National Aeronautics and Space Administration

Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project NASA Contributions to the SARP WC Definition

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NASA Controller Acceptability Study and ACES Simulation

	Final Agreed Operational Acceptability Metrics			
Acceptability Metric	NASA Controller Acceptability Study	MIT/LL Monte Carlo	USAF Open/Closed Loop Simulation	NASA ACES Simulation
TCAS II RA Rate	✓	✓	✓	✓
Controller Acceptability Considerations	✓		✓	
Well Clear Volume Penetration Rate		✓	✓	✓
Crosstrack Deviation		✓	✓	✓
Vertical Deviation		✓	✓	✓
Maneuver Initiation Point		✓	✓	✓
CPA Miss Distance/Time Given Well Clear Violation		✓		✓
Mitigated Risk Ratio		✓		

Benefits of Controller Acceptability Study (CAS1)

- Provides a direct assessment of Well Clear Boundary (WCB) operational acceptability by air traffic controllers (i.e., operators)
  - CAS1 simulates lower altitude, moderate-complexity Class E airspace operations
  - These operations are challenging for WCB definitions and DAA: more well-clear encounters, more traffic flow constraints
  - Controllers for this airspace are arguably most accustomed to well clear encounters and accommodating them along with other separation services
- Provides insight into both *minimum* and *maximum* acceptable WCB sizes
  - Air Traffic Controllers (ATC) require a WCB that works within the existing operations of the National Airspace System (NAS)
  - A WCB that is *too small* will cause safety concerns for ATC, and potentially distract attention from other encounters in the sector, *but*
  - A WCB that is *too big* will disrupt traffic flow, and increase ATC workload due to secondary conflicts and cross-sector coordination
- Provides an additional look at TCAS II Corrective RA Rates between WCB definitions, using the CAS1 encounter set

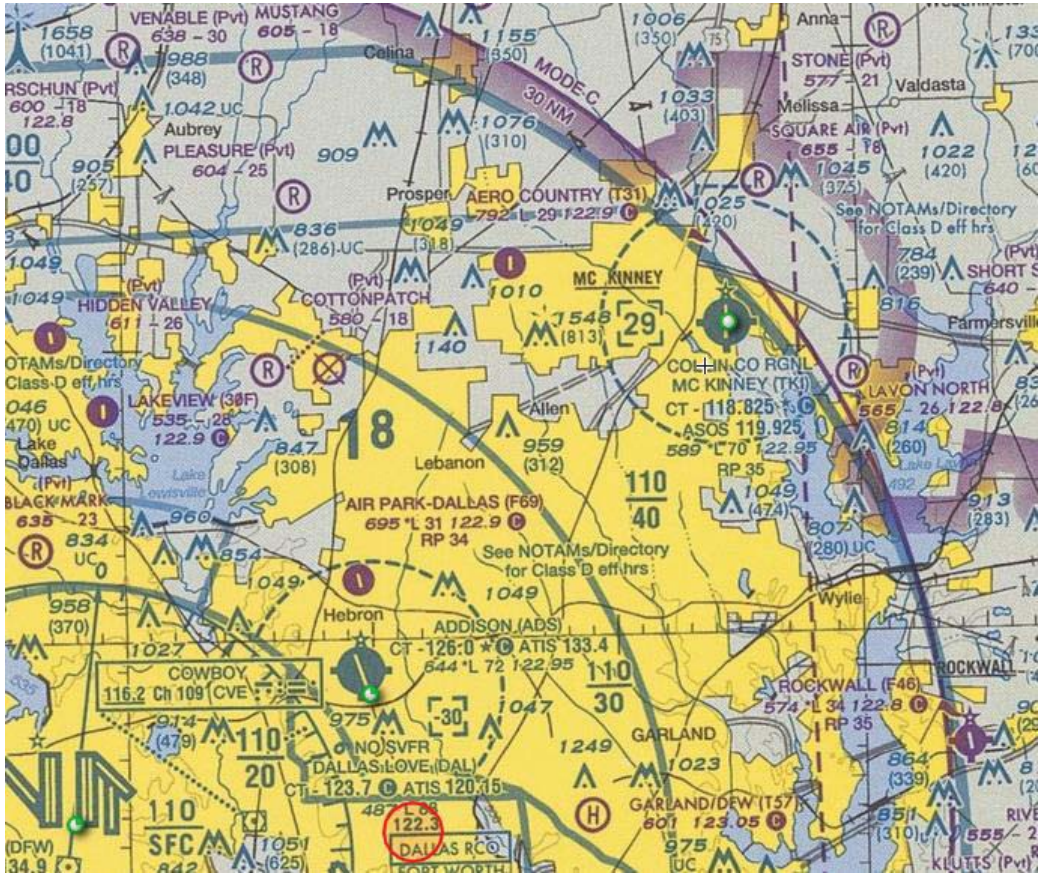
Benefits of ACES Simulations

- Airspace Concept Evaluation System (ACES) Simulations
  - Simulate UAS traffic from various proposed missions with “UAS-like” aircraft models
  - Collect NAS-wide encounter data within various classes of airspace
  - Simulate 100s of thousands of flight hours in a matter of days
  - Evaluate well-clear violation rates against historical VFR radar data (RADES)

CAS1 Research Approach

- Construct a set of simulated “well clear encounters”
  - Different miss distances, encounter geometries, relative speeds
- Embed these encounters into simulated background traffic scenarios representative of moderate-workload TRACON traffic (IFR and VFR) on a calm, clear-weather day
- Ask a series of ATC volunteers to “control” the simulated traffic scenarios, and measure the results
  - *Direct query after each encounter*
  - Workload and performance measures throughout
- Perform statistical analysis of all data afterward to assess the range(s) of acceptable horizontal miss distances
  - 14 controllers, 84 simulation hours, 1176 queries

