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Preliminary design of an ATC support tool for the implementation of the Ad Hoc Separation Minima concept in an en-route sector.

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Abstract. The current aim in response to the anticipated growth in air traffic demand is to expand airspace capacity. However, this poses a challenge, as many airspace volumes are nearing saturation. An influential factor in determining airspace capacity is separation minima, which have remained unchanged for more than two decades. It seems that technological developments in recent years, such as new aircraft capabilities and ATC (Air Traffic Control) support tools, may eventually enhance current separation minima standards. Consequently, there is a push to improve separation management by introducing new operational concepts. Ad Hoc separation minima are one such concept, allowing different separation values to be applied within the same airspace volume based on factors such as aircraft models, weights, and wind conditions, among others. These values are computed individually for each aircraft pair in each situation. Implementing different separation minima values within the same airspace volume requires a significant change in certain ATC activities. In addition, new functionalities or ATC support tools are essential, as Air Traffic Control Officers (ATCO) cannot mentally determine the appropriate separation value for each situation. To address this, a new tool, the Ad Hoc Separation Minima Tool (ASMT), is proposed. It aims to integrate this concept seamlessly into an en-route (ENR) sector without increasing ATCOs workload and altering ATC responsibilities. This study provides a high-level overview of the ASMT architecture, and its functional system has been evaluated in a simulated ENR sector using MATLAB®.

1. Introduction

The air transport system is expected to experience a continued increase in the number of movements [1]. Hence, there is a need to address the capacity growth. Airspace capacity is directly related to the Air Traffic Control Officer (ATCO) workload, which, in turn, is associated with the separation mode. Separation mode is defined as an approved set of rules, procedures, and conditions of application associated with separation minima [2]. Therefore, separation management is an area where improvement is sought to increase airspace capacity.

On the one hand, the focus on increasing airspace capacity has led to notable research in automated Air Traffic Control (ATC) tools, aiming to support ATCO tasks and reduce their workload. ATCOs are responsible for Conflict Detection and Resolution (CD&R) while simultaneously monitoring the progress of other traffic. Most research efforts have been directed toward developing ATC tools for CD. Over the last decades, various CD models have been developed. A complete review of the first CD models is given in [3]. Several studies have delved into complex probabilistic models to grasp trajectory uncertainty [4], [5], [6], [7], [8]. Recently, in the context of Artificial Intelligence (AI), Machine Learning (ML) algorithms have also been employed for CD [9], [10].

On the other hand, airspace capacity is a concept that is dependent not only on ATCO workload but also on the separation criteria itself [11]. Current standards applied in a specific airspace volume have remained unchanged for decades, prompting exploration of new operational concepts like the Ad Hoc separation minima, which refers to the application of different separation minima values in the same volume of airspace, depending on a set of factors: aircraft model, encounter geometry, etc.

Implementing this concept requires significant changes in ATC activities and requires new functionalities or new ATC support tools, because the ATCO is unable to mentally calculate which separation minimum applies in each specific situation. Moreover, current CD&R tools work with a fixed separation minima value. The proposed solution is the Ad Hoc Separation Minima Tool (ASMT), designed to seamlessly integrate this concept into an ENR sector without increasing ATCO workload and changing ATC responsibilities. Therefore, the ASMT will provide ATCOs with the necessary information so that their situational awareness could be maintained. To this end, it will display to the ATCOs the Ad Hoc separation value to be applied between aircraft pairs, and, in addition, it will alert them of possible Ad Hoc losses of separation (LOSs) and propose resolution manoeuvres to avoid them.

This work aims to provide a high-level analysis of the ASMT architecture. The functional system of this tool has been assessed in the LECMZMU ENR sector through simulations in MATLAB®. The structure of the study is outlined as follows. Section 2 provides a brief overview of the Ad Hoc Separation ConOps (operational concept). Section 3 delves into the ASMT architecture. The application to LECMZMU ENR sector is presented in section 4. Finally, section 5 summarises the main conclusions drawn from the study and further work.

2. Ad Hoc Separation ConOps

ConOps is an overview of how the concept is going to be operated in the context of the Air Traffic Management (ATM) system. The Ad Hoc separation minima concept means the application of a variable separation value for each aircraft pair within the same volume of airspace as a function of the aircraft model, aircraft weight, aircraft speed, wind conditions, encounter geometry, avoidance manoeuvre (AM) and Flight Level (FL). These separation minima values must always be greater than the corresponding Minimum Wake Vortex separation (MWS) obtained as an input from [12].

