Final Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions

Confesor Santiago
8/5/14 – 8/7/14

Supported by Marcus Johnson, Doug Isaacson, and David Hershey
Overview

• Review Traffic Scenarios

• Overview of Well-Clear ACES Simulations

• Review of Well-Clear Definitions within Autoresolver

• Lessons Learned

• Results
But First...

“Parallelisms of weak-side defense in basketball and UAS DAA systems”

- Flight hours
- Big sky theory
- Lack of intruder intent
- Maneuvering trajectories
- Limited field of regard
- Aircraft performance
UAS Missions

- Atmospheric Sampling
  - Global Hawk (RQ4-A) [2350 flights]
- Border Patrol
  - Global Hawk (RQ4-A) [665 flights]
- Cargo Transport
  - UAS Cessna 208 [1320 flights]
- Strategic Wildfire Monitoring
  - Predator B (MQ-9) [325 flights]
- Air Quality Monitoring
  - Shadow-B (RQ7B) [1050 flights]
- On-Demand Air Taxi
  - Cessna Mustang (C510) [2560 flights]
  - Cirrus (SR22T) [10500 flights]
- Flood Mapping

**Total UAS Flight Hours in a Day: 25,734**
UAS Cruise Speeds

Mean: 172 Knots

Mean Cruise Speed (knots)

UAS Mission Type

Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions
Cooperative VFR Traffic

• The 84th Rader Evaluation Squadron (RADES) data were used.
  – The data contain the radar hits collected from hundreds of radar sites in U.S., and each hit provide timestamp, latitude, longitude, Mode 3 code, Mode C code, and others.
  – There is no explicit information that could be used to determine whether radar hits come from IFR flights or VFR flights.

• Criteria for filtering out VFR traffic (for each tracked flight):
  – All tracks are below 18,000 ft,
  – At least one track has the Mode 3 code of 1200,
  – Average speed ranges from 50 knots to 250 knots.

• Non-cooperative VFR radar track coming soon...
Method for Extracting VFR Traffic

• Input: RADES data for a certain time period.

• Output: Flight plan file for a fast-time simulation system, Advanced Concept Evaluation System (ACES).

• Method (three steps):
  1. Generate tracks using a minimum spanning tree based clustering algorithm,
  2. Generate smooth tracks using a Kalman filter,
  3. Generate a flight plan file after reducing the number of waypoints and adding airports which are closest to start/end waypoints.
Cooperative VFR Traffic – July 25, 2013
Cooperative VFR Traffic Days Used

No. of Coop. VFR Flights

Date

01-14-12  01-24-12  04-04-12  04-15-12  04-24-12  07-02-12  07-05-12  10-12-12

No. of Flights

0  5,000  10,000  15,000  20,000  25,000  30,000
ACES Simulated Traffic

- ACES simulates flight paths of UAS mission using:
  - Departure times
  - Source and destination airports
  - Flight plan (route, cruise speed and altitude)
  - “UAV-like” aircraft models

- ACES simulates flight paths of cooperative VFR traffic using:
  - Departure times
  - Source and destination airports
  - Flight plan (route, cruise speed and altitude)
  - “GA-like” aircraft model
Well-Clear ACES Simulations

- ACES agent-based distributed architecture

- Typical configuration is running across three servers with 36 CPU-threads and 360 GM RAM

- Each UAV aircraft is modeled by an “agent”, and balanced across the 36 CPUs

- Within the agent a DAA “activity” was added that is configured to accept all truth states with a “gross” filter distance at a parametric detect rate
  - 2-second detect rate
  - 30 nmi range
Well-Clear ACES Simulations

**Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions**
DAA Architecture (Unmitigated)

**Measures:**
- rDot
- ModTau
- VertTau
- TimeToCpa
- HMD
- VMD
  - hDot
  - Range
  - relX
  - relY
  - relZ
  - relHeading
Integration of Well-Clear Definitions into Autoresolver

- Three well-clear definitions have been integrated into Autoresolver
- At every detect cycle, 2-minute trajectories for ownship and intruder are built
  - No sensor uncertainty
  - Only intruder position and velocities are known
- If well-clear violation is predicted to occur within a parametric time (SST), Autoresolver is triggered to generate an avoidance maneuver
  - Due to maneuvering intruders, or bends in UAV route structure may detect before the SST
Autoresolver Resolution Logic

- Detect well-clear violations with at 60 seconds SST
- A prominent feature of Autoresolver is during re-evaluation, trajectories for maneuver are built until SST plus buffer
  - E.g. detect at 60 seconds, and recommend resolution predicted to be threat-free for 120 seconds
- Another prominent feature of Autoresolver is adding buffer to horizontal separation
  - E.g. scale horz. separation by 25%
  - Usually no need to add buffer to vertical domain, because procedural significance of vertical clearances (cardinal altitudes)
- Lastly, for NASA and MIT-LL well-clear definitions, Autoresolver tries to maneuver to achieve well-clear via vertical or horizontal miss distance, modTau not considered, but TCOA is
Autoresolver Resolution Logic (cont.)

• Searches for the minimal left/right turn and climb/descent that resolves the WCV, i.e. respective WCV threshold plus a 25% scaling in horizontal
  – Integrates 5 degree turns, and 500 ft altitude increments

• Minimizes deviation, i.e. minimum cross track and vertical deviation plus buffers

• Resolution heuristic prefers horizontal maneuver when ownship is at level flight

• Prefers vertical maneuvers if the ownship is non-level

• In the event of tie in maneuver deviation, turning right or descending is preferred
Lessons Learned

• WCV with VFR traffic may end and start close to each in time
  – Merge if WCV between same aircraft pair is within 120 seconds

• Time to co-altitude’s utility not realized given limited number of high vertical closure rate encounters

• P(TCAS-RA|WCV) is high at TCAS Sensitivity Level 6 (Alt: 10,000 – 20,000) for all WC definitions
  – Parameters of TCAS model thresholds are outside NASA and MIT-LL
# TCAS RA Model Altitude Dependent Thresholds

<table>
<thead>
<tr>
<th>Own Altitude (ft)</th>
<th>SL</th>
<th>Tau (sec)</th>
<th>DMOD (nmi)</th>
<th>ZTHR (ft)</th>
<th>ALIM (ft)</th>
<th>HMD (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 - 2350</td>
<td>3</td>
<td>15</td>
<td>0.20</td>
<td>600</td>
<td>300</td>
<td>1215</td>
</tr>
<tr>
<td>2350 - 5000</td>
<td>4</td>
<td>20</td>
<td>0.35</td>
<td>600</td>
<td>300</td>
<td>2126</td>
</tr>
<tr>
<td>5000 - 10000</td>
<td>5</td>
<td>25</td>
<td>0.55</td>
<td>600</td>
<td>350</td>
<td>3342</td>
</tr>
<tr>
<td><strong>10000 - 20000</strong></td>
<td><strong>6</strong></td>
<td><strong>30</strong></td>
<td><strong>0.80</strong></td>
<td><strong>600</strong></td>
<td><strong>400</strong></td>
<td><strong>4861</strong></td>
</tr>
<tr>
<td>20000 - 42000</td>
<td>7</td>
<td>35</td>
<td>1.10</td>
<td>700</td>
<td>600</td>
<td>6683</td>
</tr>
<tr>
<td>&gt; 42000</td>
<td>7</td>
<td>35</td>
<td>1.10</td>
<td>800</td>
<td>700</td>
<td>6683</td>
</tr>
</tbody>
</table>

* MIT-LL uses 0.66 nmi
* NASA uses 475 ZTHR
* NASA uses 20 TCOA

*Source: "A TCAS-II RESOLUTION ADVISORY DETECTION ALGORITHM," Cesar Muñoz, Anthony Narkawicz, and James Chamberlain, AIAA Guidance, Navigation, and Control Conference, 2013. Table 1: TCAS Sensitivity Level Definition and Alarm Thresholds for RAs*
Final Results
(Unmitigated)
P(Corr-RA | WCV) Unmitigated ACES Result

Analyzing P(Corr-RA | WCV) as a function of TCAS Sensitivity Level 3-6

P(Corr-RA | WCV)

0.0% 0.3% 1.9% 18.0% 0.8% 2.5% 7.9% 15.7% 2.3% 5.5% 23.3% 41.9%

3 4 5 6 3 4 5 6 3 4 5 6

MIT-LL NASA USAF

Undesirable Desirable

TCAS-Level within WC Def.

TCAS-Level

3 = [1,000 – 2,350 ft] 5 = [5,000 – 10,000]

4 = [2,350 – 5,000 ft] 6 = [10,000 – 20,000]

Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions
P(NMAC|WCV)

- NASA = 1.17%
- MIT-LL = 1.23%
- USAF = 1.37%
Ownship Altitude at NMAC

Quantiles

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.0%</td>
<td>max</td>
</tr>
<tr>
<td>99.5%</td>
<td>10000</td>
</tr>
<tr>
<td>97.5%</td>
<td>10000</td>
</tr>
<tr>
<td>90.0%</td>
<td>7733.6</td>
</tr>
<tr>
<td>75.0%</td>
<td>quartile</td>
</tr>
<tr>
<td>50.0%</td>
<td>median</td>
</tr>
<tr>
<td>25.0%</td>
<td>quartile</td>
</tr>
<tr>
<td>10.0%</td>
<td>899</td>
</tr>
<tr>
<td>2.5%</td>
<td>798.15</td>
</tr>
<tr>
<td>0.5%</td>
<td>782</td>
</tr>
<tr>
<td>0.0%</td>
<td>min</td>
</tr>
<tr>
<td></td>
<td>782</td>
</tr>
</tbody>
</table>

Summary Statistics

- Mean: 3564.2338
- Std Dev: 2300.1527
- Std Err Mean: 262.12673
- Upper 95% Mean: 4086.3044
- Lower 95% Mean: 3042.1631
- N: 77

Ownship Altitude at WCV (feet)
No. of WCV per Day per Definition

![Graph showing the number of WCV per day for different definitions: MIT-LL, NASA, USAF. The x-axis represents the day, and the y-axis represents the number of WCV. The graph shows varying trends for each definition across the days.](image-url)
No. of WCV by UAS Mission

Mission Type

WC Def.
- MIT-LL
- NASA
- USAF

AirQuality
AirTaxi_Cirrus
AirTaxi_Mustang
AtmosphericSampling
Cargo
FloodMapping
StratFireMission
TactFireMission

N

Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions
## Encounter Angle at WCV

<table>
<thead>
<tr>
<th>WC Def.</th>
<th>MIT-LL</th>
<th>NASA</th>
<th>USAF</th>
</tr>
</thead>
</table>

**Encounter Angle**
- Crossing: 45-135 deg.
- Head-on: 135-180 deg.
- In-trail: 0-45 deg.

**Bearing**
Horz. And Vert. Range at WCV - NASA

- Larger vertical range is due to time to co-altitude.
- High vertical range and low horz. range may be difficult for RADAR to detect
Horz. And Vert. Range at WCV – MIT-LL