CAS1 Traffic Scenario Area



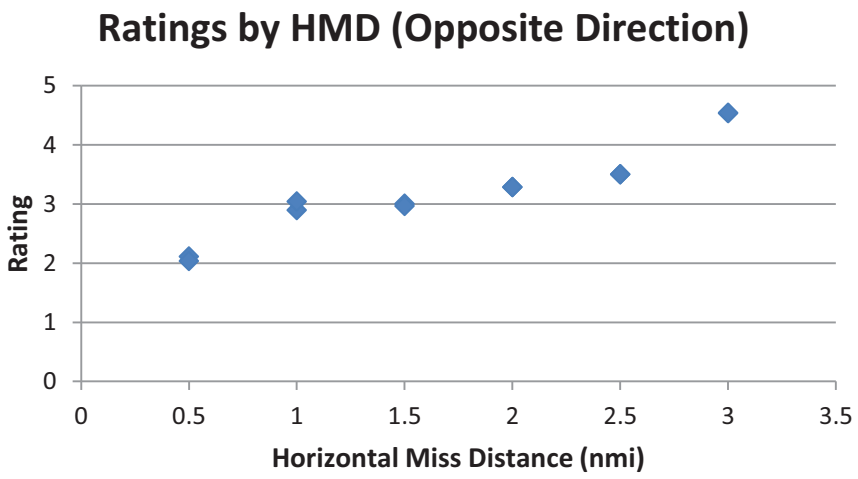
Scenarios focused on ATC sector handling arrivals to Collin County Regional (McKinney – TKI), ~28 nmi NE of DFW

Feature-rich airspace:

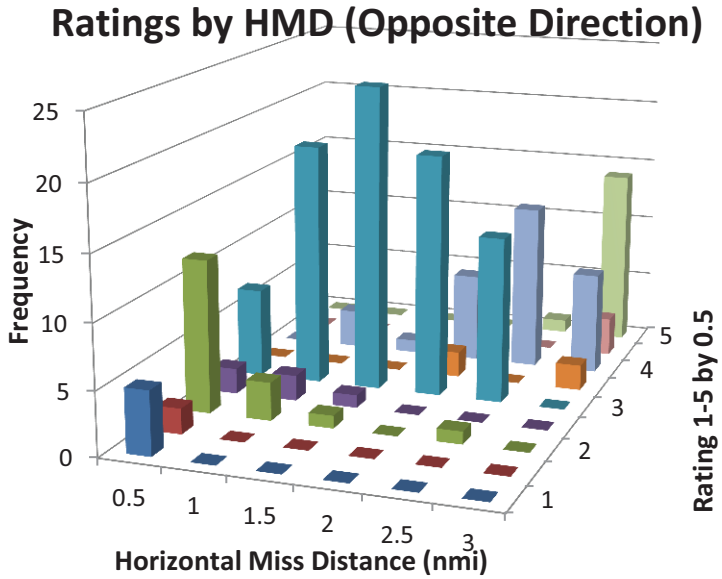
- Class B, 4000-11000' above TKI
  - VFR & IFR aircraft all under positive control, all cooperative
- Class D, SFC-2900' around TKI
  - VFR & IFR cooperative aircraft receiving Class D ATC services
- ❖Class E, 700' or 1200' AGL up to FL180 and outside Class B and D
  - IFR aircraft
  - VFR aircraft, some receiving ATC services, some not
  - CAS1 Well Clear encounters occurred in this airspace
- Class G, SFC to overlying airspace
- Nearby non-towered airports

Ratings for Opposite Direction encounters
Mean of 14 ATC subjects for each encounter

Rating Scale: After each "well clear encounter" test subjects were asked to rate the horizontal miss distance (HMD) on a five-point scale: From 1=Too Close to 5-Too large



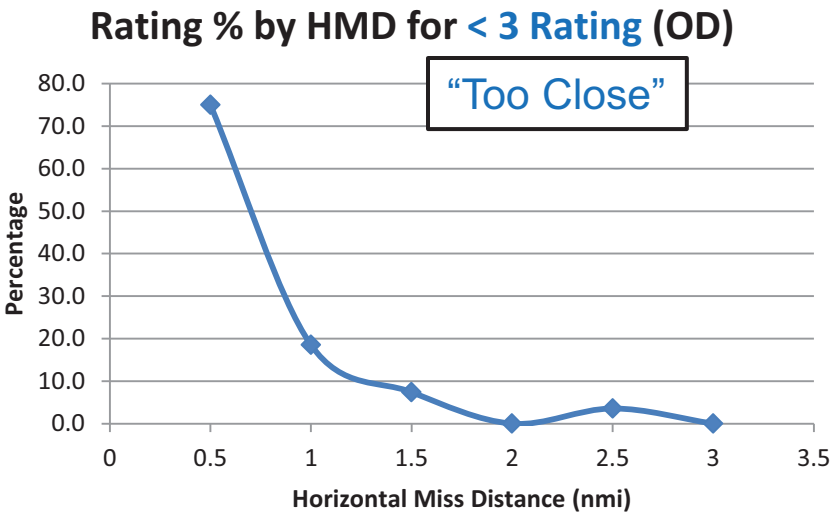
The plot above shows Mean Ratings for **opposite direction** encounters.