Therefore, the appropriate and safe separation minima to be applied in each encounter varies depending on the factors mentioned above. The layer-based model for establishing the Ad Hoc separation is based on the premise of considering the separation minima as a buffer. It aims to prevent a LOS from becoming a collision (barrier to collision). The authors recommend [13] for a detailed explanation of the model.

The key characteristic of this novel separation mode is the existence of a range of possible separation minima values. These are within the range of 3NM–5NM (Nautical Miles). Initially, Ad Hoc separation values will be specific (3NM, 4NM, or 5NM). These values are strategically calculated for a specific sector and specific aircraft pair situation (FL, aircraft models, etc.), as the safe Ad Hoc separation values are derived from a collision risk model (CRM). Therefore, they are not calculated in real time.

These minima are displayed to the ATCOs by the ASMT tool in real time, because the ATCOs are unable to mentally calculate the variable separation value, as opposed to the current fixed value (5NM). The ASMT is integrated in the control working position (ground segment). Thus, the ATCO remains the agent of separation, but the concept of operation in the control exercise will change somewhat.

In the initial phase of the development of this concept, the focus is on the Ad Hoc separation application within ENR airspace among aircraft flying at the same FL, which is common during the cruise phase. The upper ENR airspace (FL 345-660) and a scenario of predefined routes are considered. Further work will extend to TMA (Terminal Manoeuvring Area) and free route airspace, considering evolving aircraft (3D). Moreover, the compatibility of the Ad Hoc concept with current TCAS algorithms will be studied.

3. Ad Hoc Separation Minima Tool (ASMT)

In general, an ATC support tool provides automatically or semiautomatically specific information (traffic situation, weather, etc.) about the sector in which the ATCOs provide control service. This is to facilitate the ATC labour, allowing them to be aware of other kind of information, although not exempting them of their responsibility as ATCOs. The tool presented herein, denoted ASMT, aims to provide ATCOs with Ad Hoc separation values for aircraft pairs. ASMT supplies ATCOs with preventive information in a two-step process: by identifying conflicting situations and suggesting manoeuvres to resolve them. The main difference from a typical CD&R tool is that ASMT calculates specific Ad Hoc separation values for each aircraft pair and CD&R tasks are performed according to that Ad Hoc value.

The ASMT was developed for the tactical ATCO, who continuously monitors the state of the aircraft throughout the airspace. It is composed of different modules: trajectory prediction module, situation of interest (SI) detection and characterisation module, Ad Hoc separation determination module, conflict detection (CD) module and conflict resolution (CR) module. These are presented in this section.

Note that the development of the ASMT tool follows the development of the Ad Hoc separation concept. Currently, the concept of Ad Hoc separation is only applicable to ENR sectors between aircraft that fly in the horizontal plane (2D). Therefore, the ASMT tool is currently designed to be applied in ENR scenarios and between aircraft in level flight. In the future, fully developed versions of ASMT are expected to replace Short Term Conflict Alert (STCA) in scenarios where the Ad Hoc concept is implemented. ASMT, being a CD&R tool, will encompass all STCA functionalities.

3.1. Trajectory prediction module

The trajectory prediction is the process of estimating the future states of the aircraft based on the current state of the aircraft, the estimation of the pilot and the ATCO intention, the expected environmental conditions and the computer models of aircraft performance and procedures [14].

The ASMT makes predictions based on the evolution of the aircraft throughout the airspace, the FPL information, and the information provided by the aircraft such as aircraft weight and wind conditions (this is assumed as a requirement). The predictions depend on the t_{LAT} (look ahead time) and the operational features of both aircraft. The ASMT updates the prediction every c seconds and considers the aircraft within the sector and the aircraft that will pierce into the airspace in the following m minutes. t_{LAT}, c and m values should be defined in advance by Air Navigation Service Providers (ANSPs). In this research the values used are t_{LAT}, 5 minutes, c, 5 seconds and m, 30 minutes, for computing limitations, but the tool is prepared to take other values more accurate. Nevertheless, the trajectory prediction can be provided by an external tool, being the predictions an input for the ASMT. The trajectory predictions shall comply with a minimum quality factor to achieve the required accuracy level.

