simulations. Current formulation of this requirements is only very preliminary. Also it is a question if (and how) an extrapolation of the aircraft motion should be used for CDTI while waiting for the update.

PR.17: Self separation capable aircraft shall store the position data of each surrounding aircraft for at least T_{hist} (TBD).

Note: This information should be used mainly for conformance monitoring.

6.2.2 Intent Information

PR.18: Received intent information about surrounding aircraft shall be available for flight crew, preferably in the graphical form.

PR.19: When there is not update of intent information about an surrounding aircraft for 25 seconds (TBD, this number results from A3 category of ADS-B), the intent shall be marked as "degraded" and the information should be requested from SWIM or potentially from the corresponding aircraft via direct data link (air-air alternative of ADS-C). The look-ahead time of the predicted trajectory shall be reduced in this case to 4 minutes (Short Term Time Horizon (STTH) – the limit of state-based CD: TBD).

PR.20: Self separation capable aircraft shall continuously monitor the conformance between the received state information and the predicted trajectory (typically reconstructed from the received intent information) of the surrounding aircraft. When a deviation beyond associated intent uncertainty boundaries is detected, the intent information should be marked as degraded and the look-ahead time of the predicted should be reduced to 4 minutes (STTH – TBD).

6.2.3 Conflict Detection

PR.21: Self separation capable aircraft shall continuously perform the Conflict Detection (CD) function using the predicted trajectory of surrounding aircraft and its uncertainty boundaries. The look-ahead time of the predicted trajectory is determined by the received intent information but CD shall not consider the time beyond MTTH time horizon. In the case of missing or degraded intent information, the prediction will be based primarily on the position information and the look-ahead time will be reduced to Short Term Time Horizon (STTH).

Note: The initial estimation for STTH is 4 minutes. Based on the Mediterranean Free Flight results, the state-based CD is questionable beyond 5 minutes time horizon, but this value is strongly dependent on the operational environment. In this context, the 4 minutes is a conservative choice.

PR.22: The time between the moment when all information allowing a detection of the potential conflict by system are received and the detected conflict is provided to event-handling function shall not exceed the SP seconds (Surveillance Performance).

PR.23: Self separation capable aircraft shall continuously perform the short-term CD function (independent of the regular CD described above) using the straightforward extrapolation of the current position and velocity information about surrounding aircraft. The look-ahead time of this function will be BPTH (Blunder Protection Time Horizon – the initial value is 2 minutes based on the NASA research and similar ATC functions used today).

PR.24: The time between the reception of the state information allowing a detection of the potential state-based conflict within the next 2 minutes of the flight and the moment when the flight crew is informed about this potential conflict shall not exceed $SP_{blunder}$.

PR.25: Each detected potential conflict (whether from regular CD or from state-based CD function) shall be provided for further processing to the events-handling functions.

PR.26: Self separation capable aircraft shall continuously perform a detection of the potential situations that could result in overloading of its CR functions or in a serious reduction of own aircraft maneuverability. A detected event (referred as a complexity conflict) shall be provided to Events Handling FB.

Note:

The appropriate measure (complexity metric) shall be developed and validated in the context of CR algorithms implemented in ASAS equipment.

6.3 Events Handling Functional Block

This FB includes primarily the assessment of the detected events (conflicts), the presentation of relevant information to flight crew, and the launch of the appropriate CR process when needed (in line with AFR).

PR.27: For each detected potential conflict, SSEP equipment shall calculate the actual Time To Loss of separation (TTL) and the Remaining Time To Loss of separation (RTTL) at the predicted moment of initiation of the resolution maneuver (based on the performance requirements (in terms of CST) on the Trajectory Modification process and Tactical Maneuvering process).

PR.28: The ASAS equipment of self separation capable aircraft shall provide the Tactical Maneuvering functionality.

PR.29: The ASAS equipment of self separation capable aircraft flying in the airspace with SL2 or SL3 shall also provide the Trajectory Modification functionality.

PR.30: Whenever it is possible to initiate a resolution maneuver (according the corresponding onboard procedure) for a detected potential conflict before STT, and the aircraft is expected to maneuver according the AFR, the corresponding mean of CR (Tactical Maneuvering or Trajectory Modification) shall be started by SSEP equipment.

PR.31: When it is not possible to solve (i.e., initiate the resolution maneuver) a detected potential conflict before STT, the Tactical Maneuvering process shall be started.

PR.32: For a detected potential complexity conflict, the suitable mean of CR shall be started.

PR.33: For detected events requiring the modification of own flight path, the ASAS equipment of self separation capable aircraft shall start the required CR process at the latest LP (Logic Performance) after the detection of the corresponding event.

PR.34: Flight crew shall be informed about all detected potential conflicts which require maneuvering of any of the conflicting aircraft at the latest LP after the detection of the corresponding event. The same requirements applies for complexity conflicts.

PR.35: Information about all detected potential conflicts and complexity conflicts shall be available to the flight crew.

PR.36: When the CR process is launched, own aircraft shall stop broadcast intent (TC+n) reports until the new trajectory information is available and approved by flight crew. Instead the appropriate TS report shall be broadcast.

PR.37: ASAS equipment of self separation capable aircraft shall provide flight crew with the means to gain and maintain situation awareness considering the detected potential threat and to get a clear understanding of presented solutions (whether in the form of a trajectory or a tactical maneuver).

6.4 Trajectory Modification Functional Block

Trajectory Modification FB includes the Conflict Resolution (CR) functions which provides the solution in the form of a full trajectory update (up to the destination). This type of solution requires more time to be assessed by the flight crew and it is therefore used only when the threat is detected sufficiently in advance.

PR.38: Trajectory Modification function shall present the new conflict-free trajectory (ies) to the flight crew by the latest CRP_{traj} after the function initiation.

PR.39: Each new trajectory provided by the Trajectory Modification function shall be conflict-free for the following MTTH time of the flight. In addition, at any moment along the new trajectory the 2-minutes (BPTH) extrapolation of the momentary aircraft velocity vector shall be conflict-free as well.

PR.40: Flight crew shall initiate the execution of the new trajectory latest CST_{traj} (Conflict Solution Time) after he/she is informed about the potential conflict by onboard system.

Note: The initial estimation for CST_{traj} is 2 minutes, based on NASA HIL research.

PR.41: The CR trajectory(ies) provided by the Trajectory Modification function shall be a valid solution of the detected conflict for the time ED_{traj} (i.e., the Execution Delay due to the flight crew assessment and decision making process shall be incorporated in the solution(s) proposed by CR functions).

PR.42: ASAS system shall provide the flight crew with the time remaining for the initiation of a new trajectory.

PR.43: ASAS system shall actualize the proposed Trajectory Modification solution(s) according to the updated information about surrounding traffic before the new trajectory is initiated.

Note: The last requirement is still a subject of discussion – this behavior should be validated through extensive Human-In-the-Loop experiments.

6.5 Tactical Maneuver Functional Block

Tactical Maneuver FB covers the Conflict Resolution (CR) functions which provides the solution in the form of an individual maneuver(s). The aim of these functions is to allow a quick (with respect to trajectory modification) solution of the detected conflict through a maneuver which can be easily and quickly assessed by flight crew.

PR.44: The Tactical Maneuver function shall present to flight crew the CR maneuver(s) by the latest CRP_{tact} after the function initiation.

