



UAS Integration in the NAS: Encounter Rate Simulation Study with UAS Missions

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Outline

- Research Objective
- Analysis Overview, Definitions, and Metrics
- Simulation Setup
  - Background Traffic
  - UAS Missions
- Fast-Time Simulation Study Results
  - Analysis 1: Unmitigated Encounter Rate Evaluation
  - Analysis 2: Well Clear Violation Characteristics
  - Analysis 3: Alerting Threshold Evaluation

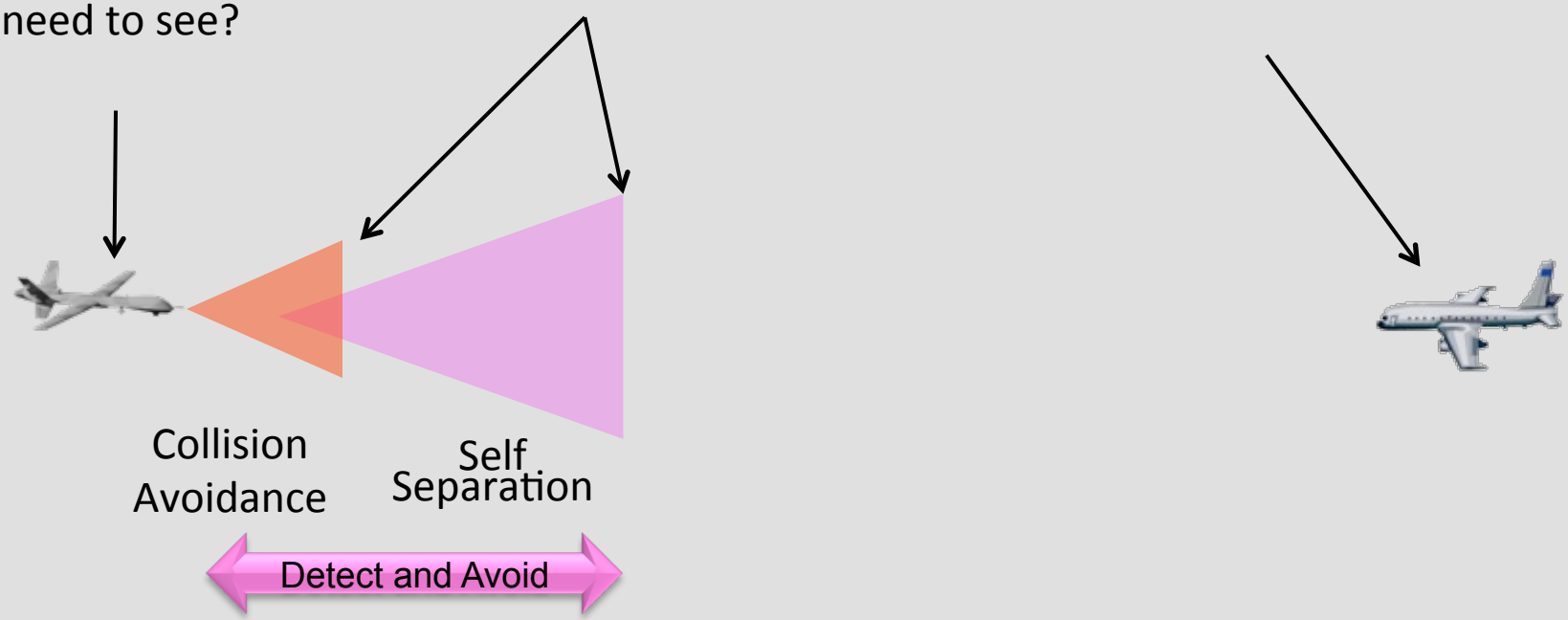


DAA Requirements

How far does my surveillance system need to see?

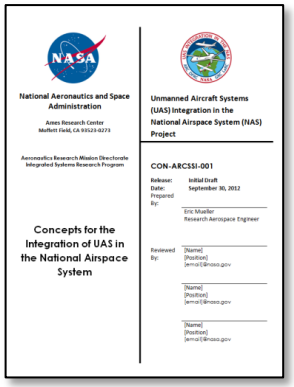
How often do I violate well clear without a DAA system?

When should I alert on an intruder?



