AD HOC MINIMUM SEPARATION: A CHALLENGE FOR AIR TRAFFIC CONTROL (ATC)

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ABSTRACT

The SESAR programme aims at developing the future European air traffic management system. It focuses on four keys areas: capacity, safety, efficiency and environment. In view of the expected growth in air traffic demand in the coming years, the current goal is to increase the airspace capacity, which is already close to saturation in many cases.

Currently, the separation standards applied in a given volume of airspace are fixed, both horizontally and vertically, which means that in many cases this is one of the determining factors of capacity. Separation management is an area where improvement is sought, in particular through the application of new operational concepts (separation modes) which include the redefinition of aircraft separation minima. One of the solutions to be investigated is the variable (Ad Hoc) separation proposal put forward by SESAR.

This future concept implies a change in the application of separation minima from the current fixed standards to a new variable approach. With this new concept, ATCo (Air Traffic Controller) would separate aircraft by applying different separation minima in the same volume of airspace. These separation values are tactically determined for each particular aircraft pair (Ad Hoc) depending on a number of factors: aircraft categories, encounter geometry, atmospheric conditions, etc.

Applying different separation minima in the same volume of airspace implies a substantial change in some of the ATC activities. Also, new functionalities in ATC support tools are needed. This study presents the Ad Hoc separation operational concept and provides the basis for the development of the algorithm for calculating variable separation minima.

1. INTRODUCTION

The SESAR (EUROCONTROL, 2020a) and NextGen (FAA, 2019) programmes in Europe and the United States are aimed at developing the future air traffic management (ATM) system. They are geared towards achieving benefits in four areas: capacity, safety, efficiency, and environment. Both programmes envisage a transition from the current system to the implementation of new operational concepts over the coming decades (BROOKER, 2011).

Since 2014 in Europe there has been a steady growth in air traffic. The year 2018 saw an all-time record of 11 million flights in European Civil Aviation Conference (ECAC) airspace, an increase of 4% over 2017 (EUROCONTROL, 2020a). Last year 2020, as a consequence of the global pandemic resulting from COVID-19, traffic levels dropped drastically (by more than 50% compared to 2019 levels (EUROCONTROL, 2021)). However, a recovery of the sector is expected in the coming years and a return to air traffic growth levels is foreseen. The most reliable traffic forecast scenarios anticipate, by 2040 in ECAC, more than 15 million flights per year (EUROCONTROL, 2020b) . In order to meet this expected growth in demand in the coming years, solutions must be found to increase current airspace capacity in some scenarios already close to saturation.

The separation standards applied in a specific volume of airspace are fixed, both in their horizontal and vertical dimensions (PÉREZ-CASTÁN et al., 2020), which means that in many cases this is one of the determining factors of its capacity. Additionally, the separation minima that are currently applied in a specific volume of en-route airspace were determined decades ago (REYNOLDS & HANSMAN, 2000) when the existing navigation, communication and surveillance systems did not provide the performance of today's systems and when the air traffic controller did not have the advanced support tools available today.

Separation management is therefore an area where improvement is sought, namely through the implementation of new operational concepts (ConOps) which include both the redefinition of the separation minima and the way they are applied. It is therefore necessary to implement a new separation mode, which consists of an approved set of rules, procedures and conditions of application associated with separation minima (ICAO, 2008).

Separation minima studies started with Reich (P.G. REICH, 1964) who developed the first collision risk model (CRM) in order to assess whether a reduction of lateral separation between tracks from 120 NM to 90 NM in the North Atlantic Region (NAT) was safe. Since then several authors have developed this initial CRM in order to extend its application to other scenarios and to overcome certain limitations of the model (MACHOL, 1975), (HSU, 1981), (ANDERSON & LIN, 1996), (BLOM et al., 2003). ICAO adopted the Reich and Hsu models and presented a unified derivation of these (the

Rice formula) based on a general framework (ICAO, 2009). In (BARNETT, 2000) it is proposed a CRM for safety assessment in a free flight scenario while the CRM developed in (SÁEZ NIETO et al., 2010) assesses risk in all three dimensions in an en-route scenario with radar surveillance.