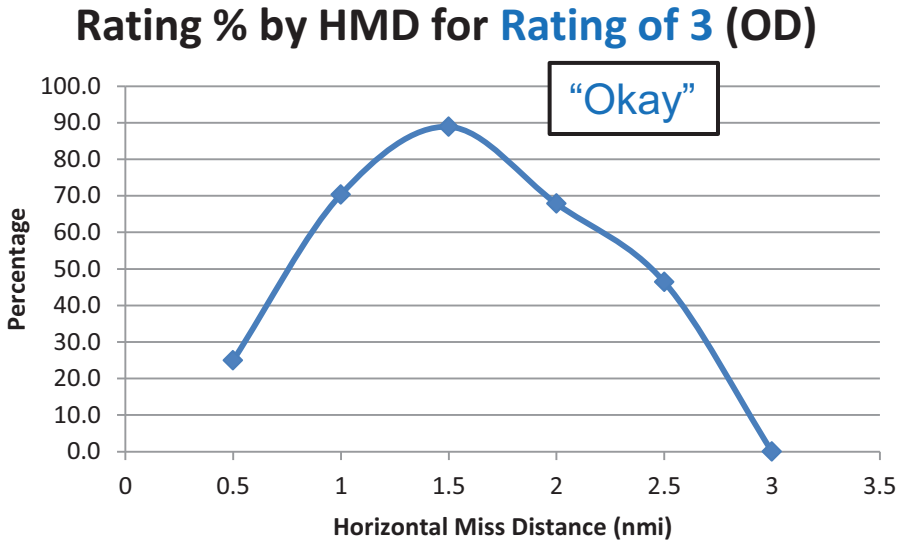


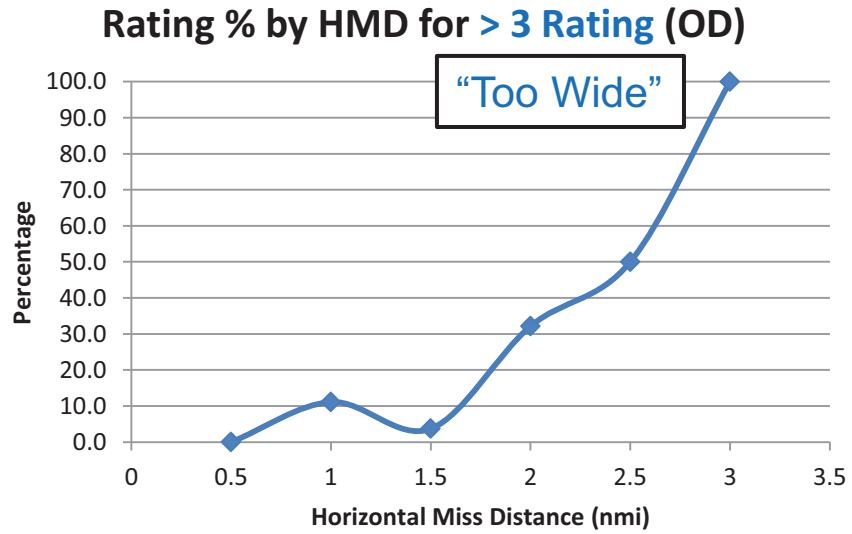
Plot of frequency of Rating responses for **opposite direction** encounters.

Note: All Horizontal Miss Distances required a UAS lateral maneuver (initially a collision course)

Ratings for Opposite Direction encounters
Rating % by HMD for <3, 3, and >3 Ratings







- Horizontal Miss Distance (HMD) of ~1.5 nmi appears optimal for ATC acceptability
- HMD range of 1-2 nmi looks good

OD = Opposite Direction encounters

CAS1 Approach to ATC Acceptability Assessment for WCB Candidates

- For each CAS1 “well clear encounter” and each WCB candidate:
  - Assess HMD value
  - Use encounter geometry and HMD to determine CAS1 ATC measured acceptability rating (interpolate as necessary)

CAS1 ATC Acceptability Assessment for WCB Candidates: Encounters Exactly at WCB

- Average HMD ratings:

	Opposite Direction		Overtake		Crossing	
Model	**HMD**	**Rating**	**HMD**	**Rating**	**HMD**	**Rating**
USAF	0.87	2.9 *	0.72	2.6 *	1.1 – 1.8	2.8 – 3.2 *
MIT LL	0.67	2.3 *	0.67	2.5 *	0.67	2.3 *
NASA	1.0	3.0	1.0	2.9	1.0	2.8

* Interpolated

CAS1 ATC Acceptability Assessment for WCB Candidates: Encounters Exactly at WCB

- Percent < 3 (“too close”) rating:

	Opposite Direction		Overtake		Crossing	
Model	**HMD**	**< 3**	**HMD**	**< 3**	**HMD**	**< 3**
USAF	0.87	30% *	0.72	40% *	1.1 – 1.8	22% – 5% *
MIT LL	0.67	55% *	0.67	46% *	0.67	55% *
NASA	1.0	19%	1.0	18%	1.0	25%

* Interpolated

- Percent > 3 (“too wide”) rating:

	Opposite Direction		Overtake		Crossing	
Model	**HMD**	**> 3**	**HMD**	**> 3**	**HMD**	**> 3**
USAF	0.87	7% *	0.72	2% *	1.1 – 1.8	2% – 34% *
MIT LL	0.67	4% *	0.67	1% *	0.67	1% *
NASA	1.0	11%	1.0	4%	1.0	2%

* Interpolated

CAS1 Approach to ATC Acceptability of Vertical Deviation

- Controller assessment of acceptable vertical deviations was performed during debrief sessions
  - All preferred 500’ or less for level VFR-IFR encounters
  - Opinions were negative when asked to assess effects of WCB “taller” than 500’, e.g.:
    - “Problematic”
    - “Would be a significant factor in congested airspace, if you’re working other aircraft it [<=500’] gives you another altitude”
    - “I don’t think it would be pretty”
    - “I would expect 500’ to be sufficient for a manned aircraft, it should be sufficient for an unmanned aircraft”
    - “Would be pretty disruptive”

CAS1 Approach to TCAS RA Rate Evaluation

- For each CAS1 “well clear encounter” and each WCB candidate:
  - Assess minimum HMD values
  - Use encounter geometry (including the respective WCB candidate’s HMD) as input to simple CAS1 TCAS model
  - Determine whether a corrective RA would have occurred for each well clear encounter geometry and WCB candidate

Tau and HMD Threshold Values for TCAS

- TCAS Tau and HMD threshold values for RA issuance are altitude-dependent (lower values at lower altitudes):

Own Altitude (ft)	Tau (sec)	HMD (nmi)	HMD + 50%
< 1000 AGL	N/A	N/A	N/A
1000-2350 AGL	15	0.20	0.30
2350-5000	20	0.35	0.53
5000-10000	25	0.55	0.83
10000-20000	30	0.80	1.2
20000-42000	35	1.1	1.7
>42000	35	1.1	1.7