For aircraft trajectory prediction, as a first approach, the BADA model has been applied [15]. BADA, developed by Eurocontrol, is a precise aircraft performance model designed to simulate the behaviour of any aircraft. It relies on the 'Total Energy Model (TEM)', a three-Degrees-Of-Freedom (3 DOF) model that correlates the rate of work performed by forces acting on the aircraft (Thrust and Drag) with the rate of change in potential and kinetic energy. However, the TEM is simplified, as shown below, because the following assumptions are considered:

1. Flights are at an established FL (2D). Climbs and descents are not modelized in this first stage.
2. The mass of the aircraft is considered constant.
3. The Mach cruise is considered constant.
4. As there is no variation in FL or speed, the TEM equation reduces to $Thr = D$ as the potential and kinetic energy components cancel out.

Due to the scarcity of data, the information used for the prediction in this initial stage is obtained from the FPL (from the NEST DDR2 files [16]) and the BADA model. The following data are considered: the route of each aircraft (sequence of waypoints given by longitude (λ), latitude (φ) and altitude (h)), the actual position of the aircraft, the indicated airspeed (IAS) and heading (θ). However, radar or ADS-B data could be integrated into the ASMT if available. For GS (Ground Speed) determination, wind is assumed constant (first approach); direction of 360º and intensity of 40 kt.

The prediction is modelled from the general equation of uniform rectilinear motion and depends on the immediately preceding position, aircraft speed, and flight time. It is assumed that the current position of the aircraft is known. The prediction is addressed by calculating the time required to arrive to the following WP_i (t_{WPi}) of the FPL. Once this time is calculated using the current speed (GS_{WPi}) for each segment of the route, the last WP with a needed time (t_{WP}) lower than t_{LAT} is selected and the position of the aircraft is calculated according to the uniform rectilinear motion. Using the position of this WP, the GS_{WP}, and the time corresponding to t_{LAT} - t_{WP}, the prediction of the aircraft is calculated (Figure 1a)). SWR2092 and AAL749 predictions by ASMT are shown graphically (red crosses) in Figure 1b).

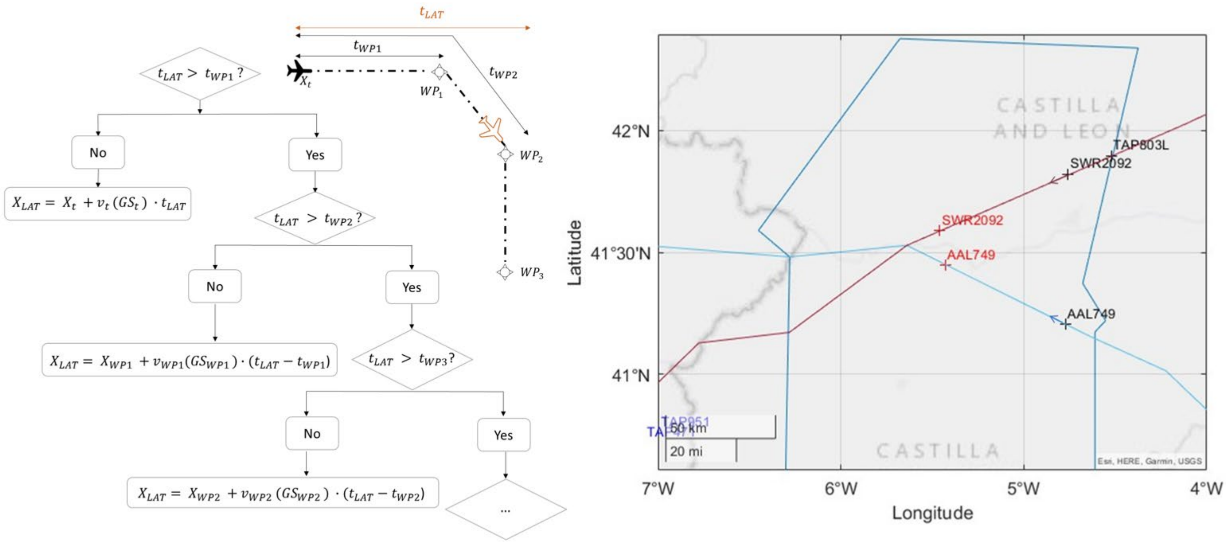


Figure 1. a) ASMT trajectory prediction flowchart. b) SWR2092 and AAL749 trajectory predictions.