PR.45: The CR maneuver(s) provided by the Tactical Maneuver function shall be conflict-free for the following STTH time. In addition, at any moment during this time horizon the 2-minutes (BPTH) extrapolation of the momentary aircraft velocity vector shall be conflict-free as well.

PR.46: The CR maneuver(s) provided by the Tactical Maneuver function shall meet the implicit coordination requirements when applicable according the AFR.

PR.47: Flight crew shall initiate the execution of the CR maneuver latest CST_{tact} after he/she is informed by the onboard system about the potential conflict.

Note: The initial estimation for CST_{tact} is 30 seconds, based on NASA HIL research.

PR.48: The CR maneuver(s) provided by the Tactical Maneuver function shall be a valid solution of the detected conflict for the time ED_{tact} (i.e., the Execution Delay due to the flight crew assessment and decision making process shall be incorporated in the solution(s) provided by the CR functions).

PR.49: ASAS system shall provide flight crew with the time remaining for the initiation of a CR maneuver (remaining time to the end of its validity as a solution of the detected conflict).

PR.50: ASAS system shall actualize the proposed Tactical Maneuvering solution(s) according to the updated information about surrounding traffic before the start of the maneuver execution.

Note: The last requirement is still a subject of discussion – this behavior should be validated through extensive Human-In-the-Loop experiments.

PR.51: For self separation capable aircraft flying in an airspace with SL2 or SL3 the Trajectory Modification function shall be started at the moment when a CR maneuver is initiated. New conflict-free trajectory shall be initiated by the latest CST_{cont} seconds from the start of the CR maneuver execution.

Note: Idea is to have a new conflict-free trajectory and therefore the corresponding intent provided to surrounding aircraft as soon as possible. The initial estimation for CST_{cont} is 90 seconds. This value is based on the CST_{traj} but it is reduced taking into account that the pilot is already aware of the situation due to Tactical Maneuvering process.

7 Performance Parameterization

Table 3: List of considered performance parameters.

Parameter	Description	Initial Value	Background	Performance Requirements
STT	Operational threshold between conflicts with priority-driven and implicitly coordinated solutions	3 minutes to LoS	Conservative choice based on MFF results.	ASSUMP-OPA.1
ADS-B Range	Required range for ADS-B equipment.	90 NM (120 NM)	A3 category of DO-242A	PR.1 (ADS-B category reqs.)
ADS-B update rates	Update rates for each type of ADS-B reports	24 s (SV)	A3 category of DO-242A	PR.1, 17, 20
$T_{traffic}$	Update rate of traffic list from ground support	2 minutes	Initial estimation based on value for blunder protection	ASSUMP-OPA.3
NAC_p	Broadcast position accuracy	5 (0.5 NM)	ATSA-AIRB (DO-319)	PR.5
NIC	Broadcast position integrity	5 (1 NM)	ATSA-AIRB (DO-319)	PR.6
T_{RBT}	Uncompensated latency in transmission domain			PR.7
NAC_v	Broadcast velocity accuracy	1 (19.4 kt)	ATSA-AIRB (DO-319)	PR.8
Track	Velocity directional accuracy	No	ATSA-AIRB (DO-319) consider 25 deg. (without CD)	PR.9
Altitude accuracy	Reported altitude accuracy	±38.1 m	ICAO Annex 10	ASSUMP-OPA.5
MTTH	Required Time horizon of reported (full) intent information	10 min.	NASA Langley research	PR.10
T_{SWIM}	Time to report RBT changes to SWIM		Should be based on 4D trajectory operations.	PR.12
T_{lat}	Uncompensated latency – receive domain	2.5 s	ATSA-AIRB (DO-319)	PR.15

T_{upd}	Required update rate of state information in surveillance functions	25s	A3 category of ADS-B	PR.16
T_{hist}	Stored history of state data about surrounding aircraft	3 minutes	Estimation	PR.17
STTH	Time horizon for state-based trajectory prediction	4 minutes	Conservative choice based on MFF results	PR.19, 20, 21
SP	Surveillance performance of CD function			PR.22
BPTH	Blunder Protection Time Horizon	2 minutes	NASA research and current ATC practice	PR.23
$SP_{blunder}$	Surveillance performance for blunder (purely state-based and independ.) CD			PR.24
LP	Logic Performance for Events Handling function (to start CR and update HMI)			PR.33
CRP_{traj}	Time for a generation of new conflict-free trajectory (ies) by Traj. Mod. function			PR.38
CST_{traj}	Time for flight crew to make a decision considering the detected conflict to be solved through a trajectory update.	2 minutes	NASA research	PR.40
ED_{traj}	Execution delay which must be incorporated in the proposed CR trajectories	(CRP-CST)		PR.41
CRP_{tact}	Time for a generation of CR maneuver by Tact. Maneuvering. Function			PR.44
CST_{tact}	Time for flight crew to make a decision	30 sec.	NASA research	PR.47

	considering the detected conflict to be solved through a tactical maneuvering.			
ED_{tact}	Execution delay which must be incorporated in the proposed CR maneuvers.	(CRP-CST)		PR.48
CST_{cont}	Time for flight crew to make a decision considering the continuation of the tactical CR maneuver through a trajectory update.	90 s	Derived from NASA research	PR.51

8 Performance Considerations

In this section some preliminary high-level performance analysis is presented. The aim is to analyze the proposed CR process in the context of communication requirements. This is performed in two steps:

- First, we consider a head-on conflict between two aircraft with ADS-B of category A3, according the DO-242A. The aim is to evaluate if the corresponding requirements are sufficient for the proposed A3 operations.
- Secondly, an evaluation of the performance of current ADS-B equipment is performed for the same purpose. This is done through a Monte-Carlo simulation of random traffic where the probability of successful reception of ADS-B report (as a function of the distance between receiving and broadcasting aircraft) is modeled using the empirical results obtained within the CASCADE program [CASCADE, 2006].

8.1 Conflict Resolution – Two Aircraft Head-On Scenario

The performance aspects of onboard CD&R process and flight crew procedures can be partially analyzed considering a head-on conflict of two aircraft. A head-on conflict represents the worst case scenario from the time perspective. Let us consider two aircraft flying with 450 kts speed in opposite direction at same Flight Levels. The margins for onboard CD&R in terms of time to collision and the distance between aircraft are shown in Figure 4.

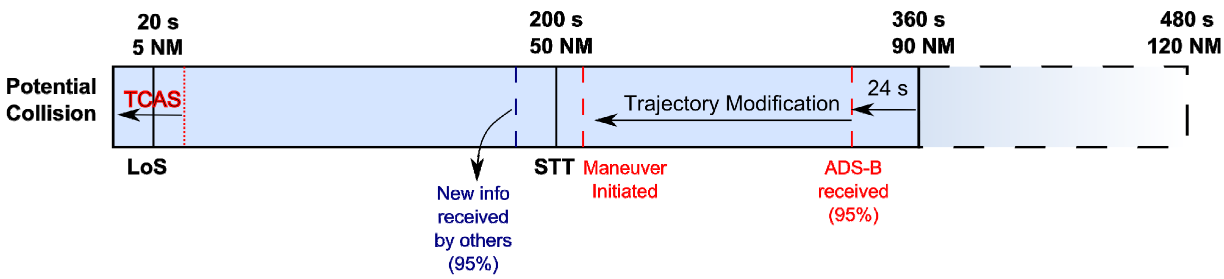


Figure 4: Overview of a model evolution of the head-on conflict in time.