Research Capabilities

New UAS-related modeling and simulation capabilities



UAS-NAS integration concepts

19 UAS mission profiles



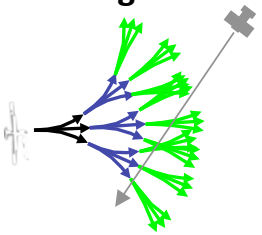
17 UAS types



UAS models, comm. link models



DAA algorithms





DAA sensor models

Human-in-the-Loop and Flight Test Evaluation



Pseudo-pilot stations





Air Traffic Control Stations



Vigilant Spirit Control Station

Traffic displays, DAA algorithms, ATC, Ground Control Station

NAS-wide Simulation



ACES: Flight plan and NAS-agent modeling system

Unmitigated Encounter Rate Evaluation

UAS Models



UAS Mission Profiles



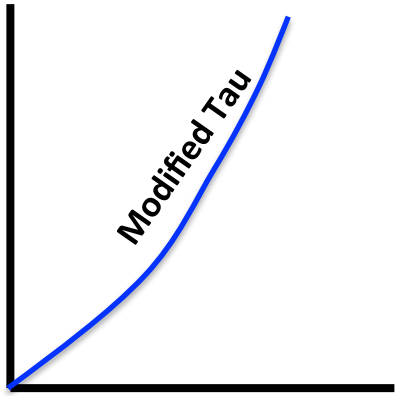
Air Defense Radar Data

NAS-wide Simulation



ACES: Flight plan and NAS-agent modeling system

Rate of Occurrence



Well Clear Threshold

Study 1: (FY14)
- **UAS Missions & Models**
- **Cooperative VFR Traffic**

Study 2: (FY15)
- UAS Missions & Models
- Cooperative and Non-cooperative VFR Traffic

Self Separation Alerting Threshold



Well Clear Violation

Analysis Overview and Metrics

- Analysis 1: Evaluating the effect of well clear definition parameters on the well clear violation (WCV) rate.
  - Metric: Encounter Rate per Flight Hour as a Function of Time Threshold

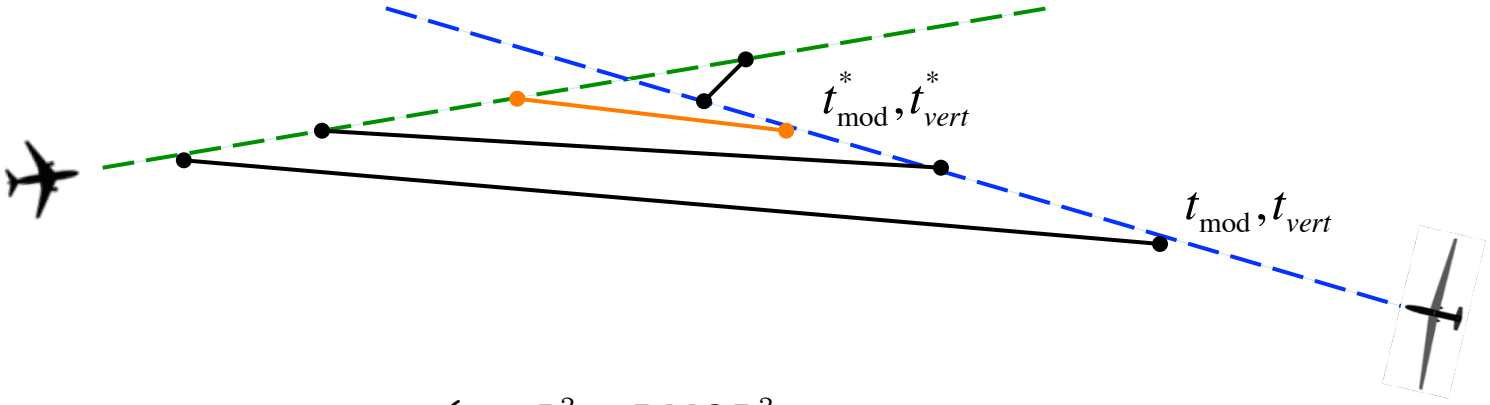
- Analysis 2: Characterizing encounters at the WCV boundary.
  - Metric: WCV rate per Flight Hour
  - Metric: Relative State information at WCV
  - Metric: Type of Violations

Analysis Overview and Metrics

- Analysis 3: Evaluating the alerting threshold definition and alerting criteria.
  - Metric: Encounter Rate at Alerting Threshold
  - Metric: Percentage of Alerts that did not lead to an WCV
  - Metric: Relative State Information at Threshold
  - Metric: Percentage of first alert that is less than the alerting threshold
  - Metric: Time to WCV at Threshold

Analysis 1: Minimum Modified Tau

- Used for Analysis 1.
- Find the minimum values between aircraft based on time histories

