IDENTIFICATION AND ANALYSIS OF PROXIMATE EVENTS IN HIGH DENSITY ENROUTE AIRSPACES

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Abstract

A 3D Collision Risk Model (CRM) is being developed by EUROCONTROL as a method of assessing the European en-route risk, due to all causes and across all dimensions within the airspace. This model is expected to be able to provide an estimation of the current risk in a suitable metric, providing measurements of the peak risks in terms of time, geographical location or traffic density. For the moment, current activities are focused in the en-route part with view to extend the work in the near future to the terminal area.

The first part of this paper describes a CRM software prototype designed to handle large volumes of flight data in an efficient way with a high level of automation to identify and analyze proximate events.

The second part of the paper presents a new method based on track segmentation to overcome the current limitations of the model.

Finally, both methods are tested and compared using a one-day traffic data sample provided by MADAP (Maastricht Automatic Data Processing and Display System) servers.

Introduction to the 3-D CRM

EUROCONTROL is aiming at developing a Collision Risk Model based on radar data for assessing aircraft to aircraft safety levels due to all causes, across all dimensions within the European airspace and for all phases of flight.

The work to develop the 3D CRM has been accomplished by EUROCONTROL on sequential steps under several contracts since 1999. A summary of the main findings is provided in [1], [2] and [3].

The 3D CRM is aimed at obtaining a quantified risk estimate associated to an airspace volume for a certain time interval. Since aircraft collision are extremely rare events that cannot be estimated by direct observation, alternative occurrences presenting a measurable frequency must be identified. In this context, proximate events are defined as situations where the aircraft involved may evolve towards a collision due to a separation minima infringement.

The 3D CRM improves significantly the scope of the Reich model since it considers crossing routes with evolving traffic, where controllers monitor air traffic with radar surveillance and provide tactical instructions to the aircraft in case of conflict.

Development of a 3D CRM Prototype

A prototype software tool has been developed to perform the 3D CRM tests in an automated way. The prototype, developed under MATLAB©, includes the following functionalities:

- ASTERIX binary files decoding (track and FPL)
- Display and Management of data
- Proximate events detection and classification
- Traffic and proximate events statistics calculation
- Detailed analysis of proximate events

The CRM software prototype has been designed to handle large volumes of flight data in an efficient way with a high level of automation. At the same time, a set of graphical interfaces allows friendly user interaction. Visual capability has been included to the exploitation of final and intermediate results. A brief description of each module is provided below.

Pre-Processing

Radar and flight plan data, provided as binary text files, are composed of many different data items that may contain errors. Therefore, various pre-processing steps are necessary to filter and prepare the data for further uses.

Pre-processing main functions comprise the decoding of track and flight plan binary files, as well as the storage and organisation of the required information into text files. It also provides data display capability and the definition of all the parameters necessary for the execution of the 3-D CRM algorithms.

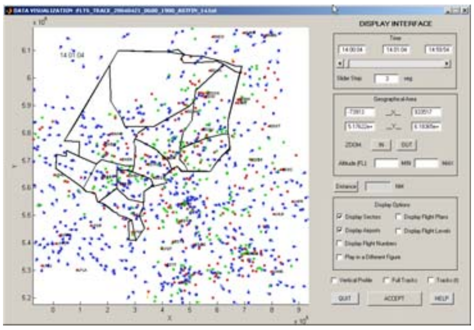


Figure 1. Data Visualization Interface

CRM Execution

The CRM execution module contains the algorithms used to detect proximate events and to perform traffic measurements.

In order to detect proximate events, the software tool reproduces the traffic evolution following a time step pattern. As aircraft move, internal calculations are made to determine relative distances and position estimations in the look-ahead horizon (projected positions are calculated every 15 seconds until reaching the maximum look-ahead time). In case of violation of the separation thresholds, actual or potential, aircraft tracks and flight plans are stored to allow further analysis. Figure 2 represents the prototype tool processes. This approach will be referred from now on as 'classic method'.

After completing the execution, this module allows for a quick access to a summary of the results. The interface also shows the tracks of the selected aircraft pairs, indicating the position of each aircraft at the starting time and their evolution in time. Additionally, the position of the aircraft in the Closest Point of Approach (CPA) is displayed, the time of the event, the horizontal and vertical distance and the look-ahead time.

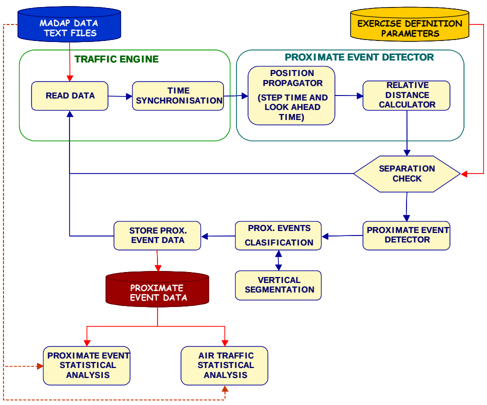


Figure 2. CRM Execution Processes

Classification of Proximate Events

The tool classifies automatically all the events depending on their nature, traffic type, vertical regime, relative heading and intervention criteria (see Figure 3). This information will be essential to carry on the statistical analysis of the proximate events.