In this figure the STT operational parameter was considered to be 3 minutes to LoS – the optimal value shall be determined during the concept validation. What can be seen is that with 90 NM ADS-B range (A3 category) and taking into account the worst case ADS-B update rate (24 s both for reception of the conflicting intent used for CD and for transmission of the new conflict-free intent after CR), there is a considerable probability that a mid-term conflict will trigger a maneuvering by both aircraft even if being already solved by lower priority aircraft. In fact, although the new conflict-free trajectory is already initialized by lower priority aircraft the new intent may be received by higher priority aircraft after STT, i.e., after it already started to search for an implicitly coordinated solution.

Therefore, it is recommended to require larger coverage by ADS-B broadcast for self separation operations. The value “desired” for A3 category of ADS-B equipment (120 NM) would be a good candidate on the corresponding requirement.

8.2 Communications Modeling

The aim of this section is to assess the role of strategic phase (flow/trajectory management prior an aircraft enters SSA) for distributed ATM system. For this purpose a completely random level traffic was simulated while measuring the rate of potential conflicts (LoS). The ADS-B communication (broadcast) performance among aircraft was modeled based on empirical data from CASCADE program [CASCADE].

8.2.1 Model for assessing capacity of the operational scenarios

In order to estimate the rate of mid-term conflicts and the risk of their unsuccessful resolutions, we have studied the following simplified model for aircraft motion and communication:

1. The aircraft fly straight at constant speed of 400 kts.
2. All aircraft fly at the same level.
3. The flights are modeled in a circle-shaped area with a given diameter.
4. The number of aircraft in the circle is kept constant.
5. Aircraft enter the circle at a random point on its border. If the aircraft would not satisfy the minimum separation at the start point, another start point is generated.
6. The direction of the flight is chosen randomly.
7. Aircraft send their position, speed vector and current target via ADS-B messages according the ADS-B 1090ES standard [DO-260B].
8. The probability of receiving an ADS-B message decreases with distance. We have modeled this function of distance by a curve obtained from simulation in the CASCADE project, for the “Raytheon Systems Ltd (RSL) advanced decoder” and the “EU2015” scenario described in the CASCADE final report.
9. The *separation minimum* is set to 5 NM. When two aircraft appear closer than the separation minimum, a *loss of separation* occurs.

This model was implemented in C++ and used for traffic simulation. For ADS-B reliability study, the aircraft entered a circle with diameter of 215 NM, however all data was analyzed for the 150 NM inner circle. This allowed a more realistic ADS-B simulation, as aircraft had a chance to collect ADS-B messages before entering the 150 NM circle. For statistics of separation losses, we have used only a 150 NM circle.

8.2.2 Communication capacity

In order to avoid a loss of separation, the pilot must obtain information about a possible conflict early enough to be able to react and complete a maneuver. To estimate the available time, we have performed a simulation of our model to obtain *the probability that an aircraft obtains ABS-B messages with necessary info about the other aircraft X nm before the loss of separation*. This immediately gives the time available for reaction, as all aircraft have the same constant speed in our model.

The relationship between distance and probability of receiving (and successfully decoding) an ADS-B message was taken from results of the CASCADE project. We have chosen data for the "EU2015" interference scenario for aircraft equipped with an "RSL advanced decoder". They can be seen as the blue curve in the next figure 5, which is a reproduction of Figure 28 from the CASCADE final report.

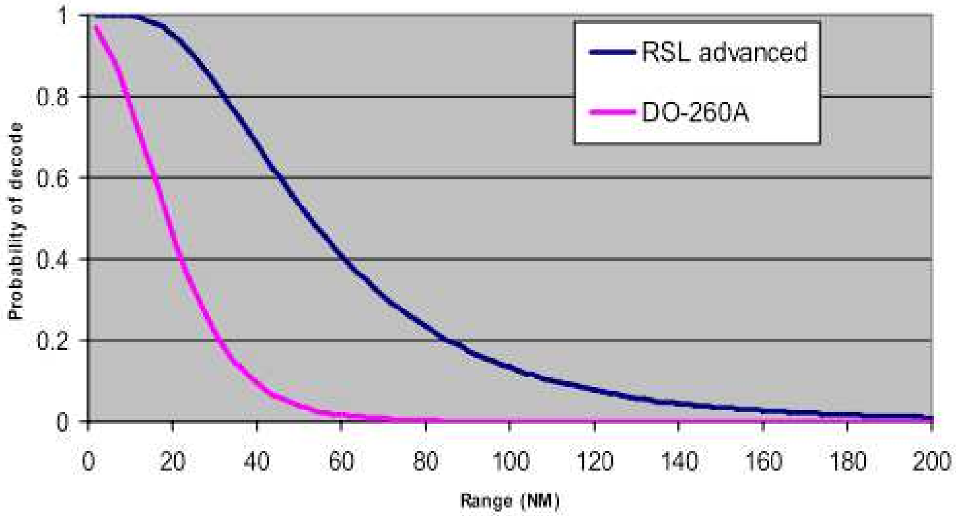


Figure 28: Airborne Decoder performance for baseline scenario 2015 with omni antenna

Figure 5: Performance of ADS-B (taken from [CASCADE]).

We have approximated this probabilistic function with an incomplete Gamma function, which gives a very good fitting of the CASCADE experimental data (see Appendix F for mathematical details). This has an advantage of using a smooth function instead of tabulated data, and also allows tweaking the function in a meaningful way by changing parameters of the incomplete Gamma function, if a different function shape is needed for further research. The fitting of the CASCADE results is shown in Figure 6.

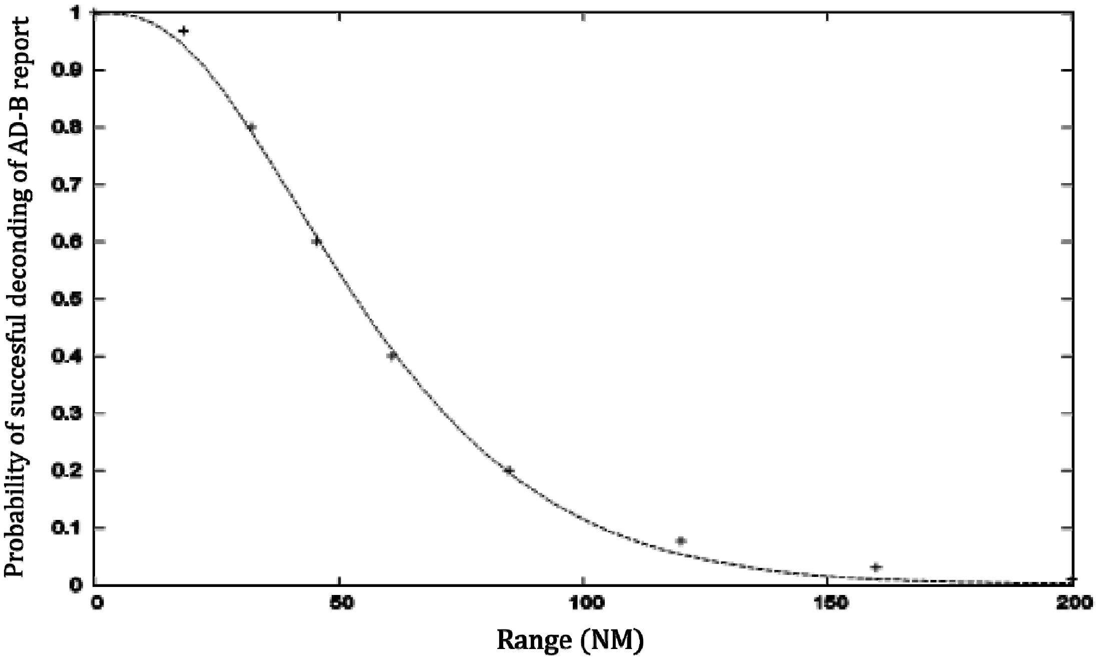


Figure 6: Fit of the CASCADE ADS-B performance data. The units are the same as in Figure 5.

