National Aeronautics and Space Administration

ACES M&S: Unmitigated Factorial Encounter Study on DAA/TCAS Interoperability

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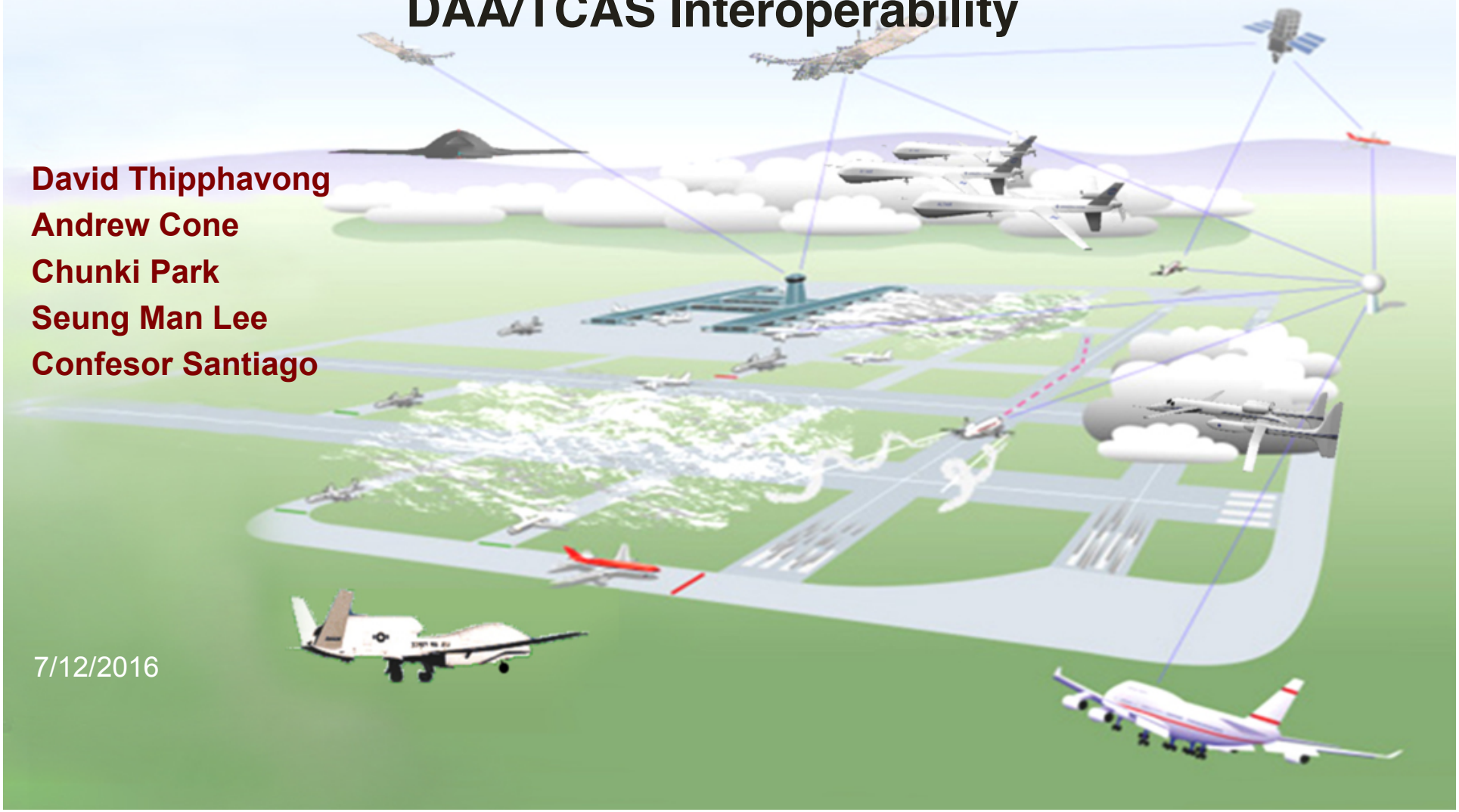

7/12/2016

Overview of ACES M&S Studies

- Presentation on fast-time simulation of **unmitigated factorial pairwise encounters to study the interoperability of TCAS RA and DAA**: 1) DAA Warning alert, 2) Well Clear Recovery (WCR) guidance, 3) DAA collision avoidance (DAA-CA) region