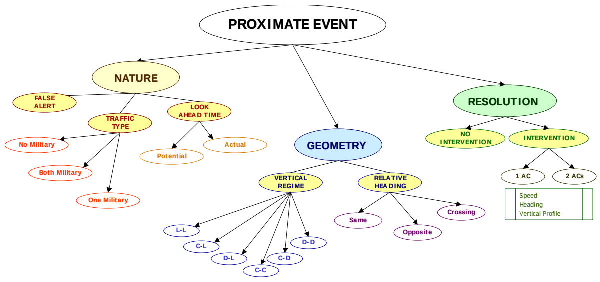


Figure 3. Proximate Events Classification

The first criterion sorts the proximate events according to their nature. Actual events are situations that have actually happened. A potential event takes place when two aircraft on converging tracks are predicted to violate separation minima within a look-ahead time. Potential events are identified projecting in the future the aircraft position by means of extrapolation techniques.

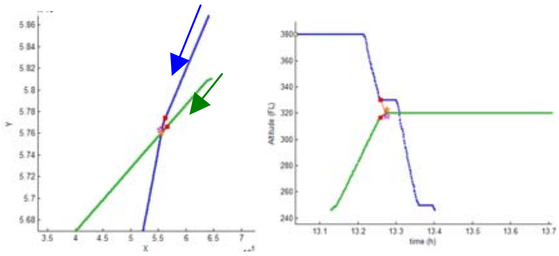


Figure 4. Example of Potential Proximate Event (Look Ahead Time = 60 s)

The traffic type applies to the air traffic rules followed by the aircraft; operational or GAT. The third and fourth criterions describe the geometry of the event. Regarding the fourth criterion, aircraft are considered to be on crossing tracks when relative headings are between 5 and 175 degrees or between 185 and 355 degrees.

The intervention criterion identifies the measure employed to restore separation.

Post Processing

Post processing provides in-depth capability to assess individual proximate events as well as general statistics and graphics. It is composed of three main functionalities:

- Proximate events display according to their classification
- Production of traffic statistics
- Proximate event statistical analysis.

The traffic statistics interface generates all the relevant statistical information of a selected scenario, including the number of flights, flight time, number of entries and exits, traffic density and the percentage of evolving aircraft.

The proximate event analysis of the CRM 3D tool calculates the frequencies of occurrence of each type of event as classified during the execution phase. The proximate event analysis interface displays several types of graphics.

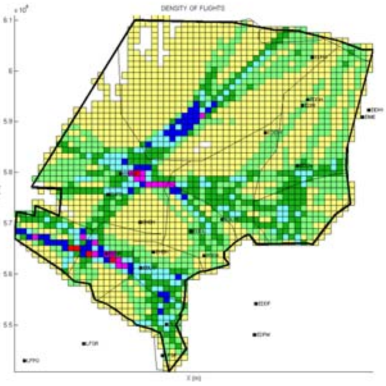


Figure 5. Traffic Density. Maastricht Upper Area (MUAC)

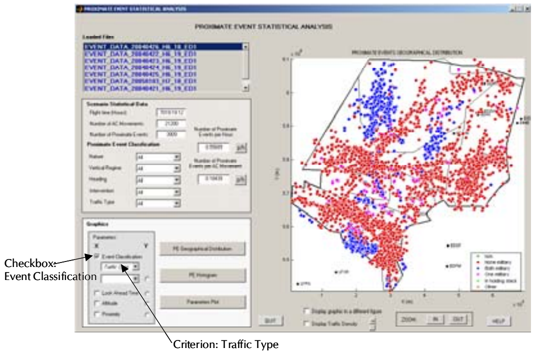


Figure 6. Proximate Events Geographical Distribution

New Approach based on Track Segmentation

This section outlines a new approach that is proposed to overcome the current limitations of the classic method.

Objectives

The use of radar data obtained from the Radar Data Processing (RDP) poses two major problems:

- the large quantity of information held to represent the track followed by each aircraft, and,
- the search for proximate events must be carried out with the use of similar algorithms to those used in STCA, with limited look-ahead time, determining the distance between the actual or potential (projected) position of each aircraft, with the positions of all other aircrafts at that moment.

This poses the need to handle very large information volumes, high execution times and low flexibility in the search and establishment of characteristics of proximate events.

However, at least in the scenarios corresponding to "en route" air spaces, most aircrafts follow a regular behaviour, with "segmented" paths. In other words, the paths are made with an ordered sequence of "straight" sections, with punctual altitude or course changes. In addition, the speed of the aircraft in each segment is mainly uniform.

The purpose of the segmentation is to replace the track of each aircraft, with a series of sections obtained from the RDP, by a line segmented by aircraft, which represents the flight path followed by the aircraft and which is characterised by a sequence of points with defined coordinates, time at which an aircraft passes a specific point and speeds for each segment. The segmented line for the *i*-th aircraft will be defined by the following set (time, position, speed):

$$R_i = \left\{ \begin{array}{l} [t_{i0}, x_{i0}, y_{i0}, h_{i0}, v_{i0}, \dot{h}_{i0}], [t_{i1}, x_{i1}, y_{i1}, h_{i1}, v_{i1}, \dot{h}_{i1}] .. \\ , [t_{in}, x_{in}, y_{in}, h_{in}, v_{in}, \dot{h}_{in}] \end{array} \right\}$$

Equation 1.

The segmentation process must be carried out with an adjustment criterion between both lines that represent the path of the aircraft, the sequence of points given by the RDP and the line that is going to be segmented.