For each aircraft the broadcast of its State and Target Reports is simulated:

- State Vector (SV) Report is sent in time intervals generated from a normal distribution N(0.5, 0.1) in seconds (it means that a SV message is sent every 0.5 second on the average).
- Target State (TS) Report is sent in time intervals generated from a normal distribution N(1.25, 0.05) in seconds (it means that a TS message is sent every 1.25 second on the average).

Note that we do not need TS messages to infer a loss separation in our simulation, as we know that aircraft keep their direction. However, in the real world it is necessary to have at least information about the next waypoint to predict the trajectory of the other aircraft.

We have assumed that it is sufficient to receive at least one SV and one TS message at any time to be able to predict a loss of separation. This is an optimistic assumption, as under general circumstances the aircraft has to receive one “odd” and one “even” SV message to determine the position of the other aircraft.

The following graph contains distribution of events according the distance (in NM) prior of a loss of separation when both aircraft have received at least one SV and at least one TS message from the other aircraft for the first time. It was obtained by simulating 200 aircraft in a circle with diameter of 225 NM as discussed above.

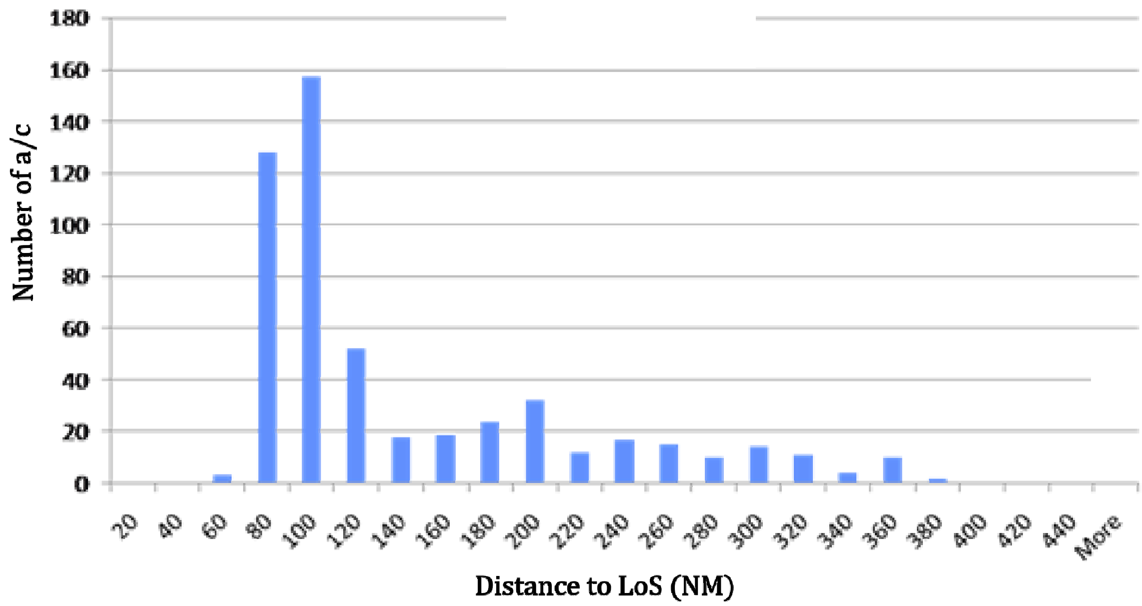


Figure 7: Histogram of a reception of ADS-B reports from conflicting aircraft regarding the distance (NM) to the Loss of Separation (LoS).

It can be seen that a significant portion of losses of separation was detected only between 60 and 80 NM before the event. In the worst case scenario, when both aircraft fly head-to-head at 400 kts, it gives the pilots about 80/800*3600 = 360 seconds to solve potential conflict.

8.2.3 Loss of separation rate

We have also analyzed simulated data to obtain mean frequency of losses of separation per flight hour. For this purpose a random traffic with predefined number of aircraft in a circle with diameter of 150 NM (generating a new aircraft when any aircraft left the circle) was simulated.

For traffic of 50 aircraft in the 150 NM circle, we have got in average about 1.0 losses of separation per flight hour. For doubled traffic density, i.e., 100 aircraft in the same area, we obtained about 4.4 separation losses per flight hour.

8.3 Conclusion

The performed analysis of the air-air communications among autonomous aircraft (in absence of any ground support, e.g., considering SWIM) shows that the current ADS-B technology may be a limiting factor for the performance of A^3 self separation operations. Furthermore, even if we consider the envisioned ADS-B equipment satisfying the A3 category definition in DO-242A, the performance may not be sufficient. It seems that only the “desirable” performance characteristics for the A3 type of ADS-B equipment could already meet the A^3 ConOps expectations but these results should be further confirmed by an extensive concept validation.

Apart from the analysis of communication requirements, a simple evaluation of loss of separation rate in the simulated random traffic sample was performed. This kind of assessment could be potentially used to assess how effective (in terms of needs for tactical maneuvering) can be an autonomous aircraft concept in absence of any strategic ATM.

9 Summary

The present document provides the results of the preliminary ED78a/DO-264 Operational Performance Assessment of the iFly A3 Concept of Operations described in D1.3 and the OSED document (D9.1). However, as already mentioned in the introduction, the ED78a/DO-264 analysis is usually performed in a later stage of the concept development cycle. The A3 ConOps development is still in E-OCVM phase V1, which means that there are several detailed design alternatives still in the running. For this reason it is not yet within scope to develop safety and performance requirements at the level that are typically considered by standardization.