- Complementary to a mitigated factorial study of encounters between UAS and non-cooperative intruders to:
  - Investigate how **vertical rate errors affect DAA WCR guidance effectiveness**
  - **Identify appropriate vertical rate error threshold** for suppressing vertical DAA WCR guidance
- Complementary to a study of NAS-wide simulations to:
  - **Explore the trade space of alerting parameters** using the MOPS alerting metrics
  - **Evaluate different alerting schemes** to provide data to DAA manufacturers
  - **Investigate the effects of sensor uncertainty** on safety and DAA alerting and guidance performance

- These three mutually complementary studies are intended to help refine and validate the MOPS alerting and guidance requirements

Features of the Factorial Approach

- Strengths:
  - Enables analysis of the **full range of encounter situations, including "corner cases"** unlikely to be simulated in NAS-wide studies due to the nature of the missions flown by UAS and the flight paths of intruders
  - **Shorter run time** facilitates rapid follow-up investigations

- Caveats:
  - **Does not naturally reflect the distribution of encounter geometries** expected in NAS
  - **Multiple intruder case not simulated**

Study Objectives

- Ensure DAA-CA definition consistent with TCAS RA logic. There are substantial gaps in the current DAA-CA definition that cause:
  - TCAS RA to occur before DAA-CA
  - TCAS RA to occur with no DAA-CA

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- Ensure DAA-CA definition consistent with TCAS RA logic. There are substantial gaps in the current DAA-CA definition that cause:
  - TCAS RA to occur before DAA-CA
  - TCAS RA to occur with no DAA-CA
- Current DAA-CA definition:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ AND } ZTHR < ZTHR^*)$$

$$\text{with } \tau^*_{\text{mod}} = 50 \text{ sec, DMOD} = 1.1 \text{ NM, } \tau^*_v = 50 \text{ sec, and } ZTHR^* = 800 \text{ ft}$$

- When the intruder is vertical RA-capable and its VRC (vertical resolution advisory complement) is unknown to the ownship, and the intruder is within the DAA-CA region:
  - Altitude-based vertical guidance is removed for the ownship
  - Vertical speed guidance changes of more than 500 ft/min are displayed as not acceptable for the ownship

Comparison 1: Current vs. "OR" DAA-CA definitions

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- Investigate "OR" DAA-CA definition that is more consistent w/TCAS:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \boxed{\text{OR}} ZTHR < ZTHR^*)$$

Comparison 2: Current vs. "OR-h" DAA-CA definitions

- Ensure DAA-CA definition consistent with TCAS RA logic. There are substantial gaps in the current DAA-CA definition that cause:
  - TCAS RA to occur before DAA-CA
  - TCAS RA to occur with no DAA-CA
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- Investigate "OR" DAA-CA definition that is more consistent w/TCAS:

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- Investigate "OR-h" DAA-CA definition that is more consistent w/TCAS and DAA Warning:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ OR } h < h^*)$$

