Traffic and Collision Avoidance System (TCAS) Tutorial

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Topics

- TCAS II Details Overview
- Ueberlingen Collision
- Sense Reversal logic
- Adjust Vertical Speed Adjust
- TCAS II Version 7.1 – US and Europe
- Hybrid Surveillance
At the end of this presentation you will have a deeper understanding of

- How TCAS II works,
- What problems have been identified how they are being fixed
- What future changes that are coming
- Some knowledge of the Military specific variants of TCAS II
TCAS II Overview - Timeline

TCAS Mandate
- (US) 1980
- (Worldwide) 2000

Timeline:
- 1975
- 1980
- 1985
- 1990
- 1995
- 2000
- 2005
- 2007

Public Laws:
- 100-223
- 101-236
- TCAS Mandate
- (US) 1980
- (Worldwide) 2000

TCAS Mandate
- (US) 1980
- (Worldwide) 2000

SICASP
- ICAO Panel - SSR Improvements and Collision Avoidance Systems Panel

SCRSP
- ICAO Panel - Surveillance and Conflict Resolution Systems Panel

ASP
- ICAO Panel – Aeronautical Surveillance Panel

BCAS - Beacon Collision Avoidance System

TCAS – Traffic and Collision Avoidance System

RTCA
- SC-147
- 6.04A
- Version 7
- Reversal, Hybrid, AVSA

ICAO
- SICASP
- SCRSP
- ASP

LIP
- Limited Installation Program
  - Allied Signal / UAL
  - Honeywell / NWA

SC-147 in hiatus
TCAS oversight moves from AND to AIR

Reversal, Hybrid, AVSA

RTCA SC-147 6.04A Version 7 Reversal, Hybrid, AVSA
TCAS II – General Architecture

- Directional Antenna – Top and optional omnidirectional or directional on bottom
- Radar Altimeter – Used to reduce Operation as the ground is approached
- Pressure Altitude – To transponder with highest precision available.
- Note that TCAS own altitude comes through the transponder.
- Control Panel
- Aural Annunciation
- Resolution Advisory (RA) and Traffic Advisories (TA) displays
What TCAS II Uses

- Identification of the aircraft in the area.
  - Mode S Address if available
- Altitude and Address of own aircraft
  - From own transponder
- Range to the intruder and Altitude
  - From interrogation of the intruder (Mode C or UF=0/16 interrogation replies)
- Equipage of the intruder (TCAS or not)
  - Coordination with the intruder if TCAS equipped
TCAS II – ATCRBS Intruders

- TCAS interrogates (1030 MHz) around 360° with Mode C (altitude) ATCRBS-only All-Call (only ATCRBS aircraft reply – not Mode S equipped aircraft)

- A track is developed on the aircraft in the TCAS processor (based on interrogation replies)

- RAs and TAs are developed per the logic

- RAs are downlinked to the ground Mode S sensor
TCAS II – Mode S Intruders

- TCAS acquires the 24-bit aircraft address (Address Announced – AA) from the Acquisition Squitter or from replies to ground interrogations.

- A track is developed on the aircraft in the TCAS processor (based on interrogation replies to UF=0 or DF=16)

- RAs and TAs are developed per the logic

- RAs are coordinated with the intruder if it is also TCAS II equipped.

- RAs are downlinked to the ground Mode S sensor
Resolution Advisories (RAs) and Traffic Advisories (TAs)

- Use Range to the intruder and the rate of change of that range to determine the time to Closest Point of Approach (CPA).