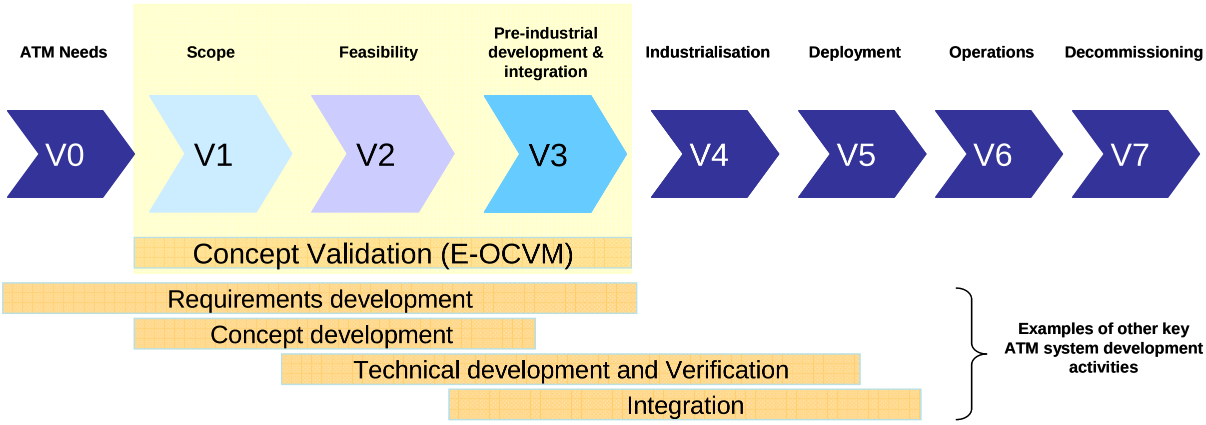
In this context, the objectives of the presented OPA are slightly modified compared to the usual standardization process. The goal is not to provide a full set of quantitative requirements that could be used for industrial implementation but rather to analyze the concept from an OPA perspective, identify the main elements affecting the performance of the overall system and provide the link with existing industrial standards, in particular, considering early airborne surveillance applications. The aim is thus to simplify and contribute to the subsequent development phases of the concept, including validation and the concept refinement.

The present document therefore compiles two types of analysis:

1. The analysis of the A3 ConOps, with regard to required functionalities and related performance characteristic (mostly not quantifiable, only initial estimation is provided whenever available in the existing research).
2. The analysis of already existing elements (technologies) in the current standards. Since ASAS applications are not fully developed yet, the second type of analysis is largely focused on the communication aspects and early ATSA applications, in particular, the recent ATSA-AIRB SPR (DO-319).

Appendix A: E-OCVM - Application Development Process

The content of this Appendix is taken from E-OCVM version 3. According this framework, the OSA/OPA are developed within the phase V2 of the process. As the scope of the iFly project lies within the phase V1 the present document does not represent the result of full OPA but the preliminary result aiming to identify the key issues and concept elements that needs to be refined in order to complete the phase V1 and subsequently proceed with the phase V2.



V1 Scope – This phase identifies the operational/technical solutions for meeting the target performance identified in phase V0. The proposed operational concept(s) and associated technical solution(s) should be defined in sufficient level of detail to enable the establishment of an appropriate performance/assessment framework, the identification of potential benefit mechanisms, scope of potential applicability and initial cost estimates (order of magnitude) to justify R&D. The identification of major research and development issues/needs (R&D needs) is also done during this phase to plan the corresponding R&D activities and establish the validation objectives. The “cases” relevant for these validation objectives are identified and established. An important activity in this phase is to develop a validation strategy and planning, setting high level validation objectives and priorities and covering activities for V1 in detail, and V2 and V3 in outline. At the end of V1, this strategy plan will be updated to cover V2 in detail and V3 in outline, taking the increasing validation knowledge into account.

V2 Feasibility – The main objective of this phase is to develop and explore the individual concept elements and supporting enablers until the retained concept(s) can be considered operationally feasible or it can be established that further development is no longer justified. To elaborate the concepts/enablers and to establish if they are feasible, this phase depends heavily on analysis, modelling and simulation (fast and real time), and may include some initial functional prototyping.

The definition of the concepts and supporting enablers is typically defined to be as open and as broadly applicable as possible thus the modelling and simulation should expose the concepts/enablers to a range of representative operational contexts to establish the actual applicability. This should help to demonstrate potential fitness for purpose across European environments. The **common performance framework** will play an important role in supporting the integration and comparison of results from different environments. However, in a small-scale validation activity, which is specifically targeted at a local change, the objective will be to define the concept(s) and validate in a local context as similar as possible to that of application.

Performance, operability and the acceptability of operational aspects should be the primary concerns. It is during this phase that operational procedures and requirements should become stable. One or more iterations may be needed depending on the complexity of the concept and the effort required to validate its performance/behaviour. In this phase, the human and technology integration, the operating procedures (for normal and important abnormal conditions) and the phraseology/communications requirements should be analysed and tested for the individual concept elements.

This stage will mainly establish the feasibility from the operational and transitional view point and provide initial elements for technical feasibility.

V3 Pre-industrial development & integration – The objective of this phase is threefold:

- firstly, to further develop and refine operational concepts and supporting enablers to prepare their transition from research to an operational environment;
- secondly, to validate that all concurrently developed concepts and supporting enablers (procedures, technology and human performance aspects) can work coherently together and are capable of delivering the required benefits;
- thirdly, to establish that the concurrent packages can be integrated into the target ATM system.

The main type of validation exercise conducted in this phase is thus concerned with integration, and establishing that the performance benefits predicted for individual concept elements in V2 can be realised collectively. It requires integration of pre-industrial prototypes in representative system platforms. This could include the use of real-time simulations and shadow mode/live trials, allowing exposure to different representative operational context environments.

At this stage the operational concept descriptions, applicable operational scenarios, operational procedures, benefit mechanisms, illustrative human-machine interfaces etc., should be stable and documented to a level which will support transfer to industry. V3 should provide adequate information, evidence and documentation to permit decision making and planning of further deployment.

This stage will complete feasibility from the operational and technical integration perspectives. It will identify costs and benefits clearly to allow decision making towards industrialisation and deployment and deliver the materials required to support industrialisation.

Appendix B: Autonomous Flight Rules (According D1.3)

Autonomous Flight Rules (AFR), as stated in (iFly: D1.3), is a set of rules obligatory for autonomous aircraft (operating in SSA and performing self-separation).

- Autonomous aircraft are responsible for maintaining separation with all other aircraft.
- Autonomous aircraft are required to maintain separation from designated areas and no-fly zones.
- Autonomous aircraft are required to adhere to flow management constrains. Renegotiation will have to take place if these constrains cannot be met.
- Lower priority autonomous aircraft involved in a medium term Intent based conflict ruled by priority are required to manoeuvre to solve it sufficiently in advance, so that the conflict does not continue until the conflict resolution becomes a short term cooperative conflict.
- Autonomous aircraft shall not manoeuvre in a way that creates a short term (3 to 5 minutes) conflict.
- The trajectory of autonomous aircraft shall at no time place the aircraft in a 2 minutes state vector conflict (blunder protection).
- Autonomous aircraft shall not enter Manager Airspace without the approval of the controlling entity of that airspace.

Appendix C: List of Operational, performance and functional requirements from SSEP OSED

Table C1: Environmental conditions and communication assumptions from OSED (D9.1).

Assumptions	Description	Location of assumption in OSED
ASSUMP-1 - EC	Only ASAS equipped aircraft – so called "autonomous aircraft" flying under AFR	Page 9
ASSUMP-2- EC	En-route phase of the flight in so called SSA, the transition procedures (SSA towards MA and vice versa) are not discussed in the iFly framework	Page 9
ASSUMP-3 - EC	User preferred routing and no flight levels binding	Page 9
ASSUMP-4 - EC	Airspace boundaries are dynamically allocated.	Page 9
ASSUMP-5 - COM	HF voice left mainly for emergency procedures.	Page 9
ASSUMP-6 - COM	No explicit communication, indirect coordination	

Table C2: Operational (OR), functional (FR) and performance (PR) requirements from OSED (D9.1).