$$\text{with } h^* = 800 \text{ ft}$$

Experiment Setup

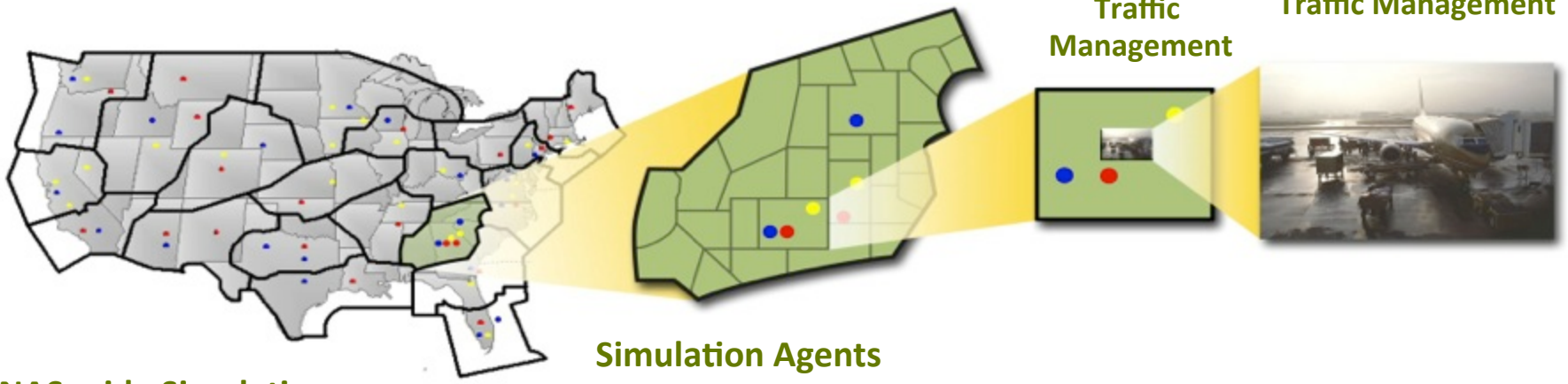
Prior ACES M&S studies were NAS-wide

National Traffic Management

Regional Traffic Management

Local Approach and Departure Traffic Management

Airport and Surface Traffic Management



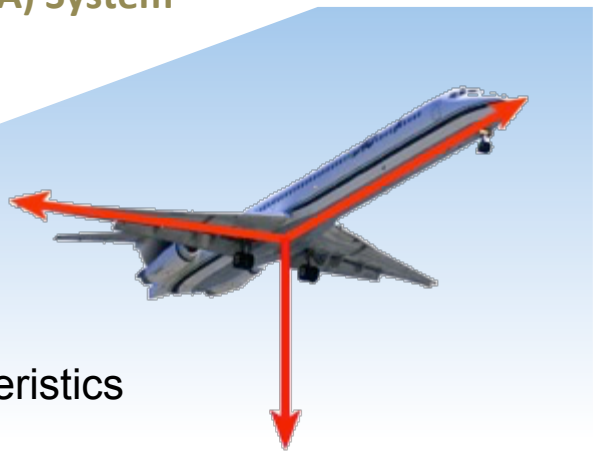
NAS-wide Simulation

- Gate-to-gate simulation of ATM operations
- Full flight schedule with flight plans
- Sector and center models with some airspace procedures

Simulation Agents

- Air traffic controller decision making
- Traffic flow management models
- Individual aircraft characteristics
- UAS Detect-and-Avoid (DAA) System [JADEM]

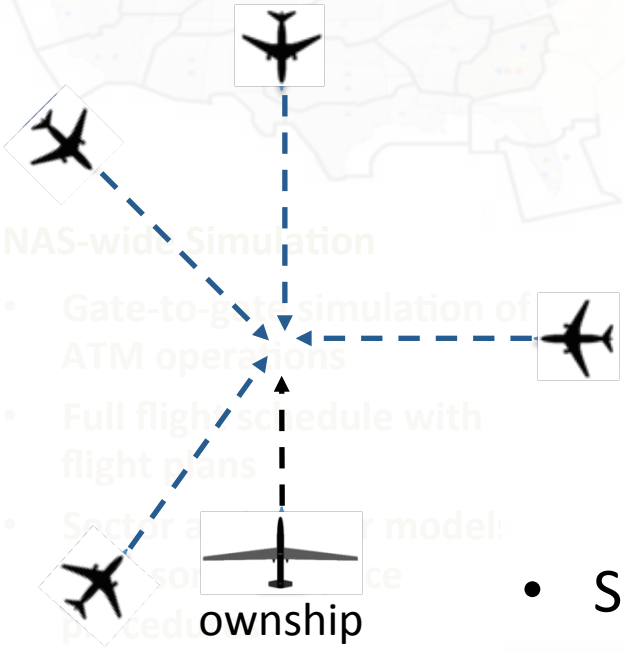
4-DOF Trajectory Model
Aerodynamic models of aircraft
Models replicate pilot behavior
User-definable uncertainty characteristics



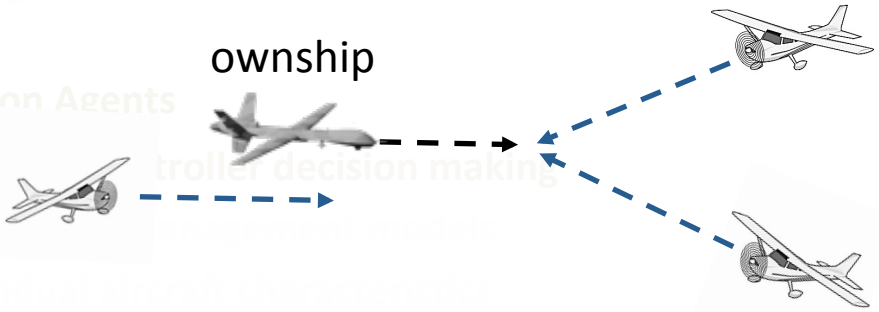
Current study uses full factorial module

- Non-accelerating (i.e., straight-line) pairwise encounters

Horizontal



Vertical



- Simple kinematic trajectory modeler
  - Ground speed
  - Heading
  - Vertical speed

Factorial Encounter Simulation Overview

- **Unmitigated simulations** of pairwise encounters
- No sensor uncertainty

- **Omnibands** is the guidance algorithm to determine WCR
- **WCR** occurs when bands are **entirely non-green**

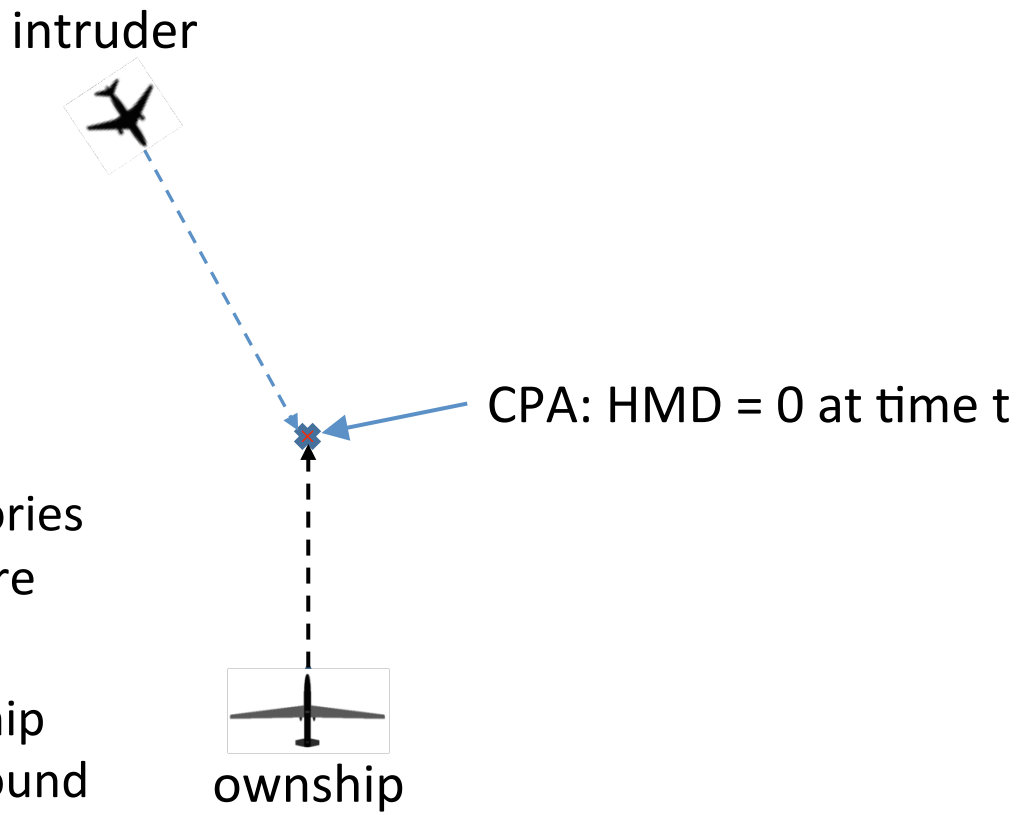
- TCAS II version 7.1 (actual code)

Factorial Encounter Parameters

1.3 million encounters simulated and analyzed

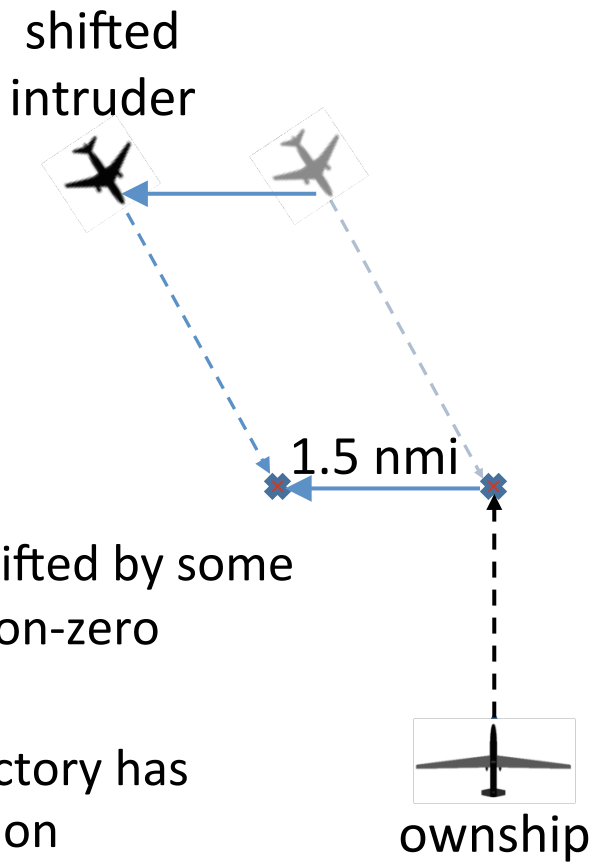
Parameter Type	# Values	Values
Ownship ground speed	4	50, 100, 150, 200 kts
Ownship heading	1	0 deg
Ownship vertical speed	1	0 ft/min (fly level at 5000 ft)
Intruder ground speed	5	50, 100, 150, 200, 250 kts
Intruder heading	12	0, 30, 60, 90, …, 330 deg
Intruder vertical speed	9	-2000, -1500, -1000, -500, 0, …, 2000 ft/min
Ownship trial plan maneuver turn rate	2	1.5, 3 deg/sec
Ownship trial plan climb/descent rate	5	(500, 500), (1000, 1000), (2000, 2000), (2000, 1000), (1000, 2000) ft/min
Horizontal intruder trajectory shifting	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 intruder trajectory shifting	7	-1000, -500, -250, 0, 250, 500, 1000 ft

Base Encounter with Zero-Separation CPA



- Ownship and intruder trajectories extrapolated from time t where HMD = 0 occurs
- Extrapolation based on ownship and intruder headings and ground speeds

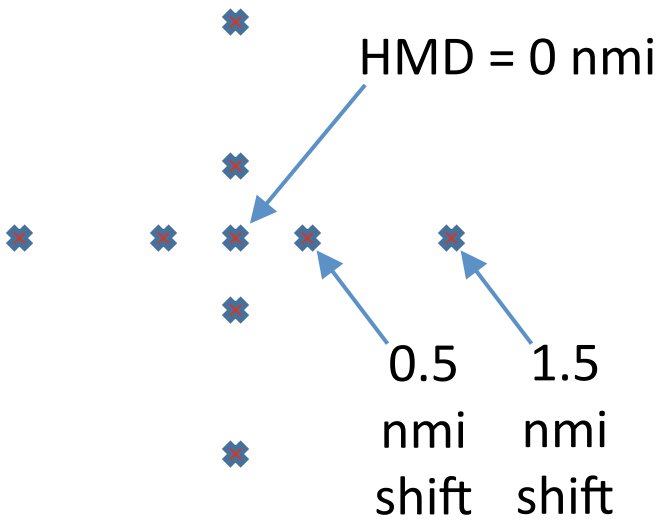
Intruder Trajectory Shifted Horizontally



- Intruder trajectory shifted by some distance to achieve non-zero separation at CPA
- Shifted intruder trajectory has different starting lat/lon

Illustration of Horizontal/Vertical Shift to Zero-Sep CPA

Horizontal



- Grid of horizontal shifts is combined with each vertical shift
- Each combination of horizontal/vertical shifts applied to each combination of ownship and intruder headings, ground speeds, and vertical speeds

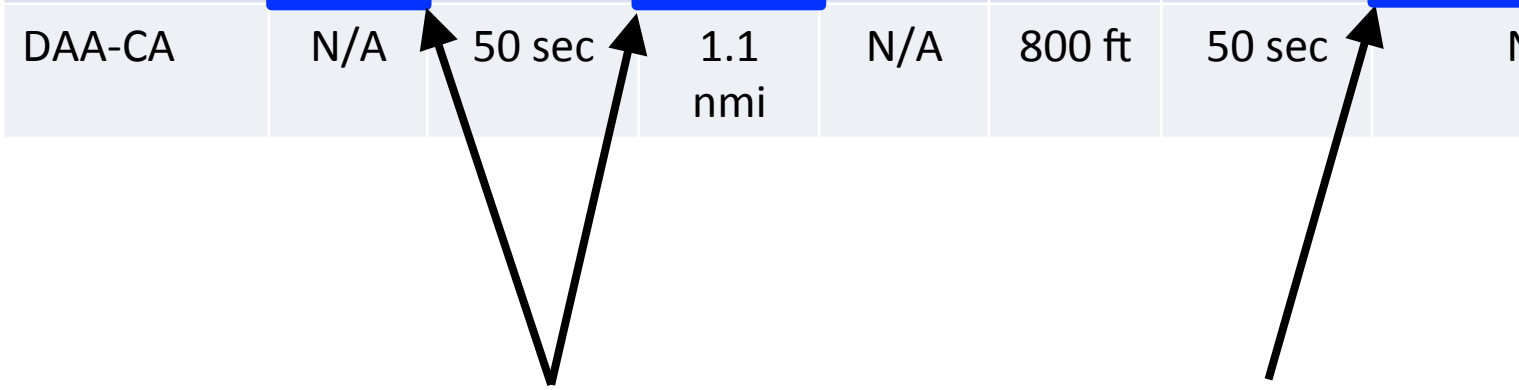
Vertical

- vertical shift: +1000 ft
- vertical shift: +500 ft
- vertical shift: +250 ft
- vertical shift: 0 ft
- vertical shift: -250 ft
- vertical shift: -500 ft
- vertical shift: -1000 ft

DAA Boundaries

- Surveillance range: 20 nmi radius

Boundary	HMD	ModTau	DMOD	h	ZTHR	VertTau	Predicted Time to Loss of Buffered WC
DAA Warning	0.75 nmi	35 sec	0.75 nmi	450 ft	N/A	N/A	40 sec
DAA-CA	N/A	50 sec	1.1 nmi	N/A	800 ft	50 sec	N/A



alerting metrics HAZ plus small buffer

alerting metrics average time of alert plus 10 sec

Omnibands Parameters

- Look-ahead time: 120 seconds
- Hysteresis: 5 sec
- Vertical guidance
  - 2000 ft above and below in 500-ft increments
- Altitude inhibition region
  - Defined same as current MOPS DAA-CA region
- Horizontal guidance
  - All the way around the ownship in 1-deg increments

Band Color	HMD	ModTau	DMOD	ZTHR	VertTau	Predicted Time to Separation Loss
Red	0.75 nmi	35 sec	0.75 nmi	450 ft	N/A	40 sec
Yellow	0.75 nmi	35 sec	0.75 nmi	450 ft	N/A	50 sec

Comparison 1:

Current DAA-CA definition

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \ \text{AND} \ (0 \le \tau_v < \tau^*_v \ \boxed{\text{AND}} \ ZTHR < ZTHR^*)$$

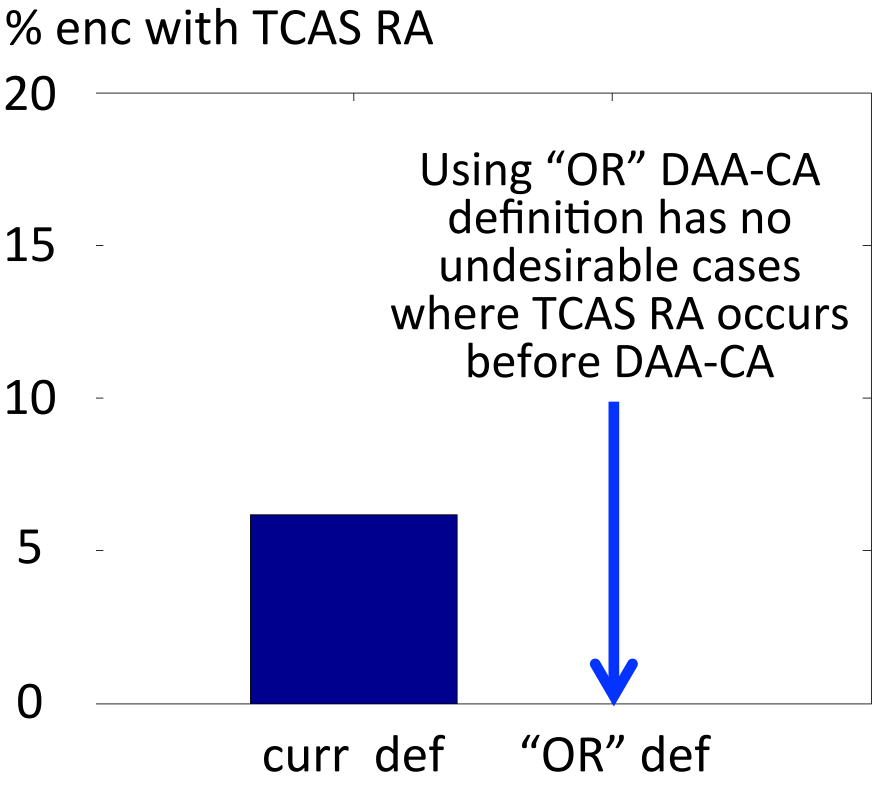
vs. "OR" DAA-CA definition

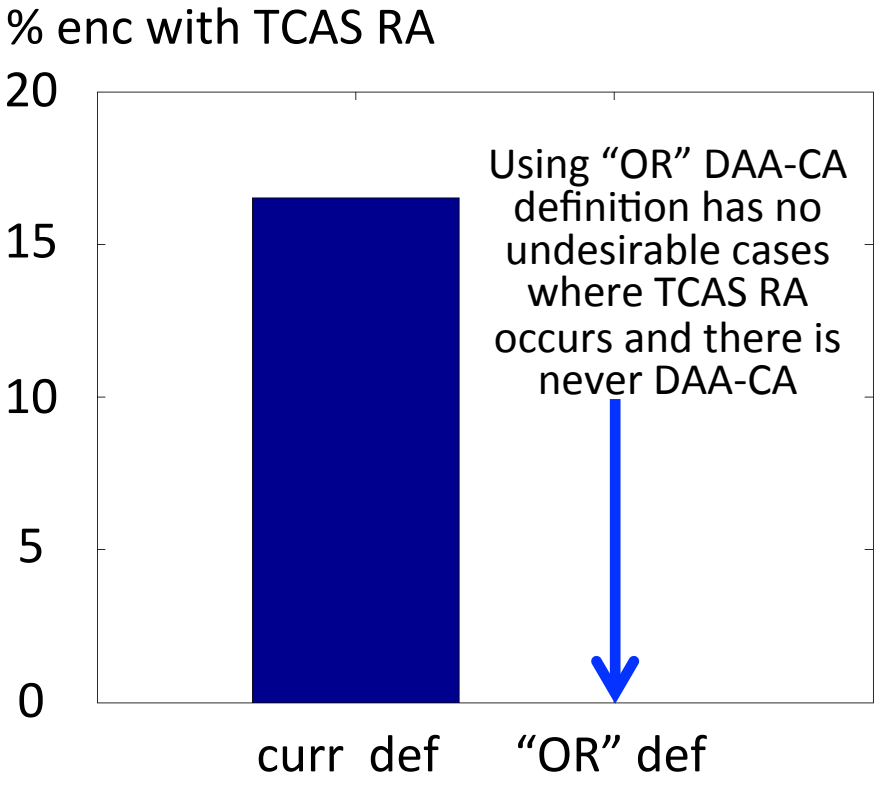
$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \ \text{AND} \ (0 \le \tau_v < \tau^*_v \ \boxed{\text{OR}} \ ZTHR < ZTHR^*)$$

DAA-CA/TCAS RA interoperability improvements

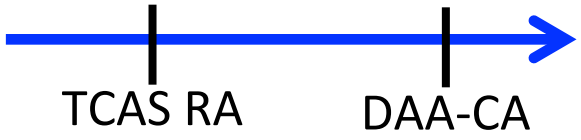
We can address TCAS RA interoperability gaps in the current DAA-CA definition by changing to the "OR" DAA-CA definition:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ OR } ZTHR < ZTHR^*)$$

