Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

Terminal Operations HITL 1
Primary Results
Presented to: RTCA SC-228 WG-1

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Objective

- Purpose: Examine issues related to the operation of the Phase 1 DAA system within a Class D terminal area. The following operations were performed:
  - Instrument approach
  - Visual approach
  - Visual pattern

- Objectives:
  - Characterize pilot and Phase 1 DAA system performance while conducting terminal area operations
  - Investigate the effect of changes to the alerting and guidance structure intended to minimize frequency of alerts
  - Investigate the effect of the location of an encounter on pilot responses

Experimental Design

- One-Way Between Subjects Factorial
  - Independent Variable:
    - Level of DAA System Alerting & Guidance (Between-subjects)
      - D1 = No corrective or warning DAA alert; no DAA guidance
      - D2 = No corrective DAA alert; DAA warning guidance only
      - D3 = Full Phase 1 MOPS DAA alerting and guidance (Class I)
  - Embedded Variables:
    - Ownship approach type
      - Instrument
      - Visual
      - Traffic Pattern
    - Encounter location
      - Early (before final)
      - Late (on final)

Experimental Design

D1

Symbol	Name
	Preventive Alert
	Remaining Traffic

No Guidance

D2

Symbol	Name
	Warning Alert
	Preventive Alert
	Remaining Traffic

Warning Remain
DWC Guidance Only

D3

Symbol	Name
	Warning Alert
	Corrective Alert
	Preventive Alert
	Guidance Traffic
	Remaining Traffic

All Remain & Regain
DWC Guidance

Note: used instantaneous turn assumption to generate guidance

Phase 1 MOPS Alerting Criteria

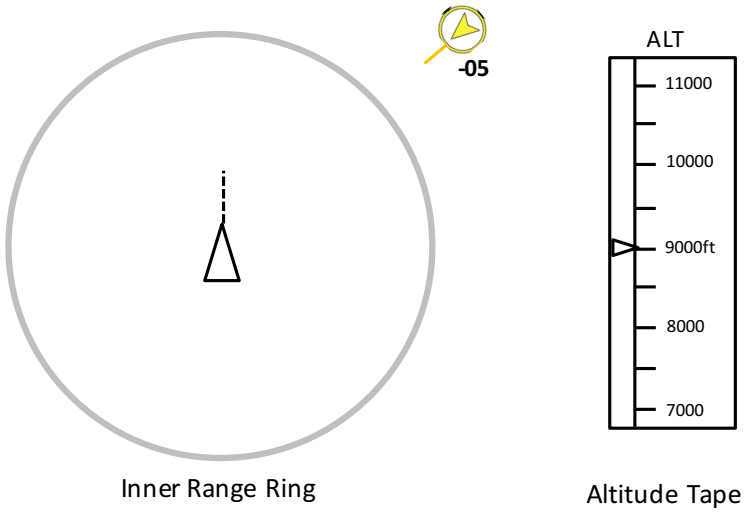
Symbol	Name	Pilot Action	DAA Well Clear Criteria	Time to Loss of DAA Well Clear	Aural Alert Verbiage
	Warning Alert	• Notify ATC as soon as practicable after taking action	DMOD = 0.66 nmi HMD = 0.66 nmi ZTHR = 450 ft modTau = 35 sec	25 sec	"Traffic, Maneuver Now" x2
	Corrective Alert	• Coordinate with ATC to determine an appropriate maneuver	DMOD = 0.66 nmi HMD = 0.66 nmi ZTHR = 450 ft modTau = 35 sec	55 sec	"Traffic, Avoid"
	Preventive Alert	• On current course, corrective action should not be required	DMOD = 0.66 nmi HMD = 0.66 nmi ZTHR = 700 ft modTau = 35 sec	55 sec	"Traffic, Monitor"
	Guidance Traffic	• Traffic generating guidance bands outside of current course	Associated w/ bands outside current course	X	N/A
	Remaining Traffic	• Traffic within sensor range	Within surveillance field of regard	X	N/A

Note: used 'unbuffered' DWC criteria

Alerting & Guidance During ***Preventive*** Threat

-- No LoDWC Predicted --

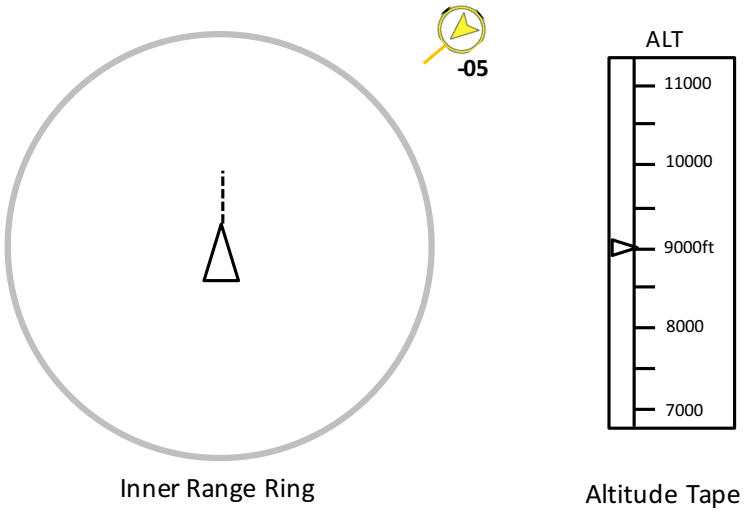
D1



Inner Range Ring

Altitude Tape

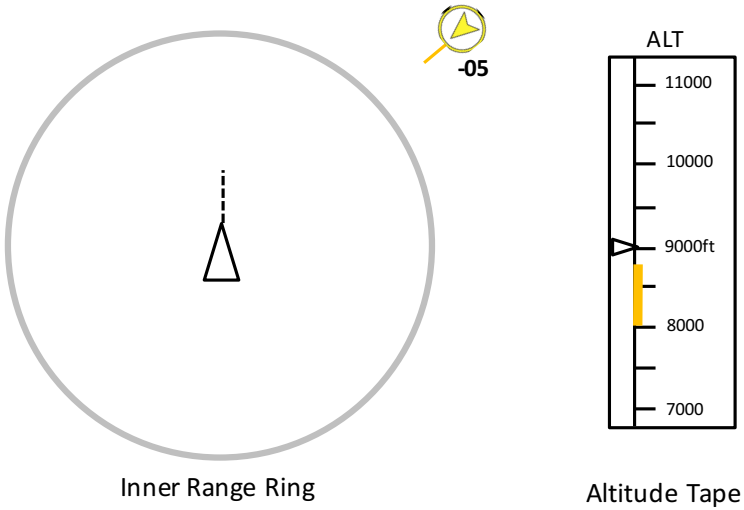
D2



Inner Range Ring

Altitude Tape

D3



Inner Range Ring

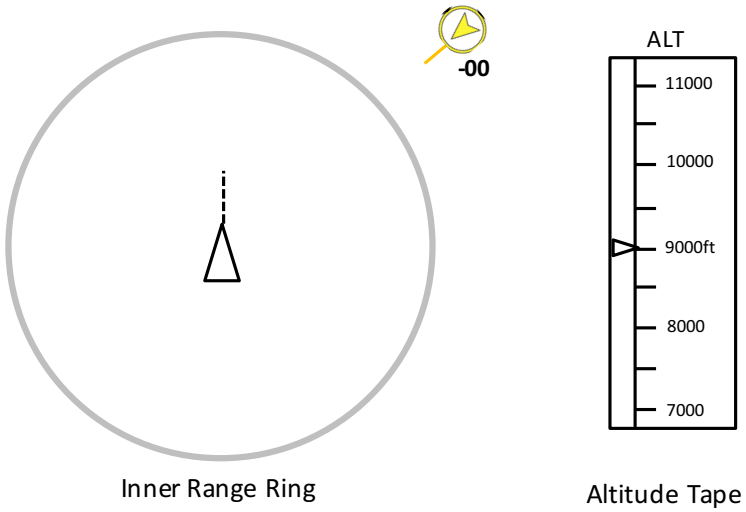
Altitude Tape

*notional encounter

Alerting & Guidance During ***Corrective*** Threat

-- LoDWC Predicted < 55 sec --

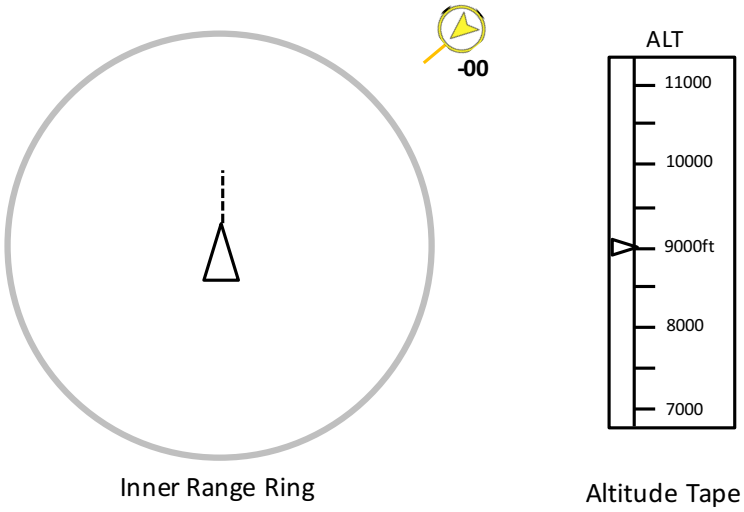
D1



Inner Range Ring

Altitude Tape

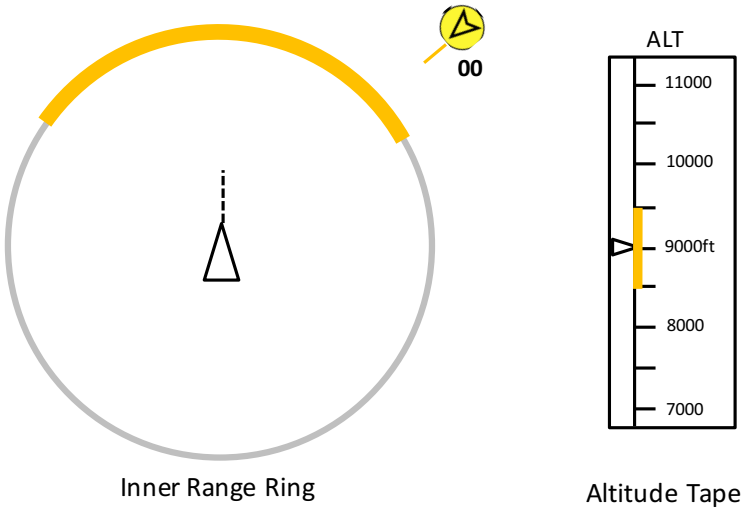
D2



Inner Range Ring

Altitude Tape

D3



Inner Range Ring

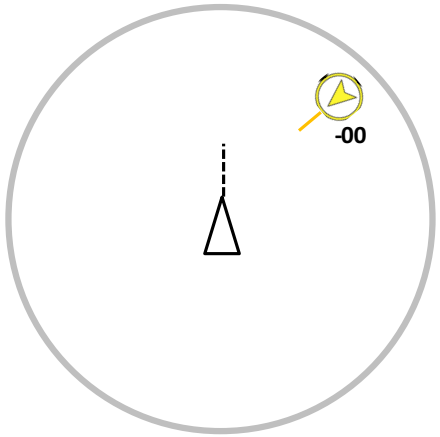
Altitude Tape

*notional encounter

Alerting & Guidance During ***Warning*** Threat

-- LoDWC Predicted < 25 sec --

D1



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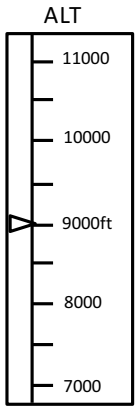
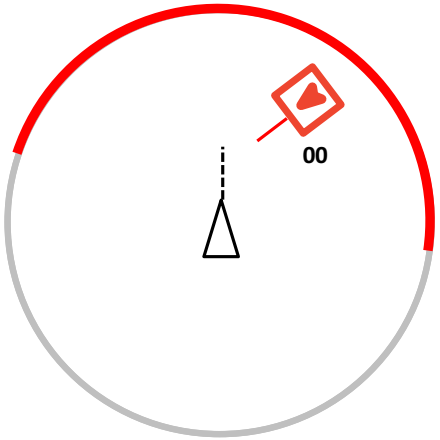


Altitude Tape

D2



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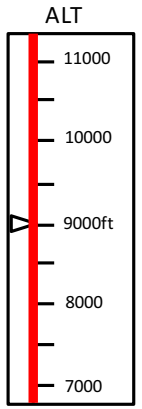
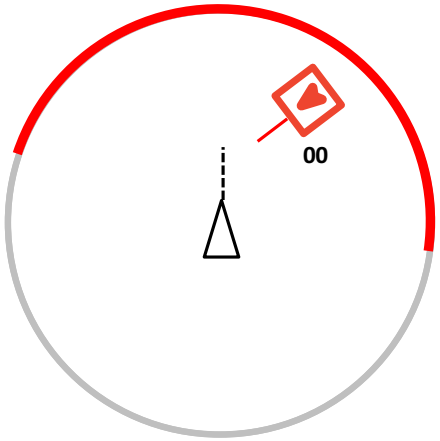
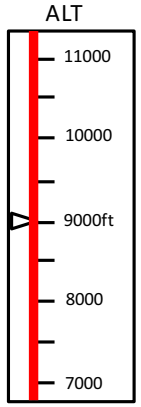


Altitude Tape

D3



Inner Range Ring

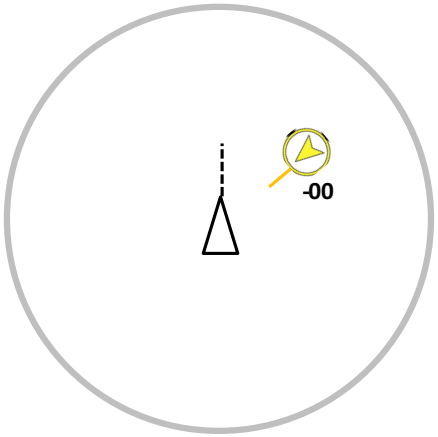


Altitude Tape

*notional encounter

Alerting & Guidance During *Well Clear Recovery*
-- LoDWC Unavoidable --

D1



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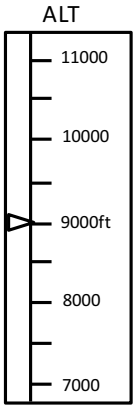
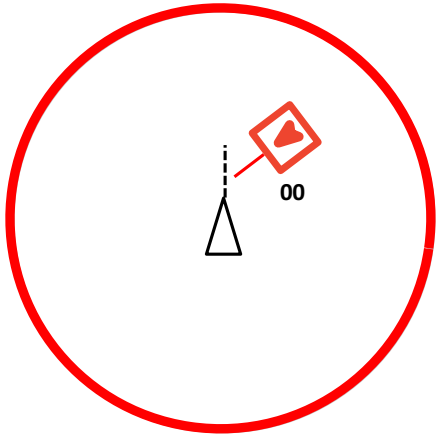


