Low C-SWaP Well Clear Trade Study Preliminary Results

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Objectives

- Investigate trade space for Detect and Avoid (DAA) Well Clear definition for UAS with low cost, size, weight, and power (Low C-SWaP) sensors that detect and track non-cooperative aircraft

- Recommend candidate DAA Well Clear (DWC) definition(s) for the SC-228 to consider
• Between non-cooperative aircraft and UAS with low C-SWaP sensors that are
  – Below 10,000 ft and above 500 ft AGL
  – During extended operations in classes D, E (non-terminal), or G (non-terminal), or
  – During transit operations in classes B and C
  – For UAS within a certain speed range
Preliminary Results: December 5, 2017 at SC-228 F2F

Final results: February 20, 2018
Performance Metrics

- **Unmitigated collision risk**
  - The probability of a near mid-air collision (NMAC) given a loss of DWC
  - Denoted as $\text{P}(\text{NMAC}|\text{LoWC})$

- **Maneuver initiation point**
  - Latest point for ownship to maneuver to maintain DWC

- **Bearing, elevation, range, and closure rate distribution of intruders at the Loss of Well Clear (LoWC)**

- **CPA miss distance/time given LoWC**
Selection Workflow

DWC Definitions

ACES Generated Encounters

Target $P(\text{NMAC} | \text{LoWC})$ Values

Encounter Model

Select DWC Definitions

Additional Performance Metrics

Maneuver Initiation Point
DWC Definitions

- DWC types and threshold values (* for threshold)
  - **DWC1**: $h^*$, $HMD^*$, $\text{modTau}^*$
  - **DWC2**: $h^*$, $HMD^*$, $t_{pz}^*$
  - **DWC3**: Static hockey puck: $h^*$, $R^*$
  - **DWC4**: Dynamic hockey puck: $h^*$, $R^*(\dot{r}) = a^* + \dot{r} \times b^*$

<table>
<thead>
<tr>
<th>Type</th>
<th>$h^*$ (ft)</th>
<th>$HMD^*$ (ft)</th>
<th>$\text{modTau}^*$ (sec)</th>
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<tbody>
<tr>
<td>DWC1</td>
<td>450</td>
<td>[1000, 9000]</td>
<td>[0, 35]</td>
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<tr>
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<th>$HMD^*$ (ft)</th>
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<th>Type</th>
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<td>DWC3</td>
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<tr>
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<th>$a^*$ (ft)</th>
<th>$b^*$ (sec)</th>
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<tr>
<td>DWC4</td>
<td>450</td>
<td>[1000, 6000]</td>
<td>[0, 20]</td>
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</table>
ACES Generated Encounters
ACES Encounters Considered

- 3.3 million encounters
  - between projected UAS trajectories and recorded VFR traffic from 21 days in year 2012
  - Cooperative aircraft regarded as surrogates of non-cooperative
- About 60% of the encounters are considered “low C-SWaP”
- 708 NMACs (for low C-SWaP)
- Number of LoWCs varies
Speed Distribution of Ownship

Probability distribution of Ownship Airspeed (knots)
Speed Distribution of Intruder

![Graph showing the probability distribution of intruder airspeeds. The x-axis represents Intruder Airspeed (knots) ranging from 0 to 460, and the y-axis represents Probability ranging from 0.00 to 0.10. The graph is centered around airspeeds of 100 knots, with a peak probability at around 0.08.]
Altitude Distribution of Ownship

Probability

0.03 0.05 0.08 0.10 0.13 0.15

0 1000 3000 5000 7000 9000 11000 13000 15000 17000 19000

Ownship Altitude (MSL)
Altitude Distribution of Intruder VFR Aircraft
Experimental Matrix

- **Modified Tau DWC**
  - Total 45 settings
  - ModTau threshold (5 levels): 0, 8, 15, 25, 35 (sec)
  - HMD threshold (9 levels): 1000, 1500, 2000, 2500, 3000, 3500, 4000, 6500, 9000 (ft.)
  - Altitude threshold (1 level): 450 (ft)

- **Time to Protected Zone (TPZ) DWC**
- **Static Cylinder DWC**
- **Dynamic Cylinder DWC**
P(NMAC|LoWC) is between 2% and 5%
  – Phase 1 P ~ 2.2%
  – Previous Lincoln Lab work recommended 5%

• Maneuver initiation point range as small as possible
Unmitigated Collision Risk $P(NMAC|\text{LoWC})$
Maneuver Initiation Point
• 2PAIRS
• Head-on, co-altitude encounter
• Only horizontal maneuver is considered
• Constant roll rate, steady-state turn rate, ownship speed, and intruder speed
• range = f (DWC, ownship speed, intruder speed)
• UAS (Ownship) speed 40 to 100 kts
• Turn rate 6 deg/s (3 and 12 deg/s results also looked at)
“Sweet Spot”

