National Aeronautics and Space Administration

Ensuring Interoperability between Unmanned Aircraft Detect-and-Avoid and Manned Aircraft Collision Avoidance

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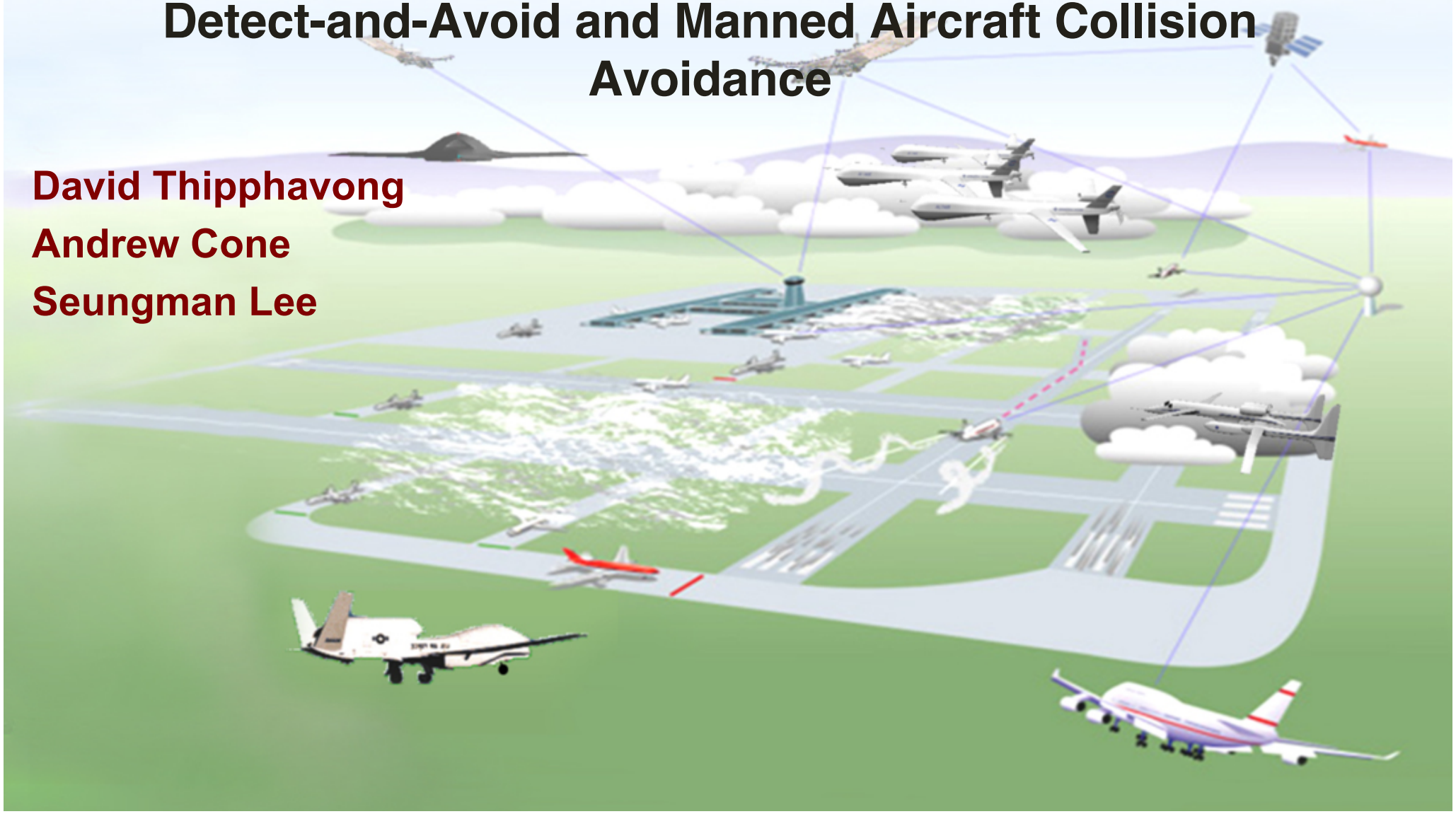


Introduction

- RTCA Special Committee-228 is in charge of developing standards for Detect-and-Avoid (DAA) for Unmanned Aircraft Systems (UAS) in the United States

- UAS DAA systems enable UAS to satisfy regulations to remain well clear from and avoid collisions with other airborne traffic

- UAS DAA systems need to interoperate with collision avoidance (CA) systems onboard manned aircraft
  - Traffic Alert and Collision Avoidance System (TCAS) in the United States
  - Airborne Collision Avoidance System (ACAS) in Europe

UAS DAA Interoperability

UAS DAA systems must not provide guidance that is incompatible with Resolution Advisories (RAs) that manned aircraft receive from their collision avoidance system

- All RAs are vertical commands

RTCA SC-228's Approach

- Restrict UAS DAA vertical guidance when UAS and manned aircraft are within a CA region:
  - No UAS altitude guidance
  - UAS vertical speed guidance is limited to UAS current vertical speed ± 500 ft/min (Londner, ATM2015)

Research Overview

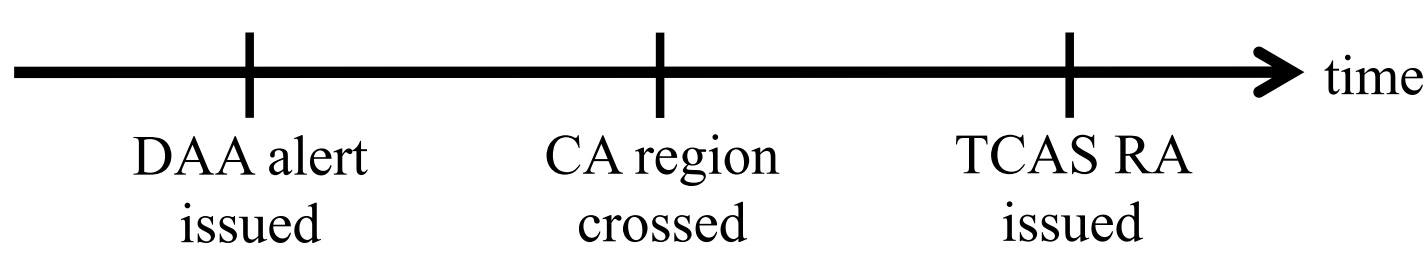
Research Goal

- Evaluate RTCA SC-228's CA region definition in the preliminary standards document in terms of interoperability with TCAS RAs and DAA alerts
- Develop alternative definitions and evaluate their interoperability