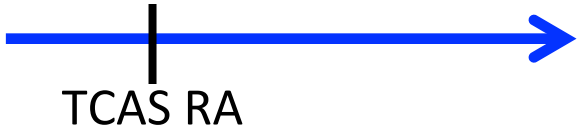




Problematic Encounters Handled by "OR" definition



vertTau greater than 50 sec: Vertical separation of ~400-600 ft (sufficient to trigger TCAS RA) and slow vertical convergence rate (500 ft/min)



Undefined vertTau: Both ownship and intruder are flying level and offset vertically by less than 600 ft, which is sufficient to trigger TCAS RA

"OR" DAA-CA definition increases DAA-CA/TCAS interoperability …

Undesirable Situations	Current DAA-CA Definition	"OR" DAA-CA Definition	Change (want decreases)
TCAS RA before DAA-CA*	**6.2%**	**0%**	**Eliminated**
TCAS RA without DAA-CA*	**16.5%**	**0%**	**Eliminated**
DAA-CA without TCAS RA**	65.5%	69.1%	Small increase
DAA-CA before Warning**	0.1%	23.8%	Large increase
DAA-CA without Warning**	31.4%	36.4%	Small increase

Desirable Situations	Current DAA-CA Definition	"OR" DAA-CA Definition	Change (want increases)
DAA-CA before TCAS RA**	32.0%	30.8%	Small decrease
DAA Warning before DAA-CA***	78.9%	63.2%	Large decrease

*: Denominator is number of encounters with TCAS RA

**: Denominator is number of encounters with DAA-CA

***: Denominator is number of encounters with DAA Warning

… at the expense of lower DAA-CA/Warning interoperability

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*: Denominator is number of encounters with TCAS RA

**: Denominator is number of encounters with DAA-CA

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"OR" DAA-CA definition addresses TCAS RA interoperability gaps in the current DAA-CA definition at the cost of creating/expanding DAA Warning interoperability gaps

Comparison 2:

Current DAA-CA definition

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ AND } ZTHR < ZTHR^*)$$

vs. "OR-h" DAA-CA definition

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ OR } h < h^*)$$

"OR-h" definition has large decreases in undesirable situations and large increases in desirable situations …

Undesirable Situations	Current DAA-CA Definition	"OR-h" DAA-CA Definition	Change (want decreases)
TCAS RA before DAA-CA*	**6.2%**	**0%**	**Eliminated**
TCAS RA without DAA-CA*	**16.5%**	**0%**	**Eliminated**
DAA-CA without TCAS RA**	65.5%	71.2%	Small increase
DAA-CA before Warning**	0.1%	3.2%	Small increase
DAA-CA without Warning**	31.4%	39.7%	Modest increase

Desirable Situations	Current DAA-CA Definition	"OR-h" DAA-CA Definition	Change (want increases)
DAA-CA before TCAS RA**	32.0%	28.7%	Small decrease
DAA Warning before DAA-CA***	**78.9%**	**94.7%**	**Large increase**

*: Denominator is number of encounters with TCAS RA

**: Denominator is number of encounters with DAA-CA

***: Denominator is number of encounters with DAA Warning

… in exchange for relatively small increases in undesirable situations and small decreases in desirable situations

Undesirable Situations	Current DAA-CA Definition	"OR-h" DAA-CA Definition	Change (want decreases)
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**: Denominator is number of encounters with DAA-CA

***: Denominator is number of encounters with DAA Warning

"OR-h" DAA-CA definition improves overall interoperability between DAA-CA and TCAS RA/DAA Warning

Concluding Remarks

Recommendation

Recommend changing DAA-CA from current definition

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ AND } ZTHR < ZTHR^*)$$

to "OR-h" DAA-CA definition

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ OR } h < h^*)$$

$$\text{with } h^* = 800 \text{ ft}$$

due to significant positive effect on DAA-CA interoperability with TCAS RA and DAA Warning with relatively small drawbacks

Future/Ongoing Work

Future Work

- Investigate the effect of adding HMD to the DAA-CA definition

Ongoing work

- Complementary mitigated factorial study for encounters between UAS and non-cooperative intruders to:
  - Investigate how vertical rate errors affect DAA WCR guidance effectiveness
  - Identify appropriate vertical rate error threshold for suppressing vertical DAA WCR guidance

- Complementary NAS-wide simulations to:
  - Estimate expected frequency of undesirable encounter situations
  - Explore the trade space of alerting parameters
  - Evaluate different alerting schemes
  - Investigate the effects of sensor uncertainty