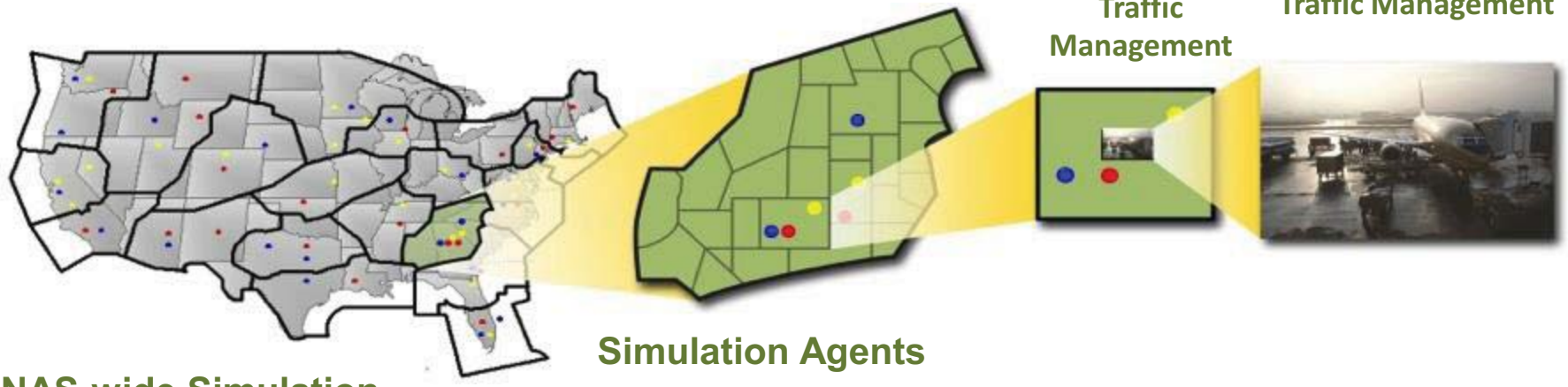
- Self Separation HMD distances should be no smaller than TCAS HMD values but may need to be larger for controller acceptability

CAS1 TCAS RA Rate Evaluation Results

- For the 42 CAS1 encounters *as simulated*, TCAS model, and WCB candidate HMD values, one TCAS RA each occurred for the USAF and LL WCB candidates
  - HMD values are generally sufficient for all WCB candidates
  - TCAS sensitivity level and aircraft speeds are also low
- Results if all encounters flown *between 5000-10000'* (e.g., 6000'):
  - USAF: 2 RAs
  - LL: 36 RAs (all but the overtake encounters)
  - NASA: 0 Ras
- Results if all encounters flown above 10000':
  - USAF: 12 RAs
  - LL: 36 RAs (all but the overtake encounters)
  - NASA: 36 RAs (all but the overtake encounters)
- HMD > 1.2 nmi avoids RAs below Class A with this TCAS model

Modeling and Simulation: ACES

National Traffic Management | Regional Traffic Management | Local Approach and Departure Traffic Management | Airport and Surface Traffic Management



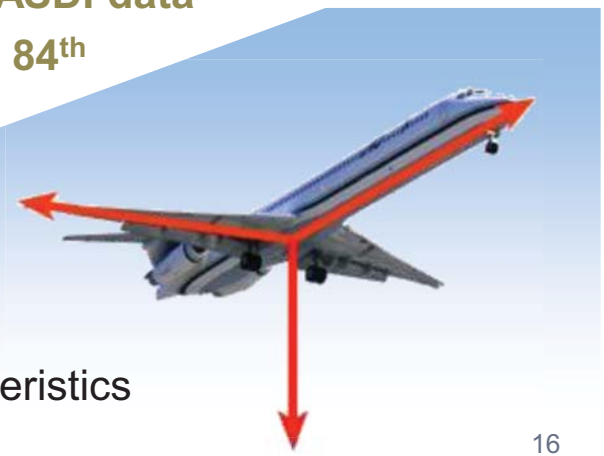
NAS-wide Simulation

- Gate-to-gate simulation of ATM operations
- Full flight schedule with flight plans
- Sector and center models with some airspace procedures