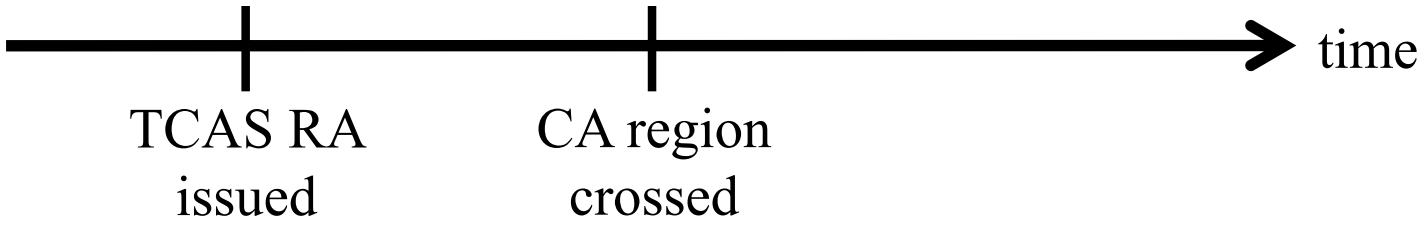
Outcome

RTCA SC-228 approved a new definition we recommended for the final standards document

CA Region Interoperability

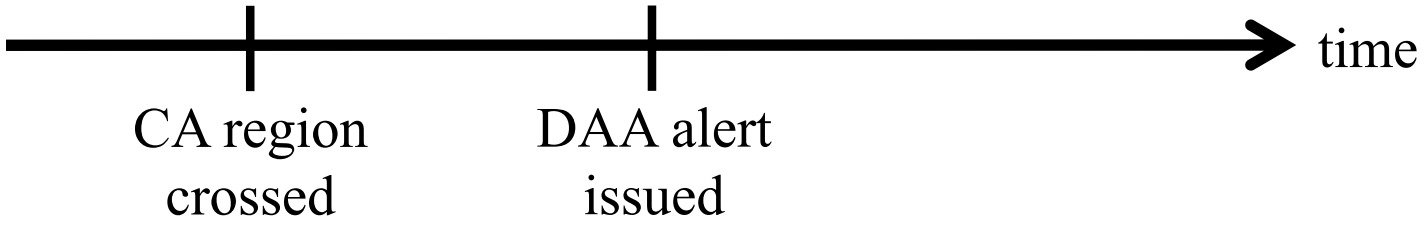


Preferred order in encounters with TCAS RA



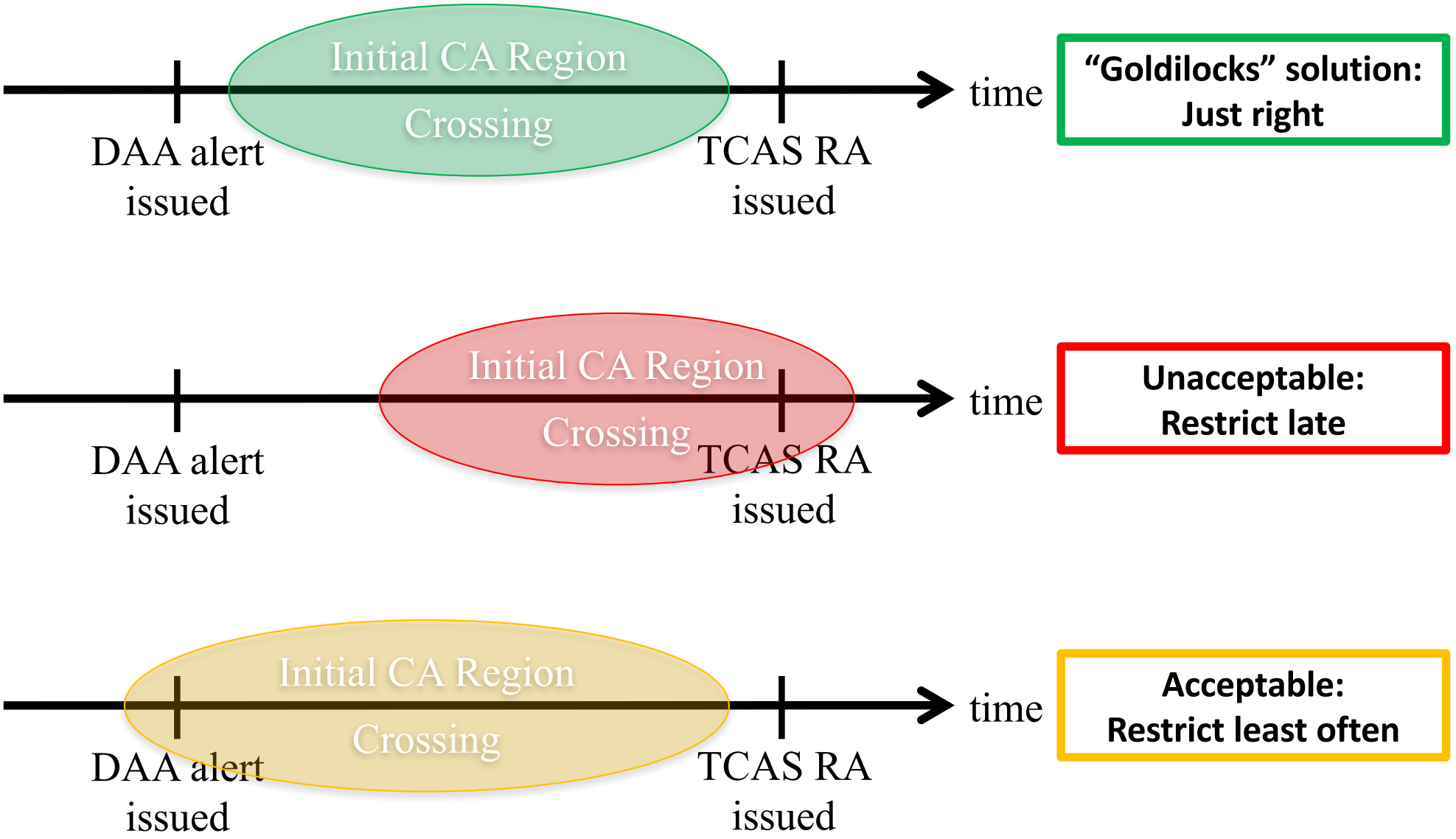
Not acceptable because UAS vertical maneuvers not restricted