This work develops the operational concept for the application of a minimum variable separation (Ad Hoc) between aircraft, already proposed in a preliminary way as a solution to be studied and developed in some ATM programmes such as SESAR (SESAR EUROCONTROL/EUROPEAN UNION, 2019). This study is organised as follows. Section 2 describes the variable separation operational concept and proposes the basis of the algorithm for the real-time implementation of the concept. Section 3 presents the approach for the reduction of separation minima, the development of which will be presented in future work. This study is concluded in Section 4.

2. VARIABLE SEPARATION (AD HOC) CONOPS

An operational concept (ConOps) is a statement of “what” is envisaged. It asks and answers what results are expected from the future ATM system. It is a vision statement (ICAO, 2005).

2.1 Operational scenario description and CNS requirements

The Ad Hoc separation concept refers to the application of a variable separation value for each aircraft pair within the same volume of airspace, depending on a set of factors (aircraft categories, encounter geometry, atmospheric conditions, etc.). This is therefore a change in the application of separation minima, migrating from the current fixed standards to a new variable approach. Thus, ATCo will separate aircraft, applying different separation minima in the volume of airspace in which the concept is implemented. Implicit in the development of this concept is the research into the reduction of separation minima in order to be able to apply new standards.

The development of this new operating mode will follow a two-step approach, similar to the RECAT project (EUROCONTROL, 2015), where initially static aircraft characteristics are considered, and at future levels a dynamic approach is adopted, considering non-stationary factors such as aircraft weight.

In the initial stage of the concept development, variable separation will be applied in a specific scenario: continental en-route airspace between the upper flight levels (FL 245 - FL 660) where control service is provided. Control sectors of low - medium complexity and traffic density are considered.

In upper airspace the aircraft mix consists mainly of medium, heavy and super heavy aircraft category according to wake turbulence.

In a first step, the airspace structure is assumed to have prefixed routes in which aircraft fly at constant altitudes. Future work will study the implementation of this concept in a free route scenario.

The fundamental factor in the Ad Hoc separation concept is the minimum separation. In this context, this term refers to surveillance minimum radar separation (MRS). However, it is relevant to consider the effects of wake vortex and thus the derived minimum separation (MWS). The variable separation minimum (DS) should always be greater than or equal to the minimum wake separation (MWS).

The main feature of this new operating mode is that there is no single fixed minimum separation value. Instead, there is a set of possible values within a range (3 NM - 5 NM, NM: nautical mile), which extreme values are:

- Upper limit value (5 NM): currently in en-route scenarios with surveillance the defined minimum separation is 5 NM.
- Lower limit value (3 NM): in en-route phase the longitudinal MWS value is considered to be 5 NM for cases where the preceding aircraft belongs to a higher category than the succeeding one. However, when the situation is the opposite, the MWS separation may be smaller (i.e., preceding aircraft of equal or lower category than the succeeding one). There are currently several projects studying the reduction of minimum wake separations and proposing new en-route MWS values: 3 NM, 5 NM (SESAR, 2018). Therefore, it has been decided to take the value of 3 NM as the lower limit of the range of variable separations. Moreover, the reduction of the ATC minimum separation is based, in first instance, on the improvement of the technical systems currently available.

In the initial stage of the development of this concept, the possible Ad Hoc separation values within the defined range will be specific (i.e., 3 NM - 3.5 NM - 4 NM - 4.5 NM - 5 NM). In future work the separation could be specified with a resolution of one tenth (0.1) in NM. These minima will be determined automatically, with a given time horizon, by the Separation Minima Tool. Ad Hoc separation values shall be determined based on a set of conditions:

- Aircraft Category (Super Heavy, Heavy, Medium or Light)
- Navigation Capability
- Surveillance Capability
- Communications Capability
- Encounter geometry
- Aircraft speed
- Wind conditions and ATC procedures.

The implementation of this concept and the consequent reduction of MRS requires aircraft to be capable of ensuring minimum performances from the improved technical systems available. Failure to comply with any of the CNS requirements would reinstate a reference separation value of 5 NM which corresponds to the current applicable standard and the maximum value of the Ad Hoc minima range.