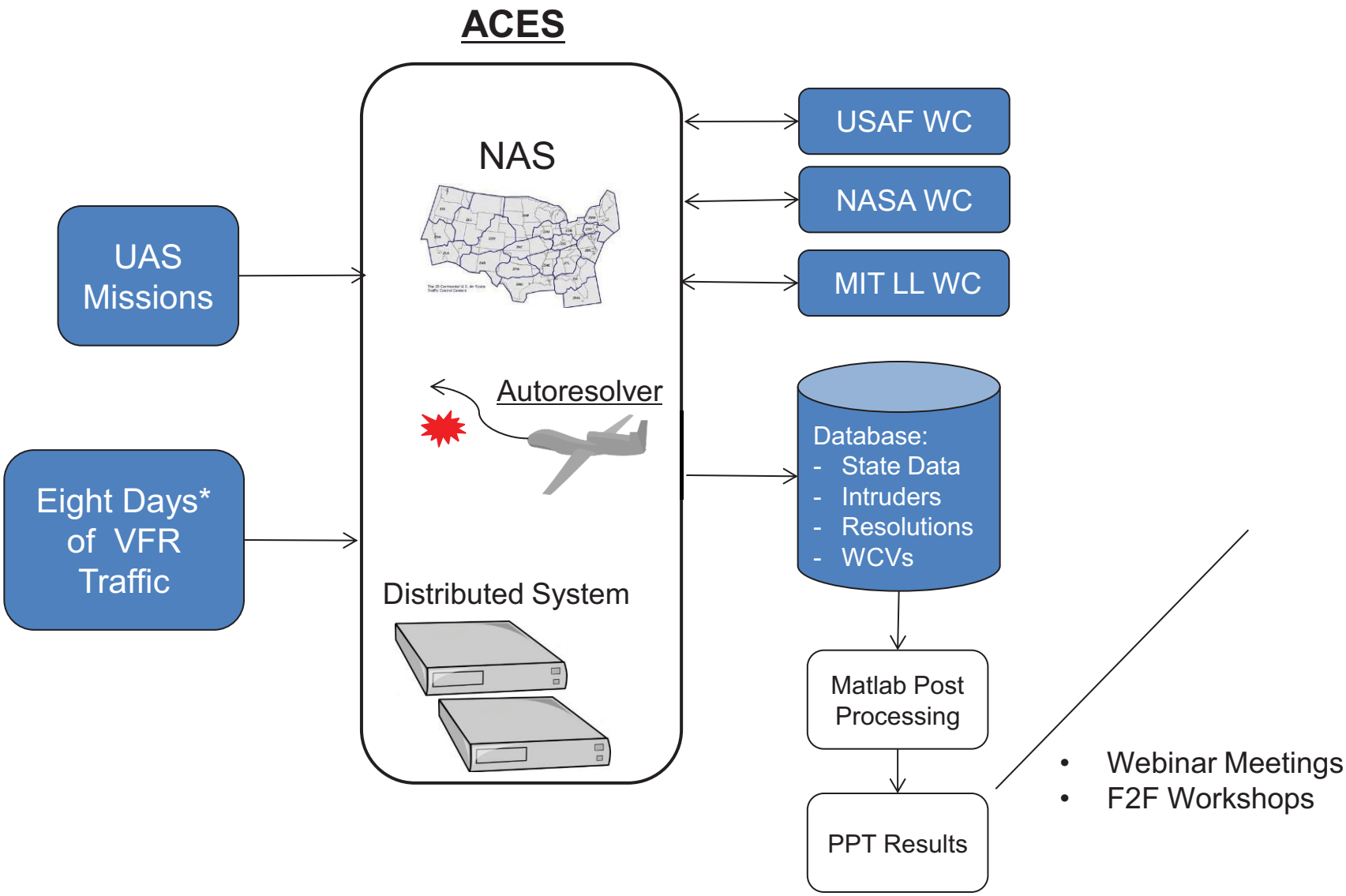
Simulation Agents

- Air traffic controller decision making
- Traffic flow management models
- Individual aircraft characteristics
- IFR Flight Tracks from ASDI data
- VFR Flight Tracks from 84th Squadron RADES data

4-DOF Trajectory Model
- Aerodynamic models of aircraft
- Models replicate pilot behavior
- User-definable uncertainty characteristics



ACES Well-Clear Simulation and Analysis



**** Over 25k UAS flight hours simulated in the NAS per day***

UAS Missions Characteristics

	UAS group	Duration (per flight)	Flights per day	Cruise Alt.	Flight Pattern
Air Quality Monitoring	Shadow-B	1-4 hrs.	104-1044	4k,5k, and 6k ft AGL	Radiator Grid Pattern
Cargo Transport	Cessna 208	varies	1.4k	2k-16k	Point to Point
Atmospheric Sampling	Global Hawk	1.5-13 hrs.	2352	5k-35k ft AGL	Radiator Grid Pattern
On-demand Remote Air Taxi -Cirrus	Cirrus SR22T	varies	8k	6k-11k	Point to Point
On-demand Remote Air Taxi - Mustang	Cessna Mustang	varies	2k-4k	9k-20k	Point to Point
Strategic Fire Monitoring	Predator-B	20 hrs.	74-324	31k ft MSL	Radiator Grid Pattern
Tactical Fire Monitoring	Shadow-B	1-1.5 hrs.	varies	varies	Circular Loitering Orbit
Flood Inundation Mapping	Aerosonde	1-4 hrs.	varies	4k ft AGL	Radiator Grid Pattern Point to Point
Flow Stream Monitoring	Aerosonde	1-4 hrs.	20-200	4k	Radiator Grid Pattern Point to Point

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.

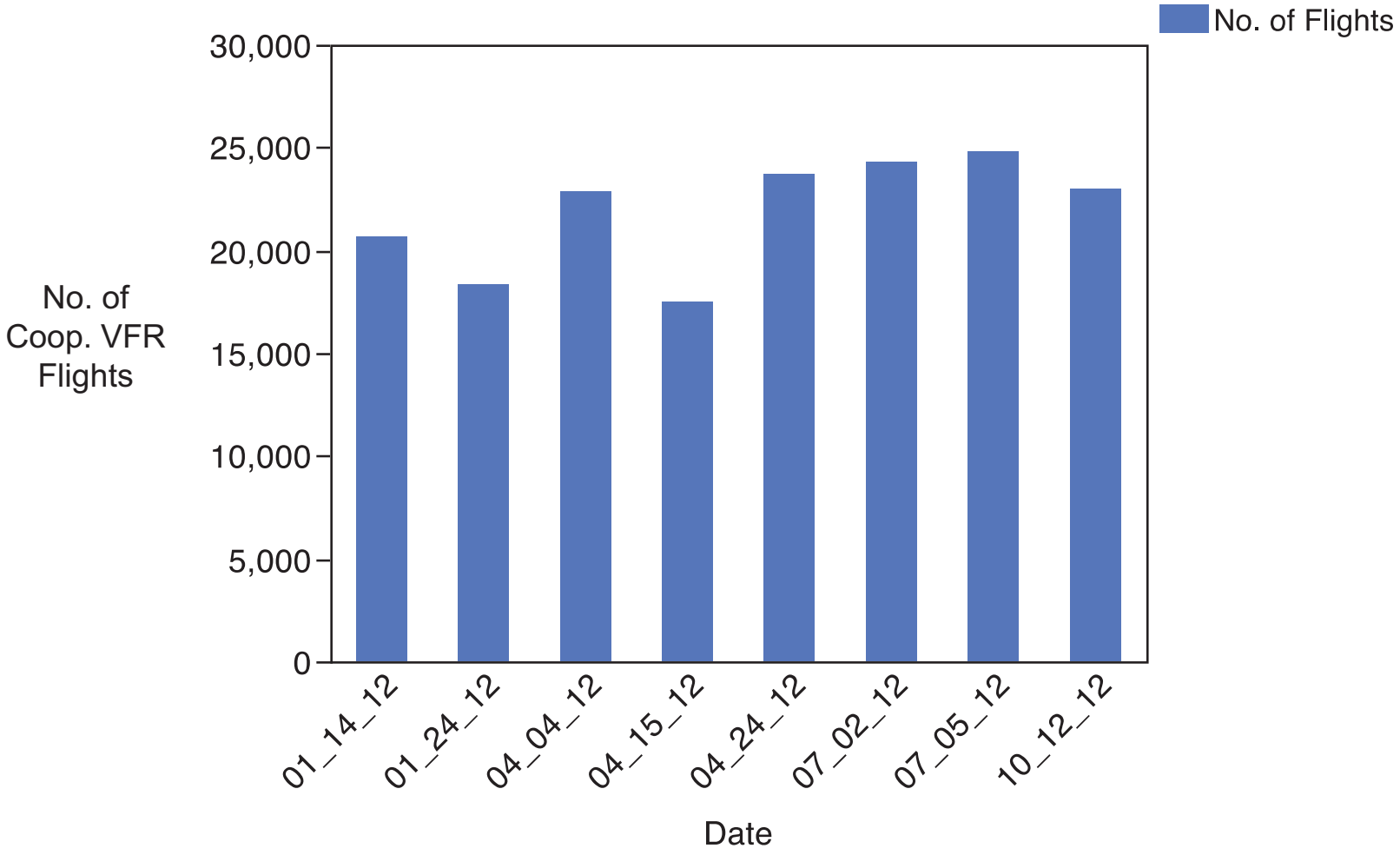
- Criteria for filtering out cooperative VFR traffic (for each tracked flight):
  - All tracks are below 18,000 ft,
  - At least one track has the Mode 3 code of 1200,
  - Average speed ranges from 50 knots to 250 knots.