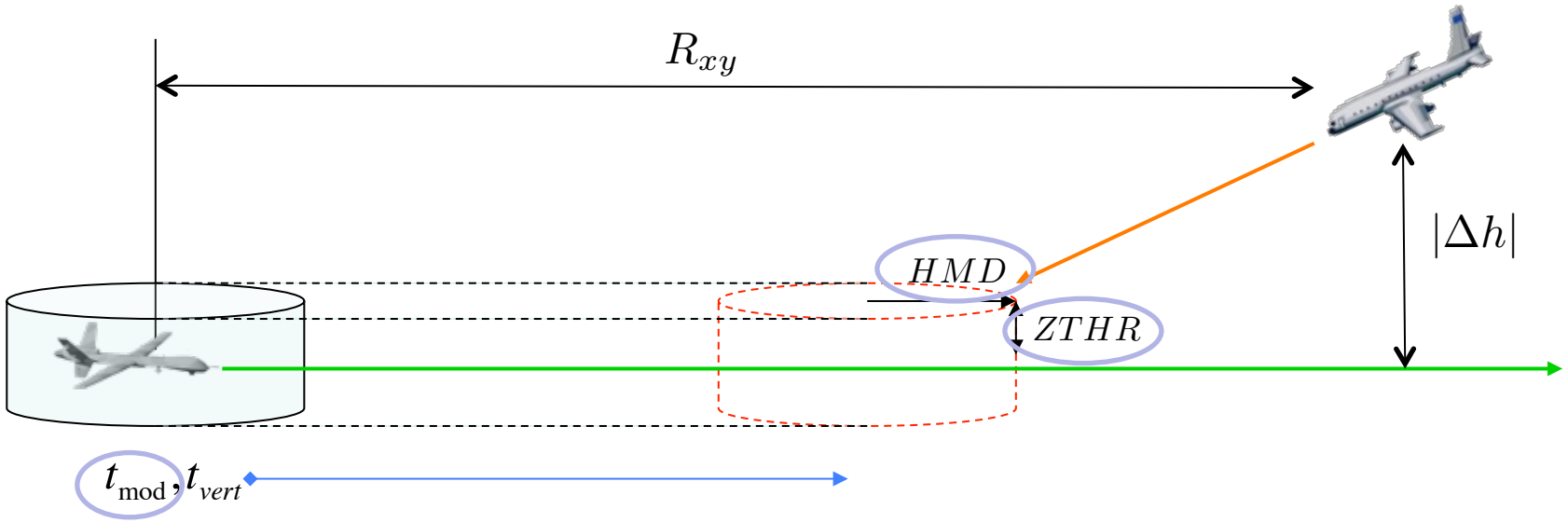


$$\tau_{mod} = \begin{cases} -\frac{R_{xy}^2 - DMOD^2}{\dot{R}_{xy} R_{xy}} & R_{xy} > DMOD \\ 0 & R_{xy} \leq DMOD \end{cases}$$

$$\tau_{vert} = -\frac{\Delta h}{\Delta \dot{h}}$$

Analysis 1: Minimum Modified Tau

- Encounter Rates at the minimum tau values between aircraft pairs



- Cost: $J = \{\tau_{mod}^2 + \tau_{vert}^2$
- Constraints:

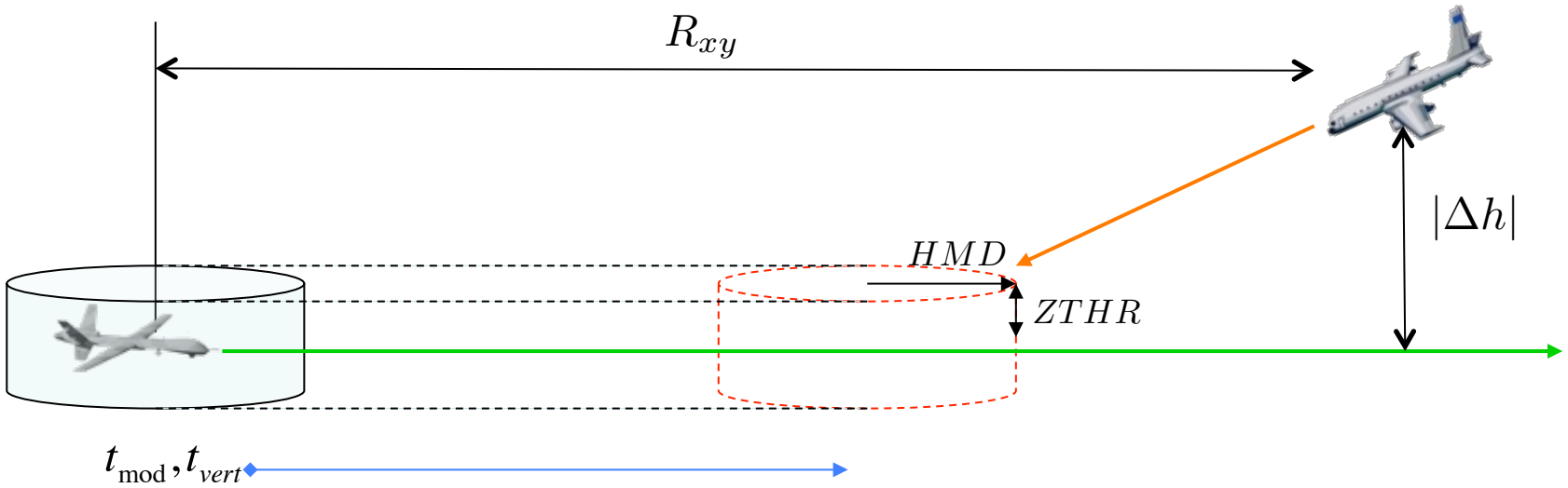
$$R_{xy}(t_{CPA}) \leq HMD, |\Delta(h)| \leq ZTHR \qquad \tau_{mod} \geq 0, \tau_{vert} \geq 0,$$