Velocity 40-100 KTAS Turn Rate 6 deg/sec

- Maneuver Initiation Range (nmi)
- Unmitigated Collision Risk

P = 5%

HMD Threshold (ft)

Tau Mod Threshold (sec)
Summary

• “Sweet spot” HMD* 2000 to 2500 ft, modTau 0 to 15 sec
  – P(NMAC|LoWC) ~ 5%
  – Maneuver initiation range ~ 2 nmi (given 6 deg/s turn rate)
  – Compared to low C-SWaP radar range that may be below 3 nmi

• To further reduce range requirements, we may
  – Go above 5% for P(NMAC|LoWC)
  – Require a higher turn rate at 40 kts (e.g., 12 deg/s)
  – Increase minimum ownship speed from 40 kts
  – Mandate a minimum turn speed > 40 kts for ownship

• Other considerations
  – Range and bearing distribution trade-off
Next Steps

• ACES encounter analysis
  – Apply additional filters
  – Analyze additional performance metrics
  – Analyze results from other DWC types
  – Analyze results from Phase 1 UAS (speed and altitude)

• Encounter model
  – Parallel work to ACES analysis
  – Comparison to ACES results for validation

• Candidate DWC definitions for further evaluations
  – May propose more than one (possibly two) definitions varying by P values

• Fast time simulation 2 for alerting and sensor (May 2018)
• HITL for low C-SWaP (Nov. 2018)
Encounter Model
• Assumptions
  – Phase 1 VFR traffic
  – Same encounter set used to define SARP WCV definition
    • Enables comparison with previous results
  – Encounters are between two aircraft, where one or both aircraft do not have transponders, or both are VFR (1200 code)
  – Looking at full encounter set (<300 kts) and subset of encounters with speeds < 100 kts

Results are preliminary. No conclusions should be drawn from the results until they can be further analyzed and understood.
Preliminary Comparison Results

- DWC3
  - $P(\text{NMAC|LoWC})$ vs. $R^*$ using ACES
  - $P(\text{NMAC|LoWC})$ vs. $R^*$ using the encounter models

Threshold for $\tau$ is 5 sec for encounter model results

Collision Risk: $0.02 \sim 0.05$
ACES Encounter Filters

• Criteria
  – Manned aircraft speed: at or below 170 kts
  – UAS speed: between 30 and 100 kts
  – Altitude - at or below 10,000 ft mean sea level (MSL)
  – Altitude – at or above 500 ft MSL

• Additional filters to be implemented
  – Airspace class
  – Altitude - above 500 ft above ground level (AGL)
• Can Phase 1 UAS have an alternative DWC for non-cooperative aircraft? Can a single DWC be defined for both Phase 1 UAS and low C-SWaP UAS (for non-cooperative aircraft)?
Select Simulation Schedule

• Well clear trade study (Fast Time 1)
  – Preliminary Results briefing: December 5, 2017 at SC-228 F2F
  – Final results briefing: February 20, 2017

• Alerting and surveillance uncertainty (Fast Time 2)
  – Planning starts in December 2017
  – Data collection May 2018
  – Final results September 2018

• HITL
  – Planning starts in April 2018
  – Data collection October 2018
  – Final results February 2019

• Closed loop (Fast Time 3)
  – Planning January 2019
  – Data collection June 2019
  – Final results November 2019
VFR Traffic

• 21 days across 4 seasons in 2012 (24 hours each day)

<table>
<thead>
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<th>January 2012</th>
<th>April 2012</th>
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<tr>
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<th>July 2012</th>
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<td>21 22 23 24 25 26 27</td>
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<tr>
<td>29 30 31</td>
<td>28 29 30 31</td>
</tr>
</tbody>
</table>

• Manned IFR data: ASDI (Airspace Situation Display to Industry)
• Manned VFR data: 84th Radar Evaluation Squadron (RADES) Air Defense Radar Data
  – Both cooperative and non-cooperative VFR traffic that satisfy speed range (<170 kts) and target airspace (< 10,000 ft and non-terminal operations) will be used
### UAS Missions

