Low C-SWaP Detect and Avoid: Defining Well Clear

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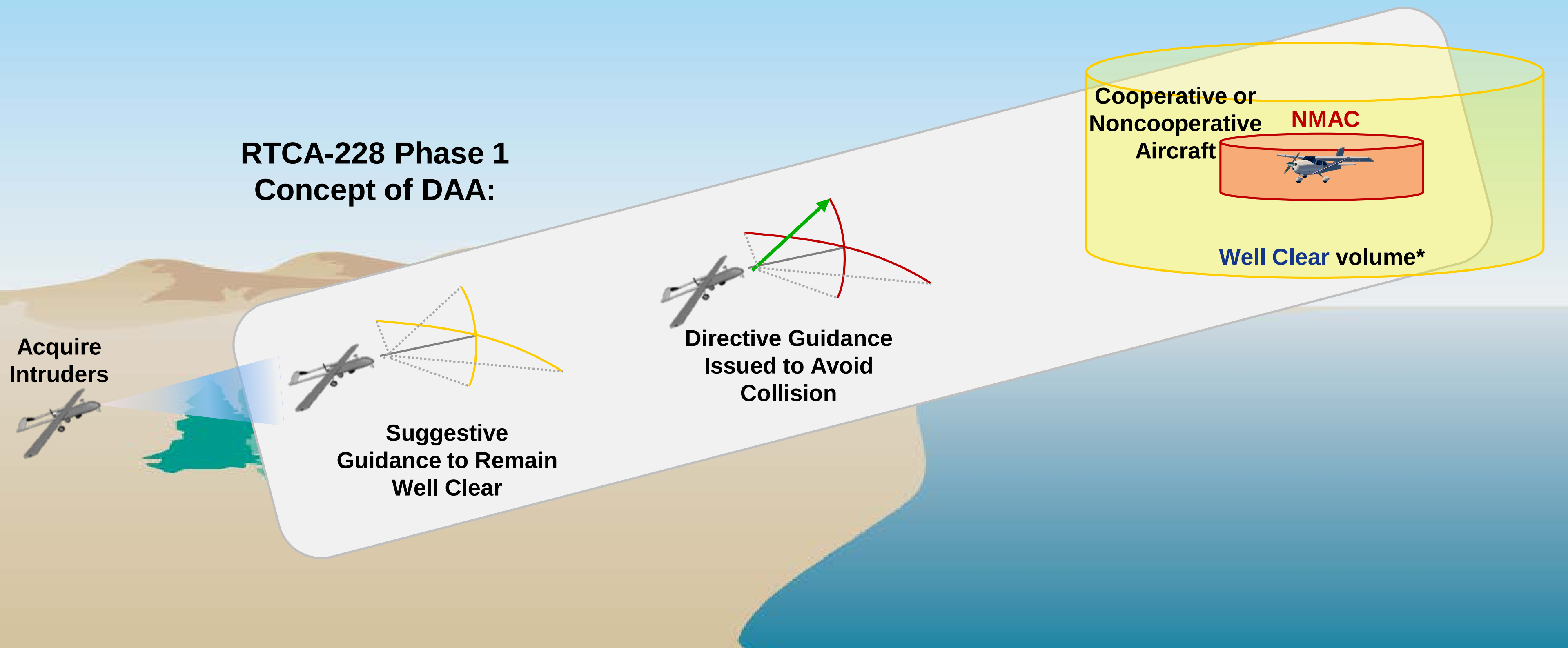
Sponsor: Gilbert Wu, NASA Ames