- Larger horz range is expected due to larger modTau
- Lack of TCOA threshold makes vertical range truncated at 700 ft
Horz. And Vert. Range at WCV - USAF

- Much shorter ranges, positive for sensor requirements
Horizontal Range at WCV

<table>
<thead>
<tr>
<th>WC Def.</th>
<th>MIT-LL</th>
<th>NASA</th>
<th>USAF</th>
</tr>
</thead>
</table>

Horz Range (feet)
Vertical Range at WCV

Vert Range (feet)
ModTau/Time-to-co-altitude Model

Question: How often does time to co-altitude get triggered with NASA WCVs?

\[
[( r \leq \text{DMOD}) \text{ or } \\
((0 \leq \tau_{\text{mod}} \leq \tau_{\text{thresh}}) \text{ and } \\
(\text{HMD} \leq \text{HMD}_\text{thresh}))]
\]

and

\[
[(h \leq \text{ZTHR}) \text{ or } \\
(0 \leq \text{vert}_\tau \leq \tau_{\text{thresh}})]
\]
## NASA Definition Violation Probability

<table>
<thead>
<tr>
<th>N(WCV)</th>
<th>P(ModTau_TCOA)</th>
<th>P(DMOD_TCOA)</th>
<th>P(ModTau_ZThr)</th>
<th>P(DMOD_ZThr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6473</td>
<td>1.3%</td>
<td>1.2%</td>
<td>80.8%</td>
<td>16.7%</td>
</tr>
</tbody>
</table>

**Key:**

- ModTau_TCOA: WCV occurs with modTau and TCOA
- DMOD_TCOA: WCV occurs with DMOD and TCOA
- ModTau_ZThr: WCV occurs with modTau and ZThr (not TCOA)
- DMOD_ZThr: WCV occurs with DMOD and ZThr (not ModTau or TCOA)
**hDot (vertical closure rate) – NASA**

![hDot Histogram](image)

**Quantiles**

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.0%</td>
<td>max 6665</td>
</tr>
<tr>
<td>99.5%</td>
<td>2359.94</td>
</tr>
<tr>
<td>97.5%</td>
<td>1465.3</td>
</tr>
<tr>
<td>90.0%</td>
<td>609.601</td>
</tr>
<tr>
<td>75.0%</td>
<td>quartile 46.9998</td>
</tr>
<tr>
<td>50.0%</td>
<td>median -151</td>
</tr>
<tr>
<td>25.0%</td>
<td>quartile -985</td>
</tr>
<tr>
<td>10.0%</td>
<td>-1562.6</td>
</tr>
<tr>
<td>2.5%</td>
<td>-2377.6</td>
</tr>
<tr>
<td>0.5%</td>
<td>-3174.8</td>
</tr>
<tr>
<td>0.0%</td>
<td>min -5268</td>
</tr>
</tbody>
</table>

**Summary Statistics**

- **Mean**: -375.2541
- **Std Dev**: 948.14354
- **Std Err Mean**: 11.784775
- **Upper 95% Mean**: -352.1521
- **Lower 95% Mean**: -398.3562
- **N**: 6473
**hDot (vertical closure rate) – MIT-LL**

**Quantiles**

- 100.0% max: 4308
- 99.5%: 2455.86
- 97.5%: 1570.62
- 90.0%: 741.701
- 75.0% quartile: 99
- 50.0% median: -31
- 25.0% quartile: -744
- 10.0%: -1438.7
- 2.5%: -2194.5
- 0.5%: -3023.7
- 0.0% min: -6730

**Summary Statistics**

- Mean: -246.0974
- Std Dev: 909.73485
- Std Err Mean: 11.742669
- Upper 95% Mean: -223.0776
- Lower 95% Mean: -269.1173
- N: 6002
hDot (vertical closure rate) – USAF

Quantiles

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.0%</td>
<td>max 4309</td>
</tr>
<tr>
<td>99.5%</td>
<td>2365.84</td>
</tr>
<tr>
<td>97.5%</td>
<td>1647.35</td>
</tr>
<tr>
<td>90.0%</td>
<td>737.699</td>
</tr>
<tr>
<td>75.0%</td>
<td>quartile 91.998</td>
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<tr>
<td>75.0%</td>
<td>quartile -756.75</td>
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<tr>
<td>50.0%</td>
<td>median -47</td>
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<tr>
<td>25.0%</td>
<td>quartile -1442</td>
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<tr>
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<td>-1442</td>
</tr>
<tr>
<td>2.5%</td>
<td>-2062.2</td>
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<tr>
<td>0.5%</td>
<td>-3095.9</td>
</tr>
<tr>
<td>0.0%</td>
<td>min -5199</td>
</tr>
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</table>

Summary Statistics

- Mean: -251.3393
- Std Dev: 910.31886
- Std Err Mean: 12.13004
- Upper 95% Mean: -227.5598
- Lower 95% Mean: -275.1189
- N: 5632
IFR-VFR 500ft Altitude Separation – Well-Clear?

- MIT-LL uses 700 feet ZTHR
- NASA uses 475 feet ZTHR

Question: If two aircraft pass at 500ft and at level flight isn’t that well-clear?