	Description	Location of assumption in OSED
ASSUMP-1-OR	Broadcast information shall include the data about accuracy and integrity of the transmitted trajectory information. The data shall reflect the actual navigation capability of own aircraft and flown guidance mode (including manual flight).	Regular flight stage Page 23
ASSUMP-2-OR	Selected action shall conform to Autonomous Flight Rules.	Initiation stage Page 24
ASSUMP-3-OR	a) Any kind of conflict has priority over the trajectory optimization. b) Short-term conflicts have priority over mid-term conflicts.	Initiation stage Page 24
ASSUMP-4-OR	a) CR maneuver shall not generate a new short-term	Tactical

	conflict. b) CR maneuver shall be conforming to AFR (implicit coordination if applicable, blunder protection, etc.) c) Tactical Maneuvering stage is followed by the New trajectory generation stage, which generates a new RBT.	maneuvering stage Page 24
ASSUMP-5-OR	a) New trajectory must be conflict-free at least up to the mid-term time horizon. b) New trajectory shall be conforming to AFR (blunder protection, etc.)	New trajectory generation stage Page 25
ASSUMP-6-PR	a) The broadcast intent allows a prediction of the aircraft planned trajectory up to MTTH (SL2 and SL3). b) Whenever the intent information of an aircraft is changed, a new intent should be broadcast **immediately** (SL2 and SL3).	Navigation FB
ASSUMP-7-OR	a) If the information about relevant traffic is not updated according to the performance requirements: a. The information must be marked as obsolete or invalid (both for state and intent data). b. If applicable (SL3), this information must be queried from the corresponding aircraft or from SWIM. b) SWIM provides a complete list of aircraft relevant to own flight up to Mid Term Time Horizon – traffic list (SL3). c) (SL3 only) In the case of missing information about an aircraft on the traffic list, the information must be queried from SWIM. d) Conflict detection will run continuously during the SSEP operation and all detected conflicts will be reported. **e) There is no change in communications as a result of detected conflicts.**	Surveillance FB Page 29
ASSUMP-8-OR	a) Conflict detection is a continuous process which runs at a given frequency (TBD) with the best	Surveillance FB

	information available. b) SP should be maximally TBD seconds/minutes	Page 29
ASSUMP-9-OR	Situation assessment runs continuously, during the time when conflict information is available.	Events handling FB Page 30
ASSUMP-10-PR	LP – should take maximally predefined time (TBD)	Events handling FB Page 30
ASSUMP-11-OR	a) The algorithm does not rely on any actions from the conflicting aircraft. b) The proposed conflict solutions follow AFR, in particular, they are conflict-free up to or beyond the MTTH, blunder protection is considered, etc. c) Optimization process (in absence of any conflict) modifies the RBT only beyond the MTTH.	Trajectory modification FB Page 31
ASSUMP-12-FR	a) The proposed solution is valid at time of execution (i.e., it has to take into account ED). Flight crew is responsible to take action to solve the detected conflict. System provides only advisories.	Trajectory modification FB Page 31
ASSUMP-13-OR	a) The algorithm does not rely on any action from the conflicting aircraft b) The proposed conflict solutions follow AFR (implicit coordination if applicable, blunder protection, etc.). c) Conflict resolution makes full use of all information available at time RT (Reference Time, see Figure 2). It remains to be investigated within OSA and OPA how to deal with updated information that is received after RT, whereas the crew has not yet decided what to do.	Tactical maneuver FB Page 31
ASSUMP-14-FR	a) Algorithm is able to solve conflicts with multiple aircraft. b) The proposed solution(s) are valid at time of execution (i.e., it has to take into account ED). Flight crew is responsible to take action to solve the detected conflict. System provides only advisories. In other words, the trajectory update is executed only after flight crew approval.	Tactical maneuver FB Page 31

Appendix D: Proposed Extension of A3 Concept of Operations considering the Priority Rules Use

A definition of self separation operations needs to address several important issues related to distributed air traffic control, such as:

- How to coordinate simultaneous maneuvering of multiple aircraft.
- How to avoid maneuvering of excessive number of aircraft.
- How to avoid excessive maneuvering of single aircraft.
- How to incorporate the global strategic aspects into ASAS distributed control.

The current A3 ConOps (D1.3) does not provide the answers to all these issues. For instance, it considers the use of priority rules in distributed ATM to avoid maneuvering of all conflicting aircraft in the situations when the potential conflict is detected sufficiently in advance and may be solved in more effective way. As the initial RBTs are planned and optimized taking into account all relevant traffic, frequent trajectory changes increase the probability of the potential conflicts. Therefore the use of priority rules contributes to the stability of the overall ATM system through a reduction of the number of maneuvering aircraft. However, the priority rules should incorporate some level of strategic considerations in the definition of priority, otherwise they could at the end, paradoxically, increase the excessive maneuvering by forcing to maneuver an aircraft for which it is more complex to solve detected issue (see, e.g., Ref. [16]).

Priority rules are directly applicable only to pair-wise conflicts, and their use to solve a multi-aircraft conflict requires some additional operational rules (e.g., token allocation strategy considered in FACES [17] which is, however, based on explicit coordination among aircraft). Currently, this issue is not completely solved in A3 ConOps. In the Ref. [19] a potential operational approach to this problem, which could be considered as one of possible extensions of the A3 ConOps, is proposed. As discussed in Chapter 2 and 5, it is necessary to keep in mind that any such refined definition of self separation operations may affect (or create new) the formulated performance and operational requirements.

Priority Number

In the absence of explicit synchronization among conflicting aircraft (as considered in A3 ConOps), priority should not be based on the dynamic onboard evaluation of the detected situation as such assessment can be considerably affected by different situation awareness onboard each aircraft. Ideally, it should be determined in advance and therefore on the basis of widely shared information. In this context, it seems logical to associate the priority (which may vary along the trajectory) of an autonomous aircraft with its actual RBT and allocate the priority determination to a centralized (ground) application.

The first important benefit of a centralized application is that it allows a straightforward introduction of global strategic objectives into distributed tactical control. Let us illustrate it on the scenario discussed in Ref. [16]: the case of a traffic flow crossing by an isolated aircraft. Obviously from a strategic point of view it is more reasonable to ensure that the isolated aircraft has lower priority in order to avoid tactical maneuvering inside the flow.

Another factor which may be easily evaluated from RBT is the "availability" (with respect to navigation and other strategic constraints) considered within the FREER project [Duong]. Finally, RBTs allow evaluating (taking into account the trajectory prediction uncertainty especially considering time) the geometrical maneuverability of aircraft.

As the initial RBTs are determined to be (a priori) conflict-free, they are not suitable to assess a dynamically arisen conflicting situation and therefore a dynamic maneuverability (conflicts usually appear due to the trajectory prediction uncertainty and the stochastic behavior of the environment). However, this factor can be implemented by different means within the ASAS system. Within the iFly project an envisioned detection of areas with high air traffic complexity (as a part of the Conflict Detection function) provides this functionality. For comparison, a straightforward evaluation and prediction of aircraft maneuverability is considered in this context in NASA [13]. In both cases, a detection of a complex area (or reduced maneuverability) triggers a trajectory change and the potentially hazardous situation is thus solved in advance (i.e., not using priority rules).

The proposed approach thus introduces a two-level process which aims to enhance and to avoid the failure of the priority-based conflict resolution:

1. Strategic objectives are incorporated in the definition of the priority by a centralized application. In this way, many situations such as, e.g., traffic flow interacting with an isolated aircraft can be handled.