Not acceptable because UAS vertical maneuvers not restricted



Minimize frequency for interoperability with DAA alerts

Summary of CA Region Interoperability



Collision Avoidance Region

- Three CA region definition candidates evaluated

- Horizontal Components:
  - Horizontal Miss Distance (*HMD*): Projected separation at closest point of approach (CPA) in the horizontal dimension
  - Modified tau (τ_{mod}): Projected time to CPA
    - Distance Modification (*DMOD*): Minimum threat range boundary

- Vertical Components:
  - d_h: Current vertical separation
  - *ZTHR*: Projected vertical separation at CPA
  - Vertical tau (τ_v): Projected time to co-altitude

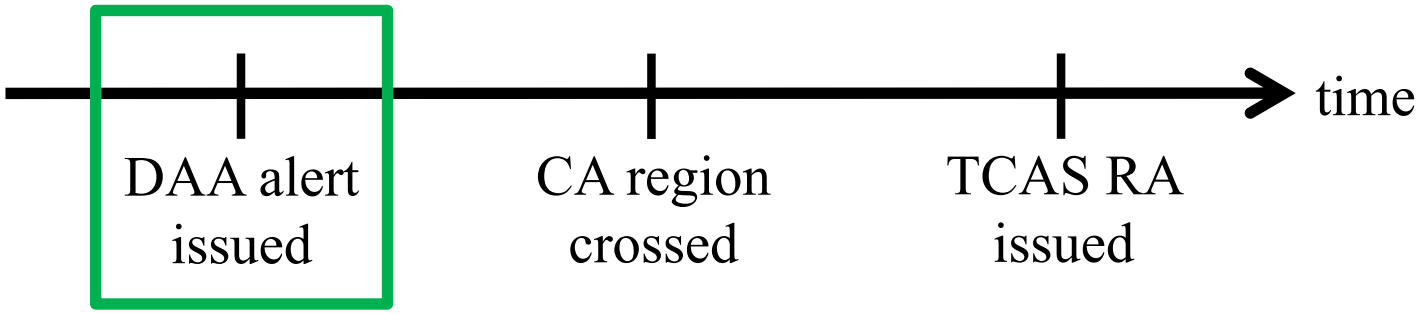
Loss of DAA Well Clear

- Loss of DAA well clear:

  $0 \le \tau_{\text{mod}} < 35\text{sec AND } HMD < 4000\text{ft AND } d_h < 450\text{ft}$

- UAS Executive Committee Science and Research Panel coordinated research efforts by:
  - NASA
  - Massachusetts Institute of Technology-Lincoln Laboratory, and
  - United States Air Force Research Laboratory
- Feedback from the FAA and RTCA SC-228 incorporated

DAA Warning alert

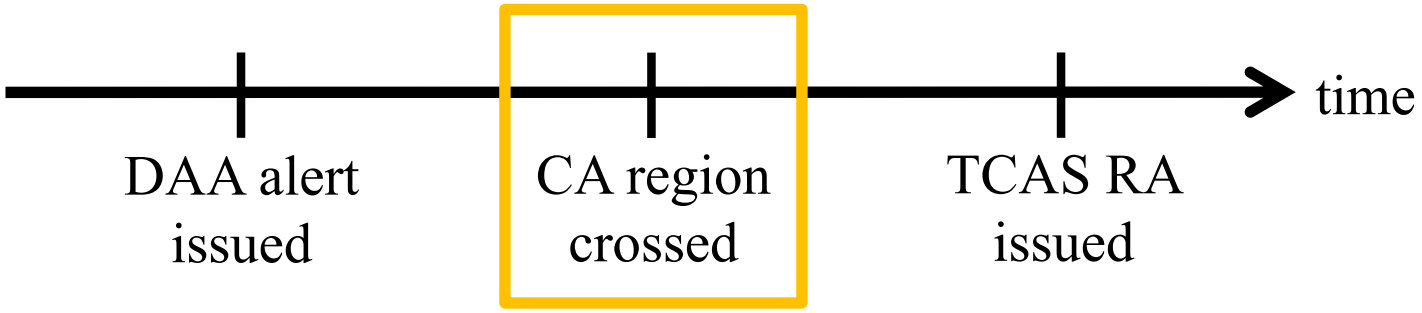


- DAA Warning alert (look-ahead time of 40 sec):

  $0 \le \tau_{\text{mod}} < 35\text{sec}$ AND $HMD < 0.75\text{nmi}$ AND $d_h < 450\text{ft}$

- Alert to the UAS pilot to execute a maneuver to remain well clear

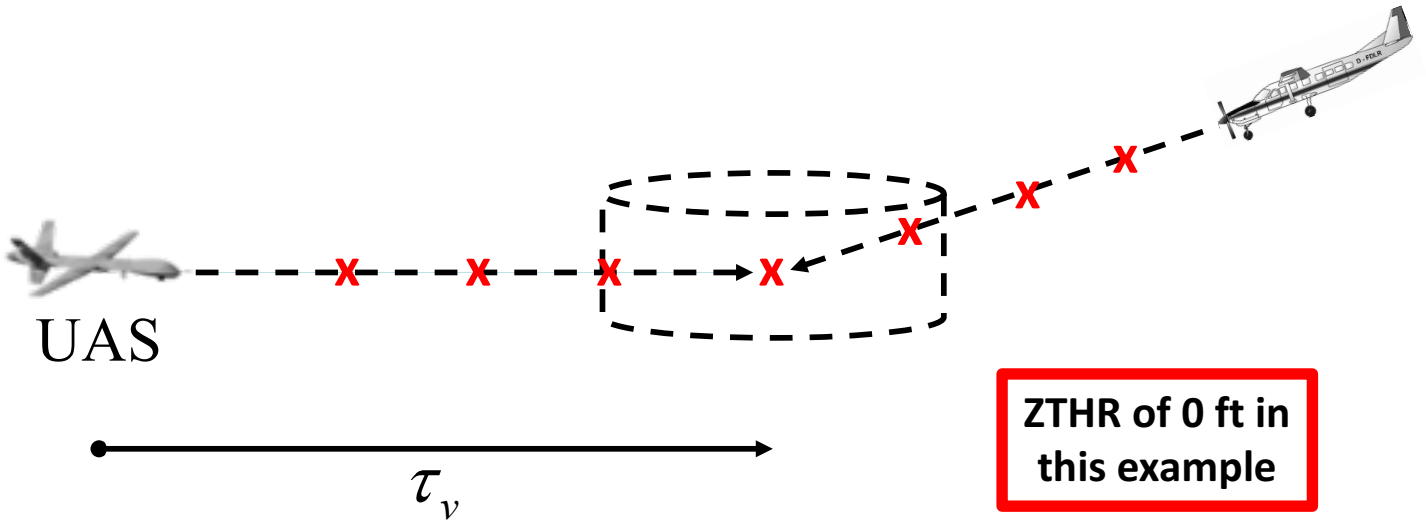
"AND" Collision Avoidance Region Definition