Altitude Tape

D2



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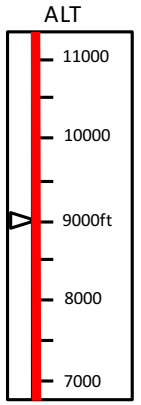
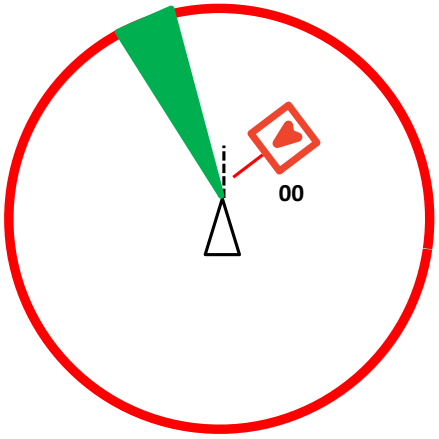
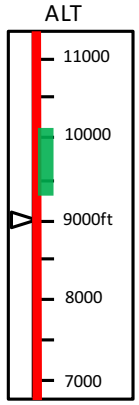


Altitude Tape

D3



Inner Range Ring



Altitude Tape

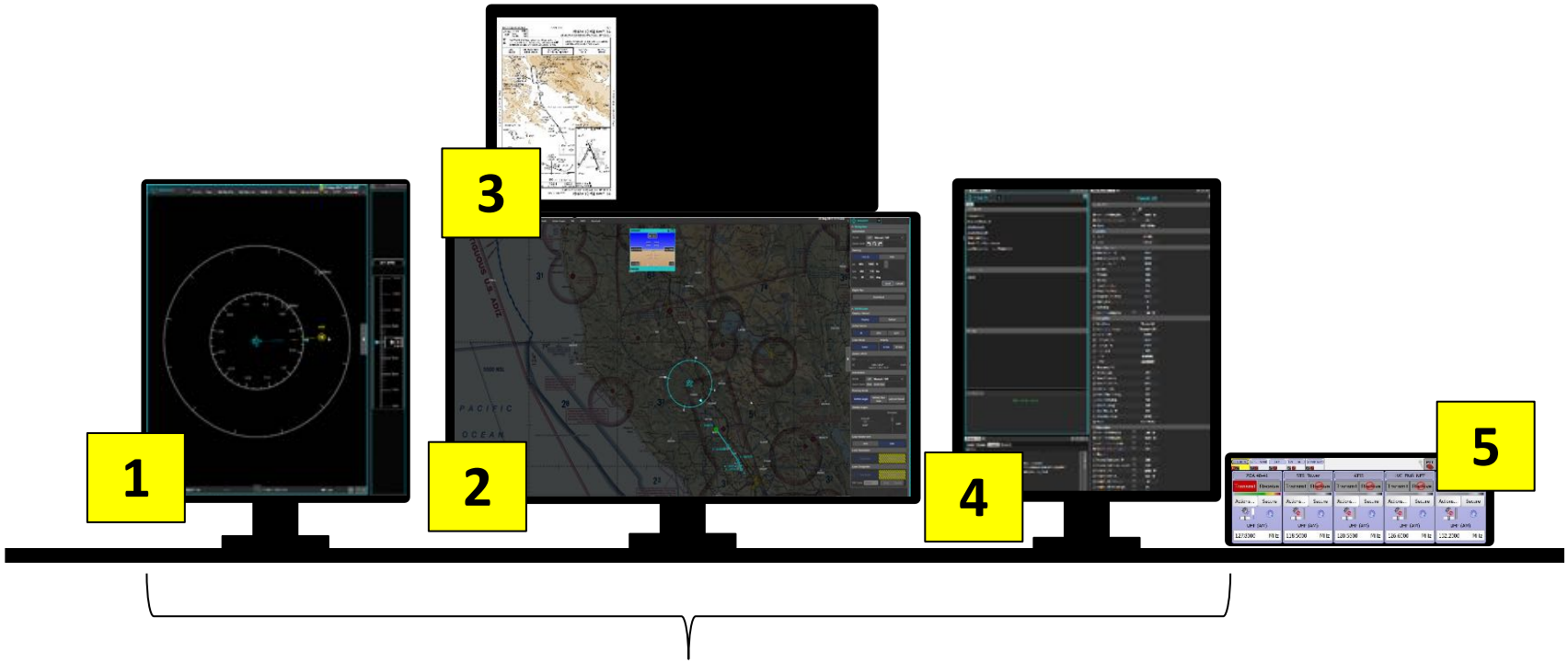
*notional encounter

Aircraft Flight Model

- Generic MQ-9 Reaper
  - Speed:
    - Cruise: 110 knots
    - Landing: 90-110 knots
    - Max: 200 knots
    - Min: 70 knots
  - Default Climb Rate:
    - 1000ft/min
  - Default Descent Rate:
    - 1000ft/min
  - Roll:
    - Max: +/- 20°
    - Rate: 5°/sec
  - Pitch:
    - Max: +/- 10°
    - Rate: 1°/sec

Ground Control Station (GCS)

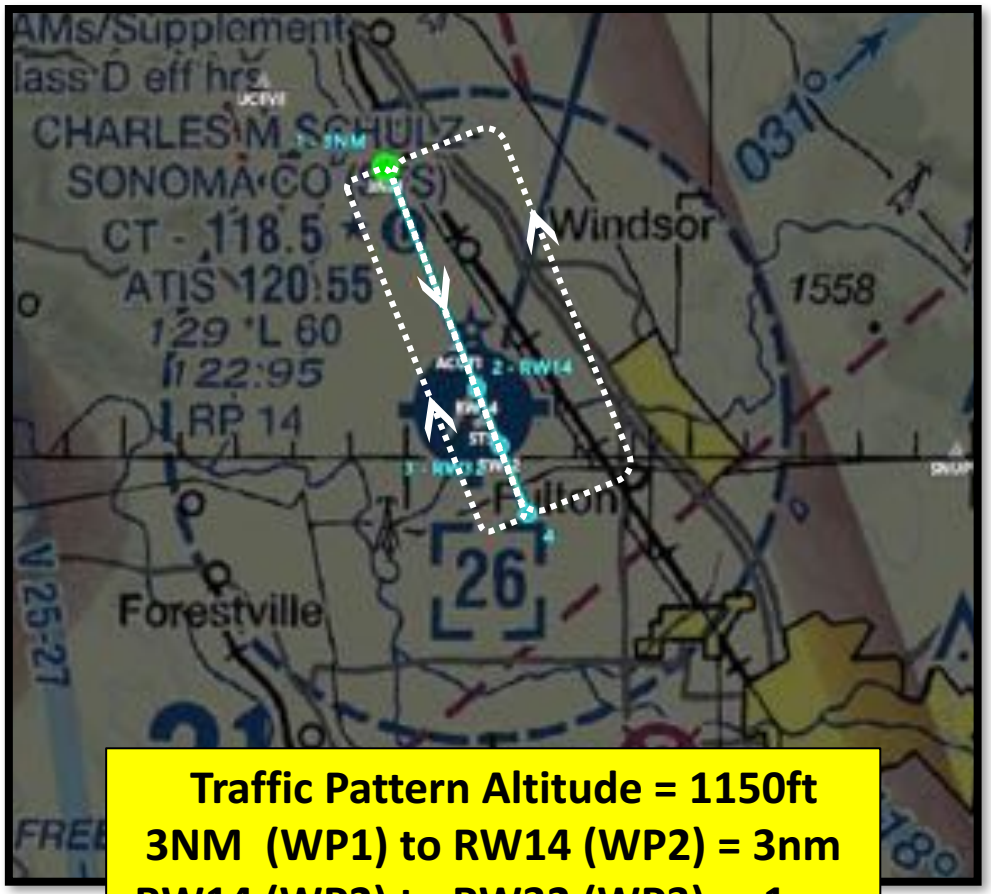
- Ground control station (GCS) contains:
  1. DAA Display – traffic & alerting
  2. Tactical Situation Display (TSD) – vehicle control interfaces & maps
  3. Viewer Tool – contains approach plate & airport facility directory (AFD)
  4. Right Panel – landing checklist and additional info
  5. Voice communication panel – touchscreen, transmit/receive on select freqs.



Vigilant Spirit Control Station (AFRL)

Sonoma County Airport

- Primary = Rwy14
- Runway 14/32
  - Length = 6000ft x 150ft
  - RNAV (GPS)
- Elevation = 129ft
- Traffic Pattern = 1150ft
- Downwind offsets:
  - Left = ~1.5nm
  - Right = ~0.5nm
- Runway 20/02
  - Not used



Traffic Pattern Altitude = 1150ft
3NM (WP1) to RW14 (WP2) = 3nm
RW14 (WP2) to RW32 (WP3) = 1nm

Simulation Components

- Pseudo-pilots monitored and managed all manned traffic (IFR & VFR)
  - Multi-Aircraft Control System (MACS) software suite
- Air Traffic Control managed UAS and manned traffic
  - Center controller managing Oakland Center (ZOA 40/41)
  - Tower controller managing Santa Rosa (KSTS)
  - Sector traffic modeled using real sector activity and data
- All participants communicated via push-to-talk headsets
  - Oakland Center frequency: 127.80
  - KSTS Tower frequency: 118.50
  - KSTS ATIS: 120.55

Training on DAA System

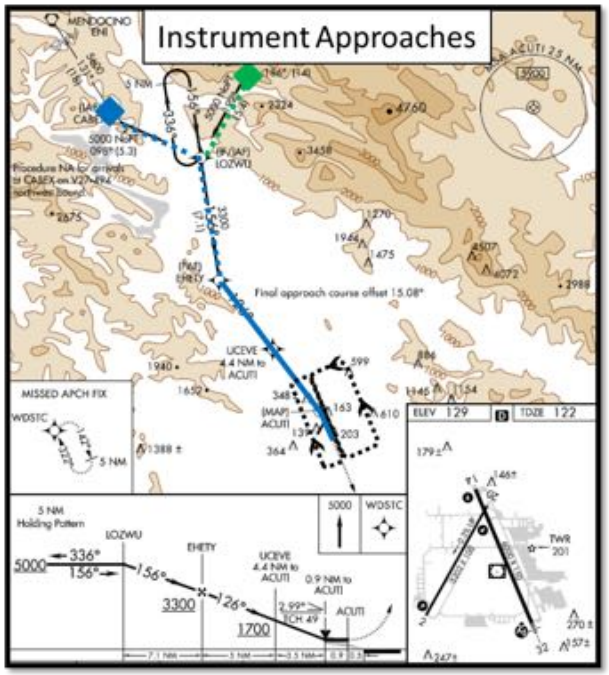
- Pilots trained first on the ground control station followed by training on the DAA system
  - Trained on the meaning of each alert/guidance type in their given configuration
- Pilots were trained last on how to fly the approach
- Informed that:
  - Phase 1 DAA system was designed to assist pilots in maintaining DAA well clear during transit/en route operations in Class D, E, and G airspace
  - A Phase 2 DAA system is being developed to support terminal operations and therefore:
    - Phase 1 DAA well clear definition and associated alerting/guidance *may or may not be suitable* in terminal environments

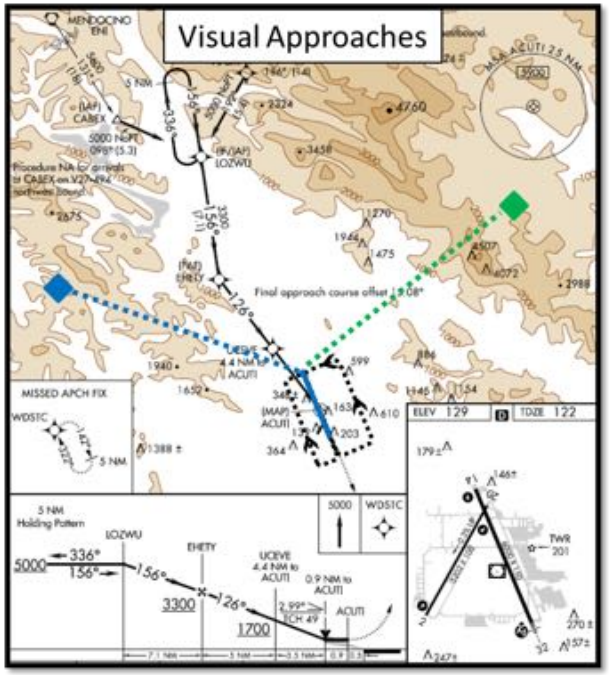
❖ Told to use the DAA system **at their discretion** to conduct safe operations in the terminal environment

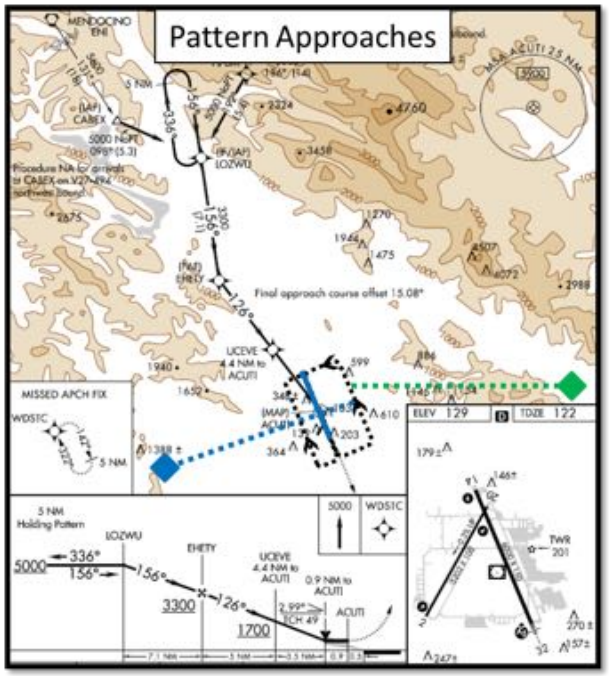
Scenario Design

- Participants flew 3 different types of approaches into Santa Rosa Rwy 14 under Instrument Flight Rules (IFR)
  - Instrument (RNAV GPS) Approach
  - “Visual” Approach
  - Traffic Pattern
- Common across scenarios:
  - Start in Vigilant Spirit’s HOLDS mode & in Oakland center airspace
  - Coordinate transfer to KSTS Tower
  - Perform checklist actions as able (e.g., check ATIS, brief approach)
  - Fly final in Vigilant Spirit’s NAV mode (enables glide slope)

Scenario Design







Instrument Approach Notes:

- Final approach coarse offset 15°
- Missed approach procedures = climb to 5000ft, fly runway heading (140°)

"Visual" Approach Notes:

- Airport "in sight" 10-12nm from runway
- Line up for 3nm final stabilized approach
- Traffic pattern @ 1150ft

Pattern Approach Notes:

- Traffic pattern @ 1150ft
- Controllers will give pattern entry instructions
  - 45° entry, mid-field entry or direct base
  - May extend downwind and call your base
- Offset from Rwy14 should be ~1.5nm

Scenarios

- Each scenario had 6 runs:
  - 4 included a scripted loss of DAA well clear somewhere along approach:
    - 2 scripted to occur **Early** - before final; 5-10nm from airport
    - 2 scripted to occur **Late** - on final; within 3nm of airport
  - 2 included no scripted conflict but interactions with traffic around airport were expected
    - Alerts and LoDWC possible due to size of DWC definition and 0.5nm offset of right downwind from runway

Participants

- Participants
  - 18 participants (*M* = 38.5 years of age)
    - All had manned flying experience (*M* = 2200 hours) and were IFR rated
      - Manned: M = 3000 hrs in civilian airspace; Unmanned: M = 1000 hrs in civilian airspace
    - ½ had experience with unmanned aircraft (*M* = 1100 hours)
  - 3 Air Traffic Control confederates
    - 1 retired tower controllers (Stockton)
    - 2 retired center controllers (Oakland Center)
  - 4 Pseudo pilot confederates (current general aviation)

RESULTS

Global Statistics

- 216 total scripted conflicts (all single-threat encounters)
  = 18 (pilots) * 3 (scenarios per pilot) * 4 (scripted conflicts per scenario)

- 536 intruders registered (***in truth***) as DAA preventive, corrective or warning
  - 40% were against scripted conflicts
  - 60% were against unscripted conflicts

- Breakdown of (truth) alert types generated by intruders:

	# of Unique Intruders	DAA Preventive	DAA Corrective	DAA Warning
Scripted	210	147 (70%)	162 (77%)	191 (90%)
Unscripted	326	160 (49%)	215 (66%)	149 (46%)

NOTE:
"Truth" alerts = actual alert level registered by DAA system, regardless of experimental condition

Notes

- Results centered on the effect of display configuration and location of encounter
  - Display configuration was primary IV
  - Encounter location resulted in most pronounced results
    - Early = before final
    - Late = on final
    - Unscripted = almost exclusively pattern traffic (similar in location to ‘late’ encounters)
- Effects of pilot background, approach type and trial were examined but not focus of this presentation
  - Metrics where they had noteworthy effect are pointed out

RESPONSE AND ALERT TIMES

Visible Alerts

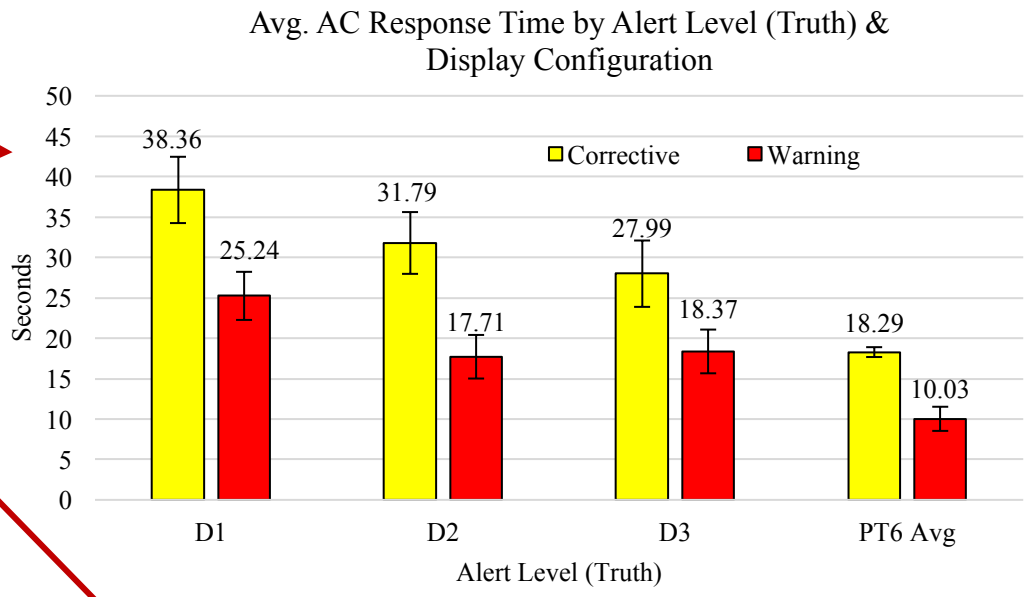
Visible Alerts (& Truth Alert) by Display Configuration

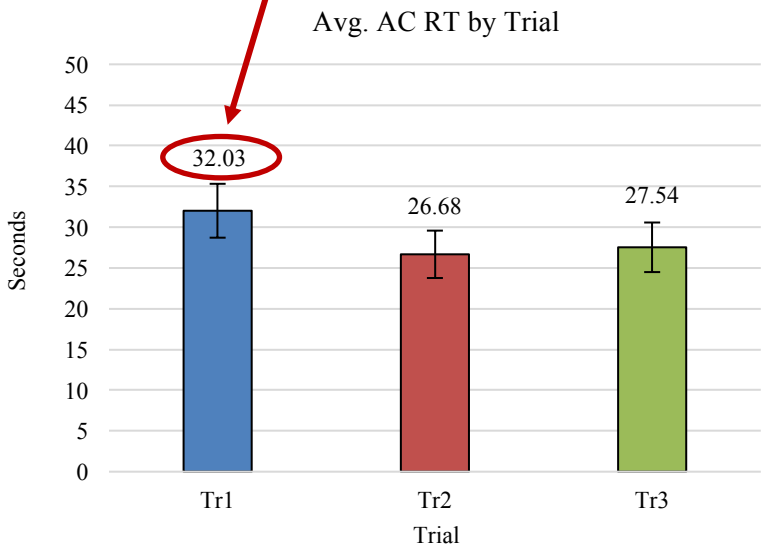
	D1		D2		D3	
	Visible	Truth	Visible	Truth	Visible	Truth
Preventive	178	97	165	107	103	103
Corrective		128 (visible as preventive)		125 (visible as preventive)	124	124
Warning		119 (visible as preventive)	117	117	104	104

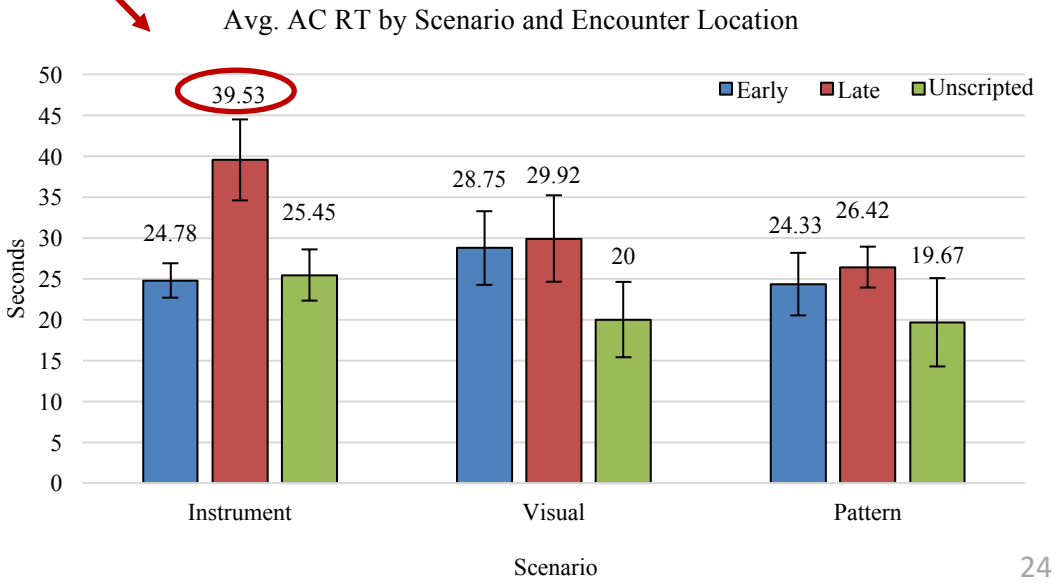
- Alert levels were suppressed in D1 and D2
  - As a result pilots received greater number of DAA Preventive alerts and had to interpret if they were a legitimate threat
- Slightly fewer (~10%) DAA Warning (truth) alerts triggered in D3

Aircraft Response Time (AC RT)

- AC RT = time to upload maneuver following alert onset
- D1 condition resulted in slower responses to both corrective and warning alerts (~ 7-10sec)
  - All conditions slower than was observed in Part Task 6
- Slowest AC RT when responding to encounters on final in Instrument Approach scenario
- Slower in first trial of day

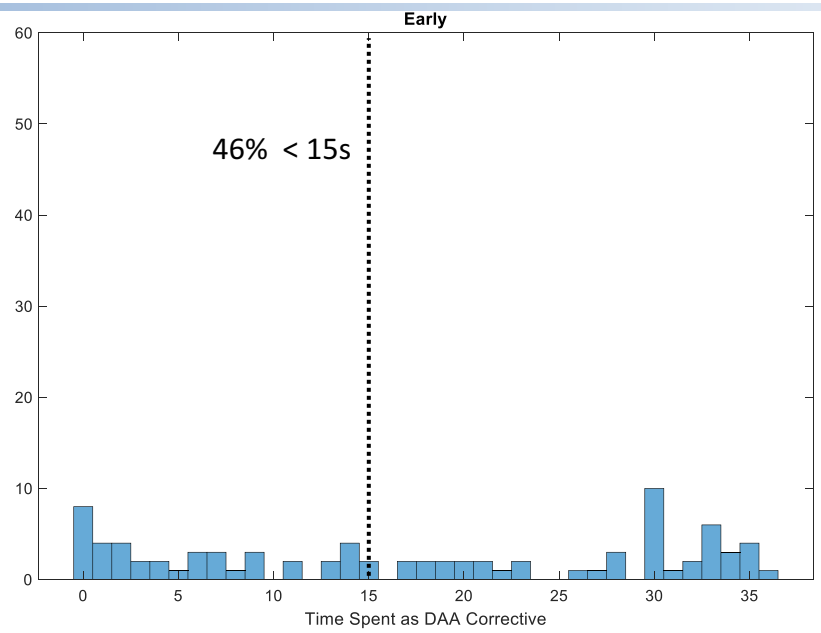


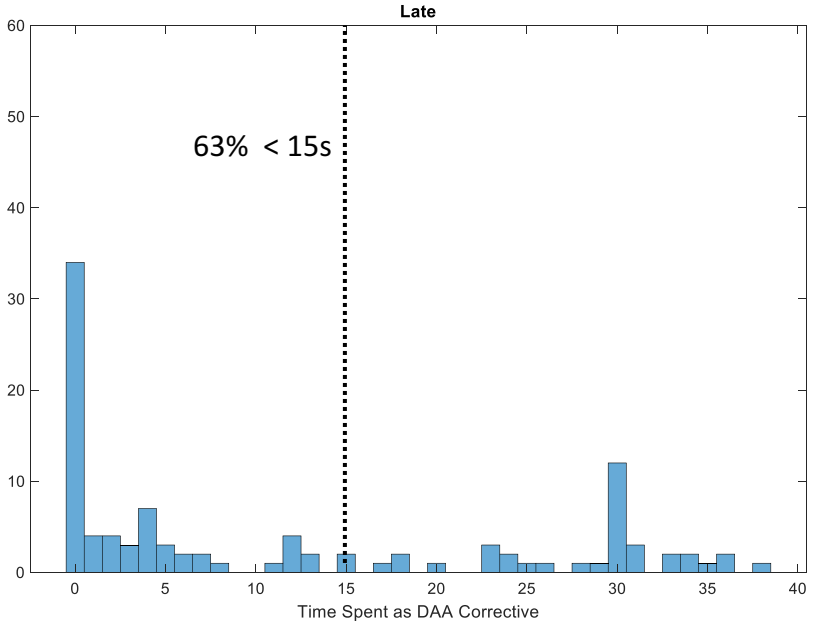


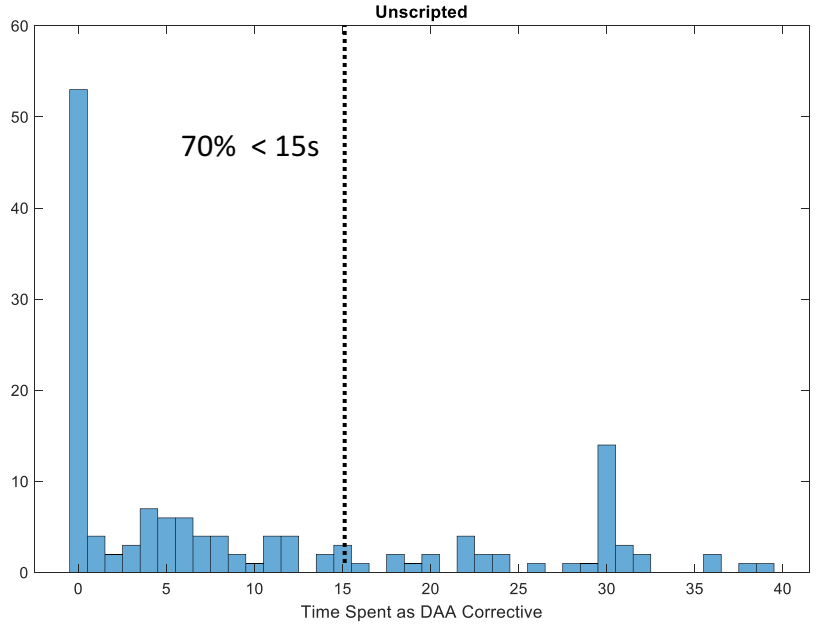


Corrective Alert Durations

- 340 intruders registered as DAA Warning
  - 29% spent 0 time as DAA Corrective
  - 63% spent < 15 seconds as DAA Corrective
- Late and Unscripted encounters most likely to spend < 15 seconds as DAA Corrective before registering as DAA Warning



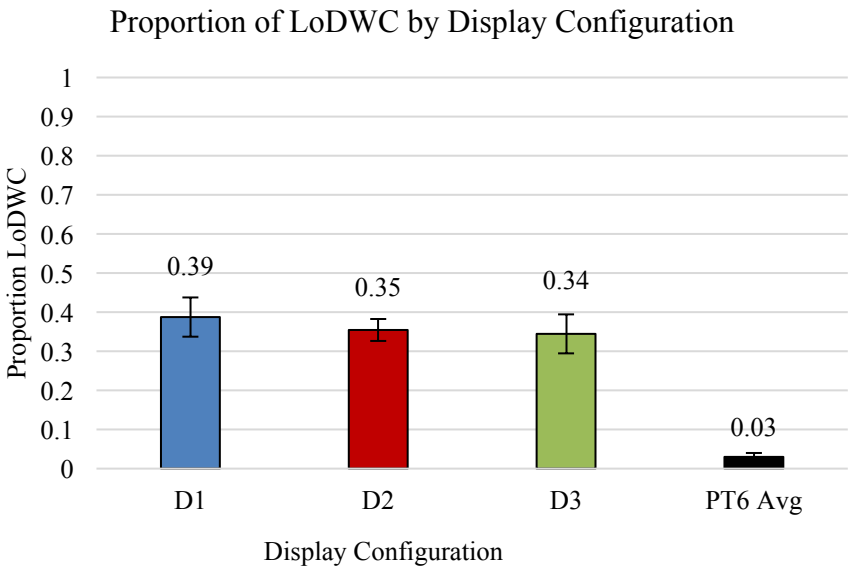


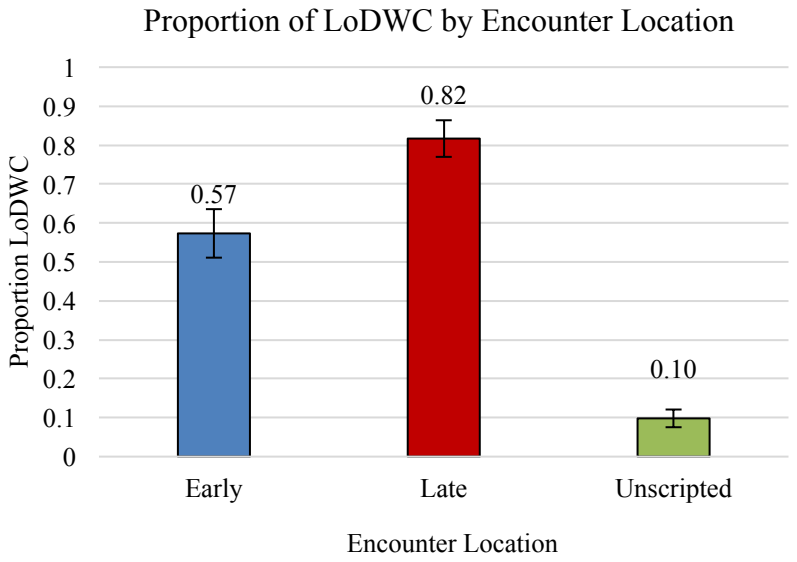


SEPARATION DATA

Proportion of Losses of DAA Well Clear

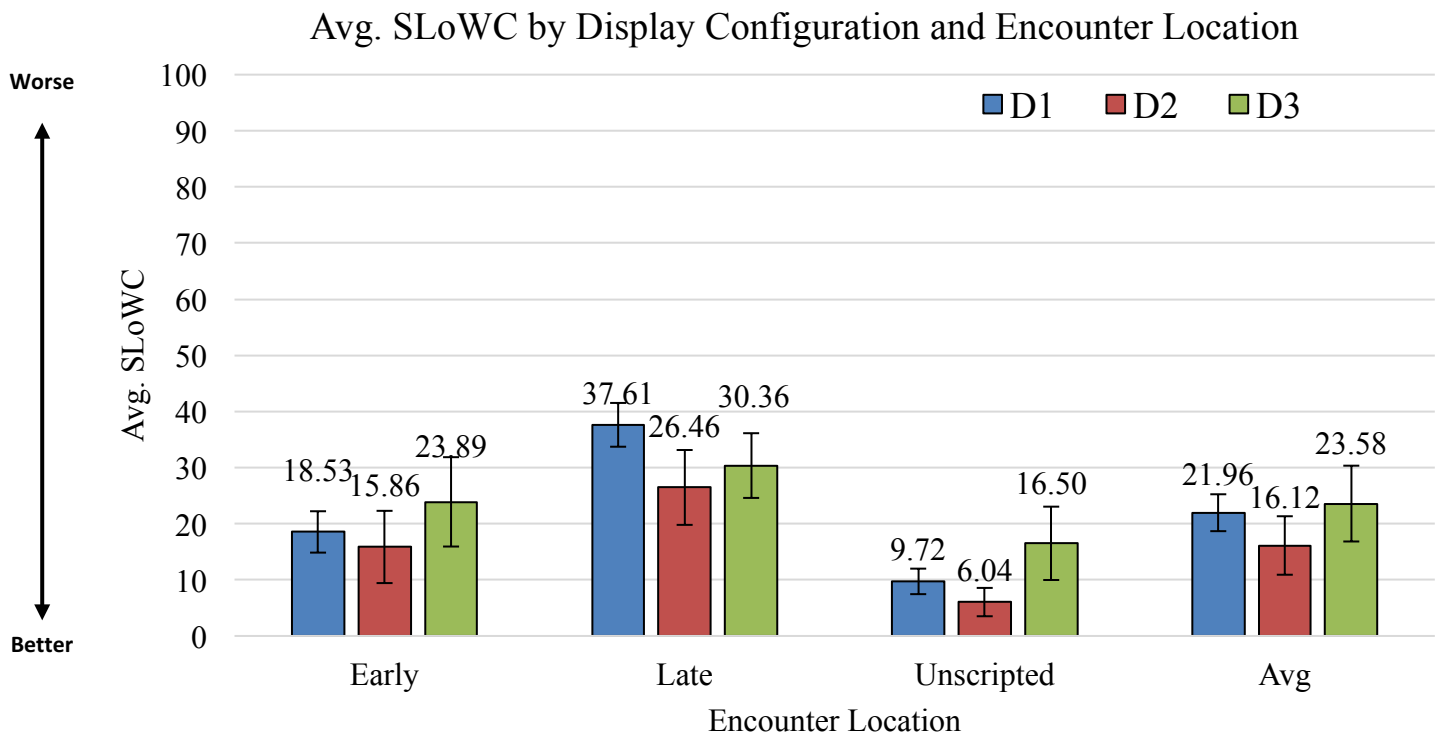
- Proportion of losses of DAA Well Clear (LoDWC)
  - # of LoDWC / # aircraft that generated a DAA Corrective or Warning
- **176** total LoDWC / **472** total DAA Corrective and/or Warning alerts **= 37% overall**
  - Consistent across conditions (34-39%)
- Alerted traffic most likely to lead to LoDWC when occurring late
  - Much smaller number of unscripted alerts actually led to LoDWC (26/249)





Loss of DAA Well Clear Severity (SLoWC)

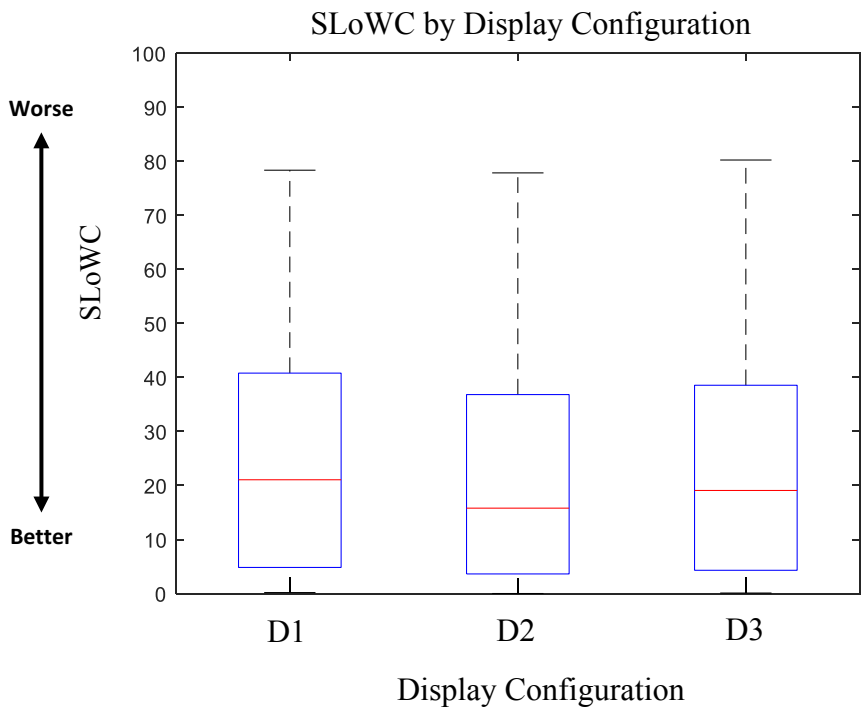
- SLoWC = % of the DAA well clear volume (including tau) penetrated by intruder
  - Higher % = greater penetration
- On average, D2 resulted in less severe LoDWC (reduction ~6-8%)
- Late encounters consistently resulted in more severe LoDWC
  - Especially pronounced in D1 condition

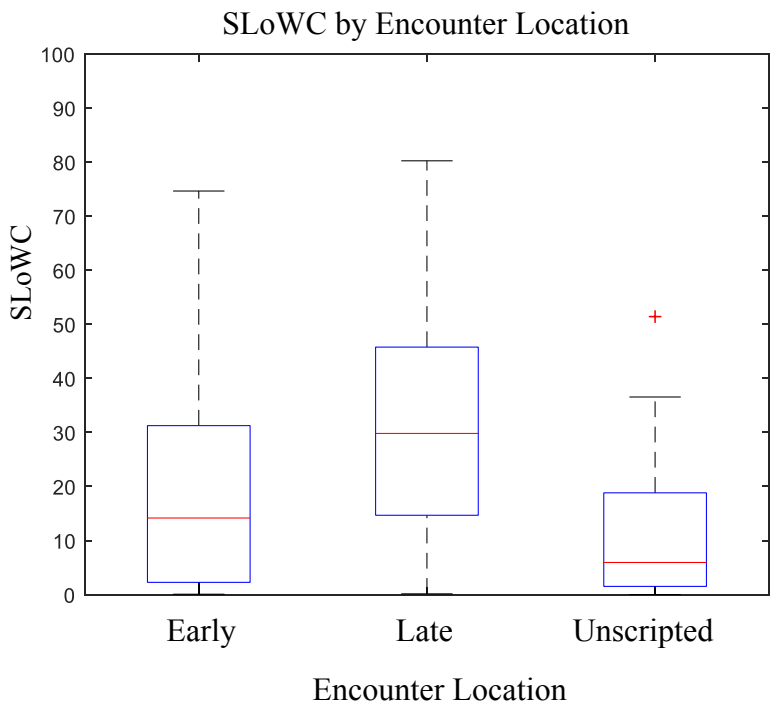


Loss of DAA Well Clear Severity (SLoWC)

- Median SLoWC generally low (< 20%) across display configurations
- Median rises to 30% for late encounters
  - Median < 15% for early and unscripted encounters

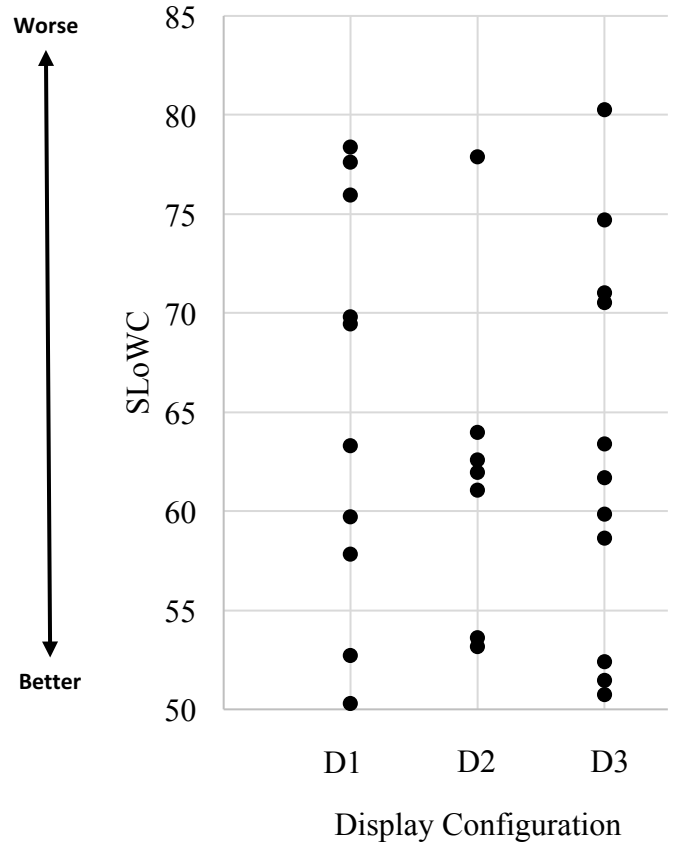
- All display configurations and both early and late encounters experienced multiple high-severity losses of DAA well clear (> 50%)





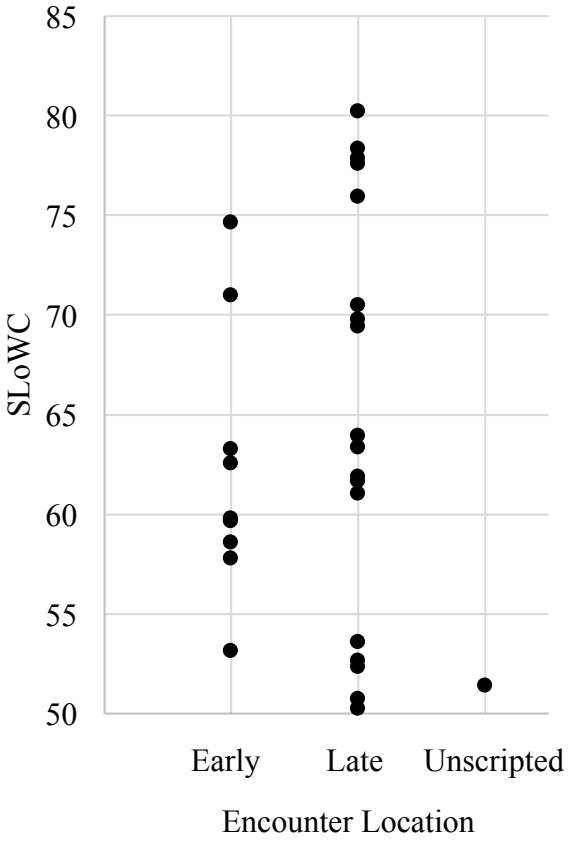
Loss of DAA Well Clear Severity (SLoWC) > 50%

- D2 showed fewer high-severity LoDWC than D1 & D3
- Late encounters resulted in disproportionate # of high-severity LoDWC



	D1	D2	D3
SLoWC Above 50	10 (15%)	7 (12%)	11 (20%)
SLoWC Above 70	3 (5%)	1 (2%)	4 (7%)

Note: 60% were pilot error; 40% ”too slow”

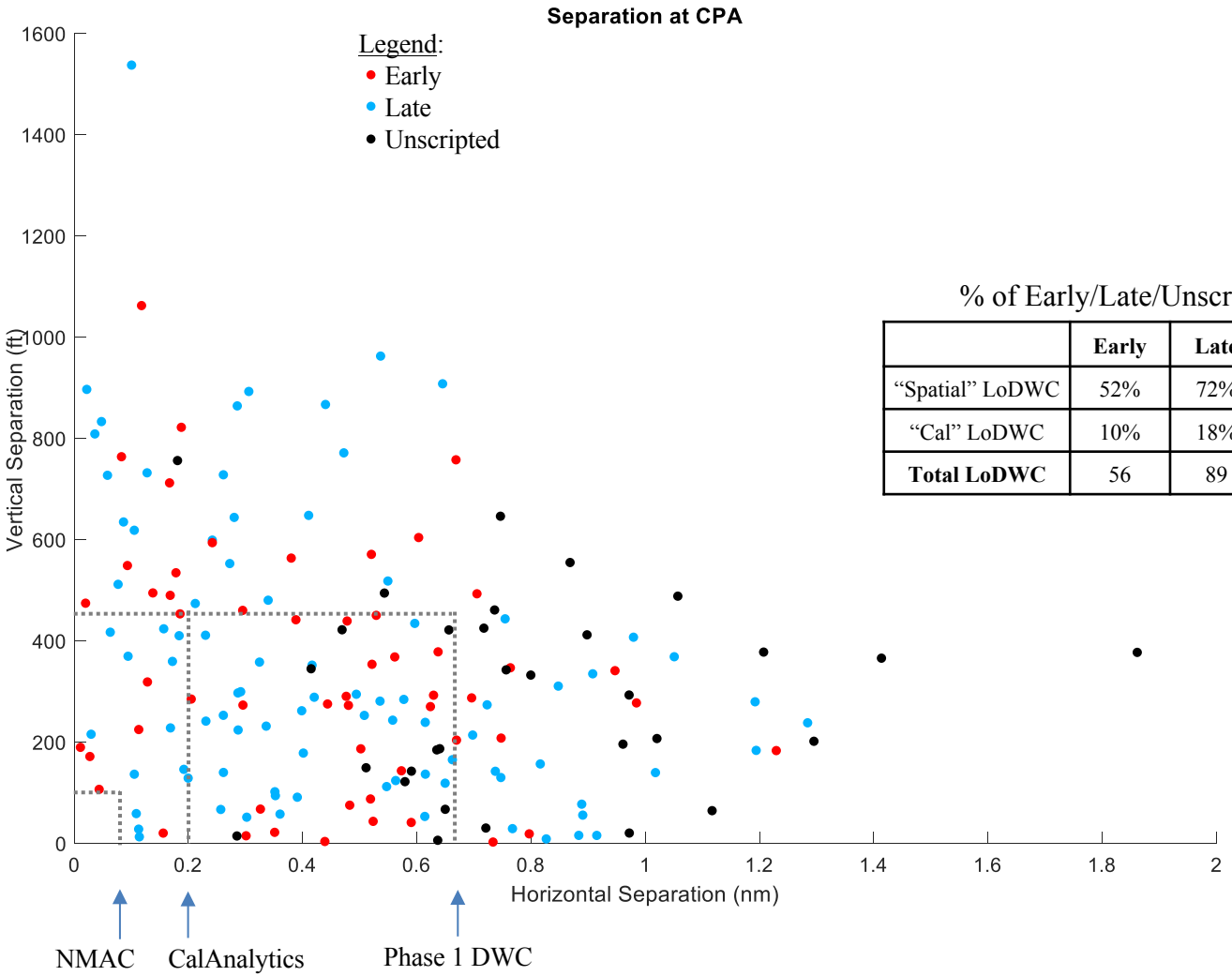


	Early	Late	Unscripted
SLoWC Above 50	9 (16%)	18 (20%)	1 (3%)
SLoWC Above 70	2 (3%)	6 (7%)	0

Note: 75% ”too slow” or “no maneuver”

Actual Separation at CPA

- 60% of all LoDWC breached the horizontal & vertical Phase 1 DWC thresholds (**discarding tau component**)
  - 13% breached CalAnalytics terminal area DWC



% of Early/Late/Unscripted LoDWC

	Early	Late	Unscripted	Total
"Spatial" LoDWC	52%	72%	40%	105
"Cal" LoDWC	10%	18%	0	22
Total LoDWC	56	89	31	176

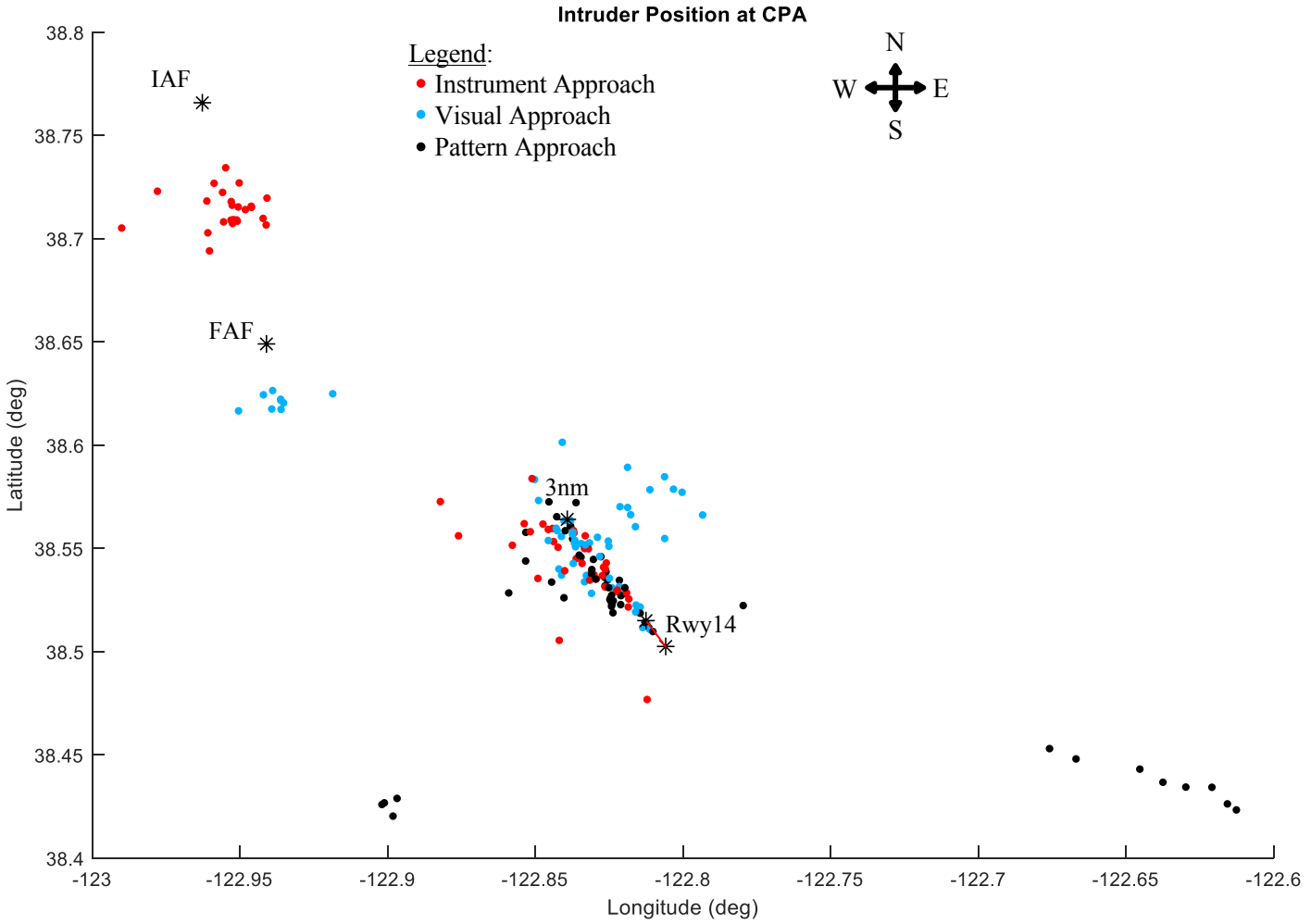
Separation Results Summary

- Display configuration smaller effect on proportion and severity of LoDWC than encounter location
  - Late encounters disproportionately bad
  - Unscripted encounters low in number and severity
- All display configurations had instances of high severity SLoWC (> 50%)
  - Slight trend of less-severe LoDWC in D2
  - Most were due to pilot error (slow responses in particular)
- 105 cases of ‘spatial’ LoDWC and 22 cases using CalAnalytics criteria
  - Unscripted encounters never reached CalAnalytics volume

LoDWC BREAKDOWN

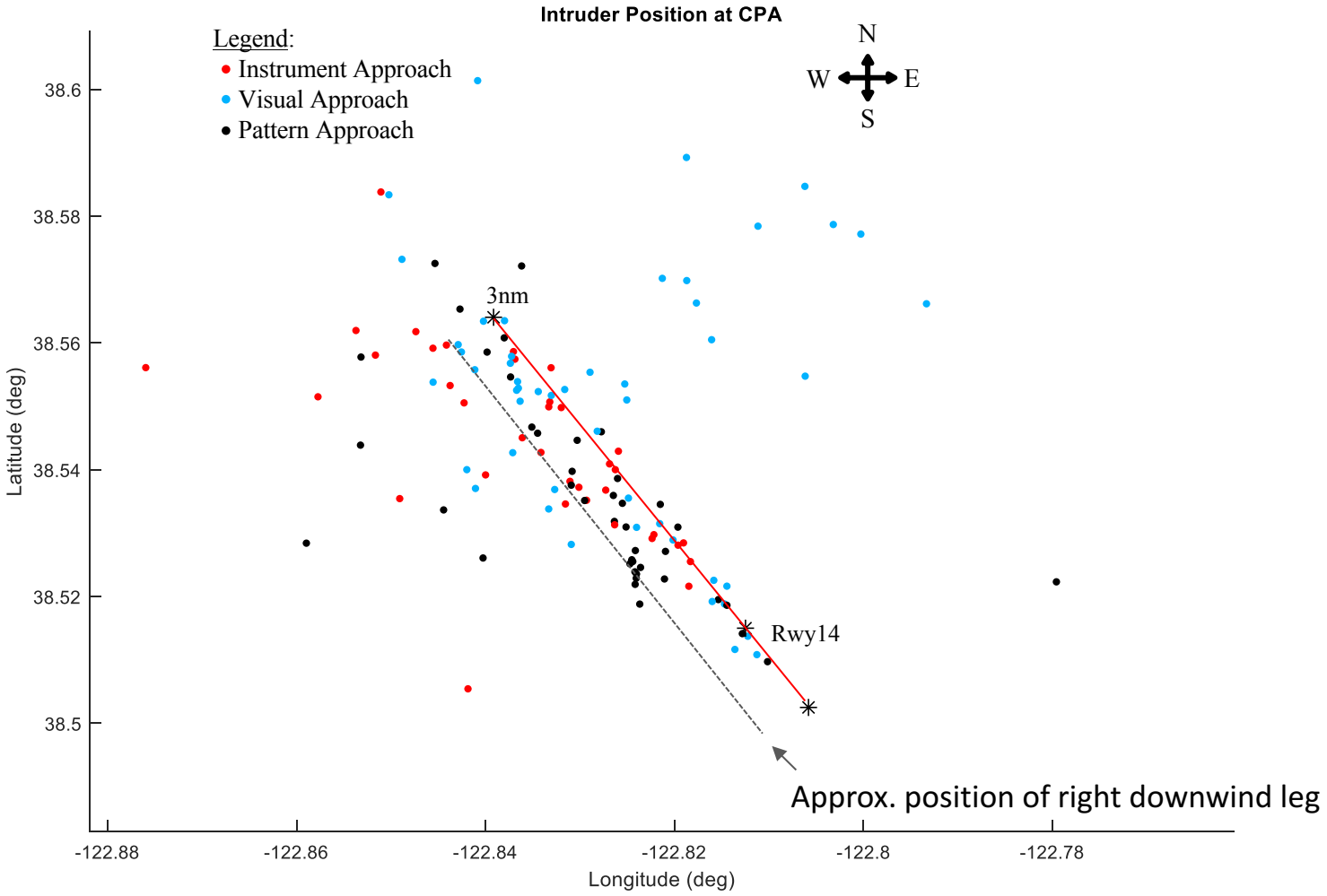
Intruder Location at CPA (For All LoDWC)

- Generally clustered around final with handful of losses during transition from Oakland center airspace to terminal area

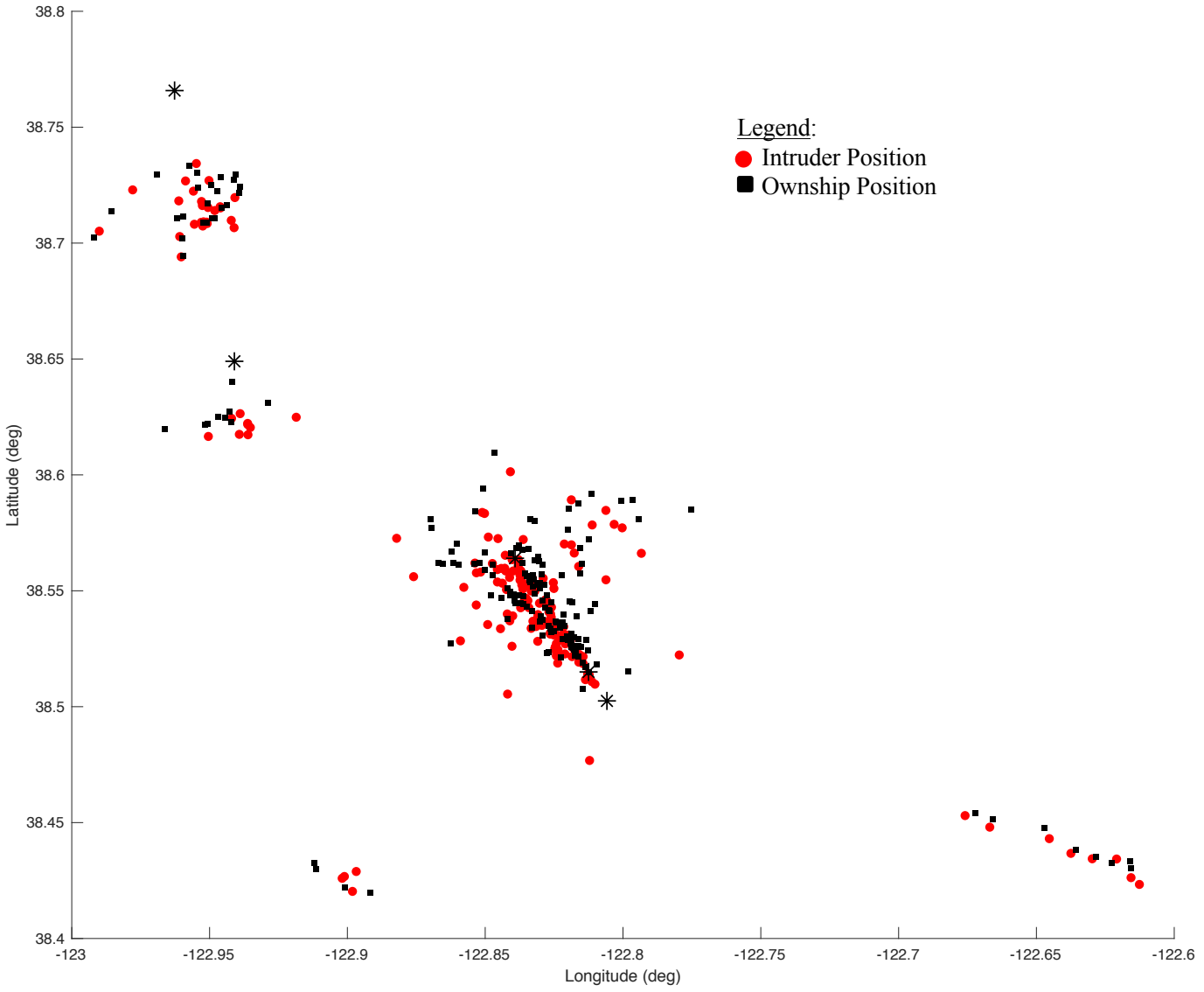


Intruder Location at CPA (For All LoDWC)

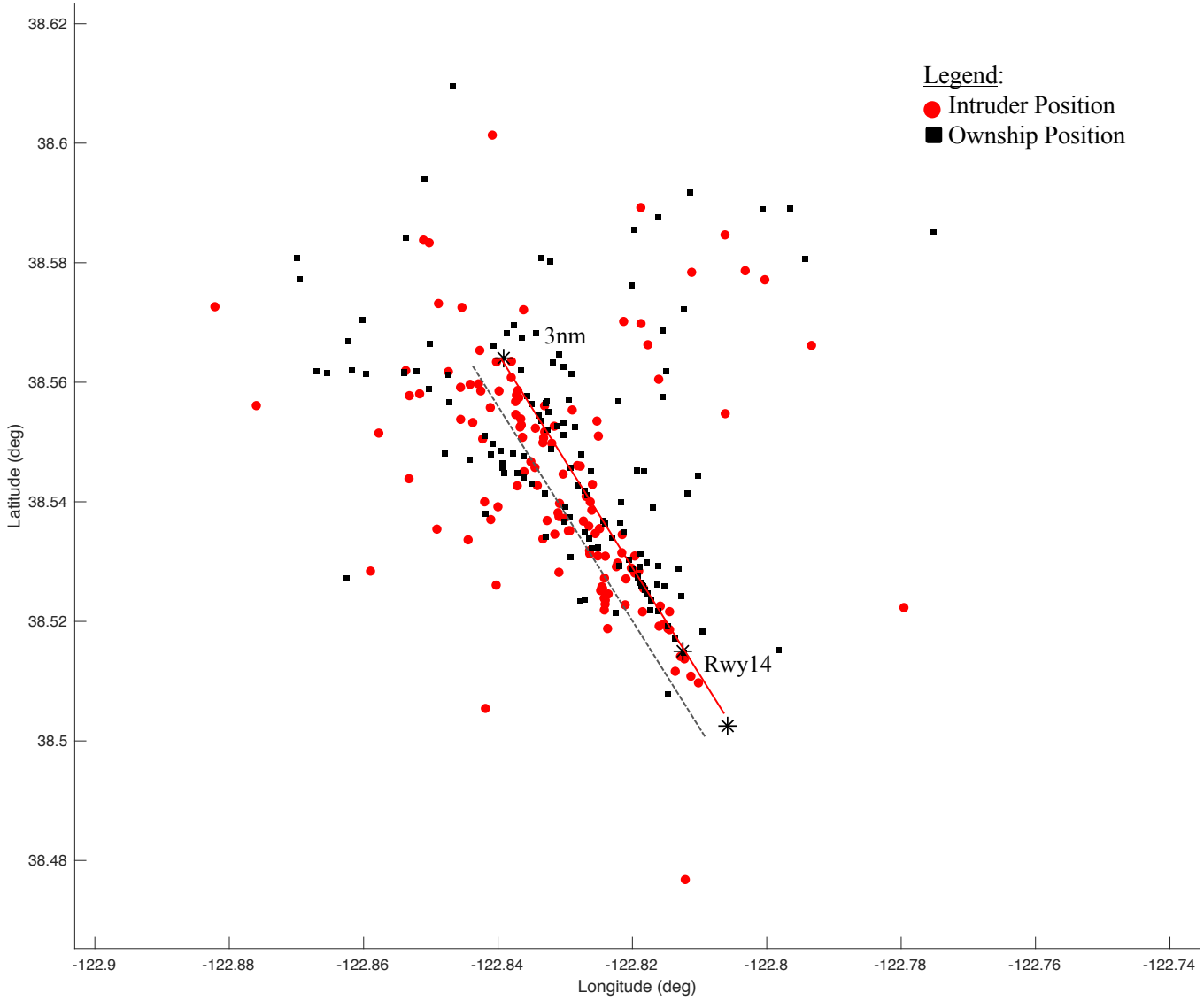
- Majority of intruders are on or near right downwind



Intruder & Own Lat/Long



Intruder & Own Lat/Long



Own Lat/Long

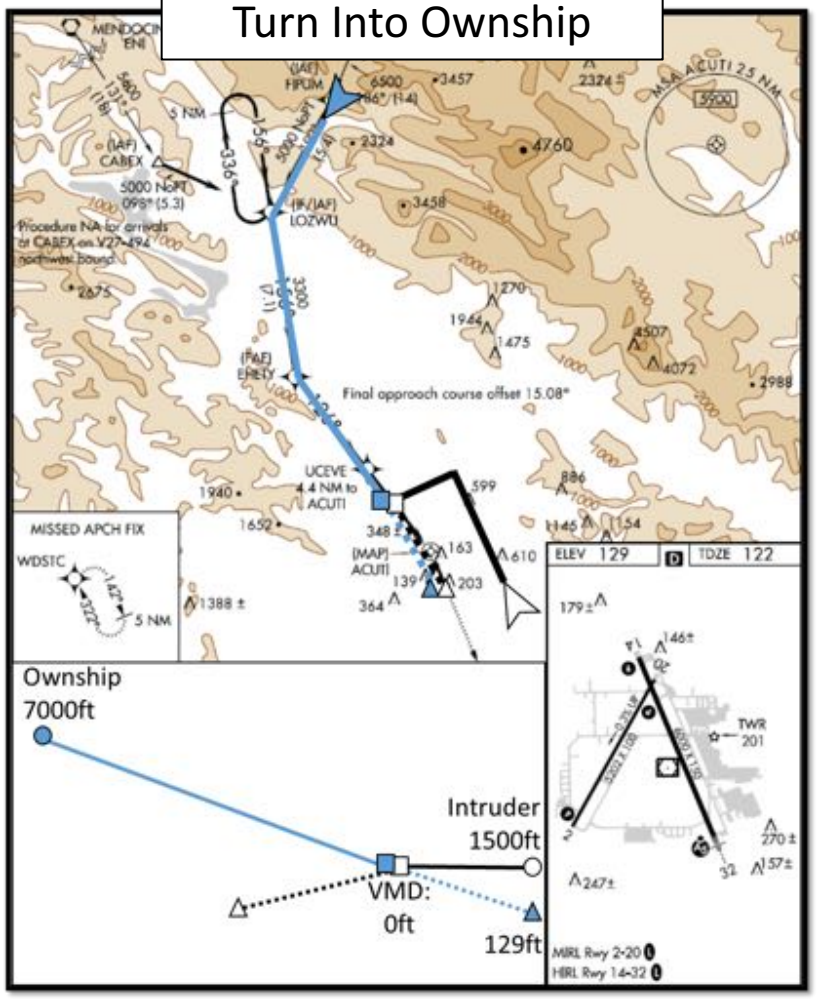
LoDWC by Encounter Type

- Encounters designed to turn directly into us while ownship was on final were most likely to result in LoDWC (97%)
- Encounters with a head-on KSTS departure while ownship was on final were most likely to result in “spatial” LoDWC (83%)

Encounter Type	Encounter Location	% LoDWC	% "Spatial" LoDWC	Total Scripted
Turn Into Ownship	Late	97%	63%	36
Departure	Late	88%	83%	18
Overflight	Late	72%	44%	18
Turn in Front	Late	69%	47%	36
Overflight	Early	61%	29%	54
Cut-Off (Base)	Early	55%	38%	18
Parallel Track	Early	50%	22%	18
Departure	Early	22%	11%	18

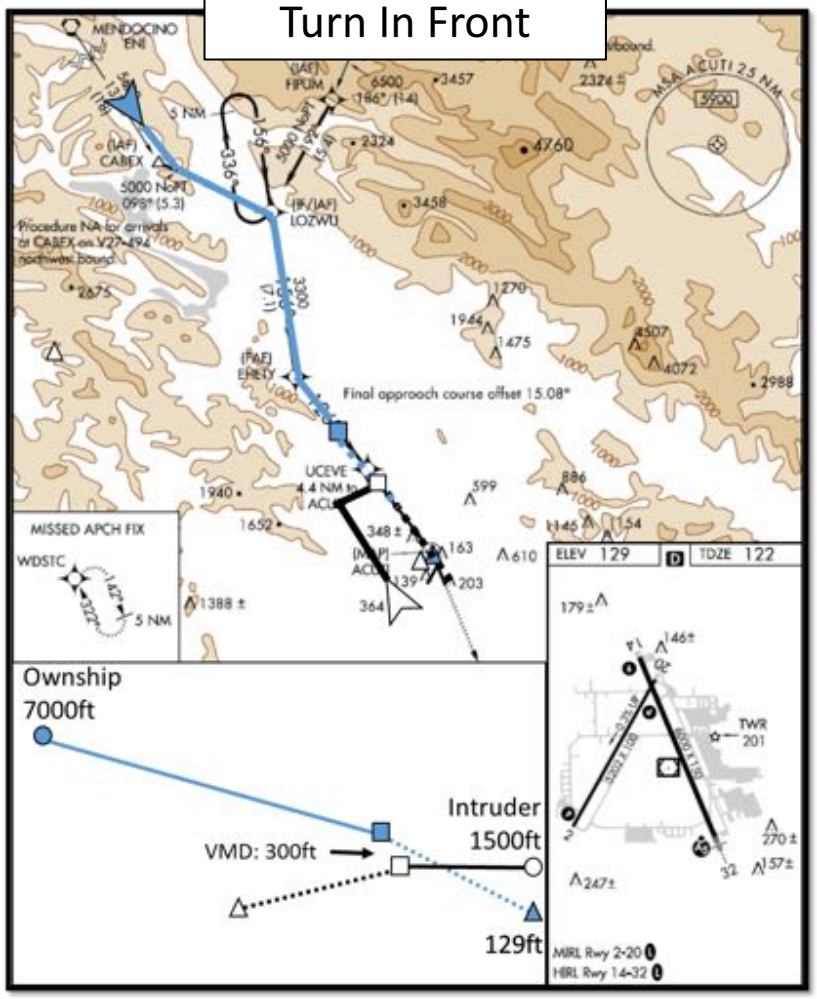
Late Encounter Examples

Turn Into Ownship



# of LoDWC	# of "Spatial" LoDWC
35 (97%)	23 (63%)

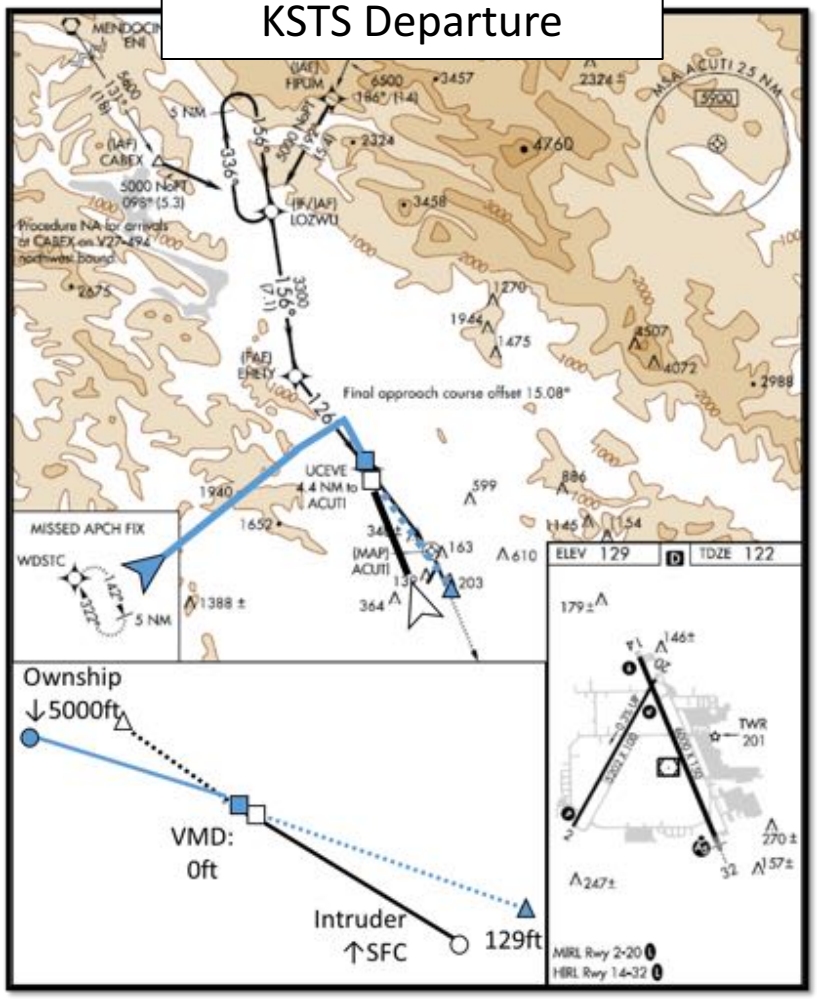
Turn In Front



# of LoDWC	# of "Spatial" LoDWC
25 (69%)	17 (47%)

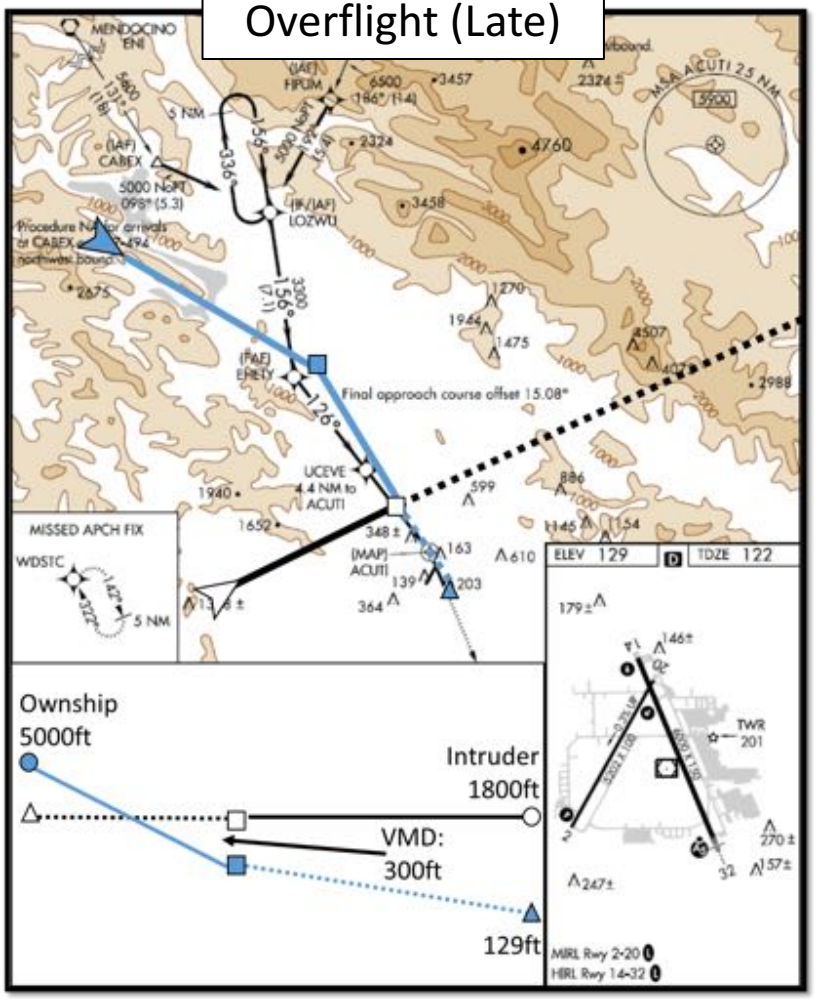
Late Encounter Examples

KSTS Departure



# of LoDWC	# of "Spatial" LoDWC
16 (88%)	15 (83%)

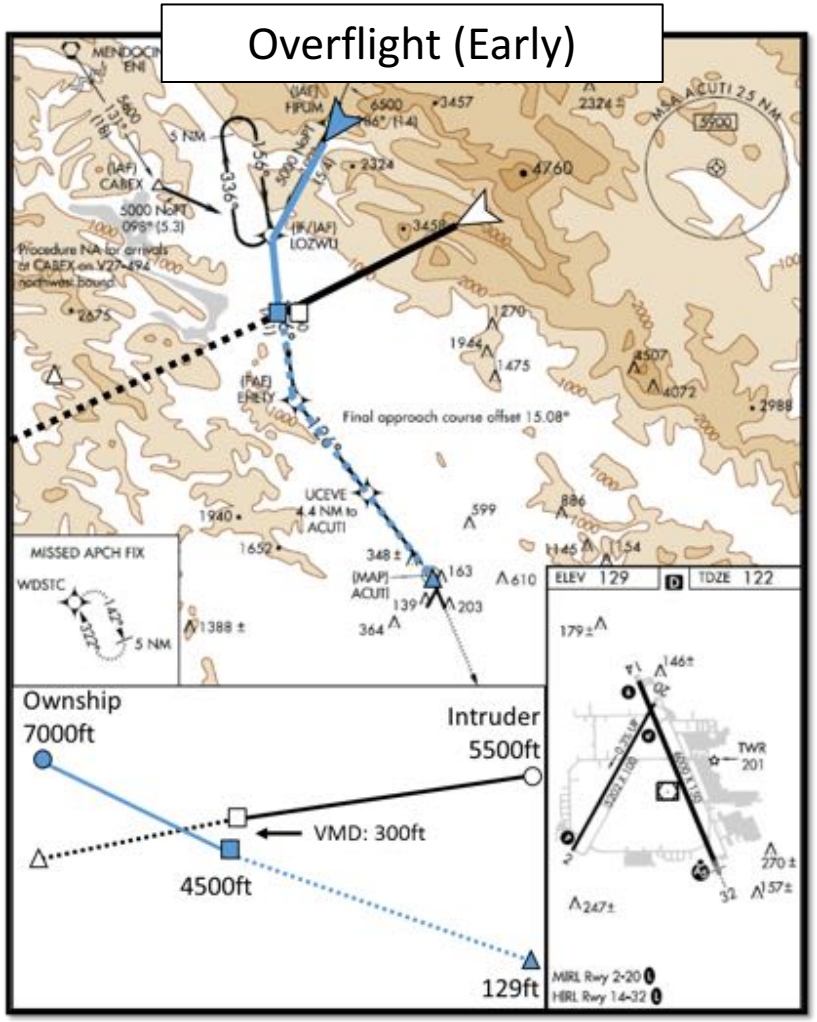
Overflight (Late)



# of LoDWC	# of "Spatial" LoDWC
13 (72%)	8 (44%)

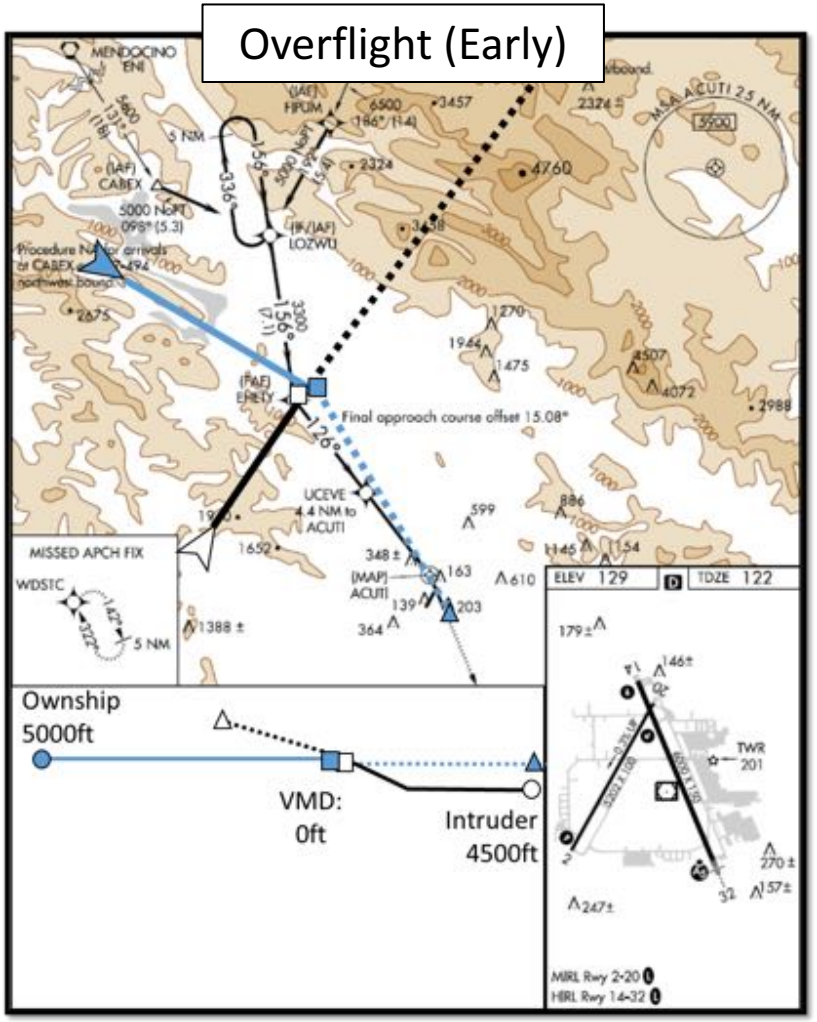
Early Encounter Examples

Overflight (Early)



# of LoDWC	# of "Spatial" LoDWC
33 (61%)	16 (29%)

Overflight (Early)



# of LoDWC	# of "Spatial" LoDWC
33 (61%)	16 (29%)

Unscripted LoDWC

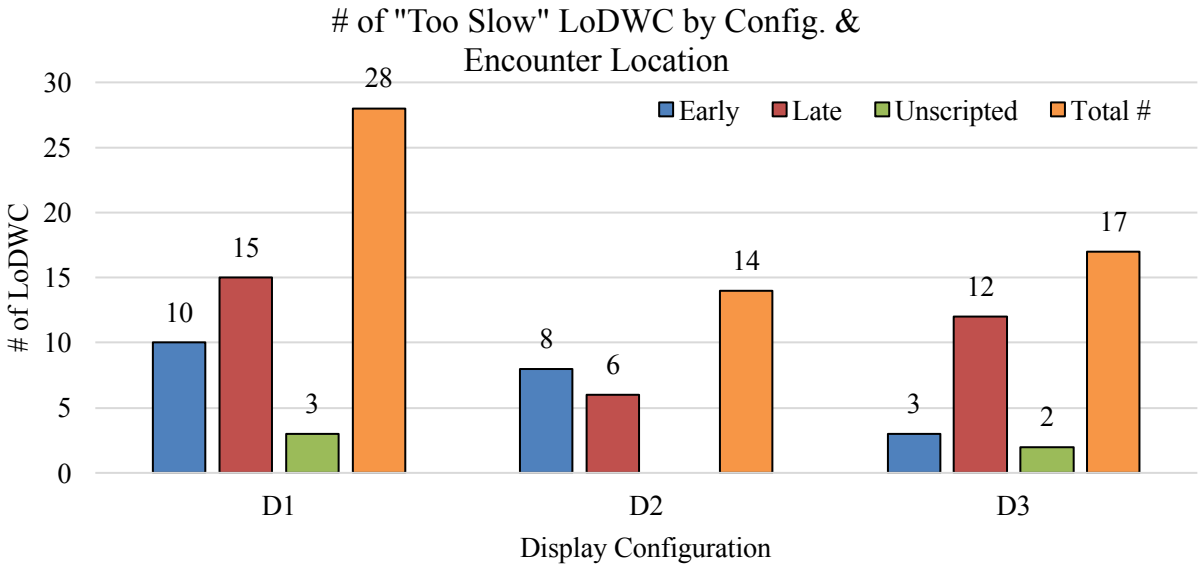
- Instances of LoDWC with unscripted encounters most often happened as intruder was on right downwind
  - Intruders turning base or final was second most common cause
- Ownship was typically established on final when these LoDWC occurred
  - Minority occurred when ownship was turning base/final or approaching the 3nm fix

Intruder Location	# LoDWC	"Spatial" LoDWC
Downwind	13	6 (46%)
Turning (Base or Final)	10	3 (30%)
On Final	4	3 (75%)
On Base	2	1 (50%)
Approaching Final	1	0
Jet Traffic	1	0
TOTAL	31	11

Causes of LoDWC

- Pilot error accounted for 63% of LoDWC
  - Most common cause of LoDWC was the pilot responding too slowly
- Late acceleration (< 15sec to LoDWC at first alert) 2nd most common cause
- D1 resulted in greatest number of slow responses
  - D2 resulted in fewer slow responses against late encounters than D1 and D3

	LoDWC Category	Total
Pilot Responsible	Too Slow	34%
	Ineffective Maneuver	11%
	Return Too Soon	9%
	Turned Base/Final Too Soon	5%
	No Maneuver	2%
	Secondary Cause by Pilot	2%
Pilot **Not** Responsible	Late Acceleration	33%
	Pattern Activity	5%



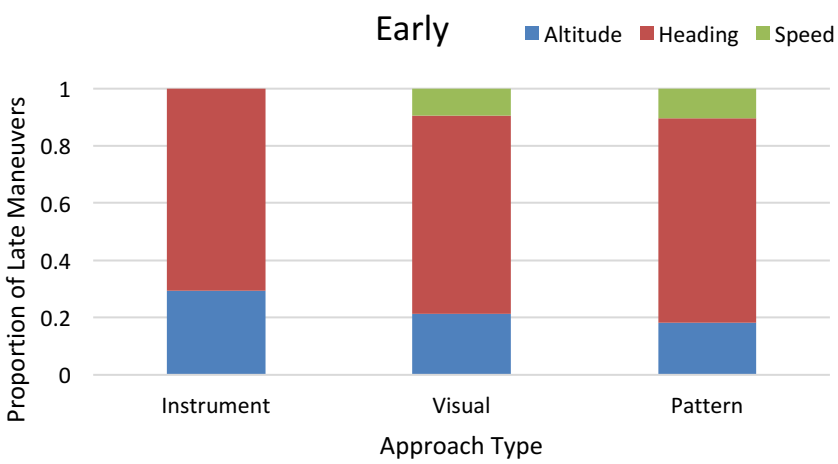
LoDWC Results Summary

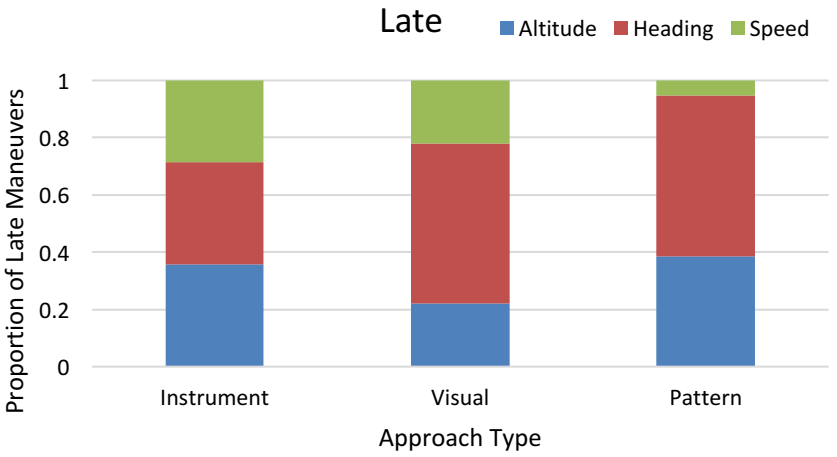
- LoDWC occurred near final, and specifically alongside right downwind
  - Turns directly into ownship on final and a departure were most likely encounter types to progress to LoDWC
  - Right downwind traffic was the biggest cause of LoDWC against unscripted intruders
- 2/3 of LoDWC a result of slow pilot response or late acceleration (both more common with late encounters)

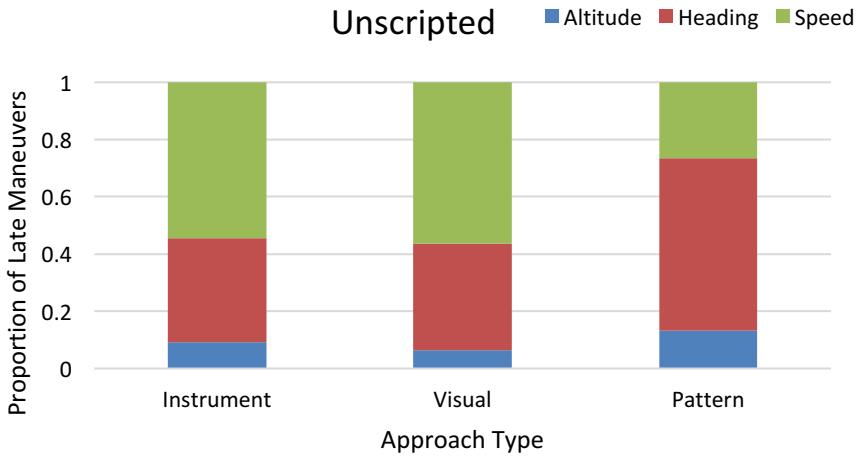
MANEUVERING & ATC INTEROPERABILITY

Maneuver Preferences

- Pilots resolved most maneuvers with heading changes
  - Late encounters resulted in more altitude and speed changes than early encounters



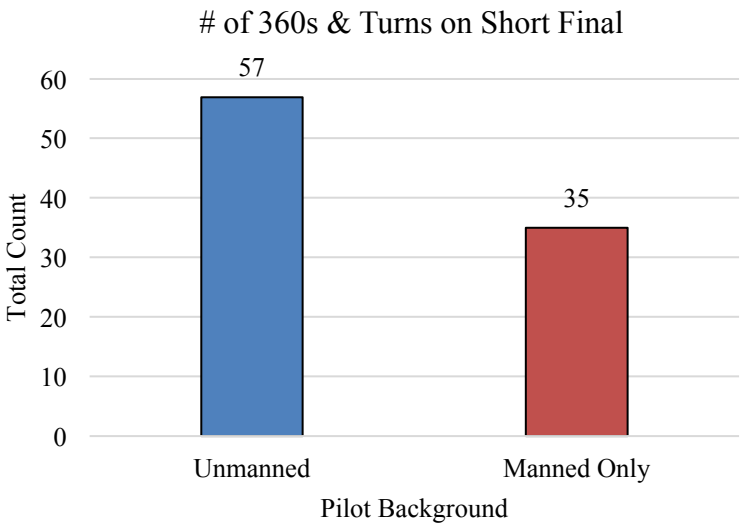


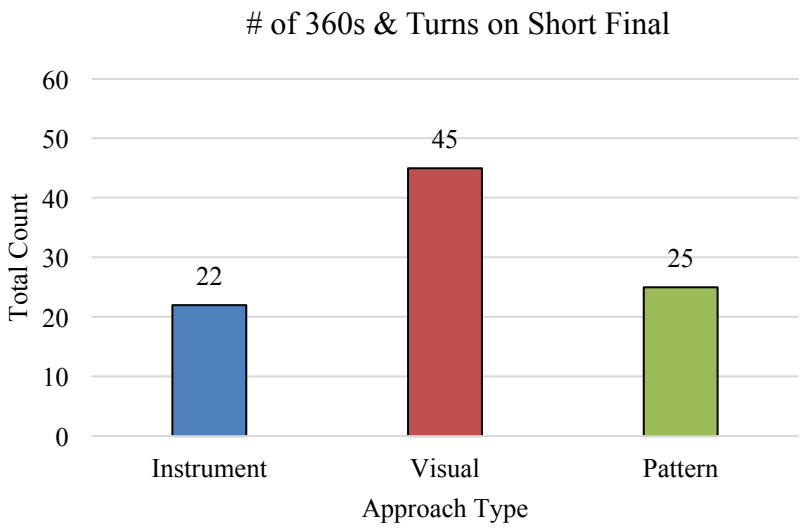


Maneuver Characteristics

- 2 flights into terrain occurred during data collection runs
  - Both occurred during “visual” approach scenario where pilots descended to pattern altitude early

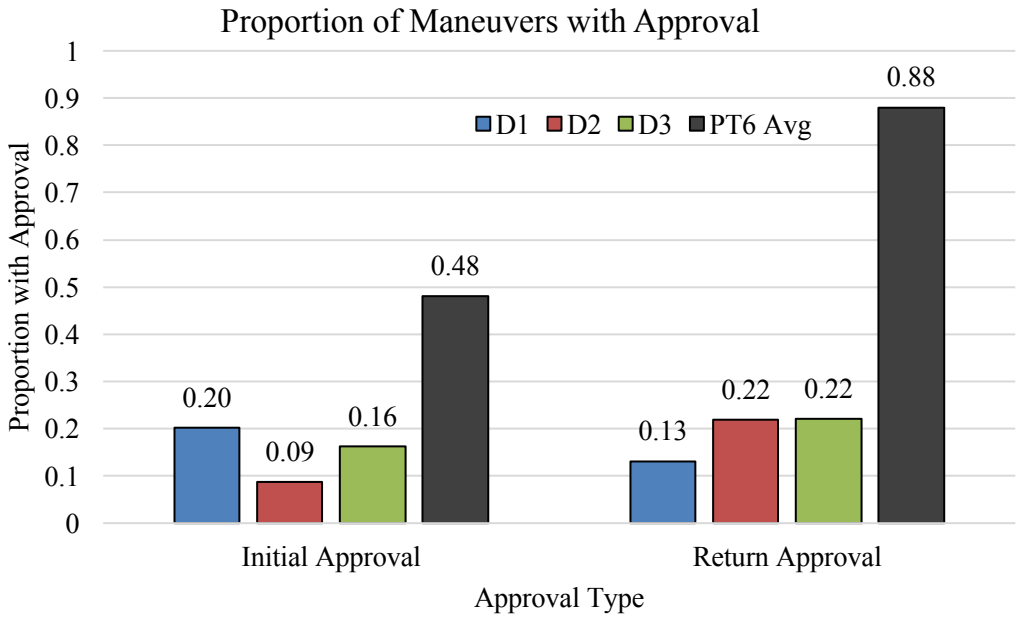
- Tower raised concern with number of 360s & turns made near runway
  - Much more common among pilots with unmanned experience and flying visual approach





ATC Coordination

- Receiving ATC approval was rare, regardless of condition
  - Slightly more frequent when returning to course
  - Far less common than PT6

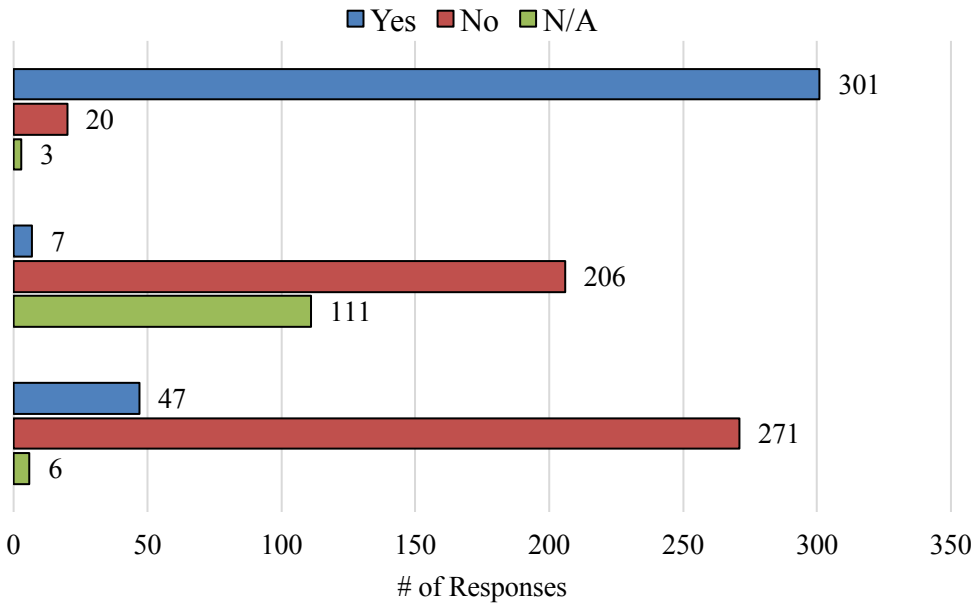


- Initial Approval = # of initial maneuvers with approval from ATC / # of total maneuvers made
- Return Approval = # of returns to course with approval from ATC / # of total returns to course

Tower Controller Feedback

- After each encounter, tower controller answered the following questions:

1. In this encounter did the UAS pilot maintain adequate separation?
2. Did the UAS pilot maneuver unnecessarily for the encounter?
3. Were there issues with UAS pilot communication?



- Tower rated UAS behavior as overwhelmingly appropriate
  - Rated 'inadequate' separation typically when SLoWC > 50%
  - Unnecessary maneuvers were noted typically identified when pilot disrupted pattern sequencing
  - Communications was the most common issue (primarily not receiving advisory from pilot on traffic or maneuver)

ATC Interoperability Results Summary

- Heading maneuvers most common, more altitude/speed changes against late and unscripted encounters
- Major maneuver issues were flights into terrain and 360s/turns near runway
- UAS actions largely rated appropriate by tower
  - Tower often called out cases with SLoWC > 50% & unnecessary turns near pattern
  - Lack of coordination biggest issue raised by Tower

Conclusion

- Phase 1 DAA Well Clear Definition
  - Pilots had a hard time judging when a maneuver was necessary to avoid high-severity LoDWC
    - None above 30% in PT6
    - 17 > 50% SLoWC; 6 > 70% due to pilot error (slow responses most common)
- Display Configuration
  - Modest benefits for D2
    - D1 resulted in slower average pilot response times and twice as many LoDWC caused by slow responses compared to D2
    - D3 had greatest proportion of high-severity LoDWC
  - Utility of corrective alert diminished near airport
    - Most Warning alerts either had no prior Corrective or Corrective < 15s
- Encounter Location
  - Late encounters responsible for most LoDWC
  - LoDWC with unscripted encounters were low in frequency and severity
- Additional
  - LoDWC typically resulted from pilot hesitation and late acceleration
  - Pilot rated well by ATC across the board with a few exceptions
    - E.g., rate of coordination, excessive maneuvering around final, flights into terrain

Terminal Operations HITL 1b

- Purpose: measure performance of DAA system using terminal-specific DAA well clear definitions
- Lessons learned to be leveraged in follow-on experiment
  - Removing pattern approach & early encounters from experimental design
  - Fewer scripted encounters
- Proposed IV's:
  - Terminal DAA Well Clear candidate definitions:
    - AFRL: Horizontal = 0.2nm (~1215ft), Vertical = ±450ft, no Tau
    - Langley: TBD
  - Alert structure: with vs. without DAA Corrective
- Data collection begins **26 JANUARY**