The adjustment criterion followed tries to minimise the number of segments in the line that represent the path of the aircraft, maintaining a maximum error limit at the same time, for the order of positioning errors produced by radar sensors, which consider 10% of the minimum distance regulations established in the scenario (D_{min}). Thus, the segmentation process is carried out to reach the error levels indicated with the following expressions:

$$\left\{ \begin{array}{l} \dfrac{\sum_i |\delta_i| \cdot l_i}{L} \leq 0.05 \cdot D_{\min} \\ \max|\delta_i| \leq 0.1 \cdot D_{\min} \end{array} \right. \quad \textbf{Eq. 2}$$

Where δ_i represents the distance between the *i*-th outline obtained from the RDP and its corresponding segmented outline, l_i is the length between outline *i* and *i*+1 and L is the total length of the path.

Horizontal Track Segmentation

Basically, the segmentation is performed in two steps. First, a statistical characterisation of aircraft performance is derived from the assessment of a large number of tracks. The goal of the statistical analysis is to characterise the mean and the standard deviation of the main parameters (heading and speed) in each phase of the horizontal flight.

By means of a simple logic, it could be possible to identify if the aircraft is flying straight, turning or accelerating / decelerating.

The way to perform such comparison implies the definition of a window containing a number of adjacent plots. This window “slides” through the track while standard deviation and mean of the heading and speed values are calculated at each step. Then, they are compared against the confidence intervals calculated in the statistical analysis.

If the calculated vertical regime of the sliding window is different from the previous state, a fine discriminator will determine which plot inside the window defines the exact limit between both flight segments.

The size of the sliding window is optimised to improve detection performance. If the sliding window is composed of few plots, the estimation of the mean and standard deviation of the flight parameters will be inaccurate and many detected transition limits could be wrong. If the window is too large it will not be able to detect short segments of flight with different attitude (see [6]).

An example of horizontal segmentation is presented in Figures 7, 8, 9 and 10. Figure 7 shows the horizontal track and the segmentation is marked with circles. Figure 8 represents the heading and speed of this aircraft while Figure 9 shows the flight parameter values of the sliding window obtained in each time step. The segmentation of the track is also represented with vertical lines.

Figure 10 shows the longitudinal and lateral errors obtained by comparing the position of the track point and the position of the aircraft provided by the segmentation.

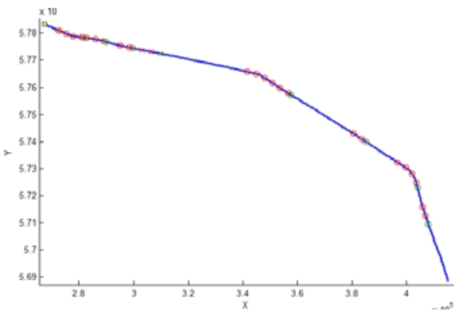


Figure 7. En-route Track. Horizontal plane.

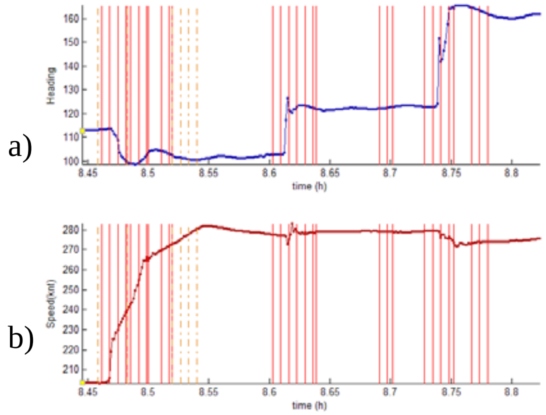


Figure 8. a)Heading vs. Time b)Speed vs. Time

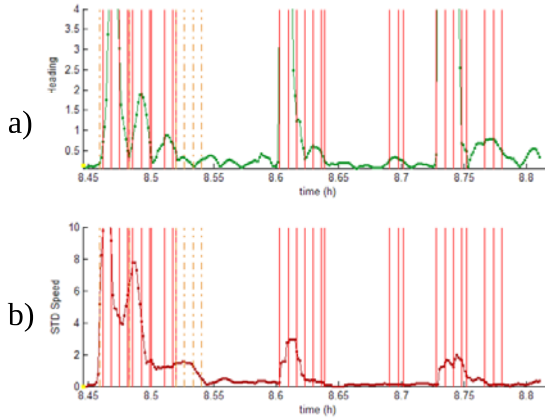


Figure 9. Sliding window values. a)STD Heading b) STD Speed

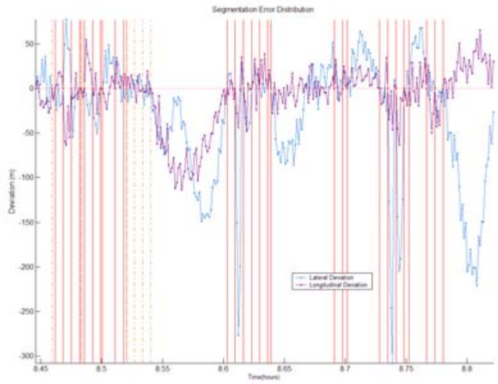


Figure 10. Longitudinal/Lateral and Vertical Deviation

Figure 11 presents the histograms associated to deviations along and across the track. As it can be observed, mean values and standard deviations are low, as well as maximums errors, which for both cases are below 300 meters.

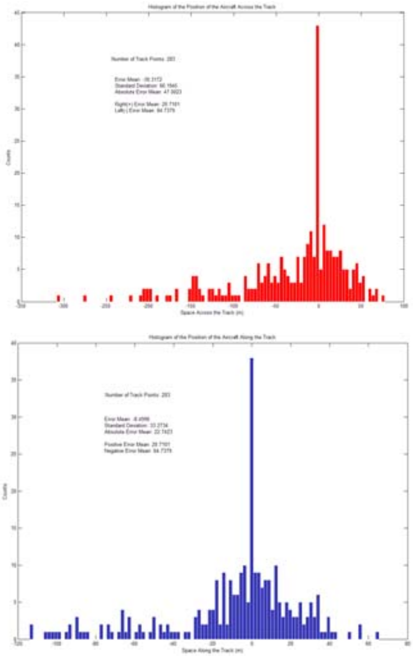


Figure 11. Across / Along Track Deviation Histogram

The previous assessment has been accomplished over a single track. Taking into account than the results may be affected by the nature of that trajectory, an extended analysis has been made on a sample composed of more than six thousands (6281) tracks. Histograms for along and across track maximum errors are shown in Figure 12 and 13. As a general conclusion, it can be stated than longitudinal and lateral deviation maximums are always less than 400m.

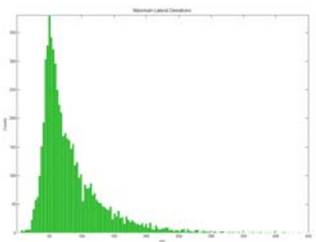


Figure 12. Maximum Lateral Deviation Histogram (6821 tracks)

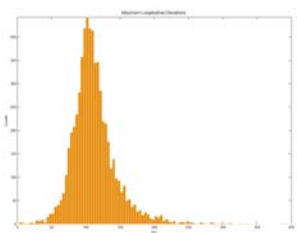


Figure 13. Maximum Lateral Deviation Histogram (6821 tracks)

The segmentation described above is able to reproduce the path of the aircraft maintaining a horizontal maximum error of less than 400 m and using an average 6% of the points from the RDP.

Vertical Track Segmentation

The vertical track segmentation process is very similar to the previously mentioned for the horizontal segmentation. The proposed method is aimed at the identification of vertical manoeuvres (levelled, climbing and descending aircraft) and their associated cinematic parameters, based on available radar data (Mode C and ROCD) (see [6]).

An example of the vertical segmentation track is presented in Figure 14. It shows the altitude and ROCD of an aircraft descending in several steps and the flight parameter values of the sliding window obtained in each time step The trigger thresholds and the calculated vertical transition limit are also represented with black dash lines and vertical lines respectively.

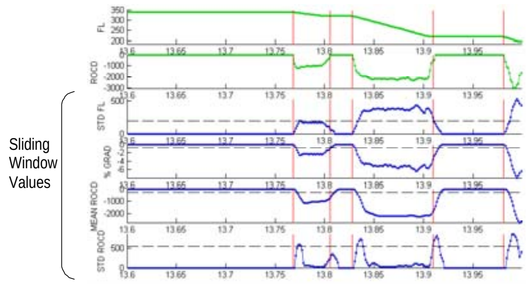


Figure 14. Example of a Vertical Track Segmentation

Identifying Proximate Events

After segmenting the paths of aircrafts in the scenario, two aircrafts will have an actual or potential proximate event when the two following conditions are met at the same time:

- The vertical separation between the segments of the outlines of both aircrafts is lower than or equal to the minimum vertical separation established by H_{min}, and,
- the separation on the horizontal plane between the outlines of the aircrafts is lower than or equal to the minimum distance established by D_{min}.

The following procedure is used to determine the separation between two aircrafts flying in accordance with a uniform movement:

We have two aircrafts *i,j*, characterised by their position on the horizontal and vertical plane on any instant, with the following parameters: positions, on a given instant t_{i0} and t_{j0} respectively, $\vec{r}_{i0}$, $\vec{r}_{j0}$ and h_{i0}, h_{j0} and speeds , considered to be constant, $\vec{v}_i$ and $\vec{v}_j$. Therefore, their position vectors will be:

$$i\begin{cases}\vec{r}_i = \vec{r}_{i0} + \vec{v}_i(t - t_{i0}) \\ h_i = h_{i0} + \dot{h}_{i0}(t - t_{i0})\end{cases} \quad \textbf{Eq. 3}$$

$$j\begin{cases}\vec{r}_j = \vec{r}_{j0} + \vec{v}_j(t - t_{j0}) \\ h_j = h_{j0} + \dot{h}_{j0}(t - t_{j0})\end{cases}$$

Taking *i* as the reference aircraft, the position of *j* will be established at instant $t>t_{j0}$ by:

$$\vec{r}_{ji} = \vec{r}_{j0} - \vec{r}_{i0} + \vec{v}_j(t - t_{j0}) - \vec{v}_i(t - t_{i0})$$

$$h_{ji} = h_{j0} - h_{i0} + \dot{h}_j(t - t_{j0}) - \dot{h}_i(t - t_{i0})$$

Calling $\Delta t_{ji}=t_{j0}-t_{i0}$, where $t_{j0}>t_{i0}$, the previous expressions can be reduced to:

$$\vec{r}_{ji} = \vec{r}_{j0} - \vec{r}_{i0} + (\vec{v}_j - \vec{v}_i)(t - t_{i0}) - \vec{v}_j\Delta t_{ji} = \Delta\vec{r}_{ji} + \vec{v}_{ji}(t - t_{i0}) \quad \textbf{Eq.4}$$

$$h_{ji} = h_{j0} - h_{i0} + (\dot{h}_j - \dot{h}_i)(t - t_{i0}) - \dot{h}_i\Delta t_{ji} = \Delta h_{ji} + \dot{h}_{ji}(t - t_{i0})$$