Aircraft operating in these scenarios are required to have PBN (Performance Based Navigation) capability, in particular RNP (Required Navigation Performance). Performance-based navigation requires that for 95% of the flight time, performance related to lateral and longitudinal accuracy, continuity, availability and integrity are guaranteed. Aircraft approved to RNP navigation specifications have an on-board monitoring and alerting system capable of predicting whether the required performance (navigation accuracy) can be met with a probability greater than 10^{-5}. Communications service is available throughout the volume of airspace. Non-urgent communications would be via data link (CPDLC) while urgent communications would be oral in the VHF band.

In scenarios where this concept is implemented the ATC surveillance service shall be based on ADS technology (upgraded with GNSS). The on-board global navigation satellite system (GNSS) receiver provides the ADS-B transmitter with a position accuracy indicator (figure of merit, FOM) and a position integrity indicator (horizontal protection level, HPL) together with other data (ALI et al., 2016). It is a prerequisite that the figure of merit corresponds to the satellite navigation system (FOM 6) and not to other systems (FOM 5 - DME/DME, FOM 3 - Inertial, etc.), otherwise the default separation value (5 NM) would be applied among those aircraft not complying with this requirement. In the event of a regional loss of GNSS positioning capability, radar surveillance would be used as a contingency system and separation management would be provided under current conditions (5 NM fixed separation value).

2.2 Separation Minima Tool

The determination of variable separation minima shall be performed by the Separation Minimum Tool (SMT) integrated in the ground segment. It shall display to ATCo the applicable minimum separation value between two aircraft. While the controller remains the separation agent, the notion in the control exercise will have to change somewhat. Applying different separation minima in the same volume of airspace means that the ATCo is unable to mentally calculate the variable separation value, as opposed to the current fixed value (5 NM). Therefore, controllers need a new tool which presents this separation value for each aircraft pair in the airspace under their responsibility. In this separation mode the supervisory/monitoring role of the controllers become more important and even more complex, so that the operational concept must be defined in order to ensure that the new situation is safe.

In the initial stage, the SMT ground system consists of a single module called 'Separation Proof (SP)'. The function of this tool will be to determine the minimum lateral or longitudinal separation value between two aircraft that meets the required safety threshold (TLS). In order to do so, it requires other systems to provide it with the necessary information.

The trajectory prediction information shall be provided by a predictor tool which will use ADS B data transmitted by the aircraft and the flight plan information (FPL) to perform the 4D prediction. The prediction shall comply with a minimum quality factor in order to achieve a required level of accuracy. The 4D trajectory prediction shall be received by the SMT 20 minutes in advance of the aircraft's planned sector entry time. Information regarding wind conditions and aircraft performance shall be provided to the SMT tool by the aircraft. The FPL information shall be received from the flight data processing system (FDP) (Figure 1).