- Find Minimum Tau

$$min(J)$$

Analysis 2: Definition of Well Clear

- Evaluating characteristics at a well clear violation



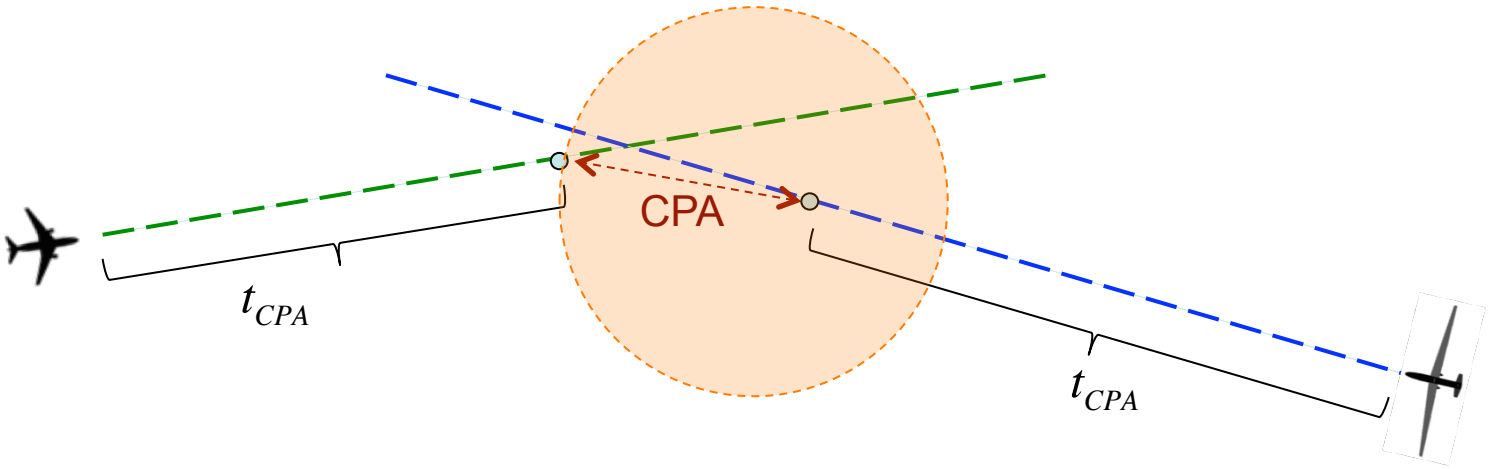
- Horizontal Criteria (H1): $0 \leq \tau_{mod} \leq \tau^*_{mod} \quad and \quad R_{xy}(t_{CPA}) \leq HMD$
- Vertical Criteria (V1): $0 \leq \tau_{vert} \leq \tau^*_{vert} \quad or \quad |\Delta h| \leq ZTHR$
- Well Clear Definition (WCV): $WCV: \quad H1 = true \quad and \quad V1 = true$

SARP Recommended Definition →

Tau [sec]	Tcoa [sec]	DMOD [nmi]	HMD [ft]	ZTHR [ft]
35	0	1.1	4000	700

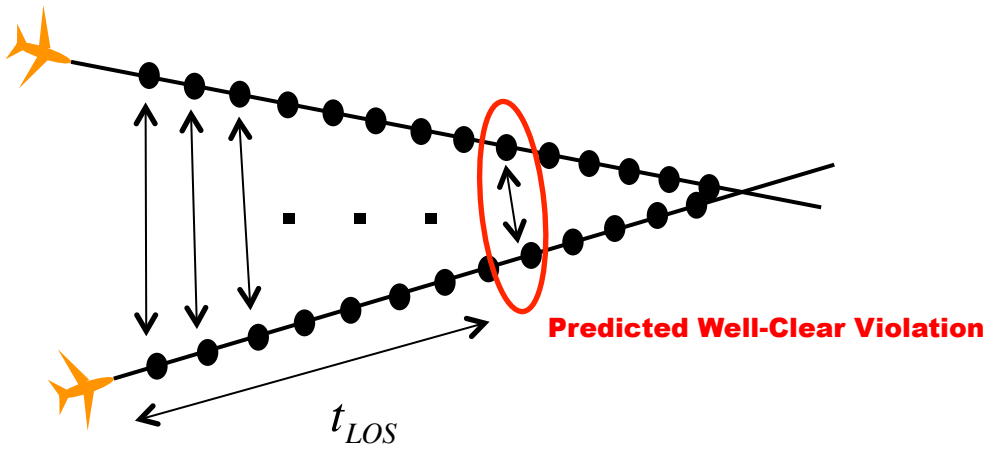
Analysis 3: Time to CPA

- Time to CPA with a horizontal and vertical miss distance filter at predicted CPA:



Time to Violation*

- Predicted Time to Well Clear Violation:
  - At each time step each aircraft projects their trajectories forward and search for a point in which well clear is violated. The time until that point is the time to violation (or time to loss of separation)
  - Could be based on dead reckoning trajectories or could include intent from the ownship