Detect and Avoid

Detect and Avoid is the capability to remain well clear and avoid collisions



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

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)**

FAR – Federal Aviation Regulations

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

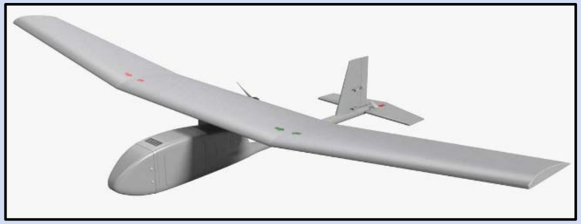
Low Size Weight Power UAS

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

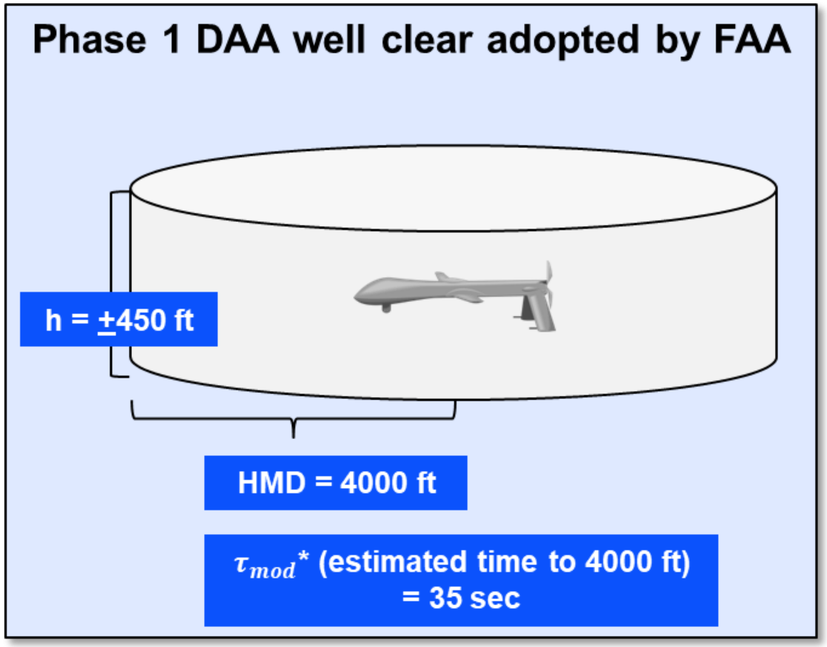


- Size: 55 lbs and below
- Flight at very low altitude
  - Currently < 400 ft
- Ops currently under Part 107
- Regulations for expanded ops in development
  - FAA IPPs
- DAA requirements developed through ASTM
  - In process

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**



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

*** Various other suitability metrics were used as well**

Phase 2 MOPS
DAA Well Clear Objective

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**

Focus of Talk

MOPS – Minimum Operational Performance Standards
RA – Resolution Advisory
Low C-SWaP – low cost, size, weight, and power

Outline

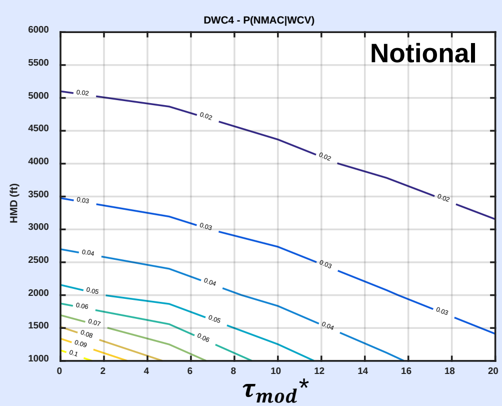
- **Background**
- **Defining Well Clear Separation for Low C-SWaP UAS Encountering Noncooperative Traffic**
  - **Approach**
  - **Results**
- **Summary**

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

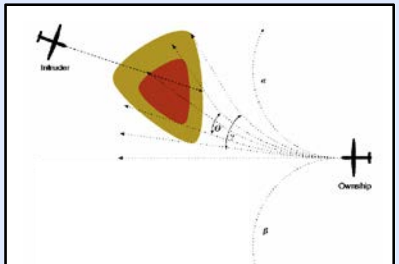
Without DAA

- **Analysis does not include response to a Detect and Avoid system**
- **Evaluates baseline collision risk**
- **Narrows tradespace**

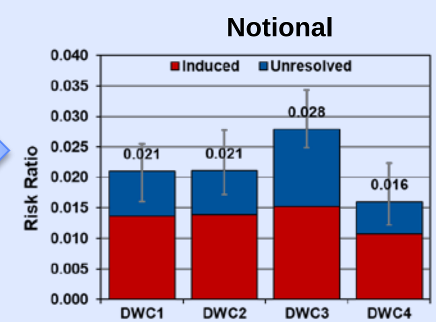


With DAA

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



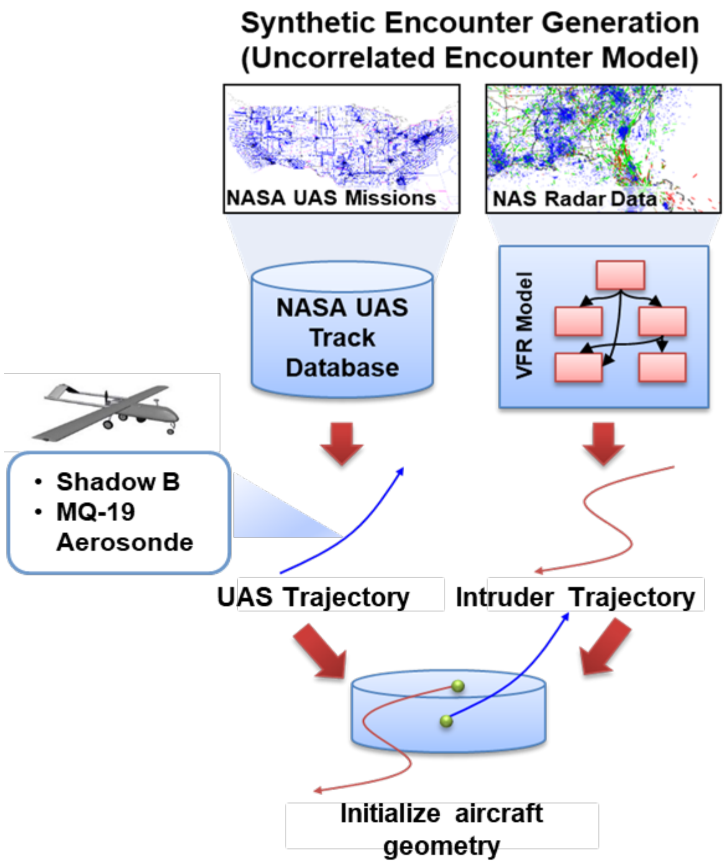
DAIDALUS
(With modified parameters for each DWC)

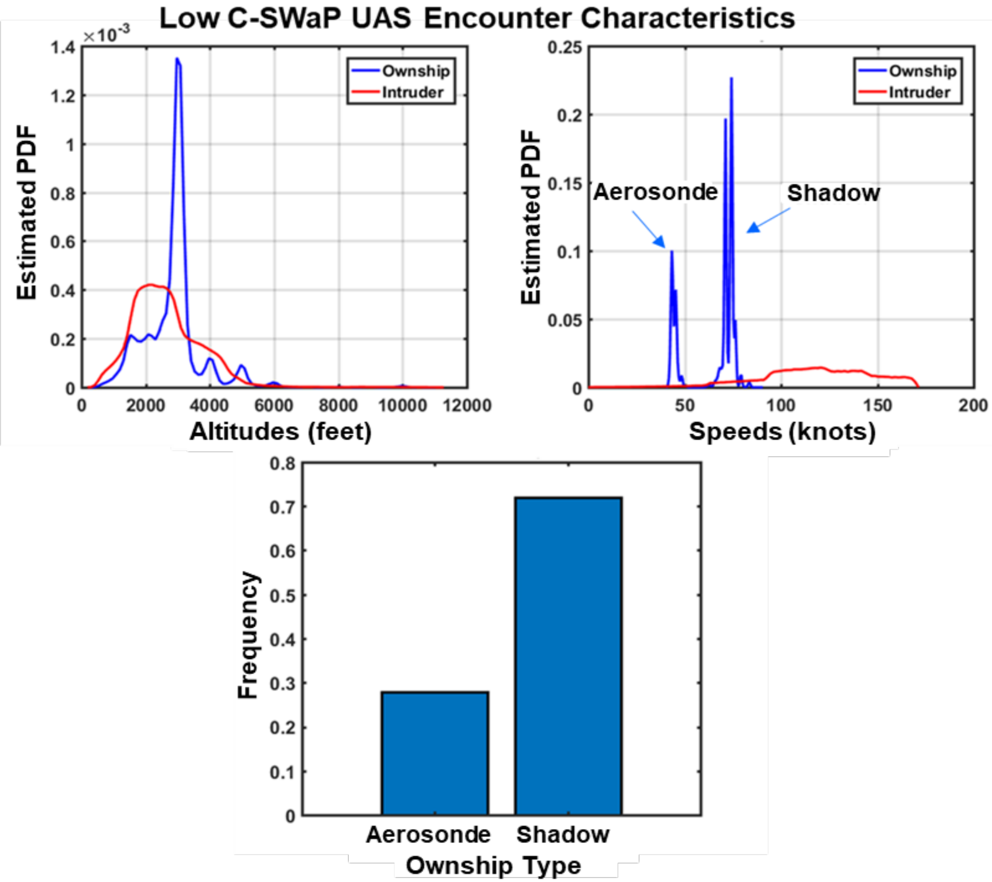


*** Assumes perfect surveillance**

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**

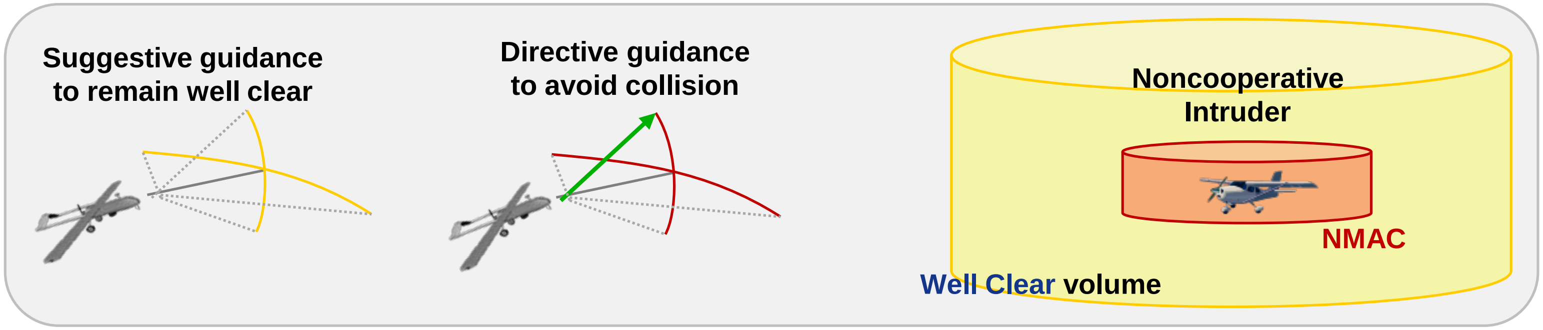
VFR – Visual Flight Rules (non-TCAS equipped aircraft)
NAS – National Airspace

Mitigated Metrics*

- **Safety metrics indicate whether desired separation is achieved**
  - Risk ratio and loss of well clear ratios: $\frac{\mathbf{P(NMAC\ or\ LoWC|encounter,\ with\ mitigation)}}{\mathbf{P(NMAC\ or\ LoWC|encounter,\ without\ mitigation)}}$
  - 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: $\frac{\mathbf{P(Alert|encounter,\ with\ mitigation)}}{\mathbf{P(NMAC|encounter,\ without\ mitigation)}}$
  - Alert ratio measures the alert frequency relative to the nominal NMAC frequency

Encounter Timeline:



***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

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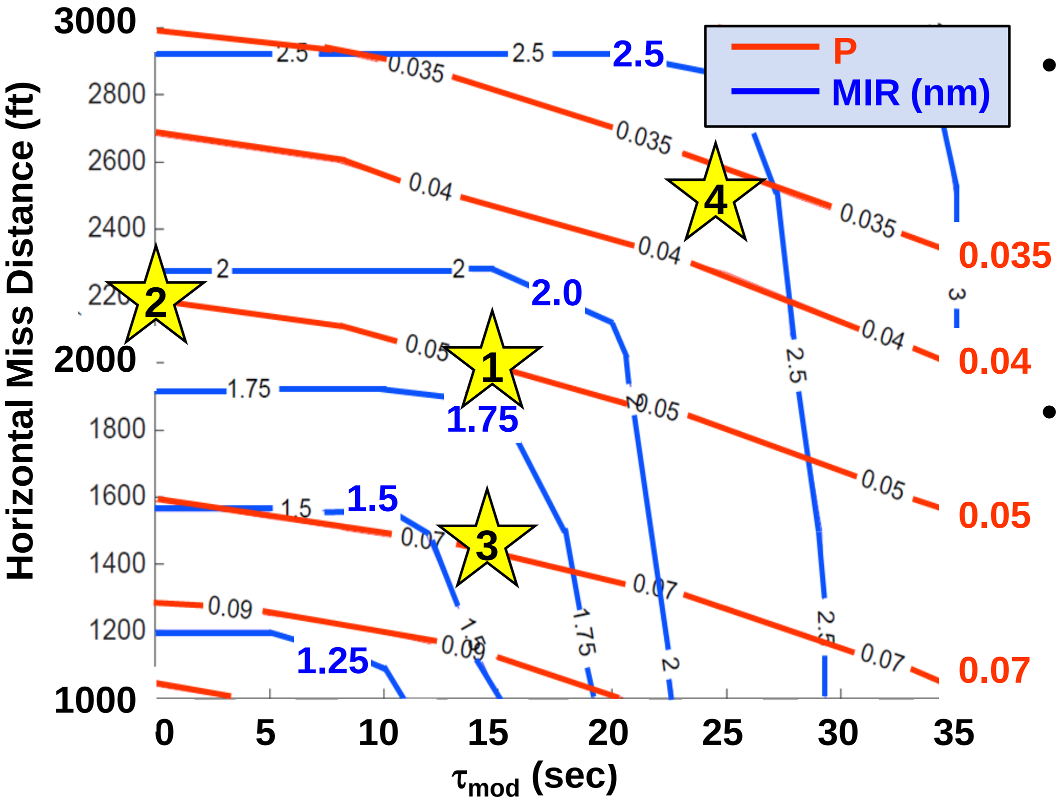
Unmitigated Analysis: Trade Space Down Selection



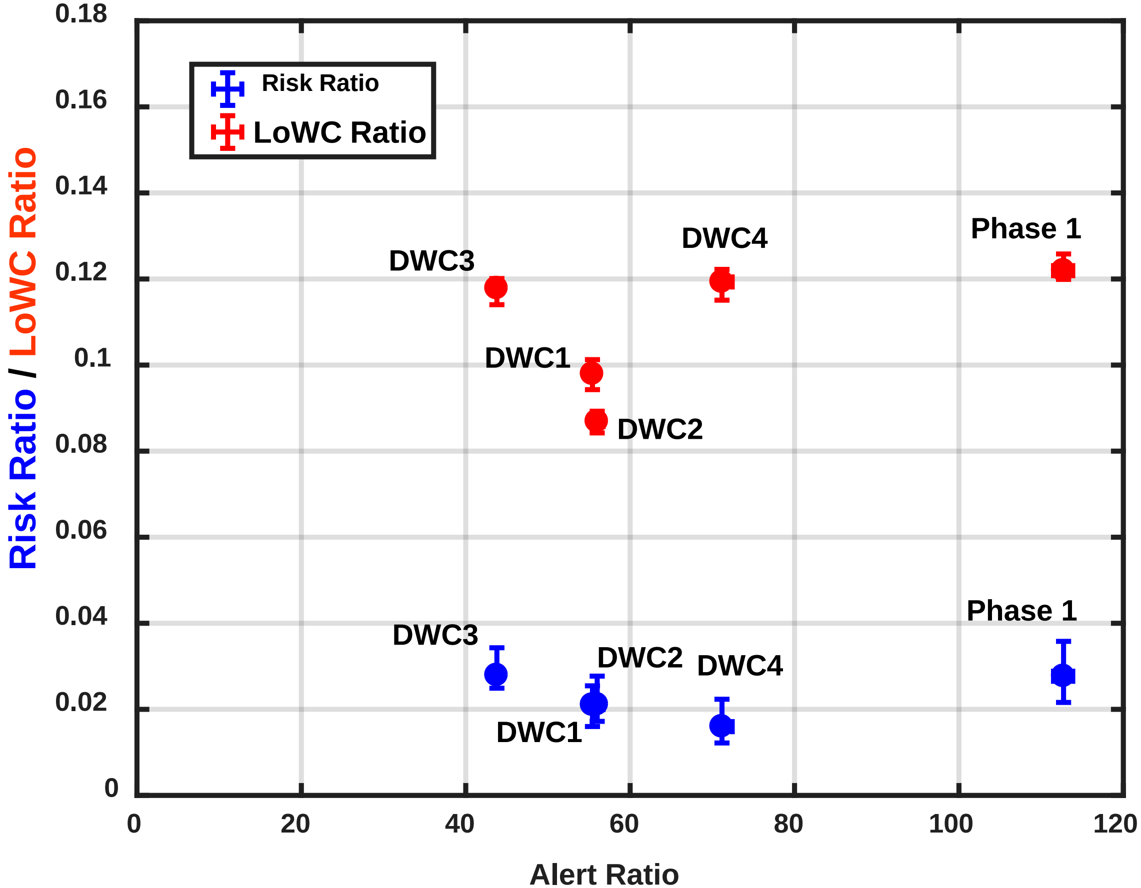
	DWC1	DWC2	DWC3	DWC4	Phase 1
HMD*	2000 ft	2200 ft	1500 ft	2500 ft	4000 ft
τ_{mod}*	15 s	0 s	15 s	25 s	35 s
h*	450 ft	450 ft	450 ft	450 ft	450 ft

HMD – Horizontal Miss Distance

- **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%**

[1] M. G. Wu, A. C. Cone, S. Lee, C. Chen, M. W. M. Edwards, and D. P. Jack, "Well Clear Trade Study for Unmanned Aircraft System Detect and Avoid with Non-Cooperative Aircraft," AIAA Aviation Conference, Atlanta, GA, 2018.

System Operating Characteristic for Low C-SWaP Encounters



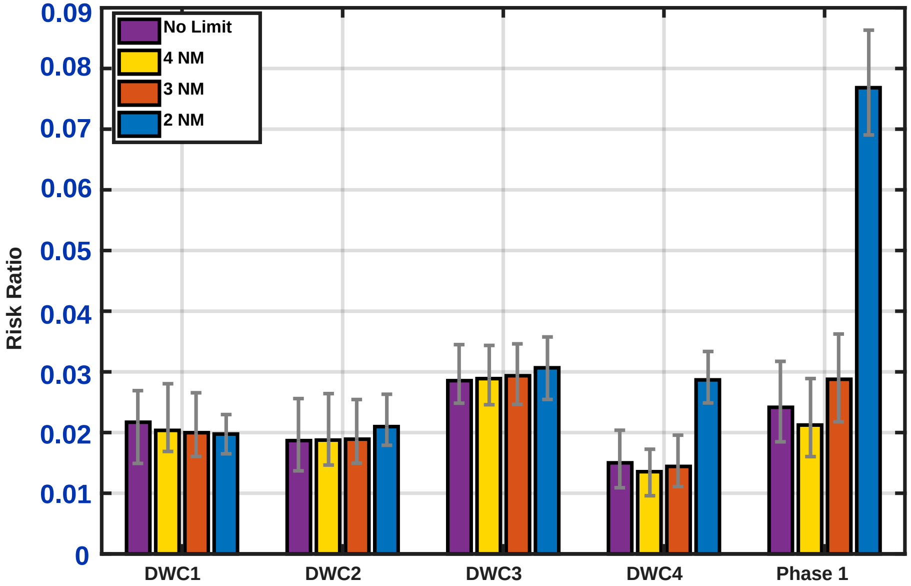
- SOC allows simultaneous evaluation of safety and operational suitability
- Risk and LoWC ratio are largely insensitive to DWC definition
- HMD appears to have the largest effect on alert ratio
  - DWC1 and DWC3 have the same τ_{mod}*, but DWC1 alerts more frequently

	DWC1	DWC2	DWC3	DWC4	Phase 1
HMD*	2000 ft	2200 ft	1500 ft	2500 ft	4000 ft
τ_{mod}*	15 s	0 s	15 s	25 s	35 s

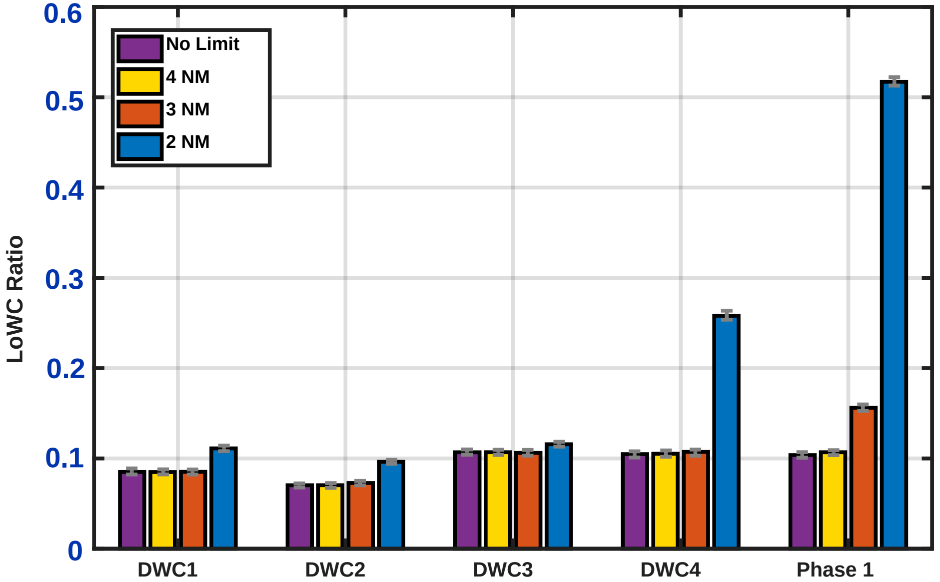
HMD – Horizontal Miss Distance

Effect of Surveillance Range

NMAC Risk Ratios



Loss of Well Clear Ratios



Note: Different y-axis scales

- **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)**

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 τ_{mod}***
    - **Indicates τ_{mod}* may not be necessary**

SC-228 selected 2200 ft horizontally, 450 ft vertically for UAS encountering noncooperative aircraft

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

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

Backup

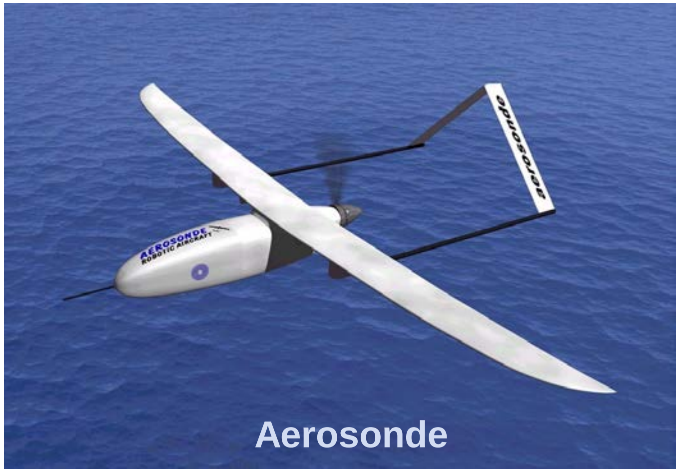
Future Work

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

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

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)**

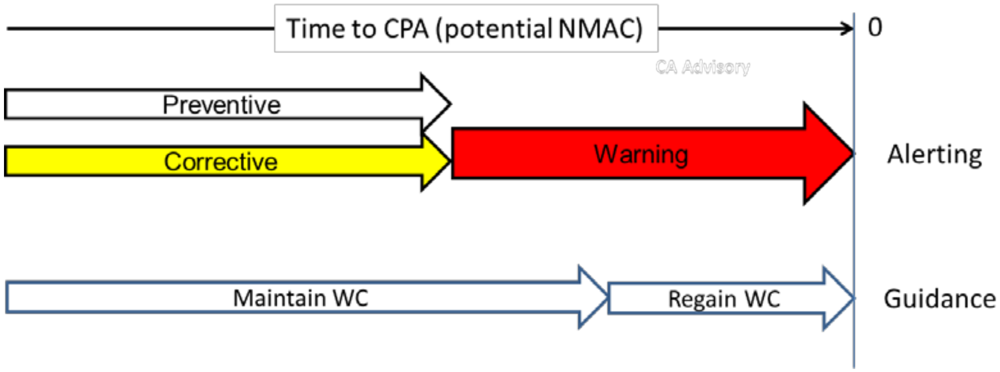


Source Image

Source Image

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**
  - **τ_{mod}* and h* are not buffered**
  - **HMD* for alerting ~ 1.519 x HMD* for DWC**
  - **Time to the volume defined by HMD*, τ_{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**



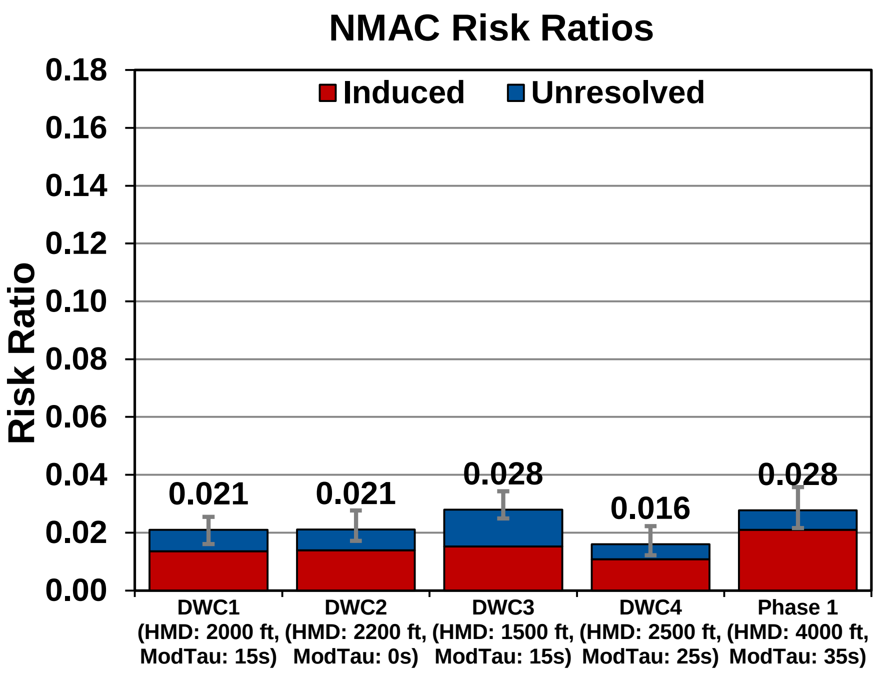
Pilot Response Model

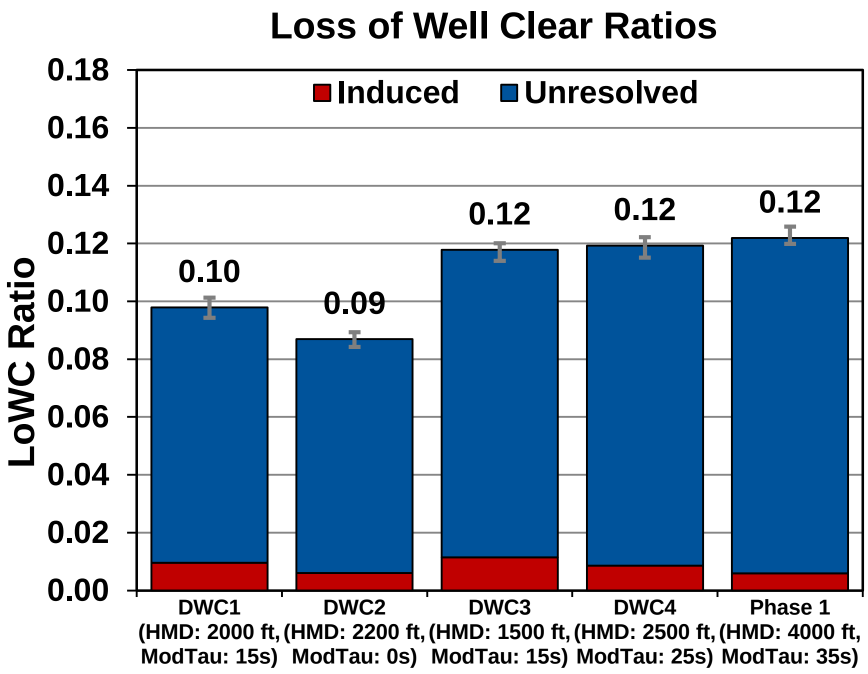
- **Use SC-228 pilot model created by Lincoln Laboratory**
  - **Executed in deterministic mode**
    - **Always maneuvers horizontally in the direction of the minimum suggested maneuver; turns left if minimum suggestion is inconclusive**
    - **Follow guidance bands without buffer**
  - **Timing:**
    - **Decision updated according to alert state**
    - **Execution delay after decision: 3 sec**

Alert Condition	Decision Update Period (s)
No Alert	24
Preventive Alert	15
Corrective Alert	9
Warning Alert	9
Regain DAA Well Clear Guidance	3

- **Analyze horizontal maneuvers only**
  - **Low-SWAP turn rate: 7 deg/sec**
    - **Suitable for UAS speeds from 40 to 100 kts**

Safety Ratios

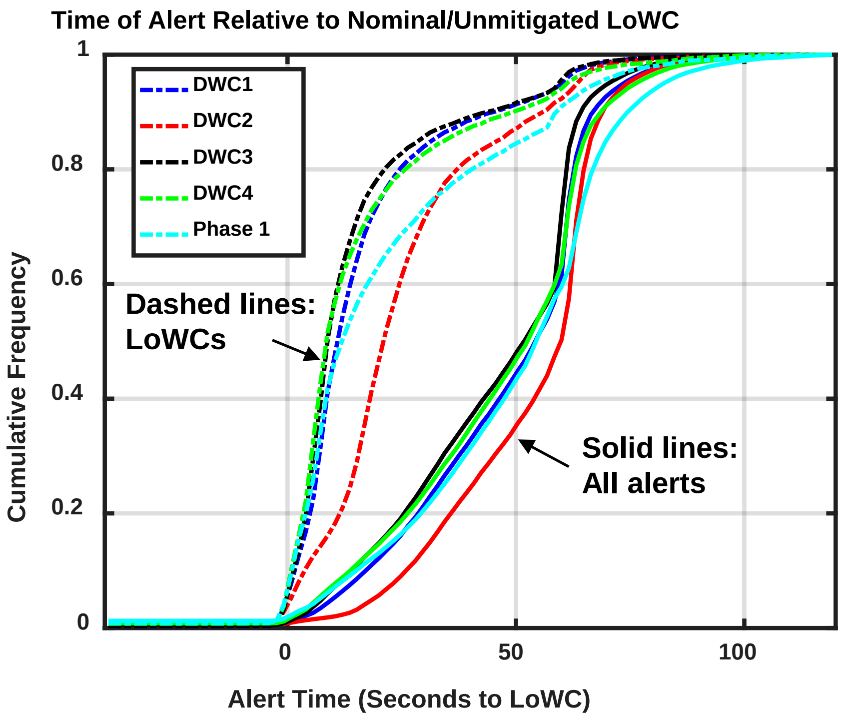


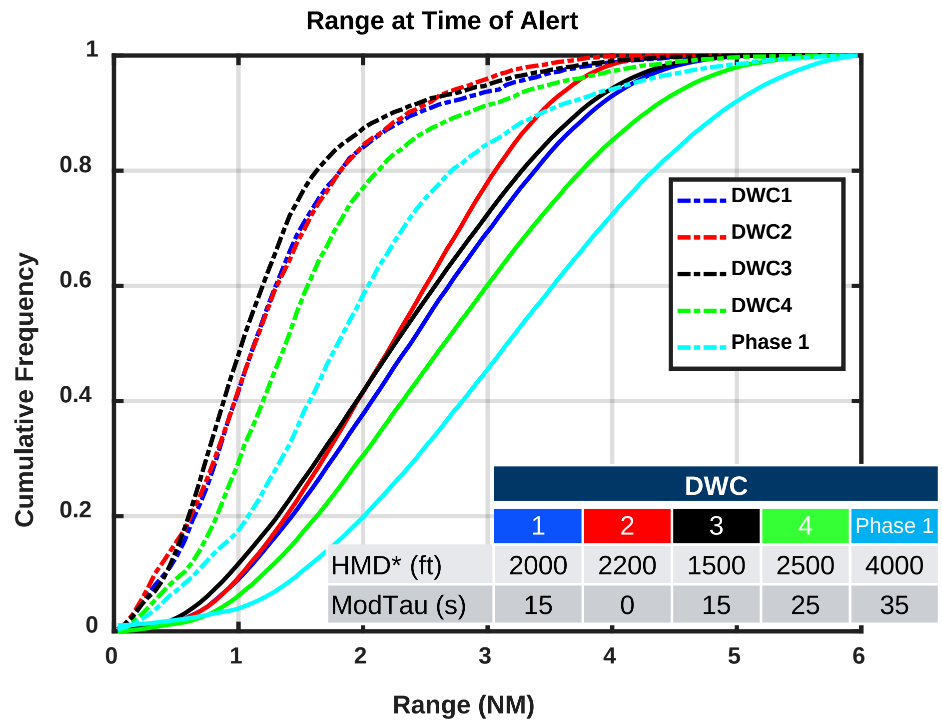


- **Risk ratios are comparable among the DWC candidates**
  - No statistically significant difference for risk ratios
- **DWC1 and DWC2 have the lowest loss of well clear ratios**

Risk ratios largely independent of DWC definition

Alerting Time and Range





	DWC				
	1	2	3	4	Phase 1
HMD* (ft)	2000	2200	1500	2500	4000
ModTau (s)	15	0	15	25	35

- **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**