- Use intruder track to estimate vertical separation at CPA

- A TA is generally developed before an RA
RA and TA criteria

<table>
<thead>
<tr>
<th>Own Altitude (feet)</th>
<th>SL</th>
<th>Tau (Seconds)</th>
<th>DMOD (nmi)</th>
<th>Altitude Threshold (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TA</td>
<td>RA</td>
<td>TA</td>
</tr>
<tr>
<td>&lt; 1000</td>
<td>2</td>
<td>20</td>
<td>N/A</td>
<td>0.30</td>
</tr>
<tr>
<td>1000 - 2350</td>
<td>3</td>
<td>25</td>
<td>15</td>
<td>0.33</td>
</tr>
<tr>
<td>2350 - 5000</td>
<td>4</td>
<td>30</td>
<td>20</td>
<td>0.48</td>
</tr>
<tr>
<td>5000 - 10000</td>
<td>5</td>
<td>40</td>
<td>25</td>
<td>0.75</td>
</tr>
<tr>
<td>10000 - 20000</td>
<td>6</td>
<td>45</td>
<td>30</td>
<td>1.00</td>
</tr>
<tr>
<td>20000 - 42000</td>
<td>7</td>
<td>48</td>
<td>35</td>
<td>1.30</td>
</tr>
<tr>
<td>&gt; 42000</td>
<td>7</td>
<td>48</td>
<td>35</td>
<td>1.30</td>
</tr>
</tbody>
</table>

SL – Sensitivity level
Tau – Time to Closest Point of Approach (CPA) in seconds
DMOD – Distance MODification – range to intruder modified to improve RA and TA performance
In a TCAS/TCAS encounter, each aircraft transmits interrogations to the other via the Mode S link to ensure the selection of complementary RAs by the two aircraft.

The coordination interrogations use the same 1030/1090 MHz channels used for surveillance interrogations and replies and are transmitted once per second by each aircraft for the duration of the RA.

Coordination interrogations contain information about an aircraft’s intended RA sense to resolve the encounter with the other TCAS-equipped intruder.
Version 7 has the ability to issue RA reversals in coordinated encounters.

The aircraft with the low Mode S address can reverse the sense of its initial RA and communicate this to the intruder. The intruder will then reverse its displayed RA.

Only one RA reversal can be issued.

The initial RA sense will not be reversed until it has been displayed for at least nine seconds (unless the low Mode S address aircraft has a vertical rate higher than 2500 feet per minute and acts contrary to the RA).
Ueberlingen Collision
Ueberlingen 1 July 2002

Source: Aviation Week,  
July 8, 2002, page 42  
July 15, 2002, page 33
Fly through
Revised Sense Reversal Logic

Either Aircraft can initiate a sense reversal
Concerns with TCAS RA reversal logic were raised in mid-1990s during Version 7 safety assessments
- Exposure to problems in actual operations was not known
- TCAS development ended before concerns were resolved

Japanese near miss (2001) and Überlingen mid-air collision (2002) brought focus to the vulnerability
- Common thread: “vertical chase” where RA reversals were not triggered when they should have been

Europeans proposed a logic change (CP112E) to improve reliability of RA reversals

2004: RTCA SC-147 tasked to assess exposure to risk in US airspace and evaluate CP112E
SA01 Characteristics

SA01a: TCAS – TCAS
One aircraft does not follow its RA
Vertical chase ensues
No RA reversal occurs to save aircraft that is following its RA

“Climb, Climb”

SA01b: TCAS – unequipped aircraft
Vertical chase ensues
No RA reversal occurs to save aircraft that is following its RA

Unexpected maneuver

“Descend, Descend”
- SA01 difficult to detect unless critical incident / accident occurs or focused monitoring is conducted
- European airspace estimates
  - SA01a events occur at $\sim 4.7 \times 10^{-6}$ per flight-hour = 58 events per year in Europe
  - Expect 1 mid-air collision due to SA01a every 4 years in Europe
- Initial US estimate based on Lincoln Lab monitoring of Boston airspace
  - Reversal problems occur at a rate comparable to Europe
TCAS Monitoring Facility

Mode S Sensor

Surveillance Data (ASTERIX format)

Data Recording Computer

Comm Data (RA Reports)

Analysis Software

Statistics
- e.g., RA number, type, location, version

Pilot Response
- Proper
- Partial
- Opposite

Filtering
- Filter for close ("ALIM") encounters, reversals

Playback
- Playback radar data through selected TCAS logic version: 6.04A, 7, CP112E