* Results not presented on this definition

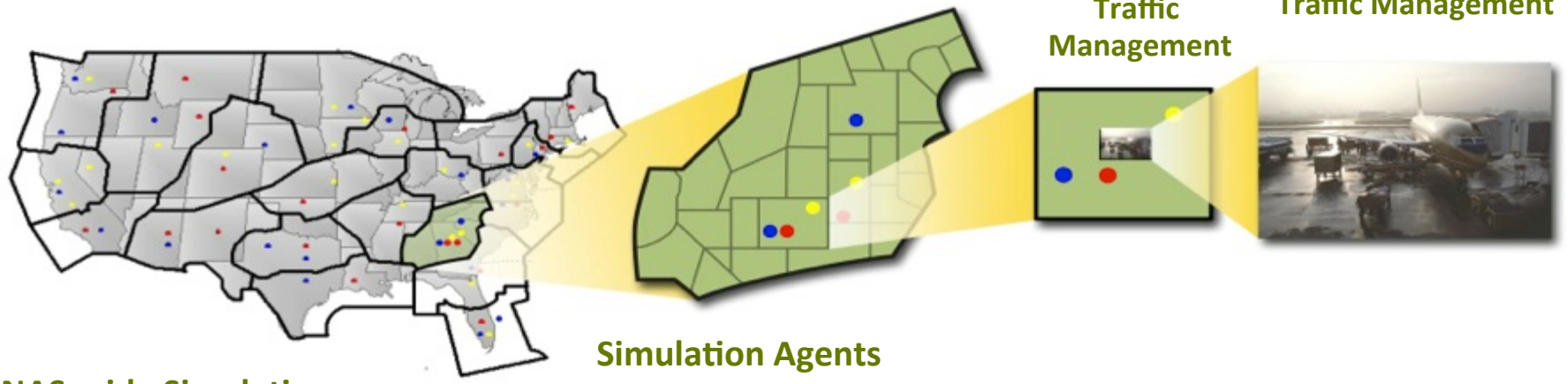
Modeling and Simulation: ACES

National Traffic Management

Regional Traffic Management

Local Approach and Departure Traffic Management

Airport and Surface Traffic Management



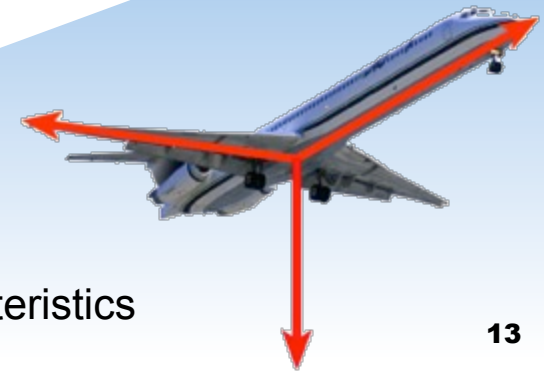
NAS-wide Simulation

- 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



VFR Traffic: Scenario Selection

- Each simulation run is a single day in the NAS (24 hours starting at 0 UTC)
- The simulation runs were chosen across 4 seasons in 2012 on days with minimal weather impacts
- 23 Days Total

January 2012

Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

April 2012

Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					

July 2012

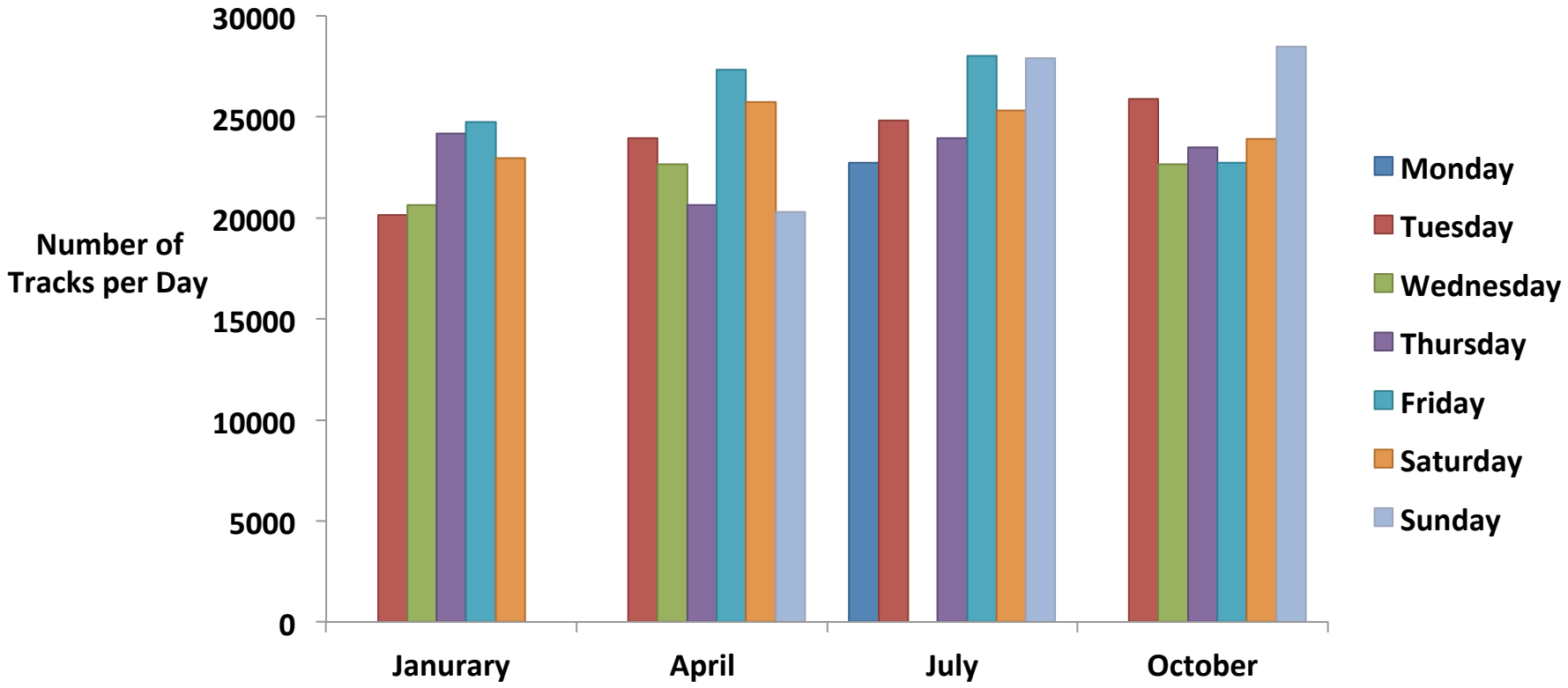
Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