<table>
<thead>
<tr>
<th>Number</th>
<th>Mission Types</th>
<th>Airspace</th>
<th>UAS Group</th>
<th>Cruise Altitude</th>
<th>Cruise Speed (KTAS)</th>
<th>Flight Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aerial Imaging and Mapping</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition</td>
<td>Aerosonde Mk 4.7</td>
<td>3000 ft. AGL</td>
<td>44 to 51</td>
<td>Radiator-grid pattern or circular pattern</td>
</tr>
<tr>
<td>2</td>
<td>Air Quality Monitoring</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition</td>
<td>Shadow-B (RQ7B)/NASA Sierra</td>
<td>4k, 5k, and 6k ft AGL</td>
<td>74 to 89</td>
<td>Radiator-grid pattern</td>
</tr>
<tr>
<td>3</td>
<td>Airborne Pathogen Tracking</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition</td>
<td>Shadow-B (RQ7B)/NASA Sierra</td>
<td>3,000 ft., 5,000 ft. and 10,000 ft. AGL</td>
<td>72 to 97</td>
<td>Radiator-grid pattern</td>
</tr>
<tr>
<td>4</td>
<td>Flood Inund. Mapping</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G</td>
<td>Aerosonde Mk 4.7</td>
<td>4,000 ft. AGL</td>
<td>46 to 51</td>
<td>Grid pattern</td>
</tr>
<tr>
<td>5</td>
<td>Flood Stream Flow</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G</td>
<td>Aerosonde Mk 4.7</td>
<td>4,000 ft. AGL</td>
<td>46 to 51</td>
<td>Grid pattern and/or along stream direction</td>
</tr>
<tr>
<td>6</td>
<td>Law Enforcement</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition</td>
<td>Aerosonde Mk 4.7</td>
<td>3,000 ft. AGL</td>
<td>44 to 51</td>
<td>Three types of pattern: 1) grid pattern, 2) random, 3) outward spiral</td>
</tr>
<tr>
<td>7</td>
<td>Point Source Emission</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G</td>
<td>Shadow-B</td>
<td>3,000 ft. AGL</td>
<td>72 to 80</td>
<td>Grid pattern and/or along stream direction</td>
</tr>
<tr>
<td>8</td>
<td>Spill Monitoring</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G</td>
<td>Shadow-B/Sierra</td>
<td>3,000 ft. to 13,000 ft. AGL</td>
<td>72 to 93</td>
<td>Up and down-wind flights in a radiator-grid pattern, Round-the-clock</td>
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<tr>
<td>9</td>
<td>Tactical Fire Monitoring</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition</td>
<td>ScanEagle/Shadow-B</td>
<td>3,000 ft. AGL</td>
<td>72 to 75</td>
<td>Circular flight path following the perimeter of a wildfire</td>
</tr>
<tr>
<td>10</td>
<td>Traffic Monitoring</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition</td>
<td>Shadow-B</td>
<td>1,500 ft. AGL</td>
<td>58 to 84</td>
<td>Geo-spatial monitoring flight path</td>
</tr>
<tr>
<td>11</td>
<td>Wildlife Monitoring</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G</td>
<td>Aerosonde Mk 4.7</td>
<td>3,000 ft. AGL</td>
<td>44 to 51</td>
<td>Radiator-grid pattern</td>
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<td>12</td>
<td>News Gathering</td>
<td>Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition</td>
<td>Aerosonde Mk 4.7</td>
<td>1,500 ft. to 3,000 ft. AGL</td>
<td>44 to 51</td>
<td>Random-path: e.g., police-chase; Circular orbit:</td>
</tr>
</tbody>
</table>
VFR Intruder Traffic

• It is assumed that unmanned aircraft will be equipped with onboard radar, active surveillance transponder (Mode C/S), and ADS-B surveillance system to detect cooperative and non-cooperative intruder aircraft.

• Types of intruders with different equipage
  – Intruders operating under IFR (Cooperative)
  – Intruders operating under VFR (Cooperative and Non-cooperative)

<table>
<thead>
<tr>
<th>Intruder Aircraft</th>
<th>Transponder Equipage</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooperative AC 1</td>
<td>ADS-B Out (1090 or UAT)</td>
<td>71%*</td>
</tr>
<tr>
<td>Cooperative AC 2</td>
<td>Mode C transponder Only</td>
<td>14%*</td>
</tr>
<tr>
<td>Non-Coop AC</td>
<td>No Transponder (or Mode A transponder)</td>
<td>15%*</td>
</tr>
</tbody>
</table>

*Based on OSED document: Table A-1. Intruder Equipage Assumptions Post-2020
Simulation Platform

• **Airspace Concept Evaluation System (ACES) and JADEM Fast-time Simulation Framework**
  – Simulate NAS-wide air traffic operations of UAS, IFR, and VFR traffic

• Various realistic encounters between UAS and IFR/VFR manned traffic in civil airspace
  – Manned IFR traffic: ASDI (Airspace Situation Display to Industry) data
  – Historical cooperative and non-cooperative VFR traffic
    • The 84th Rader Evaluation Squadron (RADES) data
  – Proposed UAS Flights
    • 12 different types of UAS missions generated by Intelligent Automation Inc.

• **UAS DAA Alerting and Guidance System [JADEM]**
  – Higher fidelity surveillance model: Honeywell sensor models
  – DAIDALUS DAA alerting and guidance algorithm
Cooperative Traffic

Coop Data 7/06
values capped at 10 hours