Encounter Model Development

Encounter Plots

Manually examine plots for safety issues

RA Reports
RA Events Monitoring

1 Nov 2004 – 31 May 2005

> 1500 RAs
Mean: 9 RAs per day
Peak: 28 RAs in one day
April 2005 Encounter in Boston Airspace

- Red: TCAS aircraft
- Blue: Intruder (without TCAS)
Earlier reversal would have improved separation

Minimum separation:
- 100 ft vertical
- 1900 ft slant range

TCAS Aircraft

Intruder (without TCAS)

Altitude (ft)

2500
2400
2300
2200
2100
2000

Time from closest point of approach (s)

-20 -15 -10 -5 0 +5 +10 +15 +20 +25

Descend RA

Reversal: Climb RA
Lincoln Laboratory TCAS Simulation

Airspace encounter model

Radar data

Filter

Encounter model distributions

Simulation

TCAS

Pilot response model

Aircraft dynamic model

Metrics

Vertical separation

Risk with TCAS

Risk without TCAS

Years between collisions

Random samples

Variable equipage, TCAS logic, sensor noise, pilot response, aircraft dynamics
Estimated Years Between Mid-Air Collisions in European Airspace
• SC-147 - SA01 to be a significant safety issue
  • Potential for 1 collision every 4 years in Europe
  • Not unique to Europe

• SC-147 Safety Report recommends that:
  (1) FAA and international authorities commence work towards regulatory action that would expedite implementation of the revised logic…
      Regulatory measures could include Airworthiness Directives, requirements to enhance pilot and controller training, and mandatory equipage of the change by specific dates…
  (2) RTCA proceed with a revision to TCAS MOPS based on CP112E
  (3) Airspace monitoring be expanded
  (4) Expertise and tools for TCAS technical analysis be sustained
## Risk Ratios for TCAS-TCAS Encounters, U.S. Encounter Model

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Altitude Quantization</th>
<th>Version 7 – Version 7</th>
<th>Version 7 – CP112 E</th>
<th>CP112E – CP112 E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both aircraft follow RAs</td>
<td>25</td>
<td>.02319*</td>
<td>.02320</td>
<td>.02334</td>
</tr>
<tr>
<td>One aircraft does not follow its RAs</td>
<td>25</td>
<td>.0903</td>
<td>.0884</td>
<td>.0766</td>
</tr>
<tr>
<td>Both aircraft follow RAs</td>
<td>100</td>
<td>.02293</td>
<td>.02288</td>
<td>.02322</td>
</tr>
<tr>
<td>One aircraft does not follow its RAs</td>
<td>100</td>
<td>.09666</td>
<td>.09436</td>
<td>.08132</td>
</tr>
<tr>
<td>Both aircraft follow RAs, one with slow response</td>
<td>25</td>
<td>.0412</td>
<td>.0411</td>
<td>.0389</td>
</tr>
<tr>
<td>One aircraft does not follow RAs, the second does with slow response</td>
<td>25</td>
<td>.3191</td>
<td>.3118</td>
<td>.3014</td>
</tr>
<tr>
<td>Both aircraft follow RAs, one with slow response</td>
<td>100</td>
<td>.0420</td>
<td>.0418</td>
<td>.0415</td>
</tr>
<tr>
<td>One aircraft does not follow RAs, the second does with slow response</td>
<td>100</td>
<td>.3249</td>
<td>.3279</td>
<td>.3076</td>
</tr>
</tbody>
</table>

* Risk Ration – lower is safer
What does the Mean?

Take the case with 25 foot vertical resolution and one aircraft does not follow the resolution – Near Miss Probability reduced to

- V7 to V7: 9.03%
- V7 to new: 8.84%
  - improvement proportion 2.1%
- New to new: 7.66% of
  - Improvement proportion 15.1%
Adjust Vertical Speed Adjust
Monitoring of TCAS performance has identified instances where flight crews respond in the opposite direction to that specified by TCAS when a negative resolution advisory (RA) is displayed and announced to the flight crews:

- Negative RAs are those that require a reduction in an existing vertical speed.
- These RAs are accompanied by an aural annunciation of ‘Adjust Vertical Speed, Adjust’ (AVSA).