October 2012

Su	M	Tu	W	Th	F	Sa
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

VFR Traffic: Traffic Volume

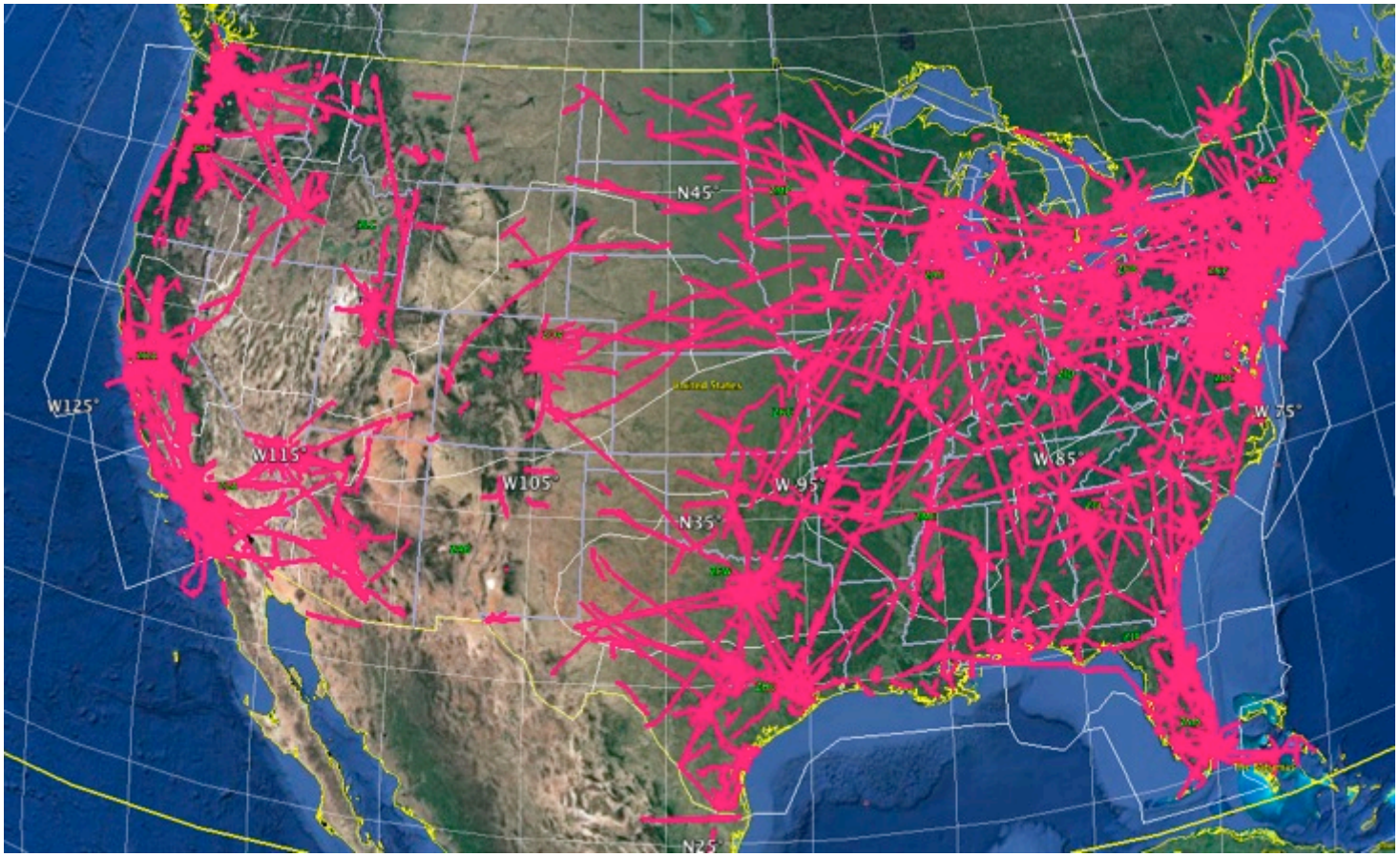
- Higher volumes in the summer and fall months
- Traffic volume ranges from 20k – 28k flights per day



Method for Extracting VFR Traffic

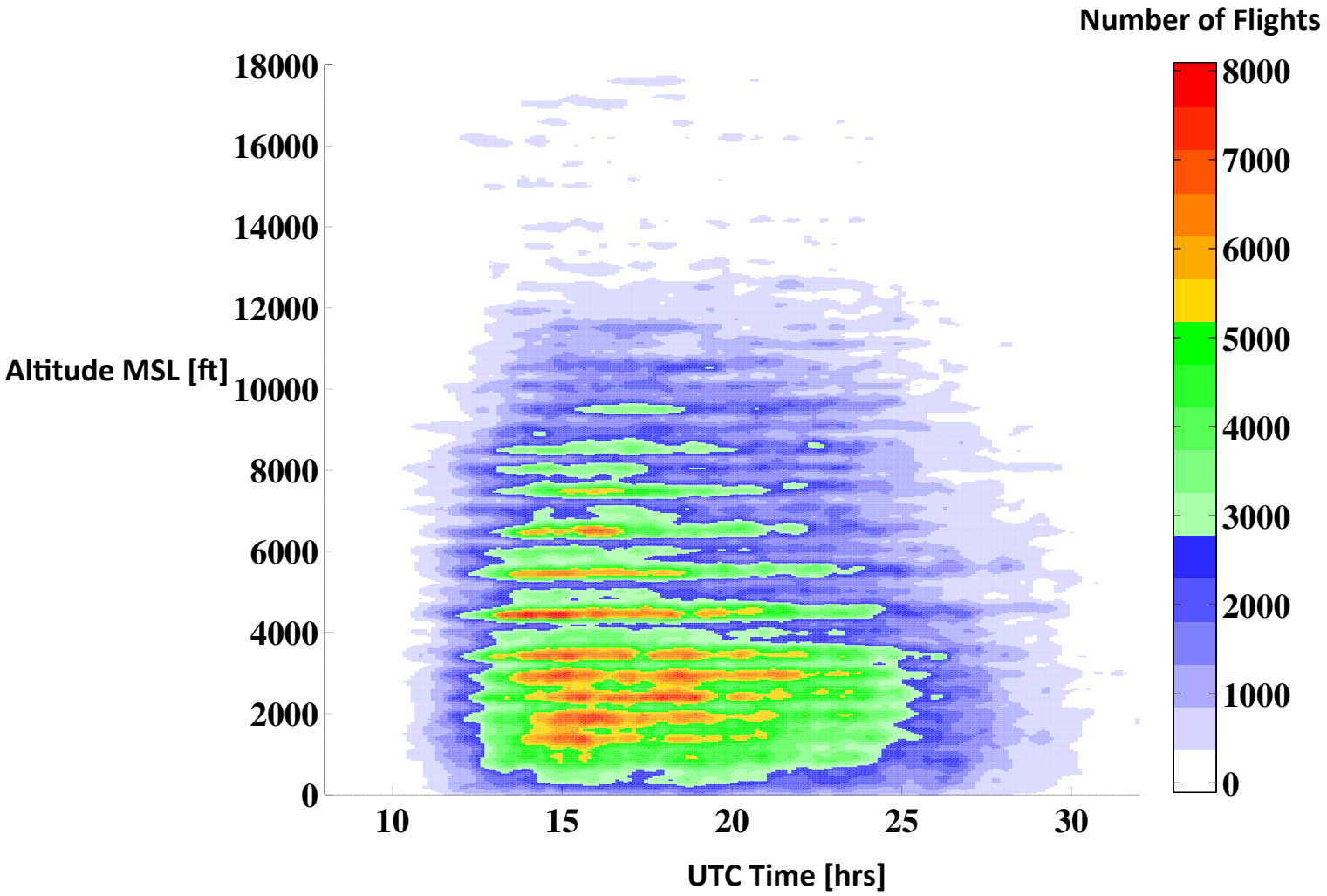
- Input: RADES data for a certain time period.
- Output: Flight plan file for a fast-time simulation system, Advanced Concept Evaluation System (ACES).
- Method (three steps):
  1. Generate tracks using a minimum spanning tree based clustering algorithm,
  2. Generate smooth tracks using a Kalman filter,
  3. Generate a flight plan file after reducing the number of waypoints and adding airports which are closest to start/end waypoints.