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.

This becomes the basis of the traffic the UAS's encounter for measuring well-clear violation rates.

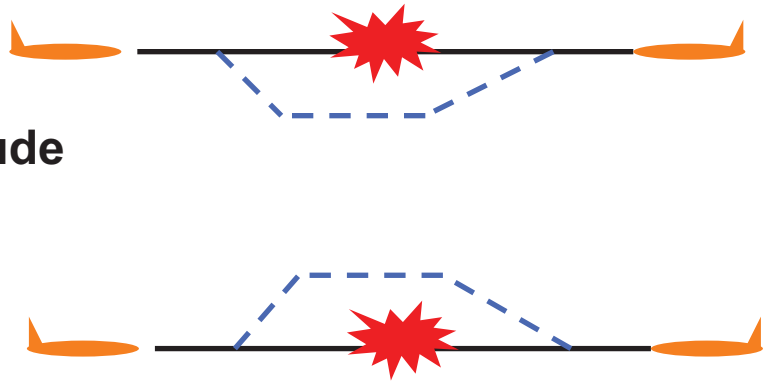
Cooperative VFR Traffic Used for SARP

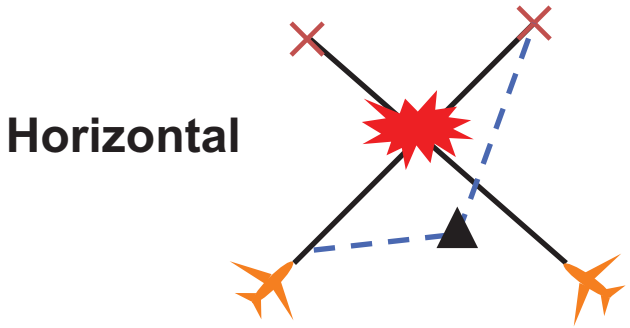


Self-Separation Algorithm (Autoresolver)

- If a WCV is predicted to occur within a parametric time, e.g. 60 seconds, Autoresolver is engaged to command a resolution that solves the problem

- Autoresolver iterates through different horizontal and altitude maneuvers options that avoid WCV
  - During this process it tries to ensure an extra safety margin by putting buffers around horizontal miss distance and time threshold
  - If ownship is level, prefers the minimum left and right turn that avoids WCV over climb or descent
  - If ownship is transitioning vertically, prefers the closest temporary altitude hold that avoids WCV





TCAS-II RA Metric

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

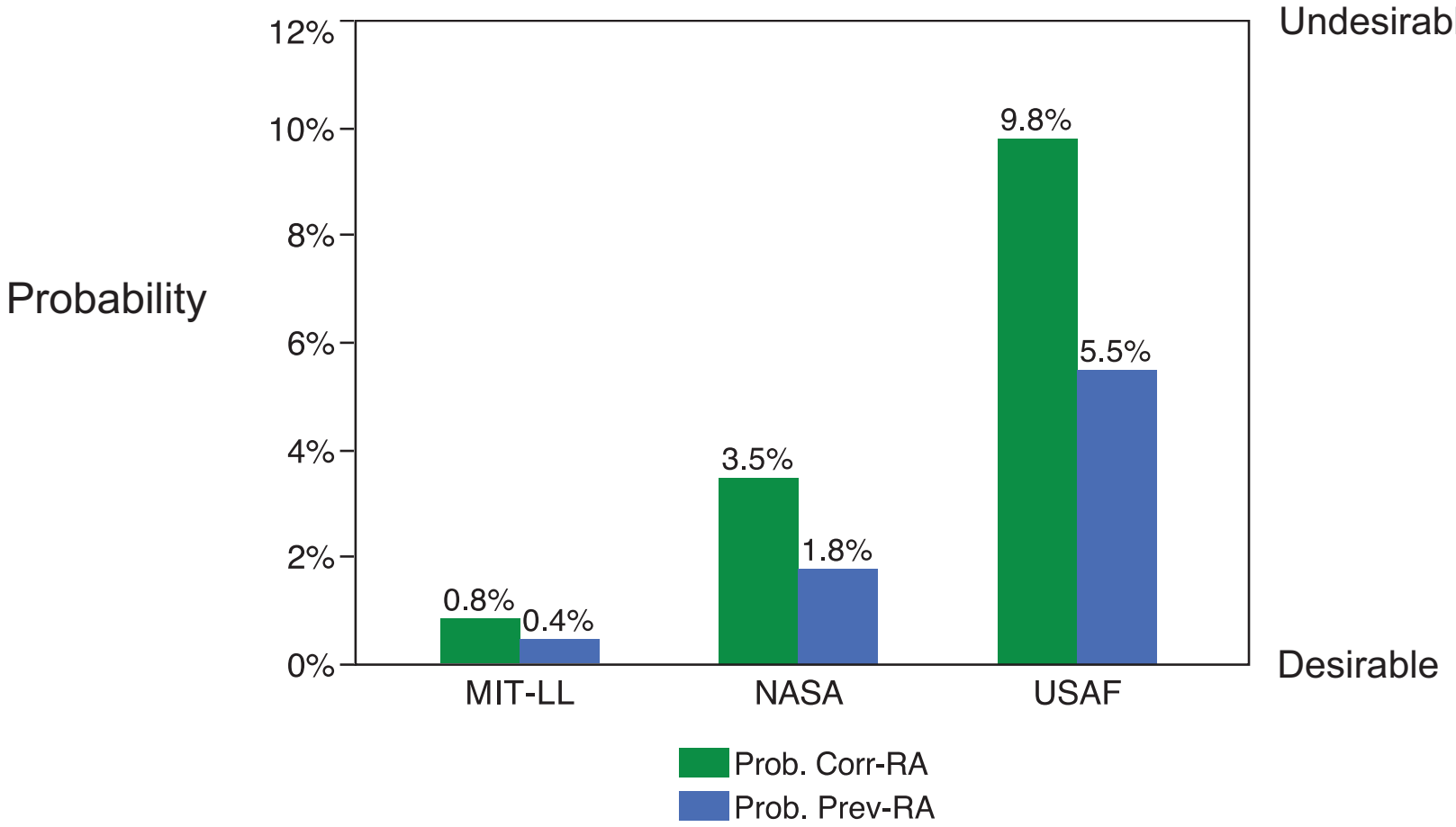
- Assumption: Intruders (manned) experiencing TCAS-RA's while UAS DAA system detects it as well-clear is undesirable. (Unmitigated)
- The smaller the better

