Low C-SWaP Detect and Avoid: Defining Well Clear

Air Traffic Control Workshop 2019
Christine Serres
21 November 2019

Sponsor: Gilbert Wu, NASA Ames
Detect and Avoid is the capability to remain well clear and avoid collisions.

RTCA-228 Phase 1
Concept of DAA:

- Acquire Intruders
- Suggestive Guidance to Remain Well Clear
- Directive Guidance Issued to Avoid Collision

*Notional Volumes
Does not indicate any temporal component that may exist

Detect and Avoid

NMAC – Near Mid-Air Collision
Cooperative – Transponder/ADS-B equipped
**Well Clear**

- **Well Clear** is a separation standard required for UAS to satisfy FAR 91.111 and 91.113

  - **FAR 91.111:** ...not operate so close to another aircraft as to create a collision hazard
  - **FAR 91.113:** Vigilance shall be maintained ... so as to see and avoid other aircraft ... pilots shall alter course to pass well clear of other air traffic

- Detect and Avoid (DAA) Systems provide surveillance, alerts, and guidance to Unmanned Aircraft Systems (UAS) to help them maintain well clear of other aircraft and avoid collisions
  - Designed as an alternative means of compliance for see-and-avoid regulations
  - DAA systems are essential for safe integration of UAS into the National Airspace System (NAS)
Classes of UAS
Example Attributes Relevant to DAA and Well Clear

**Large UAS**
- Example: Reaper
- Size: Business jet and up
- Flight in all airspace
- Integrate with all aircraft including TCAS equipped
- DAA requirements developed through RTCA
- Phase 1 DAA MOPS published – non-terminal ops in Class D/E/G – includes DAA radar
- Phase 2 includes terminal

---

**Low Size Weight Power UAS**
- Example: TigerShark
- Size: >55 lbs to several thousand pounds
- Flight below 10,000 ft
- Carry ADS-B but may not TCAS
- DAA requirements developed through RTCA
- Phase 2 MOPS includes Low C-SWAP UAS
- Too small to carry Phase 1 DAA radar

---

**Small UAS**
- Example: Raven
- Size: 55 lbs and below
- Flight at very low altitude
  - Currently < 400 ft
- Ops currently under Part 107
- Regulations for expanded ops in development
  - FAA IPPs
- DAA requirements developed through ASTM
  - In process

**Focus of Talk**
Previous Work

- In 2015, Sense and Avoid Science and Research Panel (SARP) developed a Well Clear Definition for large unmanned aircraft using distance and time, based on
  - Safety: Required Prob(NMAC) given a well clear violation < 5%, 2.2% achieved
  - Suitability*: Low rates of triggering a TCAS alert on the intruder aircraft
  - Intruder TCAS alerts were a major driver
  - RTCA SC-228 adopted definition within Phase 1 DAA MOPS (DO-365)
  - Led to DAA air-to-air radar requirements
  - Relaxing well clear definition and radar requirements may be possible when intruder is not equipped with TCAS

\[
\text{Phase 1 DAA well clear adopted by FAA}
\]

- \( h = \pm 450 \text{ ft} \)
- \( \text{HMD} = 4000 \text{ ft} \)
- \( \tau_{mod}^* \) (estimated time to 4000 ft) = 35 sec

\[\begin{align*}
\text{NMAC} & \quad \text{near mid-air collision (HMD \leq 500 ft., VMD \leq 100 ft.)} \\
\text{LoWC} & \quad \text{loss of well clear} \\
\text{HMD} & \quad \text{horizontal miss distance}
\end{align*}\]

* Various other suitability metrics were used as well
Objective: Define alternative DAA Well Clear (DWC) for UAS encountering aircraft without a transponder (noncooperative)

- Phase 1 DWC accounts for TCAS II alerts (Resolution Advisories)
  - Definition is very safe but maybe unnecessarily large for noncooperative aircraft, which do not have TCAS

- Low C-SWaP UAS are too small or budget-constrained to carry the large, high-power radar required by the Phase 1 MOPS

- A noncoop DWC may enable low C-SWaP UAS operations by reducing noncooperative surveillance requirements compared to RTCA SC-228 Phase 1

- Noncoop DWC is anticipated to be applicable to both Phase 1 UAS and low C-SWaP UAS encountering noncooperative aircraft
Outline

• Background

• Defining Well Clear Separation for Low C-SWaP UAS Encountering Noncooperative Traffic
  – Approach
  – Results