VFR Traffic: Example VFR Trajectories



* Flight Profiles from July 25th, 2012

VFR Traffic: Density by Altitude



UAS Missions Overview

UAS Mission Profiles (Delivered)

- Air Quality Monitoring Mission
- Cargo Transport
- Weather Data Collection (Atmospheric Sampling)
- On-demand air taxi
  - Mustang
  - Cirrus
- Wildfire detection and reconnaissance
  - Strategic Fire Monitoring
  - Tactical Fire Monitoring
- Flood Mapping
  - Flood Inundation Mapping
  - Flow Stream Monitoring
- Law Enforcement/Suspect Tracking
- Point-source Emissions Monitoring
- Traffic Monitoring
- Wildlife Monitoring
- Border Patrol

UAS Mission Profiles (In Development,)

- Search and Rescue
- Spill Monitoring
- Maritime Patrol
- Imaging and Mapping
- Traffic Monitoring around Metro Areas
- FAA Navaid Inspection
- Communication and Broadcast Relay
- Damage/Survey Assessment
- Extensions to Mail/Freight Demand

Used in this study

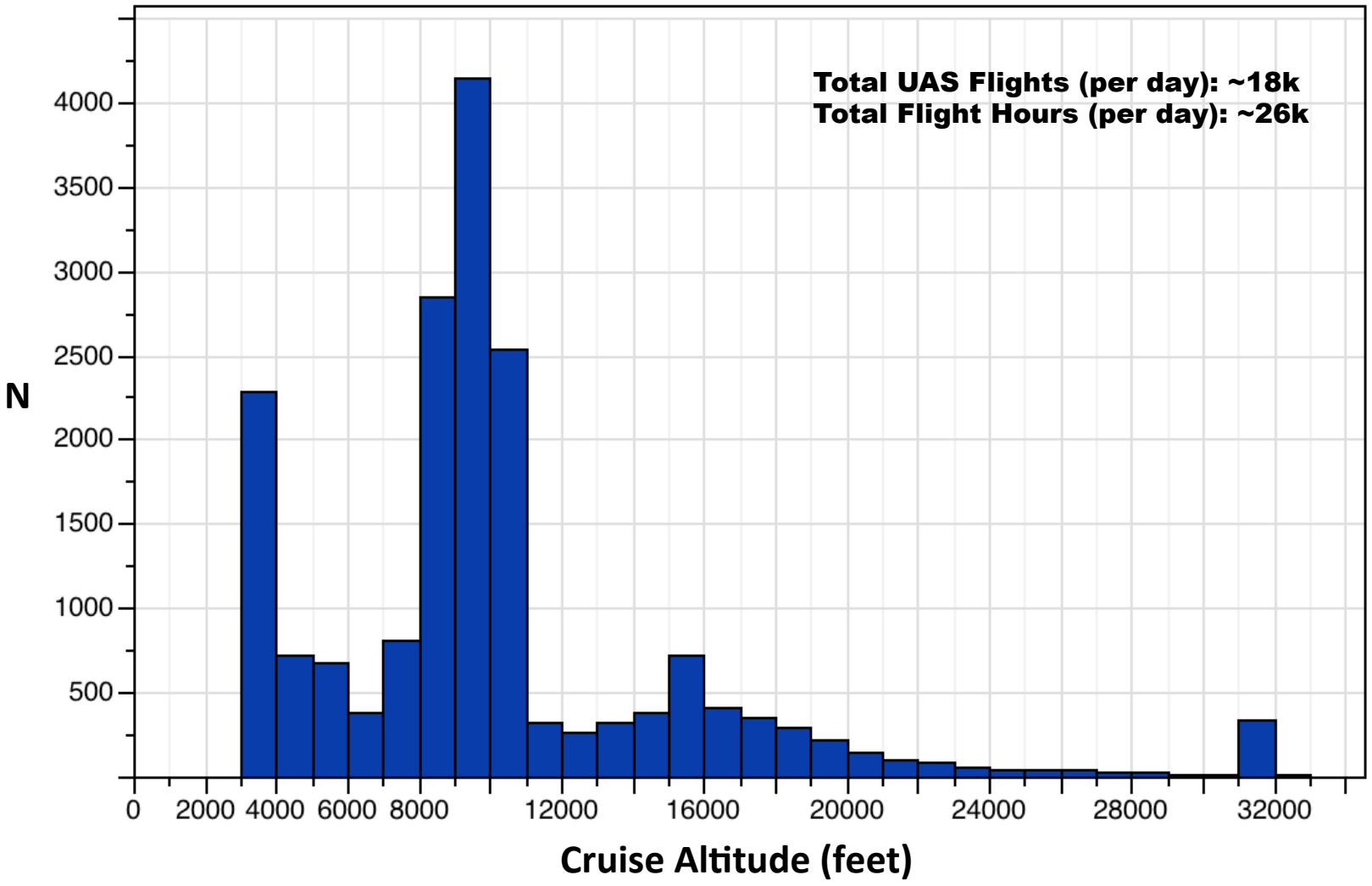
UAS Mission Development

- