HIGH DENSITY EN ROUTE AIRSPACE SAFETY LEVEL AND COLLISION RISK ESTIMATION BASED ON STORED AIRCRAFT TRACKS

(EIWAC 2010)

+E. Garcia*, F. Saez**, R. Arnaldo**
* CRIDA (ATM Research, Development and Innovation Reference Centre)
  Madrid, Spain
  egarcia@crida.es

  **Air Navigation Department
  Universidad Politécnica de Madrid (UPM)
  Madrid, Spain
  franciscojavier.saez@upm.es
  rosamaria.arnaldo@upm.es
CRIDA an Initiative from Aena
(ATM Research, Development and Innovation Reference Centre)

University

Spanish Air Navigation Service Provider

Result Oriented

Scientific Rigour

Flexibility

ineco
Transport Engineering Company
Outline

- INTRODUCTION
- NEED FOR A NEW COLLISION RISK MODEL
- BACKGROUND
- 3D CRM – GOAL
- 3D CRM – GENERAL DESCRIPTION
  - RADAR DATA PROCESSING
  - SAFETY METRICS
- CONCLUSIONS AND WORK IN PROGRESS
INTRODUCTION

EUROCONTROL has worked in the last years to develop the 3-D collision risk model (CRM).

The 3-D collision risk model was developed as a general mathematical framework to assess the level of safety in continental en-route airspace, where controllers monitor air traffic by means of radar surveillance and provide aircraft with tactical instructions.

The objective of the software prototype tool is not only to eventually produce an estimation of the level of safety achieved in the airspace under assessment but also to provide safety-related metrics and trends, which can be monitored over time.
NEED FOR A NEW COLLISION RISK MODEL

Previous models are not appropriate to assess and monitor the level of safety in high density en-route radar airspaces using as a sole source of input data the recorded aircraft trajectories. Traditional approaches to Collision Risk Models (CRM), do not capture the complexity inherent to an operational radar environment like the one in Europe, with high amount of traffic, a large number of crossings tracks, climbing and descending aircrafts and complicated route structure.

<table>
<thead>
<tr>
<th>PHASE</th>
<th>MODELO</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN-ROUTE</td>
<td>Airway structure consisting of one or more parallel routes. No radar surveillance. CRM Reich (1960)</td>
</tr>
<tr>
<td></td>
<td>Improvement of Collision Risk Models                                    CRM Reich (1993)</td>
</tr>
<tr>
<td></td>
<td>Parallel routes. Surveillance base don ADS.                             CRM ADS (1993)</td>
</tr>
<tr>
<td>TMA</td>
<td>Precision approaches                                                   CRM ILS (1980)</td>
</tr>
<tr>
<td></td>
<td>Landing on closely and ultra closely spaced runways                    BRM (1990) MIT (1997)</td>
</tr>
<tr>
<td></td>
<td>Future operational concepts                                            NLR (2001)</td>
</tr>
</tbody>
</table>
BACKGROUND

Nowadays, ANSP and Civil Aviation Authorities (CAA) mainly use ATM accident and incident databases to monitor and provide evidence of levels of safety. However, although these databases are very powerful tools and are improving constantly, they still have some weak points that need to be considered:

• Not all incidents are reported by pilots and air traffic controllers. In fact, it is very difficult to infer how many real incidents have occurred for each one that is reported.
• Incident severity is generally ranked solely on how close aircraft get, without considering the geometry of the event or other parameters, e.g. closure rate.
• Incident Classification is not homogeneous in all databases. Furthermore, special care has to be taken to train database personnel so that the same classification criteria always apply.
BACKGROUND

MANAGEMENT AND ANALYSIS OF INFORMATION

- Airspace information
  E.g. AIS, Capacity, Demand
- Meteo Information
  E.g.: METAR,......
- Aviation accidents and Incidents
- Aviation Maintenance Incident Database
- Airports Data
  E.g.: AIS,....
- ATC Procedures
- Aircraft Performances
  E.g.: BADA,....
- Aircraft trajectories from Simulations
  E.g.: RTS, FTS,....
- Real Aircraft Trajectories
  E.g.: radar data, ADS,....

CRM 3D

ANALYSIS, ASSESSMENT AND MONITORING OF OPERATIONAL SAFETY
A major objective of the 3-D CRM tool is to complement the information collected in the accident and incident databases, thereby providing:

1. Identification of all proximate events based on radar data.
2. Complete classification of all proximate events using clear and consistent criteria.
3. Detailed information on the evolution of each proximate event.
4. Collision risk estimate
3D CRM – GENERAL DESCRIPTION

Airspace Scenario

Traffic Sample

3D CRM Analytical Model

3D CRM Radar Analysis Tool

Safety Event Reports

Safety Level Estimation
3D CRM – GENERAL DESCRIPTION

Airspace Scenario

Radar Data Processing Module

Radar Data Files

Identify Proximate Events

Analyse and Classify Events

Parameter Estimation Module

Probability of Risk

Other Safety Metrics

Segmentation

Coarse Filter
The radar data processing module comprises two different:
• decoding and storage of radar track and flight plan files, and
• track segmentation of radar data.
GOAL -> Identify Proximate Events:

- Conflicts
- Potential Conflicts
- Potential Collisions

Conflicts:
Aircraft physical separation < intended margin (D, H)

Collision:
Aircraft physical separation < aircraft physical sizes
Look-ahead time (LAT): is the time horizon within which all aircraft positions are projected to explore existence of "potential conflicts/collision".

-> 10 minutes
RADAR DATA PROCESSING

MAP of HOT SPOTS
SAFETY METRICS ESTIMATION

- Analysis of Proximate Events
- Classification of Proximate Events
- Detection of Activated Alert Systems
- Identification of ATM System Weaknesses
SAFETY METRICS ESTIMATION
Analysis of Proximate Events

CPA($t_{cpa}$,[$r_{12}]_{cpa}$,[$h_{12}]_{cpa}$)

- $t_{cpa}$: time at CPA
- [$r_{12}]_{cpa}$: horizontal separation at CPA
- [$h_{12}]_{cpa}$: vertical separation at CPA
- [$r_{12}]_{cpa}$<R & [$h_{12}]_{cpa}$<H

- $t_{CI}$: time of identification of potential conflict
SAFETY METRICS ESTIMATION
Analysis of Proximate Events

New CPA*(t*_{cpa}, [r_{12}]_{cpa}, [h_{12}]_{cpa})

Change in the Rate of Climb (ROC)

\[t_{cpa}*: \text{new time at CPA}\]
\[[r_{12}]_{cpa}*: \text{new horizontal separation at CPA}\]
\[[h_{12}]_{cpa}*: \text{new vertical separation at CPA}\]

\[[r_{12}]_{cpa} < R \& [h_{12}]_{cpa} < H\]

\[t_m*: \text{time of manoeuvre}\]
SAFETY METRICS ESTIMATION
Analysis of Proximate Events

- $t_{CI}$: time of initial conflict
- $t_m$: time of conflict resolution manoeuvre
- $t_{CR}$: time of conflict resolution
- $h_{12}^{\text{cpa}}$: vertical separation at CPA
- $h_{12}^{\text{cpa}} > H$

**Climb->Level**

$V_1$ and $V_2$ represent the vertical velocities of the aircraft.
SAFETY METRICS ESTIMATION
Analysis of Proximate Events

- $r_{12}$: actual horizontal separation
- $h_{12}$: actual vertical separation
- $r_{12} < R$ & $h_{12} = H$
- $t_m$: time to entry into conflict volume
SAFETY METRICS ESTIMATION
Classification of Proximate Events

PROXIMATE EVENT

CRITERIA

NATURE
- Passing Event
- Conflict
- Potential Conflict
- Potential Collision
- False Detection

TRAFFIC TYPE
- Civil Traffic
- Both Military Aircraft
- One Military Aircraft

VERTICAL REGIME
- Level-Level (LL)
- Climb-Level (CL)
- Descend-Level (DL)
- Climb-Climb (CC)
- Climb-Descend (CD)
- Descend-Descend (DD)

RELATIVE HEADING
- Same
- Opposite
- Crossing

A/C REACTION
- Change Vertical Profile
- Modify Heading
- Change of Speed
- No Reaction

ACTIVATED ALERT SYSTEM
- TCAS RA
- TCAS TA
- STCA
- No Alert

Classification of Proximate Events
SAFETY METRICS ESTIMATION
Detection of Activated Alert Systems

- Overall Reaction Time ($t_1$)
  - Identification of potential conflict ($t_{CI}$)
  - Start of a conflict resolution manoeuvre ($t_{CR}$)

- Time to Conflict ($t_2$)
  - Predicted time of entry into conflict volume ($t_{CF}$)
  - Predicted time of CPA ($t_{CPA}$)

- Time to go to CPA ($t_3$)
  - Horizontal separation at CPA ($[r_{12}]_{CPA}$)

$t_1 = t_{CR} - t_{CI}$
$t_2 = t_{CF} - t_{CI}$
$t_3 = t_{CPA} - t_{CI}$

$t_{CI}$: identification of potential conflict
$t_{CR}$: start of a conflict resolution manoeuvre
$t_{CF}$: predicted time of entry into conflict volume
$t_{CPA}$: predicted time of CPA
$[r_{12}]_{CPA}$: horizontal separation at CPA

---

Predicted trajectory

---

Detection of Activated Alert Systems
SAFETY METRICS ESTIMATION
Detection of Activated Alert Systems

TIME TO CPA

<table>
<thead>
<tr>
<th>STRATEGIC</th>
<th>TACTICAL</th>
<th>TACTICAL</th>
<th>TCAS TA</th>
<th>TCAS RA</th>
</tr>
</thead>
</table>
| Potential Collision

Potential Collision

<table>
<thead>
<tr>
<th>STRATEGIC</th>
<th>TACTICAL</th>
<th>TACTICAL</th>
<th>TCAS TA</th>
<th>TCAS RA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>4 mins</td>
<td>2 mins</td>
<td>48 sec</td>
<td>35 sec</td>
</tr>
</tbody>
</table>

Detection of Activated Alert Systems

- No P(Pre-Tactical Failure)\(\text{Yes}\)
- No P(Tactical Failure)\(\text{Yes}\)
- No P(STCA Failure)\(\text{Yes}\)
- No P(TCASTA Failure)\(\text{Yes}\)
- No P(TCAS RA Failure)\(\text{Yes}\)

Loss of Separation?

- No loss of Sep.
- Loss of Separation
- Collision
SAFETY METRICS ESTIMATION
Detection of Activated Alert Systems

- Vertical Closure Rate (fpm)
  - Strategic ATC Action (STCA)
  - Tactical ATC Action (TA)
  - Traffic Advisory (RA)
  - Resolution Advisory (RA)

- Vertical Separation (feet)
  - H: 850, 600
SAFETY METRICS ESTIMATION
Detection of Activated Alert Systems

HORIZONTAL PLANE

VERTICAL PLANE

Time (h)

Altitude (FL)

0.0 fpm
1875.0 fpm

RA

0.0 fpm
1875.0 fpm

RA

204.0 kts
### Proximate Event Data: AC 1 - AC 2

<table>
<thead>
<tr>
<th>Tm</th>
<th>$[r_{12}]_{cpa}$ (NM)</th>
<th>$[h_{12}]_{cpa}$ (ft)</th>
<th>TTC (min)</th>
<th>Dur (min)</th>
<th>TCPA rel (min)</th>
<th>Manoeuvre AC1</th>
<th>Manoeuvre AC2</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>0.66</td>
<td>-0.00</td>
<td>5.99</td>
<td>1.67</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.42</td>
<td>00.00</td>
<td>-5.12</td>
<td>-0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>0.24</td>
<td>0.00</td>
<td>0.86</td>
<td>5.12</td>
<td>-0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>-0.00</td>
<td>-0.40</td>
<td>-0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>0.25</td>
<td>0.00</td>
<td>0.46</td>
<td>0.40</td>
<td>-0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.11</td>
<td>1000.00</td>
<td>-0.23</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>0.36</td>
<td>1000.00</td>
<td>0.22</td>
<td>0.24</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.01</td>
<td>00.00</td>
<td>-0.22</td>
<td>-0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>0.34</td>
<td>1000.00</td>
<td>0.00</td>
<td>0.48</td>
<td>-0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.44</td>
<td>-0.00</td>
<td>0.00</td>
<td>0.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>2.79</td>
<td>1000.00</td>
<td>0.00</td>
<td>0.80</td>
<td>0.26</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend**
- >Conv(85º)<
- AC1 Turn ; >>
- TCAS RA
- CL → FL
- AC2 CL → FL ; ↑ VER SEP; >Conv(88º)<
- CONFLICT RESOLVED- VERTICAL PLANE
- >Conv(93º)<
- MIN REAL SEP: 0.3 NM 1000 ft
- <Div(99º)>
As an example, this figure represents in the TCAS and STCA diagram the evolution of the encounter described before. A TCAS RA is activated if the kinetic and geometric characteristics of the event in the horizontal plane and in the vertical plane are in the red area at the same time.
SAFETY METRICS ESTIMATION
Identification of ATM System Weaknesses

<table>
<thead>
<tr>
<th>Risk Context</th>
<th>Qualification of Hazards</th>
<th>Effectiveness of Safety Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiating events leading to potential collisions</td>
<td>Detection / Resolution of potential collisions</td>
<td>ATCO  STCA  TCAS  ...</td>
</tr>
</tbody>
</table>

Traffic Density

Traffic complexity

ATC/Pilot Errors

Technical Failures

HAZARD
(potential collision)

No Safety Effect
Conflict
Collision
### SAFETY METRICS ESTIMATION
Identification of ATM System Weaknesses

<table>
<thead>
<tr>
<th>Risk Context (within selected area/time-frame)</th>
<th>Qualification of Hazards</th>
<th>Effectiveness of Safety Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight-Time</td>
<td>Hot Spots</td>
<td>Number of Real Conflicts</td>
</tr>
<tr>
<td>Number of Movements</td>
<td></td>
<td>Overall Reaction Time</td>
</tr>
<tr>
<td>Kinematics (Speed, Type of Aircraft)</td>
<td>Classification of Proximate Events:</td>
<td>Time Margin</td>
</tr>
<tr>
<td>Nº of Entries and Exits</td>
<td>• Nature</td>
<td>Time to Conflict</td>
</tr>
<tr>
<td>Route structure</td>
<td>• Traffic Type</td>
<td>Time-to-go to the CPA</td>
</tr>
<tr>
<td>Traffic Density</td>
<td>• Vertical regime</td>
<td>% of Potential Conflicts solved in:</td>
</tr>
<tr>
<td></td>
<td>• Relative heading</td>
<td>• vertical plane</td>
</tr>
<tr>
<td></td>
<td>• A/C Reaction</td>
<td>• horizontal plane</td>
</tr>
<tr>
<td>Number of Routes</td>
<td>Activated Alert System (TCAS, STCA)</td>
<td></td>
</tr>
<tr>
<td>% Evolving (non-level) Aircraft</td>
<td>Correlation between Hot Spots and Traffic Density Maps.</td>
<td>Average Nº of Aircraft “near” a Proximate Event</td>
</tr>
<tr>
<td>Separation Rules</td>
<td>Nº of potential collisions</td>
<td></td>
</tr>
</tbody>
</table>
SAFETY METRICS ESTIMATION
Identification of ATM System Weaknesses

Risk Context (within selected area/time-frame)

Descending 6%
SAFETY METRICS ESTIMATION

Qualification of Hazards

Total Number of Proximate Events: 45389
CIVIL TRAFFIC 91.2%
MILITARY TRAFFIC 3.2%
CIVIL-MILITARY TRAFFIC 5.6%

POTENTIAL CONFLICT 84.86%
ACTUAL CONFLICT 0.08%
FALSE DETECTION 14.59%
PASSING EVENT 0.46%

Total Number of Proximate Events: 35166
LEVEL-LEVEL 13.8%
LEVEL-CLIMB 59.6%
LEVEL-DESCENT 7.1%
CLIMB-CLIMB 11.9%
CLIMB-DESCENT 6.4%
DESCENT-DESCENT 1.2%

TCAS RA
SAFETY METRICS ESTIMATION

Effectiveness of Safety Barriers

- ATC STRATEGY 69.6%
- STCA 28.0%
- TCAS TA 2.1%
- TCAS RA 0.3%

Overall Reaction Time (t1)

Time-to-go to CPA (t3)
CONCLUSIONS

The 3-D CRM tool has been designed to complement the information collected in the accident and incident databases, thereby providing the following information inferred from the in depth assessment of proximate events:

- Identification of all proximate events based on radar data.
- Complete classification of all proximate events using clear and consistent criteria.
- Detailed information on the evolution of each proximate event.
- Safety metrics and other air traffic factors
WORK IN PROGRESS

• Apply the 3-D CRM too to traffic samples of different airspaces and extend the principles of 3-D CRM from en-route to Terminal Manoeuvring Area (TMA) scenarios;

• Develop a methodology to provide a complete risk picture of the scenario, identifying the ATM system weakness and characterizing the performance of the safety barriers, using all the information provided by the 3-D CRM tool that could be used by ATM service providers to monitor and improve safety levels in their operation;

• Complete an analytical model based on the 3-D CRM tool to provide true collision risk values.
Questions