2. Complexity or maneuverability prediction aims to prevent the situations when an lower priority aircraft would not be able (or with difficulties) to find the solution of the detected conflict.

If (despite the above mitigation) the aircraft with lower priority fails to find a solution, the conflict should be solved through the short-term conflict resolution process (using implicit coordination). Of course safety and effectiveness of this approach must be still verified through the validation and detailed safety assessment.

Multi Aircraft Conflict

Contrary to, e.g., a token allocation strategy [17] we do not consider the use of priority number for a coordination of multi aircraft conflict solution. Instead we suggest an alternative approach based on broadcast of the intention to change own trajectory. The basic idea is: each aircraft, which aims to modify its RBT (and therefore its intent received by surrounding aircraft), will have to share this intention by a simple flag in its state broadcast together with a time stamp saying when the flag was first issued. In the following we will use the term **change mode** for this aircraft state. Operational rules described below specify when the execution (and broadcast) of the new trajectory can be started and how to handle the coordination when multiple aircraft need to maneuver at the same time. The key benefit of this method is that it can be used without any explicit communication among involved aircraft.

Trajectory Change Initiation

Our approach suggests that an aircraft has to modify its trajectory whenever it detects any of the following events:

- A pair-wise conflict with an aircraft with higher priority number,
- Conflict with more than one aircraft,
- Passing through an area with high air traffic complexity.

Note, that a trajectory change is not triggered by a conflict with an aircraft, which is in a change mode already. In fact, as the maneuvering aircraft is looking for a new conflict-free trajectory the conflict should be inherently solved by its expected maneuvering.

Coordination among Maneuvering Aircraft

When more than one aircraft need to modify their trajectories (e.g., multi aircraft conflict, or close conflicts of disjoint pairs of aircraft), the changes are sequenced based on the First Come First Served principle taking into account the time stamp of switching to the change mode. The operational rules introduce three time constraints for this process:

- After switching to the change mode, ASAS system will wait for the time *M* (in order of seconds) before initiating a search for new trajectory. The purpose of this lag is to take into account communication delays of potential change messages by other aircraft. ASAS has to verify if there is no other aircraft in the change mode with an older time stamp. Such an aircraft would be given preference in the transition to the change mode.

- When in the change mode, there is a maximum time I (initial estimation of this time is about 2 minutes) until which the new trajectory must be broadcast and its execution started.
- In addition, when some of the surrounding aircraft is already in the change mode, own aircraft cannot switch to the change mode sooner than in time S (in order of tens of seconds) after the latest time stamp of the already maneuvering aircraft. The reason is that if two aircraft switch to the change mode immediately one after another, the latter one could receive an updated trajectory of the former one only shortly before its own time interval I elapses. Hence, it would not have enough time to incorporate the newly received information into its own trajectory generation process.

Onboard processing logic in the when own aircraft aims to modify the flight path is shown in Figure 8:

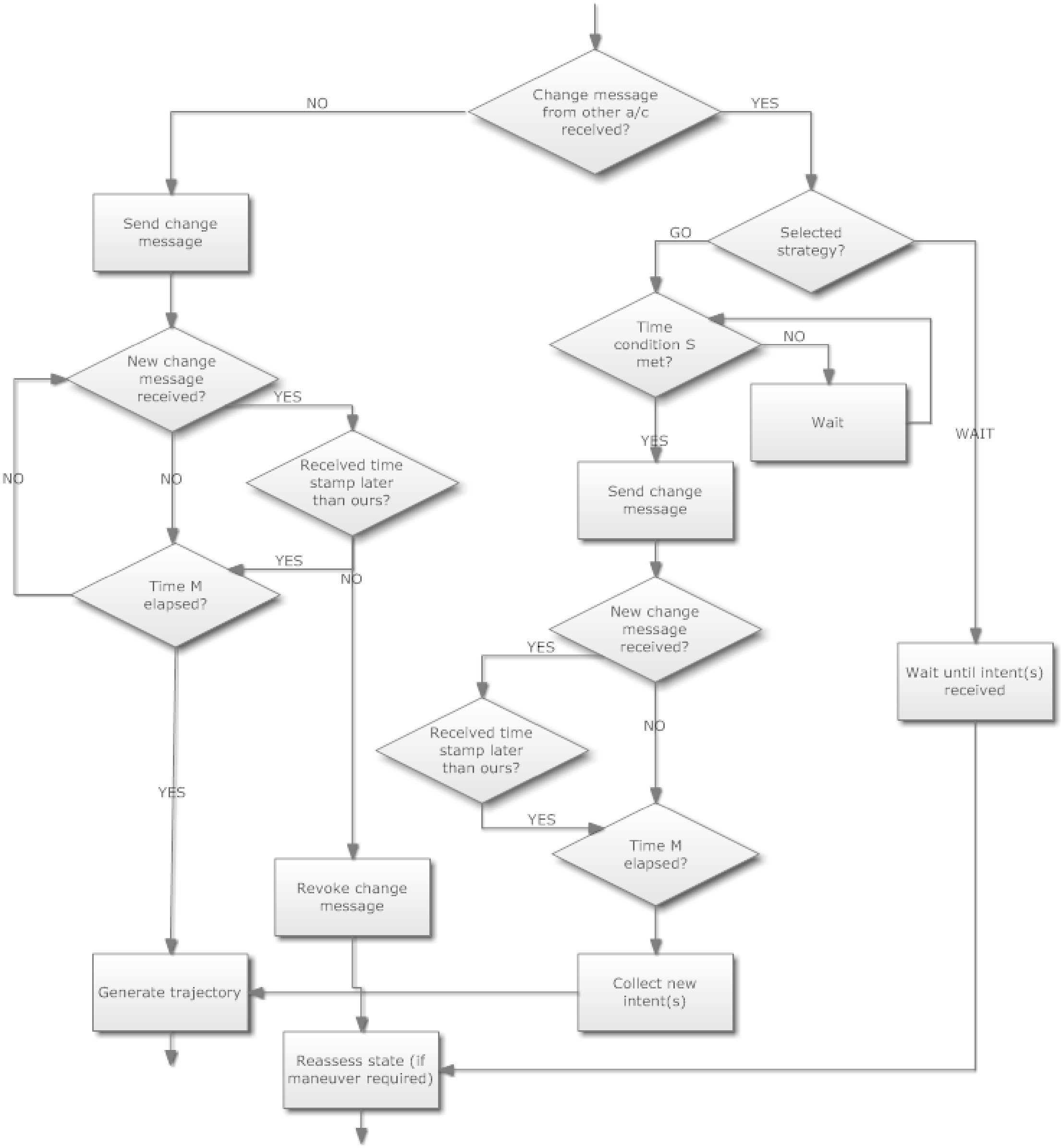


Figure 8: Proposed processing logic for an onboard trajectory modification.

Appendix E: Accuracy And Integrity Description in ADS-B

In this appendix, the basic definition of navigation accuracy and integrity categories are provided. The tables are from DO-242A.

Table 4: The definition of Navigation Accuracy Category for position (adapted from DO-242A). (V)EPU means (Vertical) Estimated Position Uncertainty.