3.2. SI detection and characterisation module

From the aircraft trajectories prediction, SI are analysed. A SI is a situation in which an aircraft pair is expected to intersect with a horizontal separation smaller than a predefined distance [10]. Usually, this predefined separation is specified by the ANSP, and is higher than the separation minima. In this study 10NM was defined. Therefore, if the Euclidean distance between two predicted aircraft trajectories (positions) is going to be lower than 10NM and both aircraft are in the same FL, a SI is detected.

The concept of SI is used for two reasons. The first is to avoid critical missed alerts (when a separation infringement has occurred between an aircraft pair, but the system erroneously calculates that no separation infringement will occur). This is because of the uncertainties associated with the aircraft position related to navigation and surveillance. SI are conflict situations, that is, situations where the separation minima could potentially be violated in a short time horizon, leading to a LOS. The second reason is as a filter for the search of the Ad Hoc separation between a pair of aircraft in a database. Aircraft crossing at distances greater than 10NM are excluded from the Ad Hoc separation minima search process. This exclusion is justified by the margin available, ensuring that the Ad Hoc separation is unlikely to be compromised. This is because the Ad Hoc separation minima are always equal to or less than the current horizontal separation value of 5NM). Conversely, when two aircraft cross within a distance below 10NM, determining the appropriate Ad Hoc separation minima values for a specific pair of aircraft becomes paramount.

When a SI is detected, to determine its Ad Hoc separation value applicable, the encounter is characterised by the ASMT according to the following features: aircraft models, aircraft weights, speeds of the aircraft, FL, crossing angle, and wind conditions.

An additional prediction is done to estimate the TCPA and DCPA of the encounter, the crossing point of the trajectories and the times at which the Ad Hoc separation is lost (5NM, 4NM and 3NM).

If the ASMT detects that an aircraft pair is expected to intersect with a horizontal separation smaller than 10NM but both aircraft are not in the same FL, the default value of the applicable separation minima is 5NM and 1000ft (i.e., the current values of separation minima).

3.3. Ad Hoc separation minima determination module

After the characterisation of the SI, the ASMT searches for the applicable value in a database which contains the Ad Hoc separation minima values for different situations and for a specific ENR sector. As mentioned above, Ad Hoc separation minima values are strategically determined because they are derived from a CRM [13]. To determine the Ad Hoc separation, the search process is as follows:

1. After characterizing the SI, the ASMT will search in the database for the predetermined Ad Hoc separation value based on this SI characterisation. These Ad Hoc separation minima values are associated with an AM in the vertical plane, either a climb or a descent. Thus, the ASMT will locate the appropriate Ad Hoc separation minima (for climb and descent AM) that best match the current situation in the sector (according to the SI characterisation), prioritizing safety.
2. In this stage, the ASMT determines whether to apply the Ad Hoc separation corresponding to the climb AM or to the descent AM. For this purpose, it assesses the vertical plane to identify nearby aircraft at adjacent FL. Three possible scenarios exist:
   - If there are no nearby aircraft flying at the immediate upper or lower FL, the ASMT selects the lowest Ad Hoc separation, which will correspond to the descent AM.
   - If nearby aircraft are flying at the immediate upper FL, the ASMT selects the separation value for descent AM, disregarding the value corresponding to the climb AM, and vice versa for nearby aircraft flying at the immediate lower FL.
   - If nearby aircraft are flying at both upper and lower FLs, the default value of 5 NM is applied.
3. Each Ad Hoc separation value corresponds to a collision risk value. The ASMT applies the lowest available Ad Hoc separation minimum value (3NM is preferred over 4NM and 4NM over 5NM). If cases where multiple options exist (i.e., it is possible to apply 4NM for AC1-AC2 encounter whether AC1 performs a descent AM or AC2 performs a climb AM) the ASMT will choose the Ad Hoc separation value corresponding to the lowest collision risk value.

In addition to determining the Ad Hoc separation to be applied for a SI, the ASMT tool calculates the distance value between the aircraft pair at the Closest Point of Approach (DCPA) and the Time to the Closest Point of Approach (TCPA) once the SI has been detected and characterised. To do so, after detecting an SI, the prediction of the trajectory is projected every second. These data (applicable Ad Hoc separation, DCPA, and TCPA) are displayed on the ATCO screen by the ASMT.

3.4. Conflict detection (CD) module

This module consists of two submodules. The first is entitled "submodule for LOS probability calculation", and the second "conflict alert submodule". These are defined in more detail below.

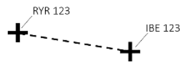
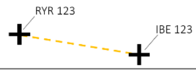
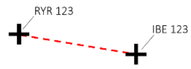
3.4.1. LOS probability calculation submodule. The main task of ATCOs is the separation management in their airspace of responsibility; that is, to avoid any LOS between aircraft. The ASMT is a tool that, in addition to determining and showing the Ad Hoc separation to be applied, aims to maintain ATCO situational awareness. It helps them in the task of detecting possible conflict situations before the occurrence of a LOS. Trajectory prediction is influenced by several uncertainties. Consequently, it is not possible to predict a LOS with absolute confidence being more appropriate to refer to probability values.

Given that in this concept, depending on the characterisation of the different SI, the Ad Hoc separation applicable is different, the LOS probability is calculated for each situation regarding the Ad Hoc separation value to be applied. For the calculation of the probability of LOS, the model proposed by Irvine and Eurocontrol [17] has been used.

In summary, this is a geometric model in which the LOS probability is calculated in the horizontal plane (2D). The geometric locus of the conflict defines an elliptical region in a rectangular coordinate system in which the axes represent the trajectories flown by both aircraft. This is obtained by applying the cosine theorem to the encounter geometry when the aircraft are separated by the separation minimum value (which in the case of the Ad Hoc separation will be different for each SI). The LOS probability corresponds to the overlap of the distribution of the average speeds ratio of the two aircraft and the elliptical conflict region. Cross-track errors in the aircraft trajectory are not considered in this model as they are assumed to be negligible compared to along-track errors. These are modelled from the normal distribution and are assumed to increase with flight time. The authors recommend [17] for a detailed explanation.

3.4.2. Conflict alert submodule. This submodule is responsible for showing to the ATCOs the information on the evolution of the conflict between the pair of aircraft classified as SI. Mainly, this information shall be provided with enough time so that any required action can be taken in advance of a critical situation. Currently, this time is set to 2.5 minutes before the LOS, but it could be modified. Based on the LOS probability information, and depending on the probability values, by means of a colour code and symbols, the unfavourable or favourable evolution in the resolution of the conflict situation is shown graphically. In this way, the ATCOs situational awareness of a compromised traffic situation in their sector is maintained as at present by graphically and audibly displaying. Table 1 shows the format used by the alert module depending on the P_{LOS} values. Other information is shown to the ATCOs such as the TCPA, DCPA, and the Ad Hoc separation value.

Table 1. Legend of codes used for the conflict alert.

P_{LOS} value	Graphic Alert	Graphic representation	Sound alert
$0.1 \leq P_{LOS} < 0.3$	Grey dashed line		No
$0.3 \leq P_{LOS} < 0.5$	Orange dashed line		No
$0.5 \leq P_{LOS} < 0.7$	Red dashed line		No
$P_{LOS} \geq 0.7$	Red and white dashed line		Yes

3.5. Conflict resolution (CR) module

This module is intended to help the ATCOs to resolve a conflict situation. It proposes a set of manoeuvres in the horizontal plane (when possible, a maximum of four) by which the LOS of the Ad Hoc separation between a pair of aircraft could be avoided. However, it is up to the ATCOs to decide when to apply it and whether to apply it. This information is presented to them as soon as it is calculated that for that SI there is a $P_{LOS} > 0.1$ and 2.5 minutes before the LOS (this time could be modified). The manoeuvres are determined considering that only one of the two aircraft execute the resolution manoeuvre.

To determine these manoeuvres, as a first option and with the aim of not diverting, or diverting as little as possible the aircraft from its route, it is proposed to evaluate if with a "direct" to the next waypoint of the route defined in the FPL, it is possible to avoid losing the Ad Hoc separation or to meet that P_{LOS} is $0 \leq P_{LOS} \leq 0.1$. This is calculated for both aircraft, although it is considered that only one of them will be the one to execute it.

In addition, it is calculated the possibility of giving other vectors for which both following requirements are met: $P_{LOS} < 0.05$ and the avoidance of further LOS with the same aircraft when performing the resolution manoeuvre (the resolving aircraft is considered to fly behind the other aircraft). These vectors are calculated in increments of 5° regarding the heading of the aircraft. Thus, one vector (port or starboard) is calculated, whose angular deviation is smaller. This vector is calculated for both aircraft. Therefore, whenever possible, to the ATCOs are presented a set of four maximum resolution manoeuvres, two possible manoeuvres for each aircraft. The ATCOs shall decide which manoeuvre prefer to clear and to which aircraft.

4. Application to LECMZMU ENR sector

This section shows the performance of the ASMT tool in the LECMZMU sector of the Madrid ACC. It presents information on the SI involving aircraft SWE2092 and AAL749, including details such as aircraft IDs, models, intersection angle, FL, DCPA, Ad Hoc separation value, time to LOS, and probability of LOS occurrence. When the estimated time to LOS approaches a critical threshold, a visual representation of the conflict situation is generated (Figure 2 a)) according to the probability of LOS. Additionally, the value of the Ad Hoc separation for that SI is displayed (4NM). Concurrently, potential resolution manoeuvres in the horizontal plane are computed and presented to the ATCOs (Figure 2 b)).

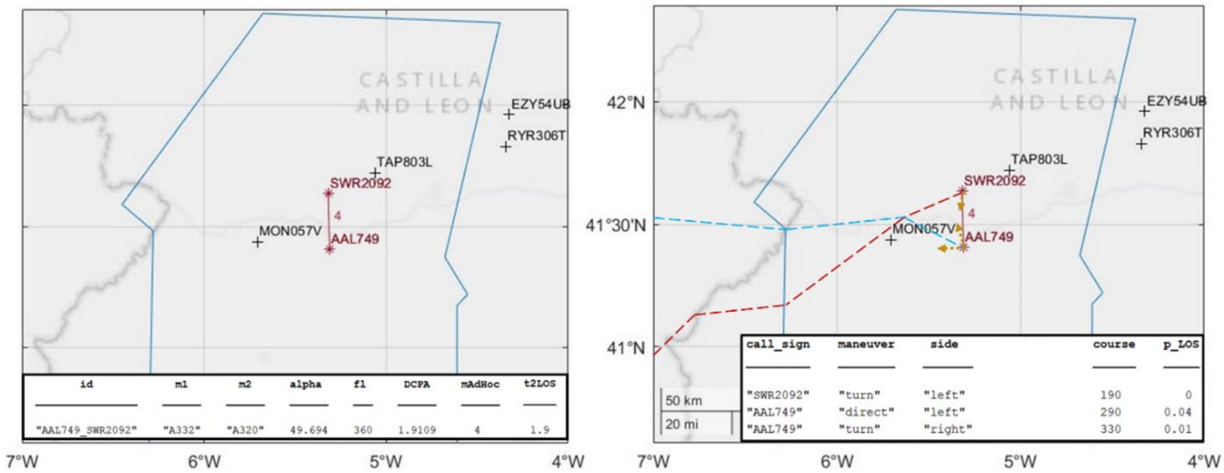


Figure 2. a) Ad Hoc LOS representation b) ATCOs conflict resolution manoeuvres proposal.

5. Conclusions and further work

New aircraft separation modes are being proposed with the expectation that they will have a positive impact on airspace capacity. The Ad Hoc separation concept, outlined in this work, allows applying different separation values in the same volume of airspace depending on factors such as aircraft model, weight, or FL, among others. This work provides a high-level overview of the ASMT architecture. The ASMT is an ATC support tool designed to implement Ad Hoc separation in an ENR sector. The tool provides ATCOs with the applicable Ad Hoc separation value and alerts them of Ad Hoc conflict situations, together with a resolution manoeuvre proposal. The Ad Hoc separation between each aircraft pair is determined from a database after having tactically characterised each encounter. Once determined, CD&R tasks are performed, and alerts are presented to the ATCO in real time. The ASMT is composed of different modules: trajectory prediction, SI detection and characterisation, Ad Hoc separation minima determination, CD and CR, which have been developed and tested. Nevertheless, some of them need to be further developed, such as the trajectory prediction module (as the prediction is based on MRU) and the CD and CR modules (only LOS between aircraft in the same FL are detected). The ASMT has been applied in a Spanish ENR sector but could be applied to any other airspace. Simulations in MATLAB® confirm at first sight the feasibility of the ASMT. However, further improvements are needed to meet the required working levels. Areas identified, among others, are: (1) enhance predictions using ML techniques and real data for 4D predictions, (2) ASMT development for 3D Ad Hoc separation and (3) validation of the ASMT from exercises with ATCOs.

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