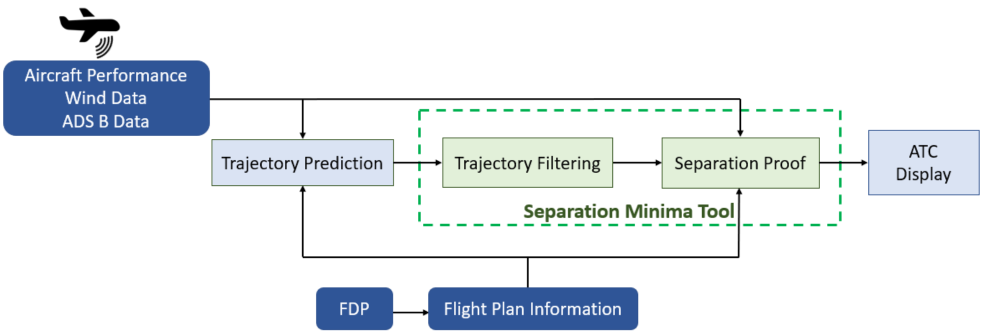

Figure 1. Information flow for Ad Hoc separation determination

Initially the SMT shall filter trajectories by discarding those situations that are not of interest, i.e. aircraft whose trajectories do not intersect, aircraft whose trajectories intersect at a crossing point but with a time difference between them of more than 2 minutes (and therefore separated by a distance of more than 15 NM), aircraft not flying on the same airway and aircraft flying on the same airway but whose time difference at the sector entry time is greater than 6 minutes (and therefore separated by a distance greater than 45 - 50 NM which assumes that differences in aircraft speeds would not give rise to overlap conflicts). After this first filtering, the SP module shall initiate the separation determination between the interest aircraft pairs. This variable separation minimum shall be determined and displayed to the controller 2 minutes in advance of the expected sector entry time of the first aircraft. This time horizon has been selected in order to allow ATCo to have some advance knowledge of the applicable minimum separation value between two aircraft. These initially proposed time values are subject to modification depending on the results obtained in the validation level.

It should be noted that some systems will need to be upgraded in order to be compatible with the proposed concept. In particular, the ATC tool "Conflict Detection" will adopt a more dynamic behaviour by monitoring that there will be no loss of separation between aircraft with the conflict limit distance being the minimum Ad Hoc distance determined.

The same applies to the ACAS system, which operates on time scales that should be analysed to avoid excessive generation of Traffic Advisory (TA) and Resolution (RA) alerts. Also, one of the future challenges to be dealt with in the development of this Ad Hoc separation project is the compatibility with the Trajectory Based Operations (TBO) concept strongly promoted by SESAR. While the former is eminently tactical, the TBO concept has a greater focus on strategic planning. The idea behind this concept is that trajectories are negotiated between all the actors involved before the flight and that the ATM system is aware of them and modifies them, if appropriate, in order to be free of conflicts. The possible discrepancy lies in what minimum separation would be used to make the trajectories strategically conflict-free, as the Ad Hoc separation would be tactically determined. The harmonisation between these two concepts will be explored in future work.

2.3 Separation Proof module

The algorithm for the Ad Hoc separation minima determination implemented in the Separation Proof module aims to determine the smallest safe separation value between two aircraft. Figure 2 shows the flowchart representing the sequence of activities carried out by the algorithm. Four activities are distinguished:

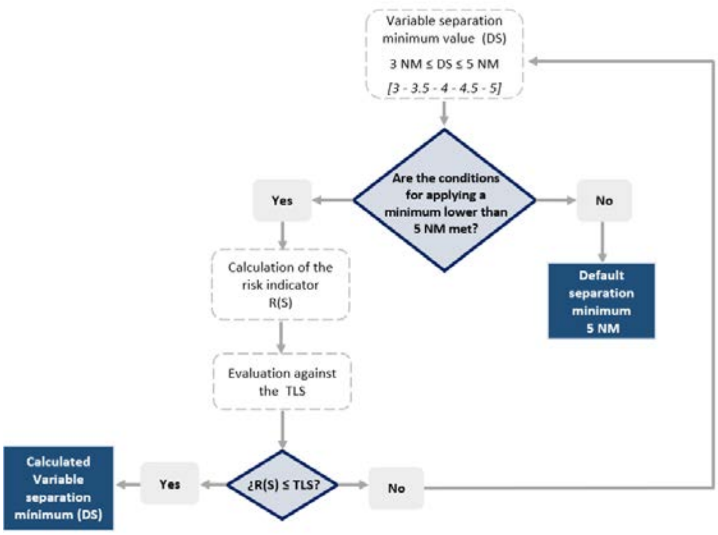

Figure 2. Ad Hoc Separation Determination Algorithm Flowchart

<u>1.- Variable Separation Minimum (DS).</u>

The algorithm has information on the aircraft pairs labelled as "pair of interest" and their specific characteristics (performances, trajectories, etc.). The en-route turbulent wake separation minima between aircraft, depending on the possible sequences (i.e., heavy-medium, medium-super heavy, etc.), are given to the algorithm.

In the initial step of the development of this concept the minimum variable separation (DS) will be determined and not calculated from this information. That is, in the first activity the algorithm will specify in real time for the “pair of interest” the lowest applicable separation value within the range of Ad Hoc separations (3 NM - 3.5 NM - 4 NM - 4.5 NM - 5 NM).