• Summary
DAA Well Clear Analysis

**Objective:** identify and assess DAA Well Clear (DWC) candidates based on safety and operational suitability metrics

**Approach:** Monte Carlo simulation* using one million realistic encounters to evaluate unmitigated (without DAA) and mitigated (with DAA) performance against noncooperative intruders

---

**Without DAA**
- Analysis does not include response to a Detect and Avoid system
- Evaluates baseline collision risk
- Narrows tradespace

**With DAA**
- Analysis includes DAA response using DAIDALUS algorithm
- Validates collision risk of DAA equipped aircraft

---

* Assumes perfect surveillance

---

**Notional**

<table>
<thead>
<tr>
<th>τmod</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**DAIDALUS**
(With modified parameters for each DWC)

---

- **Risk Ratio**
  - **Induced**
  - **Unresolved**

---

**Notional**

- **DWC1:** 0.021
- **DWC2:** 0.021
- **DWC3:** 0.028
- **DWC4:** 0.016

---

* Assumes perfect surveillance
Encounter Model
Low C-SWAP UAS vs Noncooperative Intruders

- Encounter models generate random aircraft trajectories that are statistically representative of noncooperative trajectories observed from radar data
- Results may not apply to higher speed UAS

VFR – Visual Flight Rules (non-TCAS equipped aircraft)
NAS – National Airspace
Mitigated Metrics*

- **Safety metrics indicate whether desired separation is achieved**
  - Risk ratio and loss of well clear ratios:
    \[
    \frac{P(\text{NMAC or LoWC}|\text{encounter, with mitigation})}{P(\text{NMAC or LoWC}|\text{encounter, without mitigation})}
    \]
  - Ratio less than 1 indicates that the mitigated system reduces the risk of NMAC or LoWC; e.g., risk ratio of 0.1 indicates 90% reduction in risk

- **Operational suitability metrics indicate the appropriateness and severity of alerts required to remain well clear**
  - Alert ratio:
    \[
    \frac{P(\text{Alert}|\text{encounter, with mitigation})}{P(\text{NMAC}|\text{encounter, without mitigation})}
    \]
  - Alert ratio measures the alert frequency relative to the nominal NMAC frequency

Encounter Timeline:

- Suggestive guidance to remain well clear
- Directive guidance to avoid collision

*Additional metrics were computed but are not shown here

NMAC – Near mid-air collision (HMD ≤ 500 ft, VMD ≤ 100 ft)
LoWC – Loss of Well Clear
Outline

• Background

• Defining Well Clear Separation for Low C-SWaP UAS Encountering Noncooperative Traffic
  – Approach
  – Results

• Summary
Unmitigated Analysis: Trade Space Down Selection

- DWC Candidates chosen based on trade study [1] of potential DWC based on:
  - P - collision risk without DAA
  - MIR - maneuver initiation range

- Results
  - DWC1 achieves minimum MIR for 5% unmitigated collision risk
  - DWC2 is simple because it does not have a time component
  - DWC3 was proposed for terminal area UAS operations
  - DWC4 achieves an unmitigated collision risk smaller than 5%

<table>
<thead>
<tr>
<th></th>
<th>DWC1</th>
<th>DWC2</th>
<th>DWC3</th>
<th>DWC4</th>
<th>Phase 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMD*</td>
<td>2000 ft</td>
<td>2200 ft</td>
<td>1500 ft</td>
<td>2500 ft</td>
<td>4000 ft</td>
</tr>
<tr>
<td>τ\text{mod} *</td>
<td>15 s</td>
<td>0 s</td>
<td>15 s</td>
<td>25 s</td>
<td>35 s</td>
</tr>
<tr>
<td>h*</td>
<td>450 ft</td>
<td>450 ft</td>
<td>450 ft</td>
<td>450 ft</td>
<td>450 ft</td>
</tr>
</tbody>
</table>

HMD – Horizontal Miss Distance

System Operating Characteristic for Low C-SWaP Encounters

- SOC allows simultaneous evaluation of safety and operational suitability
- Risk and LoWC ratio are largely insensitive to DWC definition
- HMD appears to have the largest effect on alert ratio
  - DWC1 and DWC3 have the same $\tau_{mod}^*$, but DWC1 alerts more frequently

<table>
<thead>
<tr>
<th></th>
<th>DWC1</th>
<th>DWC2</th>
<th>DWC3</th>
<th>DWC4</th>
<th>Phase 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMD*</td>
<td>2000 ft</td>
<td>2200 ft</td>
<td>1500 ft</td>
<td>2500 ft</td>
<td>4000 ft</td>
</tr>
<tr>
<td>$\tau_{mod}^*$</td>
<td>15 s</td>
<td>0 s</td>
<td>15 s</td>
<td>25 s</td>
<td>35 s</td>
</tr>
</tbody>
</table>