$$\frac{\text{Number of WCVs with TCAS-RA prior to WCV}}{\text{Total Number of WCVs}}$$

- While detecting and resolving WCVs (mitigated), at what rate do we trigger a TCAS-RA? (Mitigated)

$$\frac{\text{\# of TCAS-RA's}}{\text{Total UAS Flight Hour}}$$

Probability of WCV with TCAS RA prior to WCV



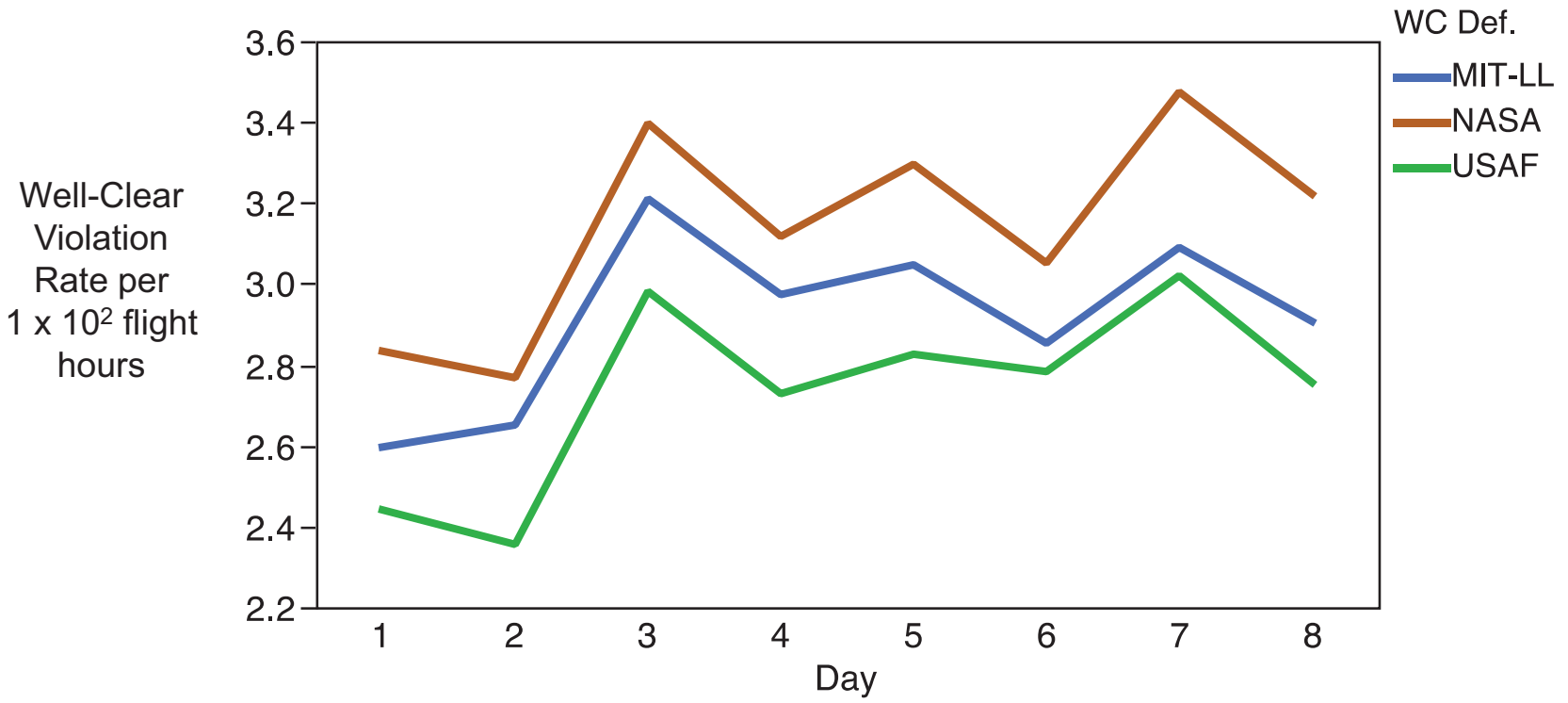
TCAS-RA Rate

- MIT-LL: 8.47×10^{-4} RAs / flt-hour (fewest)
- NASA: 3.9×10^{-3} RAs / flt-hour (middle)
- USAF: 1.52×10^{-2} RAs / flt-hour (most)