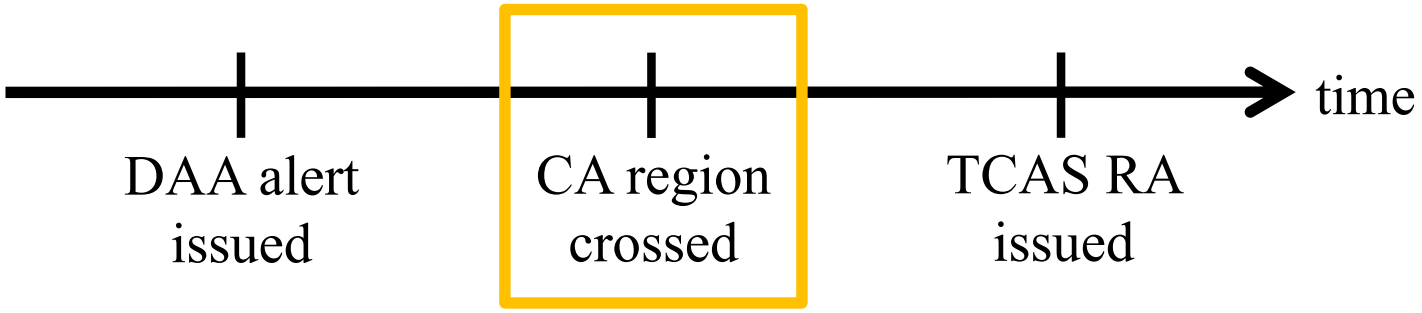
- "AND" definition in the preliminary standards (mid-2015):

  $0 \le \tau_{\text{mod}} < 50\text{sec}$ AND $(0 \le \tau_v < 50\text{sec}$ AND $ZTHR < 800\text{ft})$

- **Utilizes subset of the components used in TCAS**



“OR” Collision Avoidance Region Definition

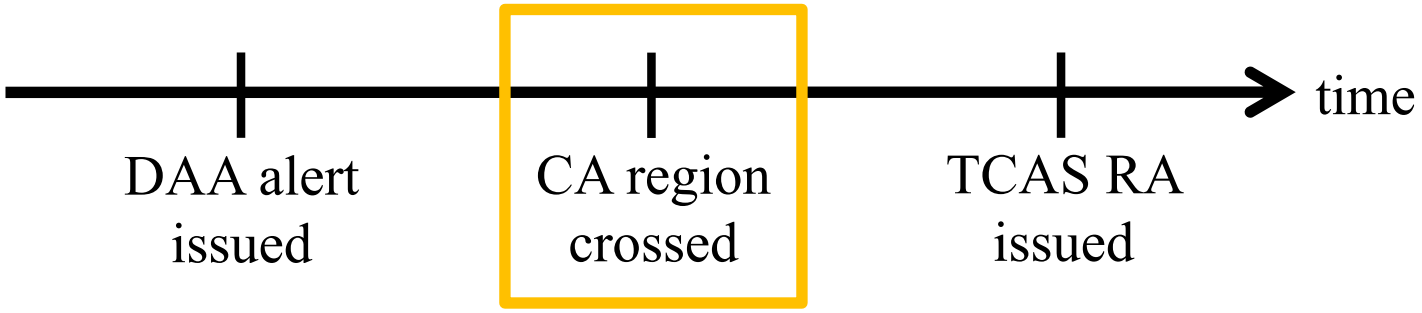


- “OR” definition:

$$0 \le \tau_{\text{mod}} < 50\text{sec AND } (0 \le \tau_v < 50\text{sec OR } ZTHR < 800\text{ft})$$

- **More similar to TCAS logic**

“OR-h” Collision Avoidance Region Definition



- “OR-h” definition:

  $0 \le \tau_{\text{mod}} < 50\text{sec AND } (0 \le \tau_v < 50\text{sec OR } d_h < 800\text{ft})$

- **Utilizes current vertical separation like TCAS and DAA alerting**

Summary of CA Region Definitions

- "AND" definition in the preliminary standards document:

  $0 \le \tau_{\text{mod}} < 50\text{sec AND } (0 \le \tau_v < 50\text{sec AND } ZTHR < 800\text{ft})$

- "OR" definition more similar to TCAS:

  $0 \le \tau_{\text{mod}} < 50\text{sec AND } (0 \le \tau_v < 50\text{sec OR } ZTHR < 800\text{ft})$

- "OR-h" definition utilizes current vertical separation like TCAS and DAA alerting

  $0 \le \tau_{\text{mod}} < 50\text{sec AND } (0 \le \tau_v < 50\text{sec OR } d_h < 800\text{ft})$