Where:

$$\Delta\vec{r}_{ji} = \vec{r}_{j0} - \vec{r}_{i0} - \vec{v}_j\Delta t_{ji} \quad \textbf{Eq. 5}$$

$$\Delta h_{ji} = h_{j0} - h_{i0} - \dot{h}_j\Delta t_{ji}$$

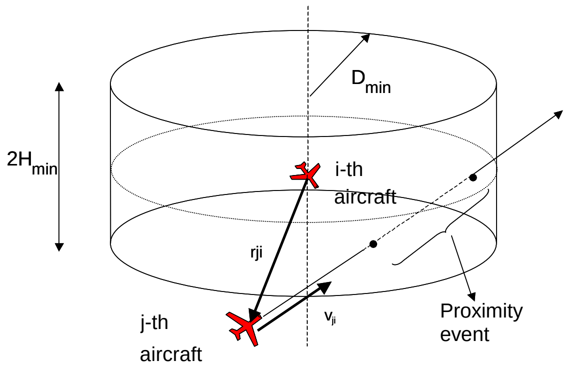


Figure 15. Proximate Events Conditions

The previous figure shows how a proximate event is only possible if the two following conditions are met:

$$\left|h_{ji}\right| \le H_{\min} \quad \textbf{Eq. 6}$$

$$\left|\vec{r}_{ji}\right| \le D_{\min}$$

Analysis of Proximate Events in Vertical Movements

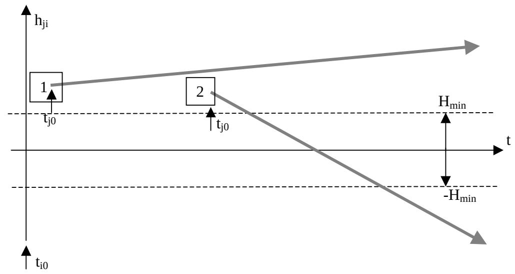
In accordance with the previous expressions, a proximate event is only possible when the two following inequalities are met.

The vertical coordinate h_{ji} can evolve with time to the forms indicated on the following figure. The results are the following:

$$[C.1] \quad \to \begin{cases}\dot{h}_{ji}h_{ji}(t_{j0}) \ge 0 \text{ and } h_{ji}(t_{j0}) \ge H_{\min} \Rightarrow no \\ \dot{h}_{ji}h_{ji}(t_{j0}) \ge 0 \text{ and } h_{ji}(t_{j0}) < H_{\min} \Rightarrow yes\end{cases} \quad \textbf{Eq.7}$$

$$[C.2] \quad \to \dot{h}_{ji}h_{ji}(t_{j0}) < 0 \Rightarrow yes$$

Proximate events are only possible in the conditions marked with "yes".



In case [C.1], when in t_{j0}, $h_{ji}(t_{j0})<H_{min}$, instant t_1 with a difference in heights $h_{ji}(t_1)$ that starts to be greater than H_{min} and the duration Δt_1 of the potential proximate event is obtained with:

$$t_1 = \frac{H_{\min} - \Delta h_{ij}}{\dot{h}_{ji}} + t_{i0} > t_{j0} \quad \textbf{Eq. 8}$$

$$\Delta t_1 = t_1 - t_{j0}$$

In case [C.2], instant t_0 on which the difference in heights between the aircrafts *i* and *j*, h_{ji}, is zero, is obtained with:

$$t_0 = -\frac{\Delta h_{j0}}{\dot{h}_{ji}} + t_{i0} > t_{j0} \quad \textbf{Eq. 9}$$

The period of time around t_0 during which the difference in heights h_{ji} is lower than H_{min}, is obtained with:

$$T_{pe} = \begin{cases}\dfrac{2H_{\min}}{\dot{h}_{ji}} \text{ if } \left|h_{ji}(t_{j0})\right| \ge H_{\min} \\ \dfrac{H_{\min}}{\dot{h}_{ji}} + t_0 - t_{j0} \text{ if } \left|h_{ji}(t_{j0})\right| < H_{\min}\end{cases} \quad \textbf{Eq. 10}$$

The previous set of expressions determine the existence of potential proximate events in the vertical coordinate and the corresponding characteristic times, supposing there is no superior limit of time. A limit t_f for the look-ahead time of the event will determine the modification of the previous values as follows.

In case [C. 1], when t_{j0}, $h_{ji}(t_{j0})<H_{min}$,

$$t_1 = lower\left[\frac{H_{\min} - \Delta h_{ij}}{\dot{h}_{ji}} + t_{i0}, t_f\right] > t_{j0} \quad \textbf{Eq. 11}$$

$$\Delta t_1 = t_1 - t_{j0}$$

In case [C.2], when

$$t_f \le t_0 - \frac{H_{\min}}{\dot{h}_{ji}} \quad \textbf{Eq. 12}$$

there is no proximity event. On the contrary, the potential event will exist in the time interval,

$$T_{pe} = \left[t_0 - \frac{H_{\min}}{\dot{h}_{ji}}, lower\left(t_0 + \frac{H_{\min}}{\dot{h}_{ji}}, t_f\right)\right] \quad \textbf{Eq. 13}$$

Analysis of Proximate Events in Horizontal Movements

A potential proximate event between two path segments for aircrafts *i* and *j*, identified after exploring the evolution of the difference in the vertical coordinate, will become a potential or actual event when, in addition to breaking the vertical separation regulations H_{min}, it simultaneously breaks the horizontal separation regulations D_{min}.

Therefore, the exploration of proximate events will be reduced to those path segments for aircrafts *i* and *j* selected as potential when analysing their vertical evolution.

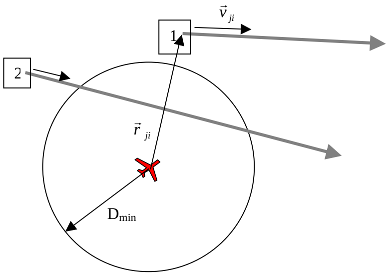


Figure 16. Horizontal movements

Again, the horizontal separation has two different cases, an initial distancing [CH.1] and an initial movement near [CH.2]:

$$[CH.1] \rightarrow \begin{cases} \vec{v}_{ji}\vec{r}_{ji}(t_{j0}) \geq 0 \ \ and \ \ \vec{r}_{ji}(t_{j0}) \geq D_{\min} \Rightarrow no \\ \vec{v}_{ji}\vec{r}_{ji}(t_{j0}) \geq 0 \ \ and \ \ \vec{r}_{ji}(t_{j0}) < D_{\min} \Rightarrow yes \end{cases}$$

$$[CH.2] \rightarrow \begin{cases} \vec{v}_{ji}\vec{r}_{ji}(t_{j0}) < 0 \ and \ \left| \frac{\vec{v}_{ji}}{|\vec{v}_{ji}|} \times \vec{r}_{ji} \right| < D_{\min} \Rightarrow yes \\ \vec{v}_{ji}\vec{r}_{ji}(t_{j0}) < 0 \ and \ \left| \frac{\vec{v}_{ji}}{|\vec{v}_{ji}|} \times \vec{r}_{ji} \right| \geq D_{\min} \Rightarrow no \end{cases}$$

Eq. 14

Only one potential proximate event will exist under the circumstances marked as "yes".

In case [CH.1], where there is a potential proximate event, *i*.e., when $\vec{r}_{ji}(t_{j0}) < D_{\min}$, the time interval in which this situation is produced can be determined as follows.

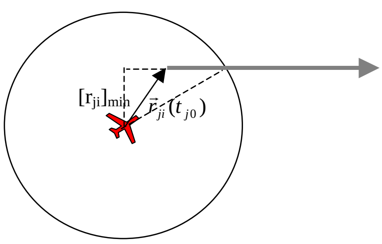


Figure 17. Case H 1.

The minimum distance reached in the former time t_{min}, by aircrafts *i* and *j*, $[r_{min}]$ can be determined with the following expression:

$$[r_{ji}]_{\min} = \left| \vec{r}_{ji}(t_{j0}) \times \frac{\vec{v}_{ji}}{|\vec{v}_{ji}|} \right| \quad \textbf{Eq. 15}$$

Instant $t_{min} < t_{j0}$ can be determined by taking into account the equations for uniform movement:

$$t_{\min} = t_{j0} - \frac{\vec{r}_{j0} \cdot \vec{v}_{ji}}{|\vec{v}_{ji}|^2} \quad \textbf{Eq. 16}$$

With the previous results, we can determine instant t when aircraft *j* is at a minimum separation D_{min} from the aircraft of reference *i*, applying the Pythagoras, as shown on the previous figure. Where:

$$t_1 = t_{\min} + \frac{\sqrt{D^2_{\min} - [r_{ji}]^2_{\min}}}{|v_{ji}|} \quad \textbf{Eq. 17}$$

Therefore, the interval of time in which a proximate event can occur in assumption [CH.1] will be determined by $T_{pe} = [t_{j0}, t_1]$, whereas t_1 will be determined by the previous expression.

In the case of the initial approximation, only the following cases are applicable:

$$[r_{ji}]_{\min} = \left| \vec{r}_{ji}(t_{j0}) \times \frac{\vec{v}_{ji}}{|\vec{v}_{ji}|} \right| < D_{\min} \quad \textbf{Eq. 18}$$

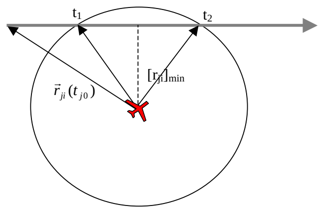


Figure 18. Case H 2

The determination of instants t_1 and t_2 where there is a potential proximity event will follow a similar process to that used to determine the previous equation [Eq.17], in other words:

$$t_1 = t_{\min} - \frac{\sqrt{D^2_{\min} - [r_{ji}]^2_{\min}}}{|v_{ji}|} \qquad t_2 = t_{\min} + \frac{\sqrt{D^2_{\min} - [r_{ji}]^2_{\min}}}{|v_{ji}|} \quad \textbf{Eq. 19}$$

Defining the interval $T_{pe} = [t_1, t_2]$.

Determining Proximate Events Between the track segments of two aircrafts

The separate determination of potential proximate events in vertical and horizontal movement for aircrafts *i* and *j*, flying through their path segments, with a uniform movement, is characterised in the previous sections.

The potential events for both movements must be simultaneous, in order to convert them into actual or potential events.

The time intervals, determined for each type of vertical or horizontal movement, are defined as follows:

$$\lfloor T_{pe} \rfloor_V = [t_{1v}, t_{2v}] \quad \lfloor T_{pe} \rfloor_H = [t_{1H}, t_{2H}] \quad \textbf{Eq. 20}$$

A proximate event will exist when:

$$\lfloor T_{pe} \rfloor_V \cap \lfloor T_{pe} \rfloor_H \neq \phi \quad \textbf{Eq. 21}$$

In this case, the time interval is defined by:

$$T_{pe} = [\max(t_{1v}, t_{1H}), \min(t_{2v}, t_{2H})] = [t_1, t_2] \quad \textbf{Eq.22}$$

The full characterisation of the event will be established by the temporary evolution of the vertical and horizontal movements and, particularly, by the following data:

- Minimum horizontal distance and corresponding instant.
- Minimum difference between heights and corresponding instant.
- Highest approximation point and corresponding instant.
- Geometry of the kinematics of the event.

The minimum distance and corresponding instant are established by expressions [Eq.15] and [Eq.16], respectively. This is where $t_{min} \subset T_{pe}$, otherwise, the time will be $\max(t_{1v}, t_{1H})$ and the corresponding minimum distance between aircrafts will be obtained with expression [Eq.4], obtaining:

$$\lfloor \vec{r}_{ji} \rfloor_{\min} = \Delta\vec{r}_{ji} + \vec{v}_{ji}[\max(t_{1v}, t_{1H}) - t_{i0}] \quad \textbf{Eq. 23}$$

The minimum difference in heights will be zero with instant t_0, determined by expression [Eq.9], which is part of interval T_{pe}. On the contrary, the instant will be $\max(t_{1v}, t_{1H})$ as in the horizontal case and, likewise, the minimum difference in heights will be given by:

$$[h_{ji}]_{\min} = \Delta h_{ji} + \dot{h}_{ji}[\max(t_{1v}, t_{1H}) - t_{i0}] \quad \textbf{Eq. 24}$$

Expressions [Eq.23] and [Eq.24] show situations of proximate events that are going to be eliminated or ruled out, i.e., when the aircrafts start to move away from each other. However, the following information is focused on situations that represent a process where aircrafts move near each other, followed by the process where they move apart. Therefore, these cases will be governed by equations [Eq.4], [Eq.9], [Eq.15] and [Eq.16].

If time is counted from the instant given by equation [Eq.16]

$$t_{\min} = t_{j0} - \frac{\vec{r}_{j0} \cdot \vec{v}_{ji}}{|\vec{v}_{ji}|^2}$$

Then, equations [Eq.4] are converted in the following:

$$\vec{r}_{ji}(t') = \Delta\vec{r}_{ji} + \vec{v}_{ji}(t' - t'_{i0}) \quad h_{ji}(t') = \Delta h_{ji} + \dot{h}_{ji}(t' - t'_{i0}) \quad \textbf{Eq. 25}$$

with

$$t'_{i0} = t_{i0} - t_{\min} \quad \textbf{Eq. 26}$$

The equations [Eq.25] can be reformulated as follows:

$$\vec{r}_{ji}(t') = \vec{r}_{ji}(0) + \vec{v}_{ji}t' \quad h_{ji}(t') = \Delta h_{ji}(0) + \dot{h}_{ji}t' \quad \textbf{Eq. 27}$$

Where:

$$\vec{r}_{ji}(0) = \lfloor \vec{r}_{ji} \rfloor_{\min} \lfloor \hat{v}_{ji} \rfloor_{\perp} \quad \textbf{Eq. 28}$$

Potential and Actual Proximate Events

Each proximate event, identified in accordance with the information in the previous sections, has been determined by the projection of the segments that define the track of an aircraft in an unlimited period of time, as shown in expressions [Eq.3]. However, expression [Eq.1] shows how each segment for aircraft *i* has a duration that is limited by instants t_{ik} and t_{ik+1}. This can be also stated for the segments of aircraft *j*, with segments limited temporarily by t_{jm} and t_{jm+1}, where k and m are the discrete variables that begin at 0 and end with the value corresponding to the number of segments.

With two segments k and m corresponding to the paths for aircrafts *i* and *j*, respectively, we will obtain a actual proximate event between both when the conditions of the following relation are met:

$$t_{ik+1} > t_1 \;\&\; t_{jm+1} > t_1 \quad \textbf{Eq.29}$$

Where t_1 is defined by the previous expression [Eq.22].

There are three different situations in a real proximate event:

Aircraft *i* reacts by modifying its path;

$$t_{ik+1} < t_2 \quad \textbf{Eq.30}$$

Aircraft *j* reacts by modifying its path;

$$t_{jm+1} < t_2 \quad \textbf{Eq.31}$$

There is no reaction by the aircrafts involved;

$$t_{ik+1} \geq t_2 \;\; y \;\; t_{jm+1} \geq t_2 \quad \textbf{Eq.32}$$

Where t_2 is defined by the previous expression [Eq.22].

Obviously, the conditions given by [Eq.30] and [Eq.31] can occur simultaneously and in this case the reaction to the proximate event is produced by both aircrafts.

A potential proximate event occurs when the circumstances that are complementary to those expressed by [Eq.29] occur, i.e., when:

$$t_{ik+1} \leq t_1 \; or \; t_{jm+1} \leq t_1 \quad \textbf{Eq.33}$$

Potential Proximate Events and Look Ahead Time

Potential proximate events are defined as those events that are solved by a modification of the path/s of aircrafts involved before breaking the separation regulations established in the scenario, as stated in expression [Eq.33].

In the method describe above to identify proximate events it is not given a maximum look-ahead time. This consideration can lead to the assessment of situations that do not have sense in a realistic point of view as proximate events. Therefore, we must establish a maximum limit to the time used to explore for proximate events.

The establishment of a limit for the look-ahead time must be done following a criterion that simultaneously satisfies the gathering of all information about potential events, ruling out situations that do not have a meaning in real terms.

The method followed in a short-term conflict alert or STCA in the radar data treatment systems involves the establishment of a fixed look-ahead time (for example, 120 seconds). This option used to establish potential proximate events would rule out corrective actions of the previous tactic event, which, in principle, would not have to be eliminated from the analysis.

The method proposed involves ruling out the potential proximate events that meet any of the following conditions:

The proximate event between segments k and m for aircrafts *i* and *j* is produced out of the scenario analysed, i.e., when the following set is met:

$$t_1 > \min\{t_{ikb}, t_{jmb}\}$$

where t_{ikb} and t_{jmb} are the instant when segments k and m of aircrafts *i* and *j*, respectively, intercept the limits of the scenario; t_1 represents the instant when the proximate event starts, in accordance with expression [Eq.22]. Considering that the scenario is marked by a set of surfaces, which are usually flat, the establishment of the previous instants is reduced to the resolution of searching the intersection between straight lines and planes.

The proximate event between segments k and m for aircrafts *i* and *j* is produced when both aircrafts have abandoned the scenario, i.e., when the following set is met:

$$t_1 > \min\{t_{ik\max}, t_{jm\max}\}$$

where t_{ikmax} and t_{jmmax} are the instants when the aircrafts abandon the scenario. These instants are included between the segmented lines that represent the paths.

Application of Both Methods to a MUAC Data Sample

The classic approach and the segmentation method have been implemented in the 3D CRM prototype and have been compared performing an analysis over a traffic data sample provided by MADAP (Maastricht Automatic Data Processing and Display System) servers. The data sets are composed of radar and flight plan information corresponding to one day (26^{th} April 2004 between the 6:00 and 19:00).

Both analyses give the same information to characterise the traffic behaviour: the number of flights, flightime, number of entries and exits and traffic density.

	Flight Time (hours)	**Aircraft**	**Entries**	**Exits**
26/04/2004	1.119,39	3.241	2.936	3.044

Table 1. Traffic Statistics (26^{th} April 2004)

The classic approach identified around 500 proximate events between General Air Traffic (GAT) aircraft in the traffic sample, 90% were potential conflicts (with a look-ahead time of less than 60 seconds) and 10% actual events. The analysis of GAT proximate events shows that the majority of encounters are passing events, where two aircraft in levelled flight pass each other within a given horizontal distance. For 70% of the cases, both aircraft are flying levelled, and in 95 % of these cases, the vertical separation is very close to 1000 ft.

Proximate events are normally located in the intersection of the main flows of traffic. Only 3% of the encounters involved two aircraft flying in the same direction.

The proximate events identified using the new approach based on the segmentation of the tracks are slightly different. As it can be observed in table 2, the new method detects more actual events.

D min= 5 NM H min= 1000 ft	**Classic Approach**	**Segmentation**
Nº Actual events	45	78
Nº Potential Events (LAT <=60 secs)	454	--

Table 2. Number of Proximate Events

However, only 60% of the actual events identified in the classic method are contained in the list of events obtained with the new method as the segmentation smoothes the small deviations of the vertical profiles of the aircraft. The following figure shows as an example the vertical profiles of two aircraft, which trigger the identification of an event in the classic method when having small vertical deviations simultaneously:

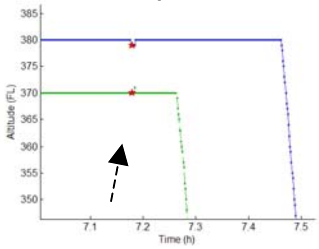


Figure 19. Vertical profile with small Deviations

The new approach identifies more actual events than the classic method due to two different reasons:

- It is possible to detect conflicts with a shorter time interval than the step pattern (e.g. 5 seconds).
- The segmentation introduces small deviations that may induce events when the separation between aircraft are very close to the limits.

Figure 20 shows the geographic location of the events detected with both methods:

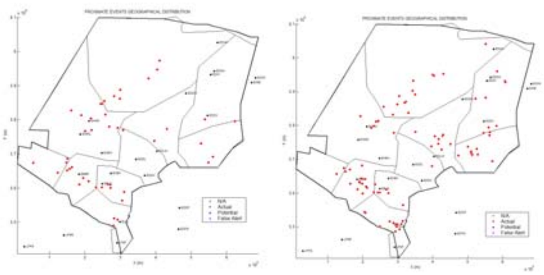


Figure 20. Actual events
a)Classic method b) New Approach

Additional studies will be required to compare the results obtained in the identification of potential events as the new method provides more information about these events. Besides, the identification of the potential events is foreseen to be more accurate using the segmentation as the extrapolation of the positions of the aircraft is done more precisely.

Conclusions

First, this paper has described a software prototype, which aims at processing and analysing radar data in order to identify and classify all the proximate events within an airspace volume and time period. This tool is being developed to contribute to deriving the main statistical components of the 3D CRM of EUROCONTROL.

Then, a new approach based on the track segmentation has been presented to reduce the large information volumes and high times of execution of the classic method and improve the analysis of the scenario.

Finally, a preliminary study has been carried out, using one day of traffic sample, to compare the results obtained with both methods. Further work will be required to assess all the benefits that the segmentation can provide.

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CRM, 3D-separation, risk estimation, safety.

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