NAC_P	95% Horizontal and Vertical Accuracy Bounds
0	EPU ≥ 10 NM
1	EPU < 10 NM
2	EPU < 4 NM
3	EPU < 2 NM
4	EPU < 1 NM
5	EPU < 0.5 NM
6	EPU < 0.3 NM
7	EPU < 0.1 NM
8	EPU < 0.05 NM
9	EPU < 30 m and VEPU < 45 m
10	EPU < 10 m and VEPU < 15 m
11	EPU < 3 m and VEPU < 4 m

Table 5: The definition of Navigation Integrity Category (NIC) for position (adapted from DO-242A).

NIC	Horizontal and Vertical Containment Bounds
0	$R_C \geq 20$ NM
1	$R_C < 20$ NM
2	$R_C < 8$ NM
3	$R_C < 4$ NM
4	$R_C < 2$ NM
5	$R_C < 1$ NM
6	$R_C < 0.6$ NM
7	$R_C < 0.2$ NM
8	$R_C < 0.1$ NM
9	$R_C < 75$ m and VPL < 112 m
10	$R_C < 25$ m and VPL < 37.5 m
11	$R_C < 7.5$ m and VPL < 11 m

Table 6: The definition of Surveillance Integrity Level (SIL) for position (adapted from DO-242A).

SIL	Probability of Exceeding the R_C Integrity Containment Radius Without Detection
0	Unknown
1	1 x 10^{-3} per flight hour or per operation
2	1 x 10^{-5} per flight hour or per operation
3	1 x 10^{-7} per flight hour or per operation

Table 7: The definition of Navigation Accuracy Category for velocity (adapted from DO-242A).

SIL	Horizontal Velocity Error (95%)	Vertical Geometric Velocity Error (95%)
0	Unknown or ≥ 10 m/s	Unknown or ≥ 50 feet per second
1	< 10 m/s	< 50 feet per second
2	< 3 m/s	< 15 feet per second
3	< 1 m/s	< 5 feet per second
4	< 0.3 m/s	< 1.5 feet per second

Appendix F: Communications Modeling Details

Prediction of loss of separation for linear steady motion

Let p_0 and v_0 be the position and velocity vectors for the first aircraft and let p_1, v_1 be the position and velocity for the second aircraft.

We want to compute time t at which both aircraft get to distance of m (minimum separation distance). It means that

$$\|p_0 + t.v_0 - (p_1 + t.v_1)\| = m$$

After some calculation this leads to a quadratic equation in variable t.

If we denote v^2=v.v, where "." is the dot product, we have

$$[(p_0 - p_1) + t.(v_0 - v1)]^2 = m^2$$

$$[(p_0 - p_1)^2 - m^2]+ 2t.(p_0 - p_1).(v_0 - v_1) + t^2.(v_0 - v_1)^2 = 0$$

This reduces the problem to solving a quadratic equation.

Fitting ADS-B success rate by the incomplete Gamma function

The incomplete gamma function Q(a, x) is defined as follows:

$$Q(a, x) = \frac{1}{\Gamma(a)} \int_x^\infty t^{a-1} e^{-t} dt$$

$$\Gamma(a) = \int_0^\infty t^{a-1} e^{-t} dt$$

The incomplete Gamma function is typically used to express cumulative distribution functions for Gamma distributions.

In fitting the probability of receiving an ADS-B message on distance *d* for data obtained in the CASCASE project (for the "EU2015" interference scenario and "RSL advanced decoder"), we found that the best fit is

Q(3.231, d/18.467)

The fitting was done by the gnuplot program.

Appendix G: Suggested Automation Levels for <u>an example SSEP implementation</u> (from iFly D2.4)

In the current level of maturity of SSEP operations and system architecture it is difficult to define specific requirements for HMI. However, in order to provide at least some guidelines considering an adequate level of automation support to flight crew, the following table was adopted from the iFly D2.4 document.

OODA categories* and tasks, which fall under**	**Tasks (handled by the SSEP operation) associated with OODA categories**	**SSEP Functional Blocks***	**Proposed level of automation (iFly: D2.4, p. 31)** for an example SSEP implementation described in (iFly: D1.3, p.67)**
OBSERVE – gathering, monitoring and filtering data	Collecting and maintaining surveillance information	Surveillance	Automation level 5 or 4 respectively (OBSERVE category)
ORIENT – deriving a list of options through analysis, trend prediction, interpretation and integration	Detection of conflicts, detection of other hazard, checking for opportunities of own flight optimization	Surveillance	
DECIDE – decision-making based on ranking available options	Conflict processing , assessment, situation prioritization and choice of suitable CR process	Situation assessment	Automation level 4 up 6
	Conflict resolution process	Tactical maneuver & Trajectory Modification	Automation level 6 or 7 (Action automation does not exceed level 3). Sheridan's level of Automation for decision 3 or 4

ACT – execution or the authority to act on the chosen decision	Initiation of conflict solution execution and immediate broadcasting of approved solution (possibly sending RBT to SWIM)	Tactical maneuver & Trajectory Modification	Automation level 1-3

*The Functional block *Navigation* excluded, due to the fact, that the functionalities covered by *Navigation* are not SSEP specific.
** For NASAs' Level of Autonomy Assessment Scale see iFly: D 2.4, p. 30, for Sheridan's levels of Automation for decision and action selection see iFly: D 2.4, p. 24.
*** Boyds' (1996) "Observe, Orient, Decide, and Act" loop.

Appendix H: Abbreviations

ADS-B/C	Automatic Dependent Surveillance – Broadcast/Contract
AFR	Autonomous Flight Rules
ARV	Air Referenced Velocity report (ADS-B)
ASA	Airborne Surveillance Applications
ASAS	Airborne Separation Assistance Systems
ASPA-S&M(IM)	Airborne SPAcing – Enhanced Sequencing & Merging operations (Interval Management)
ASSUMP	Assumption
ATM	Air Traffic Management
ATSA-AIRB	Enhanced Airborne Traffic Situation Awareness during flight operations
ATSA-ITP	Enhanced Airborne Traffic Situation Awareness – In-Trail Procedure in oceanic airspace
ATSA-SURF	Enhanced Airborne Traffic Situation Awareness on the airport surface
BPTH	Blunder Protection Time Horizon
CC	Capability Code
CD&R	Conflict Detection & Resolution
CDTI	Cockpit Display of Traffic Information
CRP	Conflict Resolution Performance
CST	Conflict Solution Time
EC	Environmental condition
E-OCVM	European Operational Concept Validation Methodology
FB	Functional block
FMS	Flight Management System
LP	Logic performance
LoS	Loss of Separation
MCP	Mode Control Panel
MFF	Mediterranean Free Flight
MS	Mode Status report (ADS-B)
MTTH	Mid Term Time Horizon
NAC	Navigation Accuracy Category
NIC	Navigation Integrity Category
OSA	Operational Safety Assessment
OSED	Operational Services and Environment Description
OPA	Operational Performance Analysis
RBT	Reference business trajectory
RNP	Required Navigation Performance

RTTL	Remaining Time to loss of separation
SIL	Surveillance Integrity Level
STT	Short term Time Threshold
STTH	Short Term Time Horizon
SL	Service Level
SP	Surveillance performance
SSEP	Airborne Self-Separation Procedure
SWIM	System Wide Information Management
SSEP	Airborne Self-Separation Procedure
SV	State Vector report (ADS-B)
TC	Trajectory Change report (ADS-B)
TCAS	Traffic Collision Avoidance System
TMA	Terminal Maneuvering Area
TS	Target State report (ADS-B)
TTL	Time To Loss of separation

Appendix I: List of References

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