HMD – Horizontal Miss Distance
Effect of Surveillance Range

NMAC Risk Ratios

- DWC 1, 2, 3 are largely insensitive to reduced surveillance ranges
- DWC 4 and Phase 1 experience large increases in risk ratio and loss of well clear ratio when surveillance range is reduced (see 2 NM blue bars)

Loss of Well Clear Ratios

Note: Different y-axis scales

New DWC candidates support surveillance ranges down to 2 NM
Summary

• Well Clear used in RTCA SC-228 Phase 1 is not well suited for encountering noncooperative aircraft
  – Overly conservative against aircraft not equipped with TCAS
  – Results in DAA radar requirements that cannot be met by Low C-SWaP UAS

• Objective was to examine if a smaller Well Clear would be suitable for DAA using low C-SWaP sensors

• Performed simulation analysis of four candidate well clear definitions for low C-SWaP UAS against noncooperative equipped intruders
  – NMAC and LoWC risk not sensitive to DWC parameters examined
  – Safety and operational suitability not dependent on $\tau_{mod}^*$
    • Indicates $\tau_{mod}^*$ may not be necessary

SC-228 selected 2200 ft horizontally, 450 ft vertically for UAS encountering noncooperative aircraft
Bibliography (images)

- MQ-9 Reaper by Lt. Col. Leslie Pratt, source image, public domain
- TigerShark by Ken Ulbirch, source image, NASA
- Raven by USGS, source image, public domain
Future Work

- Develop and validate sensor requirements based on the noncoop DWC
- Human factors evaluation of noncoop DWC
- Safety analyses in the presence of sensor noise
Low C-SWaP UAS

- Typically operate at 500-10,000 ft MSL with speeds at or below 100 kts
- Extended operations in airspace classes D, E (non-terminal), or G (non-terminal) with transit operations in classes B and C
- Missions include air quality monitoring, aerial imaging and mapping, and law enforcement
- Can carry ADS-B and TCAS but typically will not be able to carry the Phase 1 radar (> 50 lbs)
Alerting and Guidance Algorithm

- Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) as reference DAA algorithm
- Parameters for Corrective and Warning based on standard configuration for Phase 1
  - $\tau_{mod}^*$ and $h^*$ are not buffered
  - HMD* for alerting $\sim 1.519 \times$ HMD* for DWC
  - Time to the volume defined by HMD*, $\tau_{mod}^*$, and $h^*$ for alerting
    - 30 seconds for Warning
    - 60 seconds for Corrective
- Guidance based on 7 deg/sec turn rate
- 4 second persistence and 2-of-4 (m of n) alerts
Pilot Response Model

- Use SC-228 pilot model created by Lincoln Laboratory
  - Executed in deterministic mode
    - Always maneuvers horizontally in the direction of the minimum suggested maneuver; turns left if minimum suggestion is inconclusive
    - Follow guidance bands without buffer
  - Timing:
    - Decision updated according to alert state
    - Execution delay after decision: 3 sec
- Analyze horizontal maneuvers only
  - Low-SWAP turn rate: 7 deg/sec
    - Suitable for UAS speeds from 40 to 100 kts

<table>
<thead>
<tr>
<th>Alert Condition</th>
<th>Decision Update Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Alert</td>
<td>24</td>
</tr>
<tr>
<td>Preventive Alert</td>
<td>15</td>
</tr>
<tr>
<td>Corrective Alert</td>
<td>9</td>
</tr>
<tr>
<td>Warning Alert</td>
<td>9</td>
</tr>
<tr>
<td>Regain DAA Well Clear Guidance</td>
<td>3</td>
</tr>
</tbody>
</table>
Safety Ratios

- Risk ratios are comparable among the DWC candidates
  - No statistically significant difference for risk ratios
- DWC1 and DWC2 have the lowest loss of well clear ratios

Risk ratios largely independent of DWC definition
Alerting Time and Range

- Time and range of alert are for any alert level
- Time of alert is the projected time to CPA when the alert occurs (to prevent DAA maneuvering from affecting the metric)
- Alerting time and range driven more by ModTau than HMD (DWC 1/2 difference)
- LoWCs have later alert times and ranges: indicates that LoWCs may be caused by late nominal (non-DAA) maneuvers