The Ad Hoc value shall always be higher than the corresponding MWS for that situation. If the Ad Hoc value does not meet the requirements of the following activities in the flowchart (target level of safety) the algorithm, following the feedback, would return to the initial step, would take the variable separation (DS’) value immediately above the previous one and would repeat the sequence until an Ad Hoc separation value judged as safe is obtained. It is a prerequisite that the required conditions are met in order to be able to apply variable separation. Among those aircraft that do not meet these conditions, the default value of 5 NM shall always be applied.

2.- Calculation of the aircraft pair risk indicator R(S).

After determining the minimum variable separation (DS) the algorithm estimates the risk of collision R(S) of the aircraft pair for which the minimum variable separation (DS) has been calculated. The input variables for the calculation of the risk indicator are:

- Characteristics of the encounter geometry (angle of intersection between trajectories, aircraft speeds, altitudes, etc.).
- Minimum variable separation value determined (DS).
- Aircraft horizontal overlap probability (as a function of DS separation)
- Errors (aircraft position uncertainties, human factor, time windows, etc.)
- Meteorological conditions (wind) affecting aircraft ground speed (GS).
- ATC Intervention Capability

3.- Safety assessment.

After estimating the risk of collision R(S), it is compared with the Target Level of Safety (TLS) whose value is fixed. In making this comparison, the possibilities are:

- If the risk indicator R(S) ≤ TLS, then the minimum variable (DS) is applied.
- If the risk indicator R(S) > TLS, then:

    1. A new variable separation minimum (DS') value is determined that is higher than the previous DS value which did not comply with the TLS threshold.
    2. It is checked whether the new DS' value satisfies with the TLS fixed safety target level. If yes, the applicable separation value is DS'.
    3. If not, the process is iteratively repeated until the value of the minimum variable separation is 5 NM. This value corresponds to the current en-route (with surveillance) separation standard and therefore satisfies with the defined TLS.

<u>4.- Display of the applicable minimum variable separation value to ATCo.</u>
Finally, the minimum variable separation value applicable between the aircraft pair is displayed to the controller with a reasonable amount of time in advance.

3. APPROACH FOR THE ATC SEPARATION MINIMA REDUCTION STUDY.

Separation minima can be described as a function of three factors: navigation performance, risk exposure and intervention capability (Communications, Surveillance and ATC procedures and tools) (ICAO, 2020).

ICAO adopted collision risk models for the purpose of determining minimum separation in airspace with procedural control. However, in scenarios with ATS surveillance services (ATS surveillance systems: radar, ADS-B, etc.), the determination of separation minima appears to lack rigorous formal development. To determine the appropriate radar separation minima the analysis is related to the effect of inaccuracies, in the displayed radar data, so as to estimate the risk of collision and to decide whether the risk, for the implementation of a separation minimum, is acceptably safe (EUROCONTROL, 1998). Some authors have followed this approach and address the determination of the separation in scenarios with surveillance from the uncertainties of the different elements that make it up (REYNOLDS & HANSMAN, 2000). These uncertainties associated with the errors can be approximated by probability density functions (generally Gaussian and Double Exponential distributions).

The separation between aircraft displayed on screen to ATCo (apparent separation) does not correspond to the actual separation between aircraft, due to the associated errors. The actual separation value will depend on the probability density functions of the errors (Figure 3). The limiting case occurs when the apparent separation between aircraft is 5 NM (current separation standard), a value for which the collision risk meets the absolute target level of safety (TLS), but the actual value is less than the standard.

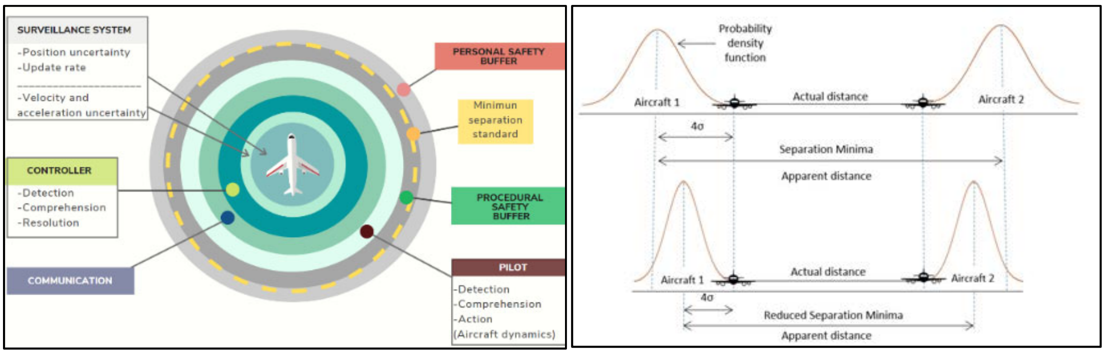

Figure 3. Representation of: left) Separation assurance budget components (REYNOLDS & HANSMAN, 2000) and right) errors probability density functions

The reduction of the ATC separation minimum is based on improvements in the technical systems currently used, in particular in the field of surveillance and navigation. These, not only offer better performance, but also predict whether this performance will be maintained during the flight, as is the case with RNP navigation. In addition, ATC is now equipped with more advanced support tools. The aim is to reduce the uncertainty associated with the various factors influencing separation (modification of the density function). Thus, the actual separation between aircraft would be maintained and, consequently, so would the risk of collision. However, the minimum separation (apparent separation) could be smaller.

In the framework of the minimum separation definition, the navigation and surveillance domains are the ones where most progress has been made. The progress achieved with Performance Based Navigation has been discussed in Section 2. In the surveillance domain, ADS overcomes some of the limitations of radar (positioning accuracy and system update time). In radar, accuracy is dependent, among other factors, on the distance to the target. Furthermore, different separation values are applied depending on the surveillance signal processing mode (5 NM multi-radar, 10 NM mono-radar, etc.). The information captured by the radars is not displayed directly to ATCo but is processed beforehand. This entails a processing time, especially in multi-radar processing, which means that the information displayed on the screen to ATCo corresponds to positions from previous time instants. Likewise, it should be considered that the mode S radar update frequency or information refresh time (speed at which the position of the aircraft is updated to users) is 4 - 15 seconds. In ADS the positioning accuracy is dependent on the aircraft avionics and therefore independent of the sensor range. With the GNSS navigation system (FOM 6) the position accuracy values achieved are less than 0.25 NM. In addition, since the information is received directly from the aircraft, the processing time is shorter than with multi-radar processing, with the update rate in the ADS typically being 1 second.

Research on the reduction of ATC separation minima will be developed in future studies and will be mainly based on the improvements referred above.

4. CONCLUSIONS AND FUTURE WORK

The SESAR and Next Gen macro programmes propose new projects in order to drive the future development of air traffic management (ATM) and ensure benefits in the capacity, safety, efficiency and environment areas. This study has laid the foundations for the development of the concept of variable separation in continental en-route airspace. In particular, the Ad Hoc separation framework or operational concept is defined. Variable separation involves applying different separation minima between aircraft in a specific volume of airspace according to a specific set of characteristics (aircraft category, navigation performance, surveillance, etc.) and external characteristics (conflict geometry, ATC procedures, wind conditions, etc.).

There is no fixed separation value, but a range of possible values that define new standards. For this reason, implicit in the development of this concept, research will be carried out on the reduction of the current separation minima. The approach to be followed to study this reduction lies in maintaining a fixed safety threshold (risk of collision) by reducing the uncertainties associated with the different factors that determine the minimum separation (surveillance, navigation, ATC procedures, etc.) thanks to improvements in the technical equipment currently available. This study also describes the operation of the Separation Minima Tool and the steps carried out by the algorithm in charge of determining the variable separations. Different operational issues are identified that need to be developed in future work to make new concepts proposed by SESAR (Trajectory Based Operations, TBO) compatible with the one proposed in this study. Finally, the implementation of variable separation has the final goal of increasing capacity. This study will be carried out in parallel.

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