<table>
<thead>
<tr>
<th>TCAS Sensitivity</th>
<th>Ownship Altitude (ft)</th>
<th>Percentage of WCVs that pass above 500ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1,000-2,350</td>
<td>2.4%</td>
</tr>
<tr>
<td>4</td>
<td>2,350-5,000</td>
<td>4.1%</td>
</tr>
<tr>
<td>5</td>
<td>5,000-1,0000</td>
<td>3.4%</td>
</tr>
<tr>
<td>6</td>
<td>10,000-20,000</td>
<td>0.5%</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>10.5%</td>
</tr>
</tbody>
</table>

Magnitude of MIT-LL that pass above 500ft and vertical closure rate is less than 100 FPM (level).
WCV Duration – NASA

Quantiles

100.0% max 314
99.5% 169.26
97.5% 100
90.0% 66
75.0% quartile 50
50.0% median 36
25.0% quartile 18
10.0% 8
2.5% 2
0.5% 2
0.0% min 2

Summary Statistics

Mean 38.042021
Std Dev 27.380679
Std Err Mean 0.3403231
Upper 95% Mean 38.709166
Lower 95% Mean 37.374875
N 6473
**WCV Duration – MIT-LL**

**Quantiles**

- 100.0% max 552
- 99.5% 141.97
- 97.5% 87.85
- 90.0% 58
- 75.0% quartile 48
- 50.0% median 38
- 25.0% quartile 18
- 10.0% 8
- 2.5% 2
- 0.5% 2
- 0.0% min 2

**Summary Statistics**

- Mean 36.176608
- Std Dev 24.139063
- Std Err Mean 0.311582
- Upper 95% Mean 36.787421
- Lower 95% Mean 35.565795
- N 6002

**Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions**
WCV Duration – USAF

Quantiles

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.0%</td>
<td>max</td>
</tr>
<tr>
<td>99.5%</td>
<td>131.67</td>
</tr>
<tr>
<td>97.5%</td>
<td>76.35</td>
</tr>
<tr>
<td>90.0%</td>
<td>44</td>
</tr>
<tr>
<td>75.0%</td>
<td>quartile</td>
</tr>
<tr>
<td>50.0%</td>
<td>median</td>
</tr>
<tr>
<td>25.0%</td>
<td>quartile</td>
</tr>
<tr>
<td>10.0%</td>
<td>4</td>
</tr>
<tr>
<td>2.5%</td>
<td>2</td>
</tr>
<tr>
<td>0.5%</td>
<td>2</td>
</tr>
<tr>
<td>0.0%</td>
<td>min</td>
</tr>
</tbody>
</table>

Summary Statistics

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>23.896662</td>
</tr>
<tr>
<td>Std Dev</td>
<td>20.776644</td>
</tr>
<tr>
<td>Std Err Mean</td>
<td>0.2768497</td>
</tr>
<tr>
<td>Upper 95% Mean</td>
<td>24.439394</td>
</tr>
<tr>
<td>Lower 95% Mean</td>
<td>23.35393</td>
</tr>
<tr>
<td>N</td>
<td>5632</td>
</tr>
</tbody>
</table>
Ownship Altitude at WCV – NASA

**Quantiles**

- 100.0% max: 17
- 99.5%: 10.8118
- 97.5%: 10
- 90.0%: 8
- 75.0% quartile: 5
- 50.0% median: 3.44
- 25.0% quartile: 2.1085
- 10.0%: 1.2882
- 2.5%: 0.82985
- 0.5%: 0.759
- 0.0% min: 0.75

**Summary Statistics**

- Mean: 3.9361542
- Std Dev: 2.3863824
- Std Err Mean: 0.0296611
- Upper 95% Mean: 3.9942997
- Lower 95% Mean: 3.8780086
- N: 6473

Ownship Altitude at WCV (10^3 * feet)
Ownship Altitude at WCV – MIT-LL

Quantiles

- 100.0% max: 16.191
- 99.5%: 10.5522
- 97.5%: 10
- 90.0%: 8
- 75.0% quartile: 5
- 50.0% median: 3.471
- 25.0% quartile: 2.14875
- 10.0%: 1.321
- 2.5%: 0.83
- 0.5%: 0.761
- 0.0% min: 0.752

Summary Statistics

- Mean: 3.9732962
- Std Dev: 2.407336
- Std Err Mean: 0.0310734
- Upper 95% Mean: 4.0342113
- Lower 95% Mean: 3.9123812
- N: 6002

Ownship Altitude at WCV (10^3 * feet)
Ownship Altitude at WCV – USAF

![Histogram and density plot of ownship altitude at WCV - USAF. The histogram shows the distribution of altitudes in units of 10^3 feet. Quantiles are provided for various percentiles, along with summary statistics.

**Summary Statistics**
- **Mean**: 4.0715243
- **Std Dev**: 2.5496832
- **Std Err Mean**: 0.0339746
- **Upper 95% Mean**: 4.1381277
- **Lower 95% Mean**: 4.0049209
- **N**: 5632
Conclusion

- Tomorrow I will dig deeper in results for the SARP accepted metrics

- P(NMAC|WCV) is in the ball-park of the tuned 1.5%

- For all UAS mission types each WC definition has similar performance

- TCAS Sensitivity level between 10,000-20,000 feet shows high P(TCAS-RA|WCV) for all WC definitions

- Doesn’t look like TCOA really captures many encounters given LL encounter model and ACES UAS vs. VFR encounters
ACES Unmitigated (and Some Mitigated) Results
Supporting Selection of SARP Well-Clear Definition

Confesor Santiago
8/5/14 – 8/7/14

Supported by Marcus Johnson, Doug Isaacson, and David Hershey
TCAS Model Summary

- As a proxy for whether a TCAS Corrective RA would be presented we use model published by NASA Langley in GNC 2013 paper
- Given UAV encounter, TCAS RA model is computed from standpoint of the intruder (assumed TCAS equipped)
- At every cycle as intruder encounters UAV, we compute if Equation (12) and Equation (14) are true, then its marked as a TCAS RA
- Mathematical model is the same as the one used by NASA and MIT-LL for well-clear definition (modTau and time to co-alt)
- However, altitude dependent thresholds are used based on intruder’s own altitude
- Also, there is a single tau threshold (for SARP we decoupled modTau and time-to-co-altitude)
## TCAS RA Model Altitude Dependent Thresholds

<table>
<thead>
<tr>
<th>Own Altitude (ft)</th>
<th>SL</th>
<th>Tau (sec)</th>
<th>DMOD (nmi)</th>
<th>ZTHR (ft)</th>
<th>ALIM (ft)</th>
<th>HMD (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 - 2350</td>
<td>3</td>
<td>15</td>
<td>0.20</td>
<td>600</td>
<td>300</td>
<td>1215</td>
</tr>
<tr>
<td>2350 - 5000</td>
<td>4</td>
<td>20</td>
<td>0.35</td>
<td>600</td>
<td>300</td>
<td>2126</td>
</tr>
<tr>
<td>5000 - 10000</td>
<td>5</td>
<td>25</td>
<td>0.55</td>
<td>600</td>
<td>350</td>
<td>3342</td>
</tr>
<tr>
<td>10000 - 20000</td>
<td>6</td>
<td>30</td>
<td>0.80</td>
<td>600</td>
<td>400</td>
<td>4861</td>
</tr>
<tr>
<td>20000 - 42000</td>
<td>7</td>
<td>35</td>
<td>1.10</td>
<td>700</td>
<td>600</td>
<td>6683</td>
</tr>
<tr>
<td>&gt; 42000</td>
<td>7</td>
<td>35</td>
<td>1.10</td>
<td>800</td>
<td>700</td>
<td>6683</td>
</tr>
</tbody>
</table>


### Intruder Altitude: 2,000 ft – 17,999ft

Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions
TCAS RA Model

\[
[ (r \leq DMOD) \textbf{or} \\
\quad (0 \leq \tau_{mod} \leq \tau_{thresh}) \textbf{and} \\
\quad (HMD \leq HMD_{thresh})] \\

\textbf{and} \\
\]

\[
[ (h \leq ZTHR) \textbf{or} \\
\quad (0 \leq \tau_{vert} \leq \tau_{thresh})] \\

\text{Preventive:} \quad \text{vertDistCPA} \geq \text{ALIM} \\
\text{Corrective:} \quad \text{vertDistCPA} < \text{ALIM}
P(\text{TCAS-RA}|\text{WCV}) \text{ Unmitigated ACES Result}

Probability of Well-Clear Violation (WCV) with TCAS RA prior to WCV

- Assumption: Intruders (manned) experiencing TCAS-RA’s while UAS DAA system detects it as well-clear is undesirable.

- The smaller the better

- \[
\text{Number of WCVs with TCAS-RA prior to WCV} \leq \frac{\text{Total Number of WCVs}}{2}
\]

- To measure TCAS RA used data from 2 seconds prior to WCV
TCAS-RA Rates Mitigated Result

- While detecting and resolving for WCVs (mitigated), at what rate do we trigger a TCAS-RA?
  - Didn’t have time for break-out of Corr-RA and Prev-RA

| # of TCAS-RA’s | Total UAS Flight Hour |
### P( TCAS-RA | WCV ) Unmitigated ACES Result

<table>
<thead>
<tr>
<th>WC Definition</th>
<th>No. of Corrective RAs</th>
<th>No. of Preventive RAs</th>
<th>No. of Total RAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT-LL</td>
<td>50</td>
<td>27</td>
<td>77</td>
</tr>
<tr>
<td>NASA</td>
<td>224</td>
<td>114</td>
<td>338</td>
</tr>
<tr>
<td>USAF</td>
<td>551</td>
<td>308</td>
<td>839</td>
</tr>
</tbody>
</table>

**Total TCAS-RA Counts for all 8 days simulated**
P(\text{TCAS-RA} | \text{WCV}) Unmitigated ACES Result

<table>
<thead>
<tr>
<th></th>
<th>MIT-LL</th>
<th>NASA</th>
<th>USAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossing</td>
<td>0.7%</td>
<td>4.6%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Head-on</td>
<td>1.3%</td>
<td>5.3%</td>
<td>1.3%</td>
</tr>
<tr>
<td>In-trail</td>
<td>3.2%</td>
<td>7.1%</td>
<td>10.6%</td>
</tr>
</tbody>
</table>

Bearing within WC Def.

Undesirable

Desirable
P(Corr-RA|WCV) Unmitigated ACES Result

![Diagram showing P(Corr-RA|WCV) for different encounter angles and organizations.](image)

**MIT-LL**
- Crossing: 0.4%
- Head-on: 0.9%
- In-trail: 2.2%

**NASA**
- Crossing: 2.8%
- Head-on: 3.7%
- In-trail: 4.8%

**USAF**
- Crossing: 8.7%
- Head-on: 12.7%
- In-trail: 7.4%

**Bearings within WC Def.**

- Red: Crossing
- Green: Head-on
- Blue: In-trail
P(TCAS-RA | WCV) Unmitigated ACES Result

Analyzing P(TCAS-RA | WCV) as a function of TCAS Sensitivity Level 3-6

<table>
<thead>
<tr>
<th>TCAS-Level within WC Def.</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT-LL</td>
<td>0%</td>
<td>0.5%</td>
<td>2.7%</td>
<td>28.1%</td>
</tr>
<tr>
<td>NASA</td>
<td>2.0%</td>
<td>4.0%</td>
<td>10.6%</td>
<td>24.5%</td>
</tr>
<tr>
<td>USAF</td>
<td>4.0%</td>
<td>8.5%</td>
<td>36.8%</td>
<td>56.4%</td>
</tr>
</tbody>
</table>

TCAS-Level

3 = [1,000 – 2,350 ft]  5 = [5,000 – 10,000]
4 = [2,350 – 5,000 ft]  6 = [10,000 – 20,000]

Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions
P(Corr-RA | WCV) Unmitigated ACES Result

Analyzing P(Corr-RA | WCV) as a function of TCAS Sensitivity Level 3-6

<table>
<thead>
<tr>
<th>TCAS-Level within WC Def.</th>
<th>3 = [1,000 – 2,350 ft]</th>
<th>4 = [2,350 – 5,000 ft]</th>
<th>5 = [5,000 – 10,000 ft]</th>
<th>6 = [10,000 – 20,000 ft]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT-LL</td>
<td>0.0% 0.3% 1.9%</td>
<td>0.8% 2.5% 7.9%</td>
<td>2.3% 5.5% 15.7%</td>
<td>41.9%</td>
</tr>
<tr>
<td>NASA</td>
<td>18.0%</td>
<td>15.7%</td>
<td>23.3%</td>
<td></td>
</tr>
<tr>
<td>USAF</td>
<td></td>
<td></td>
<td></td>
<td>41.9%</td>
</tr>
</tbody>
</table>

Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions
P(TCAS-RA | WCV) Unmitigated ACES Result

P(TCAS-RA | WCV)

<table>
<thead>
<tr>
<th></th>
<th>0%</th>
<th>2%</th>
<th>4%</th>
<th>6%</th>
<th>8%</th>
<th>10%</th>
<th>12%</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT-LL</td>
<td>0.8%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NASA</td>
<td>3.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USAF</td>
<td>9.8%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Undesirable

Desirable

Prob. Corr-RA
Prob. Prev-RA

Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions
Illustration of Typical USAF Case with TCAS-RA

- A lot of the time, TCAS-RA model, which is based on modTau, triggers farther out than the length of the horizontal cone for head-on and crossing encounters.
- More of an issue in the modTau, rather than the Z_THR.
NASA vs. MIT-LL Unmitigated TCAS-RA Comparison

- Identified 266 NASA WCVs where:
  - An associated MIT-LL WCV occurred with same encounter pair
  - Altitudes at WCV are within 300 feet of MIT-LL
  - TCAS-RA occurred prior to time of NASA WCV
  - TCAS-RA occurred after MIT-LL WCVs

- These cases are the majority of why $P(\text{TCAS-RA} \mid \text{WCV})$ is higher for NASA WC definition.

```
<table>
<thead>
<tr>
<th>Stat</th>
<th>Value (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>14.9</td>
</tr>
<tr>
<td>Std Dev</td>
<td>9.8</td>
</tr>
<tr>
<td>Median</td>
<td>10</td>
</tr>
<tr>
<td>Min</td>
<td>2</td>
</tr>
<tr>
<td>Max</td>
<td>76</td>
</tr>
<tr>
<td>N</td>
<td>266</td>
</tr>
</tbody>
</table>
```

Distribution of (NASA WCV Time – MIT-LL WCV Time) seconds
At the lower vertical closure rates (hDot), MIT-LL’s 700 feet ZTHR protects against TCAS-RA at 600 feet

97.5% of the WCVs occur below 10,000ft; TCAS uses at 25 tau threshold there

In case of larger vertical closure rates, TCOA of 20 is within TCAS limits, hence TCAS-RA occurring prior to WCV

MIT-LL’s 700 feet Z_THR equates to ~33.5 seconds TCOA for median hDot = 1253 fpm, which is outside TCAS’s 25 tau threshold, and ~29 seconds TCOA for TCAS-RA model
P(TCAS-RA | WCV) Unmitigated ACES Result

Final Result

<table>
<thead>
<tr>
<th>Probability</th>
<th>MIT-LL</th>
<th>NASA</th>
<th>USAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undesirable</td>
<td>0.8%</td>
<td>1.8%</td>
<td>9.8%</td>
</tr>
<tr>
<td>Desirable</td>
<td>0.4%</td>
<td>3.5%</td>
<td>5.5%</td>
</tr>
</tbody>
</table>

Legend:
- Green: Prob. Corr-RA
- Blue: Prob. Prev-RA
TCAS-RA Rate Mitigated

- NASA: $3.9 \times 10^{-3}$ RA/flt-hour (filtered out anomaly WCVs)

- MIT-LL: $8.47 \times 10^{-4}$ RA/flt-hour (filtered out anomaly WCVs)

- USAF: $1.52 \times 10^{-2}$ RA/flt-hour (filtered out anomaly WCVs)
WCV Rate Unmitigated and WCV/Encounter Rate Mitigated ACES Result
WCV Rate Unmitigated ACES Result

Well-Clear Volume Penetration Rate per Flight Hour

- Intuition tells me the lower the rate the better.
- The complement is interesting, because the higher the rate points to presumably that the well-clear definition is larger, which may make the system safe, however may have negative affect on interoperability to ATC.
- There is a tradeoff here...

<table>
<thead>
<tr>
<th>Number of WCVs</th>
<th>Number of flight hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of SST Encounters where Maneuver is Required</td>
<td>Number of flight hours</td>
</tr>
</tbody>
</table>
WCV Rate Unmitigated ACES Result

Well-Clear Violation Rate per $1 \times 10^3$ flight hours

<table>
<thead>
<tr>
<th>Bearing within WC Def.</th>
<th>MIT-LL</th>
<th>NASA</th>
<th>USAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossing</td>
<td>13.9</td>
<td>15.0</td>
<td>13.7</td>
</tr>
<tr>
<td>Head-on</td>
<td>11.2</td>
<td>11.7</td>
<td>8.9</td>
</tr>
<tr>
<td>In-trail</td>
<td>4.2</td>
<td>4.9</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Bearings: Crossing, Head-on, In-trail
WCV Rate Unmitigated ACES Result

Well-Clear Violation Rate per 1 x 10^3 flight hours

MIT-LL

NASA

USAF

TCAS-RA_Alt within WC Def.

3 = [1,000 – 2,350 ft]  5 = [5,000 – 10,000 ft]

4 = [2,350 – 5,000 ft]  6 = [10,000 – 20,000 ft]

Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions
WCV Rate reveals similar trends within each day for each WC definition.
WCV Rate Unmitigated ACES Result

WCV Rate reveals similar trends within each day for each WC definition.
WCV Rate Unmitigated ACES Result

Well-Clear Violation Rate per $1 \times 10^2$ flight hours

Mission Type

*Aggregate at $\sim 3$ WCV per flt-hour
WCV Rate Unmitigated ACES Result

Flight hours per mission type within each day simulated

<table>
<thead>
<tr>
<th>Mission Type</th>
<th>Flight Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>AirQuality</td>
<td>2,000</td>
</tr>
<tr>
<td>AirTaxi_Cirrus</td>
<td>6,000</td>
</tr>
<tr>
<td>AirTaxi_Mustang</td>
<td>1,000</td>
</tr>
<tr>
<td>AtmosphericSampling</td>
<td>5,000</td>
</tr>
<tr>
<td>Cargo</td>
<td>3,000</td>
</tr>
<tr>
<td>FloodMapping</td>
<td>4,000</td>
</tr>
<tr>
<td>StratFireMission</td>
<td>2,000</td>
</tr>
<tr>
<td>TactFireMission</td>
<td>2,000</td>
</tr>
</tbody>
</table>
Well-Clear Violation Rate per $1 \times 10^2$ flight hours

WCV Rate reveals similar trends within each day for each WC definition.
WCV Rate Mitigated ACES Result

Final Result

<table>
<thead>
<tr>
<th>WCD</th>
<th>WCV_rate (flt-hours)</th>
<th>SST_rate (flt-hours)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA</td>
<td>$1.97 \times 10^3$</td>
<td>$1.30 \times 10^1$</td>
</tr>
<tr>
<td>MIT-LL</td>
<td>$1.55 \times 10^3$</td>
<td>$1.05 \times 10^1$</td>
</tr>
<tr>
<td>USAF</td>
<td>$5.60 \times 10^3$</td>
<td>$1.76 \times 10^1$</td>
</tr>
</tbody>
</table>

* SST_rate is the rate in which mitigation was needed, i.e. crossing SST

- For all WC definitions mitigation was able to reduce WCV rate by an order of magnitude (100s of flt-hours to 1000s flt-hours)
- Similar to WCV rate in unmitigated, the rate of “requiring” self-separation maneuver is about the same
- NASA and MIT-LL in ballpark, USAF is a couple multiples larger
Miss Distances at CPA
and
Minimum Time Until NMAC from WCV

Unmitigated ACES Result
Miss Distances at CPA

- Intuition tells me the higher the miss distances the better.
- Although, based on unmitigated encounters only, miss distances may not be a good indicator of WC definition performance.
- Two definitions of CPA:
  - Minimum slant range between ownship and intruder
  - Minimum slant range normalized for NMAC 500ft hSep and 100ft vSep (5-to-1 ratio)
Minimum Time Until NMAC from WCV

- Intuition tells me the higher the minimum time until NMAC the better.
- In other words, the more time between becoming a WCV to becoming NMAC the “safer”.
- Since the unmitigated $P(\text{NMAC}|\text{WCV})$ and WCV rate is about the same, this is a way to analyze that not every WCV is created equal. Which definition is generally closer to an NMAC.
- Not only is minimum shown, but also the distribution.

$$\text{Min (NMAC\_time – WCV\_time)}$$
Miss distances for NASA and MIT-LL perform as expected given their specific DMOD/HMD

USAF without a miss distance filter at CPA results in larger HMDs
• Miss distances for NASA and MIT-LL perform as expected given their specific DMOD/HMD
• USAF without a miss distance filter at CPA results in larger HMDs
Minimum Time Until NMAC from WCV (sec)

**Stats**

<table>
<thead>
<tr>
<th></th>
<th>NASA</th>
<th>MIT-LL</th>
<th>USAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum</td>
<td>238</td>
<td>232</td>
<td>216</td>
</tr>
<tr>
<td>3-rd quartile</td>
<td>52.5</td>
<td>47.5</td>
<td>44</td>
</tr>
<tr>
<td>median</td>
<td>42</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>1-st quartile</td>
<td>34</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>minimum</td>
<td>16</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>Mean</td>
<td>50.0</td>
<td>49.2</td>
<td>40.4</td>
</tr>
<tr>
<td>Std Dev</td>
<td>37.1</td>
<td>35.9</td>
<td>37.2</td>
</tr>
<tr>
<td>N</td>
<td>75</td>
<td>74</td>
<td>72</td>
</tr>
</tbody>
</table>

Overview of ACES Simulation for Evaluating SARP Well-Clear Definitions
NASA Min. Time Until NMAC from WCV

- NASA WCV case for minimum time until NMAC, and how it compares to similar case for other WC definitions.

<table>
<thead>
<tr>
<th>WCD</th>
<th>Time To NMAC (sec)</th>
<th>hSepWCV (ft)</th>
<th>vSepWCV (ft)</th>
<th>modTau (sec)</th>
<th>TCOA (sec)</th>
<th>encAngle (deg)</th>
<th>rDot (knots)</th>
<th>hDot (fpm)</th>
<th>ownAlt (ft)</th>
<th>intrAlt (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA</td>
<td>16</td>
<td>11,222</td>
<td>476</td>
<td>11.7</td>
<td>18.2</td>
<td>146.4</td>
<td>-241</td>
<td>-1,572</td>
<td>3,036</td>
<td>2,560</td>
</tr>
<tr>
<td>MIT-LL</td>
<td>24</td>
<td>16,715</td>
<td>686</td>
<td>22.9</td>
<td>26.1</td>
<td>146.4</td>
<td>-241</td>
<td>-1,572</td>
<td>3,245</td>
<td>2,560</td>
</tr>
<tr>
<td>USAF</td>
<td>14</td>
<td>9,849</td>
<td>424</td>
<td>-</td>
<td>-</td>
<td>146.4</td>
<td>-241</td>
<td>-1,572</td>
<td>2,984</td>
<td>2,560</td>
</tr>
</tbody>
</table>

Take-away:
- Given -1,572 FPM vertical closure rate the MIT-LL WC definition is triggered 8 seconds prior to NASA’s, because when violating the TCOA is above 20 seconds (26.1 seconds).
- USAF time to NMAC is later due to smaller vSep requirement
MIT-LL Min. Time Until NMAC from WCV

- MIT-LL WCV case for minimum time until NMAC, and how it compares to similar case for other WC definitions.

<table>
<thead>
<tr>
<th>WCD</th>
<th>Time To NMAC (sec)</th>
<th>hSepWCV (ft)</th>
<th>vSepWCV (ft)</th>
<th>modTau (sec)</th>
<th>TCOA (sec)</th>
<th>encAngle (deg)</th>
<th>rDot (knots)</th>
<th>hDot (fpm)</th>
<th>ownAlt (ft)</th>
<th>intrAlt (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA</td>
<td>22</td>
<td>4,600</td>
<td>842</td>
<td>0</td>
<td>18.9</td>
<td>23.7</td>
<td>-74.0</td>
<td>-2,673</td>
<td>4,858</td>
<td>4,016</td>
</tr>
<tr>
<td>MIT-LL</td>
<td>18</td>
<td>3,779</td>
<td>666</td>
<td>0</td>
<td>15.2</td>
<td>23.6</td>
<td>-72.9</td>
<td>-2,616</td>
<td>4,734</td>
<td>4,069</td>
</tr>
<tr>
<td>USAF</td>
<td>12</td>
<td>2,250</td>
<td>408</td>
<td>-</td>
<td>-</td>
<td>23.5</td>
<td>-71.6</td>
<td>-2,568</td>
<td>4,549</td>
<td>4,141</td>
</tr>
</tbody>
</table>

Take-away:
- Given -2,673 FPM vertical closure rate the NASA definition is triggered 4 seconds prior to NASA’s, because when violating the TCOA is below 20 seconds (15.2 seconds).
- USAF time to NMAC is later due to smaller vSep requirement, and large vertical closure rate
USAF Min. Time Until NMAC from WCV

- USAF WCV case for minimum time until NMAC, and how it compares to similar case for other WC definitions.

<table>
<thead>
<tr>
<th>WCD</th>
<th>Time To NMAC (sec)</th>
<th>hSepWCV (ft)</th>
<th>vSepWCV (ft)</th>
<th>modTau (sec)</th>
<th>TCOA (sec)</th>
<th>encAngle (deg)</th>
<th>rDot (knots)</th>
<th>hDot (fpm)</th>
<th>ownAlt (ft)</th>
<th>intrAlt (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA</td>
<td>36</td>
<td>12,030</td>
<td>337</td>
<td>27.7</td>
<td>0</td>
<td>34.9</td>
<td>-114.2</td>
<td>90.9</td>
<td>1,957</td>
<td>1,619</td>
</tr>
<tr>
<td>MIT-LL</td>
<td>36</td>
<td>12,030</td>
<td>337</td>
<td>32.8</td>
<td>0</td>
<td>34.9</td>
<td>-114.2</td>
<td>90.9</td>
<td>1,957</td>
<td>1,619</td>
</tr>
<tr>
<td>USAF</td>
<td>8</td>
<td>2,916</td>
<td>122</td>
<td>-</td>
<td>-</td>
<td>35.8</td>
<td>-112.5</td>
<td>-345.6</td>
<td>1,851</td>
<td>1,729</td>
</tr>
</tbody>
</table>

Take-away:
- NASA and MIT-LL triggered much earlier than (24 sec) USAF due to modTau
- Due to smaller vSep requirement of USAF, and the fact that the ownship and intruder suddenly accelerate towards each in vertical closure rate, time to NMAC is short
  - Note, when NASA and MIT-LL WCV triggered, vertical closure is diverging
Minimum Time Until NMAC from WCV

**Final Result**

<table>
<thead>
<tr>
<th>WCD</th>
<th>Min Time Until NMAC (sec)</th>
</tr>
</thead>
<tbody>
<tr>
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