Data Collection

Approach

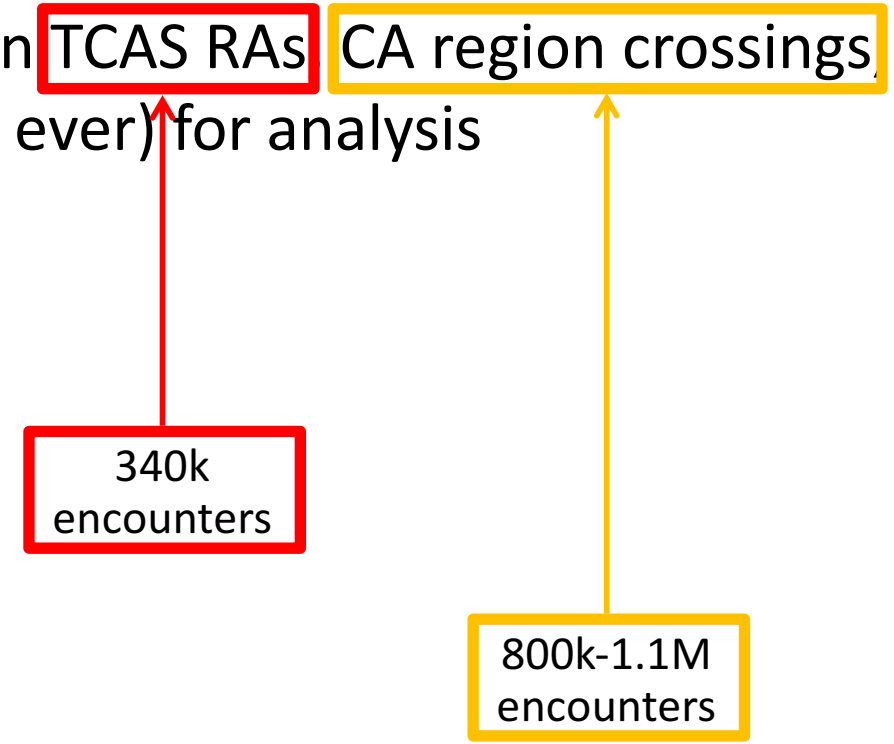
- **1.3 million simulated pairwise encounters between UAS and manned aircraft**
  - NASA's Java Architecture for DAA Extensibility and Modeling (Abramson, NASA-TM-2017-219507)

- Combinatorial approach
  - Covers a wide range of horizontal and vertical closure rates, angles, and miss distances
  - Capture "corner cases" unlikely to occur in nationwide simulations

Encounter Details

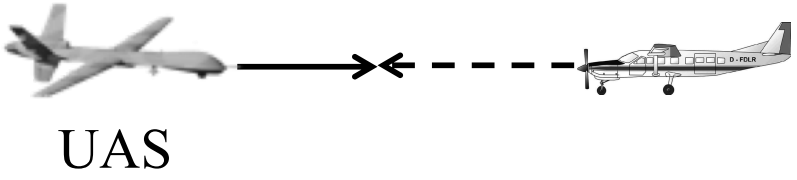
- Straight-line, non-maneuvering pairwise encounters
- Simple kinematic trajectory modeler
- No uncertainty
- TCAS II version 7.1

- Recorded when TCAS RAs, CA region crossings, and DAA Warning alerts occur (if ever) for analysis

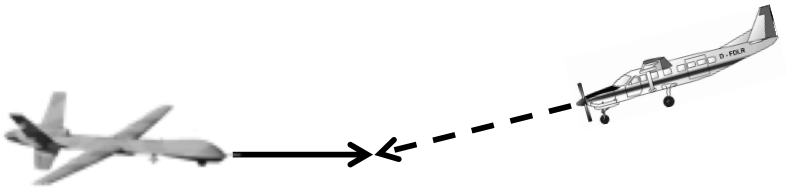


Vertical Encounter Types

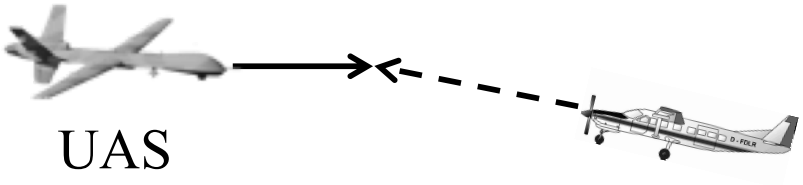
Level-Level Encounters



Level-Descent Encounters

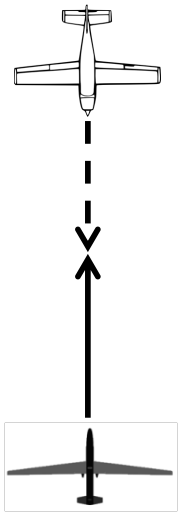


Level-Climb Encounters

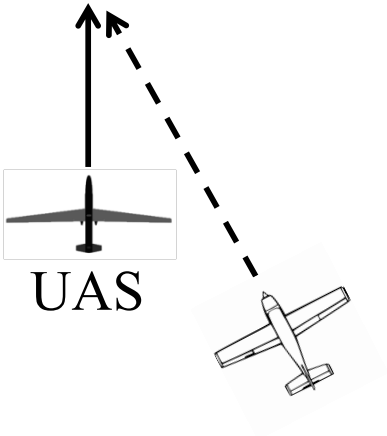


Horizontal Encounter Types

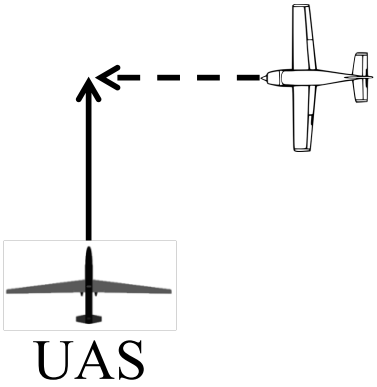
Head-On Encounters



Overtaking Encounters

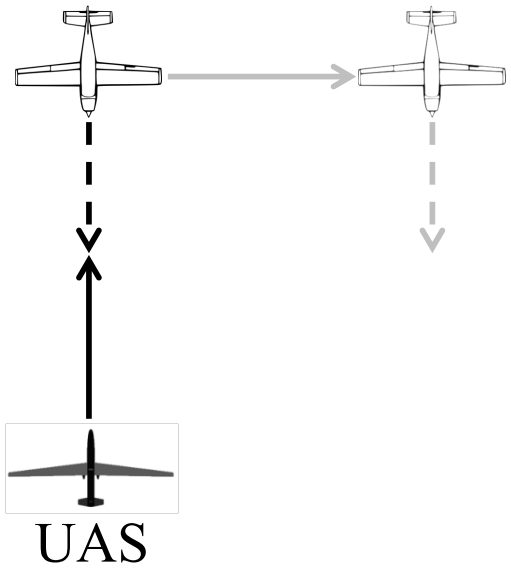


Crossing Encounters

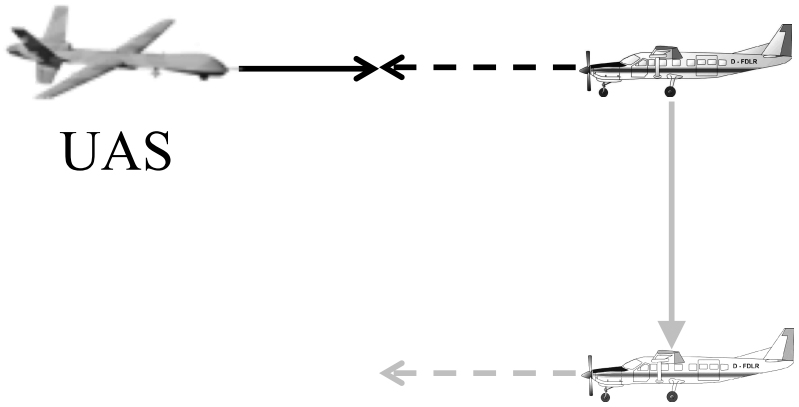


Encounters with Non-Zero Miss Distances

Manned aircraft trajectory is offset horizontally



and also offset vertically



to evaluate performance of CA region definitions in encounters with non-zero miss distances

Encounter Parameters

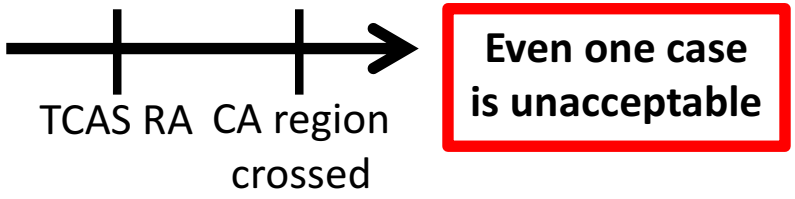
1.3 million pairwise encounters between UAS and manned aircraft

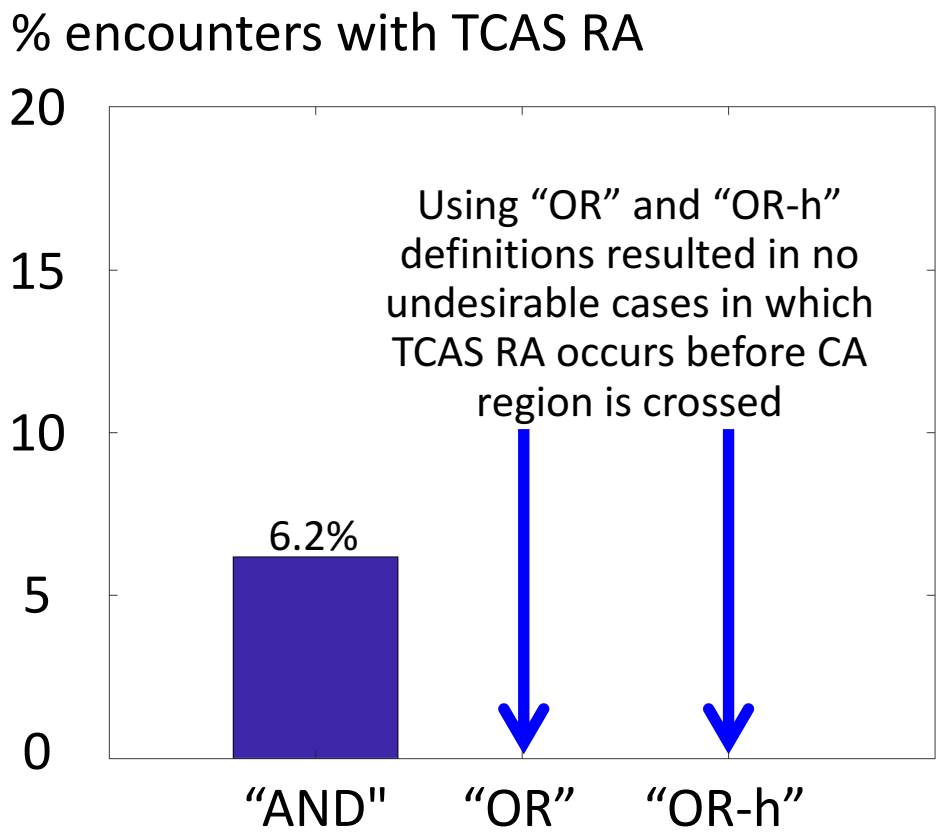
Parameter Type	# Values	Values
UAS ground speed	4	50, 100, 150, 200 kts
UAS heading	1	0 deg
UAS vertical speed	1	0 ft/min (fly level at 5000 ft)
Manned vertical speed	9	-2000, -1500, -1000, -500, 0, …, 2000 ft/min
Manned heading	12	0, 30, 60, 90, 120, 150, 180, …, 330 deg
Manned ground speed	5	50, 100, 150, 200, 250 kts
Horizontal manned trajectory offset	9	0 nmi: (x,y) = (0,0) 0.5 nmi: (x,y) = (0.5, 0), (-0.5, 0), (0, 0.5), (0, -0.5) 1.5 nmi: (x,y) = (1.5, 0), (-1.5, 0), (0, 1.5), (0, -1.5)
Vertical manned trajectory offset	7	-1000, -500, -250, 0, 250, 500, 1000 ft
UAS trial plan maneuver turn rate	2	1.5, 3 deg/sec
UAS trial plan climb/descent rate	5	(500, 500), (1000, 1000), (2000, 2000), (2000, 1000), (1000, 2000) ft/min

Result 1: “AND” Collision Avoidance Region Definition Not Suitable

“AND” CA Region Definition Not Suitable

The “AND” definition does not ensure that the CA region is always crossed before a TCAS RA is issued

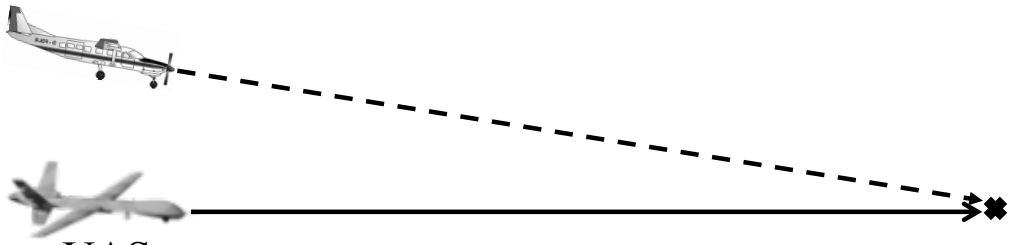




Slow Vertical Closure Rate when TCAS RA was issued before the "AND" CA region was crossed

"AND"

$$0 \le \tau_{\text{mod}} < 50\text{sec AND } (0 \le \tau_v < 50\text{sec AND } ZTHR < 800\text{ft})$$



UAS

Vertical separation: 592 ft
Vertical closure rate: 500 ft/min (i.e., converging)
Vertical tau: 71.0 sec

Manned aircraft TCAS issues RA because current vertical separation is less than 600 ft

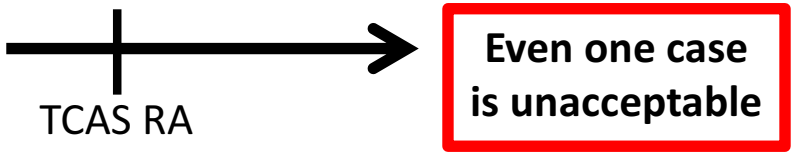
But, "AND" CA region not crossed due to slow vertical closure rate

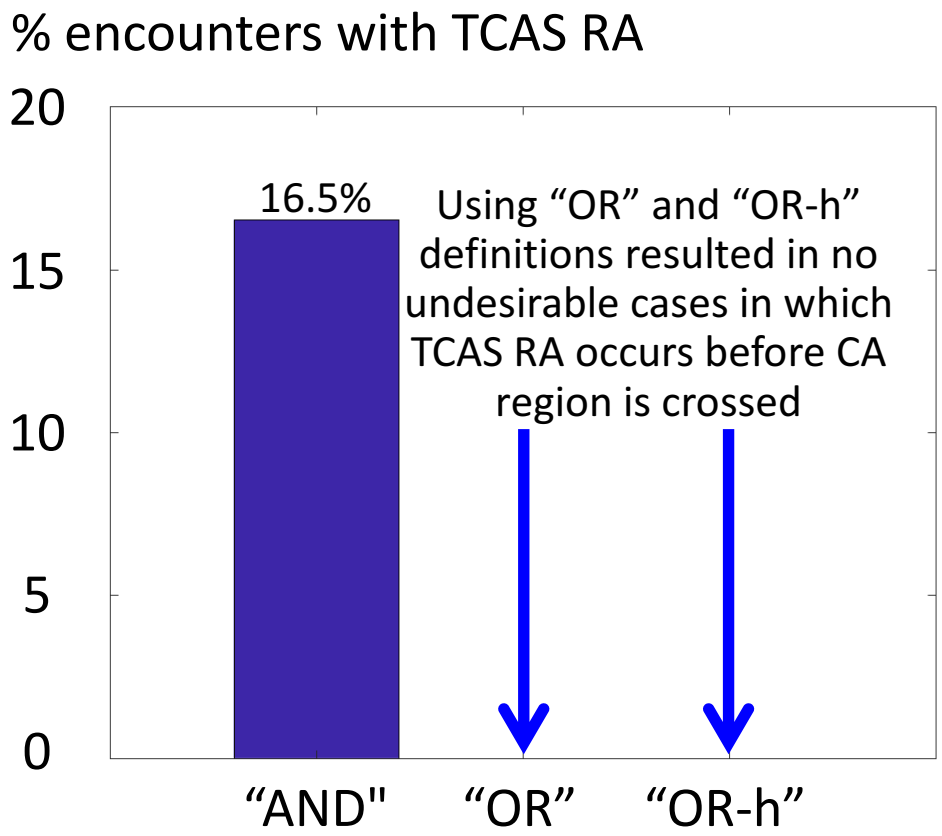
Horizontal separation: 0 nmi
Horizontal closure rate: 0 kts
Horizontal encounter angle: 0 deg
Modified tau: 0 sec

"AND" definition does not capture slow vertical closure rate cases --> Need to use "OR" like in TCAS

“AND” CA Region Definition Not Suitable

The “AND” definition does not ensure that the CA region is always crossed before a TCAS RA is issued

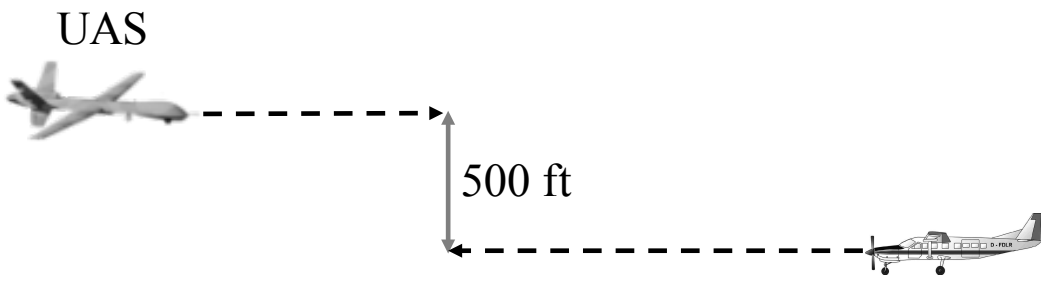




Level-Level Encounter when TCAS RA was issued without the "AND" CA region ever being crossed

"AND"

$$0 \le \tau_{\text{mod}} < 50\text{sec AND } (0 \le \tau_v < 50\text{sec AND } ZTHR < 800\text{ft})$$



Vertical separation: 500 ft
Vertical closure rate: 0 ft/min
Horizontal separation: 1.17 nmi
Horizontal closure rate: 200 kts (i.e., converging)
Horizontal encounter angle: 180 deg (i.e., head-on)
Modified tau (DMOD 1.1 nmi): 2.4 sec

Manned aircraft TCAS issues RA because current vertical separation is less than 600 ft

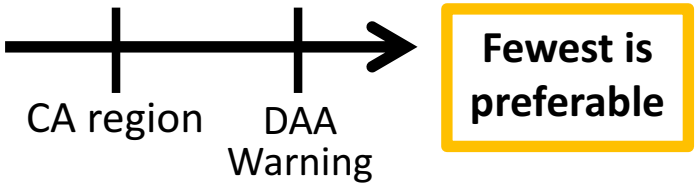
But, "AND" CA region not crossed because aircraft in level-level encounter with offset are never co-altitude

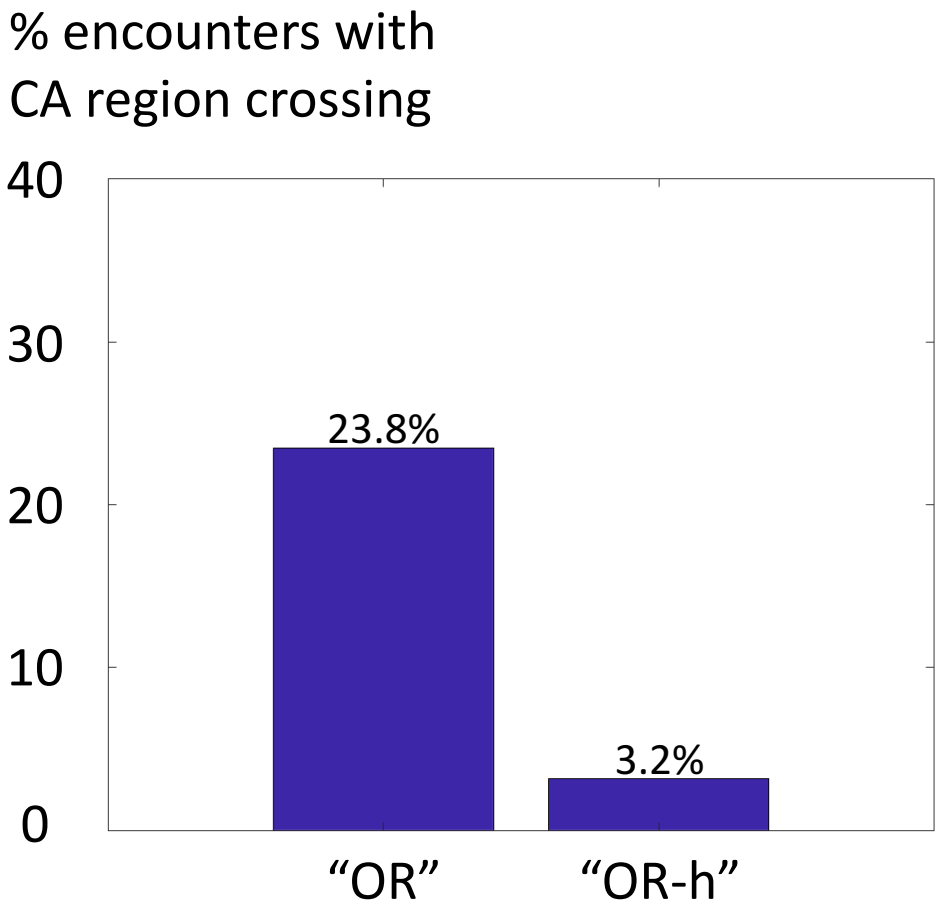
"AND" definition does not capture zero vertical closure rate cases --> Need to use "OR" like in TCAS

Result 2: “OR-h” Collision Avoidance Region Definition has Lower Non-Interoperability with DAA Warning Alerts

“OR-h” CA Region Definition has Lower Non-Interoperability

The “OR-h” definition restricted vertical guidance at DAA Warning alerts less often

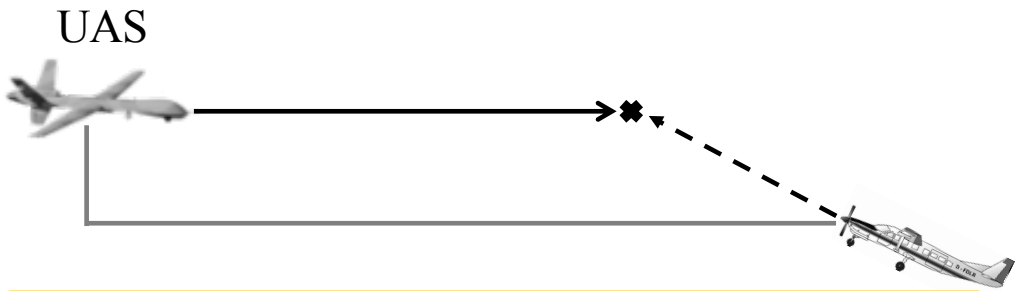




High Vertical Closure Rate when "OR" CA region was crossed before DAA Warning alert was issued

"OR"

$$0 \le \tau_{\text{mod}} < 50\text{sec AND } (0 \le \tau_v < 50\text{sec OR } ZTHR < 800\text{ft})$$



Vertical separation: 2033 ft
Vertical closure rate: 2000 ft/min (i.e., converging)
Vertical tau: 61 sec
Predicted vertical separation at CPA: 0 ft

"OR" CA region is crossed because the two aircraft are predicted to have 0 ft of vertical separation at CPA

Horizontal separation: 2.54 nmi
Horizontal closure rate: 150 kts (i.e., converging)
Horizontal encounter angle: 180 deg
Modified tau (DMOD 1.1 nmi): 49.5 sec

But, there is no DAA alert or "OR-h" CA region crossing since vertical separation at this time is more than 800 ft

"OR" definition is too conservative in high vertical closure rate cases due to ZTHR

--> Use current vertical separation like in DAA Warning alert

Concluding Remarks

Recommendation to RTCA SC-228

Recommended changing CA region from the "AND" definition in the preliminary standards document to the "OR-h" definition in the final standards document: $0 \leq \tau_{\text{mod}} < 50\text{sec AND } (0 \leq \tau_v < 50\text{sec OR } d_h < 800\text{ft})$

- "OR-h" is most interoperable with TCAS and DAA Warning alerts because it uses:
  - "OR" operator instead of "AND" operator for the vertical conditions
  - Current vertical separation instead of predicted vertical separation at CPA
- "OR-h" definition was accepted by RTCA SC-228 for the final standards document for UAS DAA systems

Future Directions

- Encounters in which UAS climb and descend
- Encounters in which UAS and manned aircraft maneuver

- Uncertainty:
  - Sensor models
  - Tracker models
  - Pilot models

- ACAS Xa (active) for manned aircraft
- ACAS Xu (unmanned) for UAS

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Questions?

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