Well Clear Violation Penetration Rate

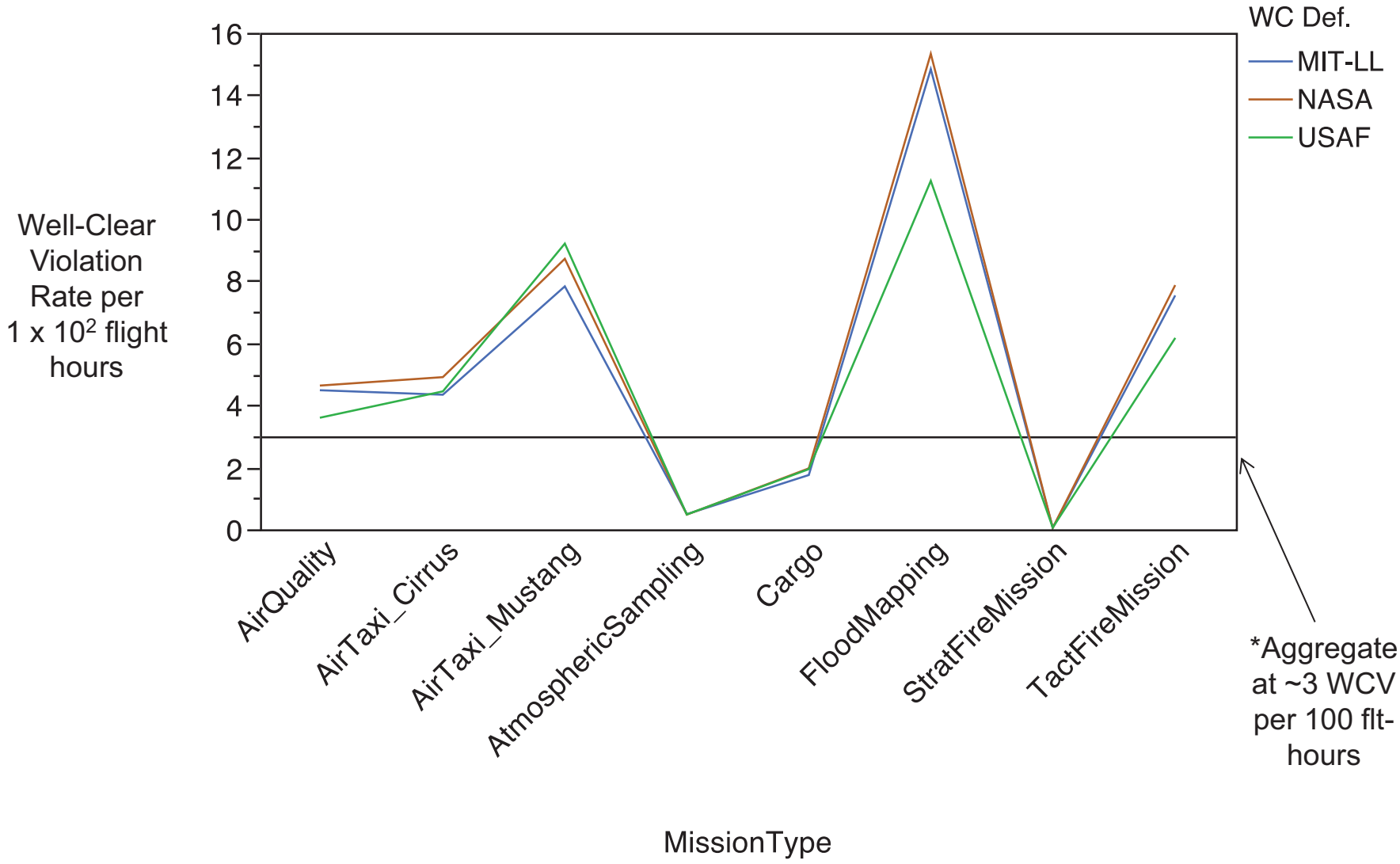
- When analyzing well clear violation rates between the three different models, it wasn't clear if higher or lower rates were better.
- As a group, SARP weighted this metric of lower importance.
- All three models had about the same WCV rate.
- However, what was found to be interesting is verifying there were no unusual trends in WCV rate for the three WC models by different VFR traffic days or UAS mission profiles.

WCV Rate by Day



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

WCV Rate by UAS Mission Type



Other Metrics

- We also collected the following metrics using ACES to support SARP Well-Clear Workshop:
  - Maneuver Initiation Point – points to surveillance performance requirements for detecting WCVs
  - CPA Miss Distance for WCVs – evaluates severity of WCVs
  - Minimum Time from WCV to NMAC – identifies worse case scenarios where little time is available from violating well-clear to having an NMAC

Summary of CAS1 Results

- Controller Acceptability Considerations
  - NASA WCB rated highest, followed by USAF WCB, followed by LL WCB
  - LL HMD of 4000’ (0.67 nmi) elicits a higher “too close” rating from controllers, but actual HMD values would likely be higher in practice due to horizontal buffers added for DAA sensor uncertainty
  - LL WCB “height” of 700’ rated low by controllers but subsequent FAA/RTCA modification of WCB to 450’ fixes this controller acceptability concern

- TCAS II RA Rate
  - For the CAS1 encounter geometries and TCAS model, the NASA model had the fewest RAs below 10000’ and the USAF model had the fewest above 10000’
  - Small HMD values cause higher RA rates, especially at higher altitudes and high closure rates
  - HMD values > 1.2 nmi minimizes RA issuance below Class A airspace with this TCAS model

Summary of ACES Simulations

- Collected encounter data with characteristics that resemble envisioned UAS missions interacting with historically cooperative VFR traffic in different classes of airspace with different “UAS-like” aircraft models
- Results complimented the analyses provided by USAF’s stressing cases and MIT LL’s Monte Carlo simulations
- Each well-clear model had areas of high and low performance with respect to the SARP-accepted metrics
- Overall, over 200,000 UAS flight hours of envisioned missions were simulated NAS-wide and used to help SARP determine a well-clear definition recommendation