Probability of AVSA occurrence (European Estimate) = $3.82 \times 10^{-6}$ per flight hour (15 opposite reactions in France in 2004 & 2005 leading to altitude busts):

- Probability of collision given that an AVSA event has occurred = $1.41 \times 10^{-3}$ (5.4 collisions per 109 flight hours – equivalent to a collision every 15 years in Europe).
TCAS – AVSA Continued

- AVSA issue & proposed European fix requires additional U.S. operational analysis – currently not funded

- European Aviation Safety Agency (EASA) letter to RTCA (09/22/06)
  - Formally requests that RTCA “actively investigate a possible modification of the ‘Adjust Vertical Speed, Adjust’ aural annunciation”
  - Formal change proposal (CP115) submitted to SC-147 at Oct 2006 Plenary – specifically addresses a fix for the aural annunciation “Adjust Vertical Speed, Adjust”
  - Follow-up analysis presented at Feb 2007 Plenary indicates not just European problem
Scope of AVSA Change

- Aural
  - “Level Off, Level Off" vs. "Adjust Vertical Speed, Adjust"

- Logic
  - Collapse 4 possible vertical speed reductions to 1: a true level-off of 0 feet-per-minute
TCAS II V 7.1 - FAA & Eurocontrol

- Agreement on Sense Reversal logic need
  - Disagree on Urgency – Eurocontrol wants it done by 2010, FAA date is much later.

- Eurocontrol is clear that AVSA needs correction.
  - FAA is not certain that it is necessary – operational testing will be needed

- Uncertainties
  - What will Version 7.1 include?
  - When will Version 7.1 be required?
Hybrid Surveillance
What is Hybrid Surveillance?

It is a surveillance technique that
- Enables TCAS to reduce its active interrogation rate by using position information received passively via ADS-B
- Modifies the basic surveillance logic inside the TCAS unit

It is NOT a display technique for combining ADS-B and TCAS outputs on a cockpit display

<table>
<thead>
<tr>
<th>Control (8 bits)</th>
<th>Mode S Address (24 bits)</th>
<th>GPS Position (56 bits)</th>
<th>Parity (24 bits)</th>
</tr>
</thead>
<tbody>
<tr>
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Mode S Extended Squitter

ADS-B data received via hybrid surveillance is not passed to the CAS logic
TCAS Hybrid Surveillance
Why is it needed?

Interference Limiting algorithms were developed to keep TCAS utilization of transponders < 2%
How does it work?

Passive surveillance (ADS-B Only)

Validate intruder position using TCAS active interrogation. If it matches, continue to track passively.

1.0 Hz Active TCAS Interrogation (intruder is a near threat in altitude and range)

0.1 Hz Active TCAS Interrogation (intruder is a near threat in altitude or range)

Resolution Advisory

Traffic Advisory

Passive surveillance (ADS-B Only)
How do we proceed?

- Minimum Operational Performance Standards (MOPS) have been developed to ensure consistent requirements and implementation:
  - Hybrid surveillance will migrate to civil TCAS systems
  - Military TCAS systems need to demonstrate proper operation for access to civil airspace, nationally and internationally
  - FAA needs MOPS in order to certify Hybrid Surveillance systems
- The three TCAS manufacturers are pursuing Hybrid surveillance and ADS-B applications
Military Variants

- **Honeywell**
  - E-TCAS (Enhanced TCAS) on C/KC-135, KC-10, C-130, HC-130 P/N
    - Used for Refueling and Formation flight
    - Some restrictions on use over US, UK, and Germany
  - MILACAS FR on C-17
    - Used for Formation flight
    - On path for full International approval for use
    - First formal use of Mode S UL=19 and DL=19 (formats set aside by ICAO for Military use)

- **ACSS has some products in development**
  - Military Airborne Surveillance System (MASS)
    - Used by Formation Flying – used on the Italian military B767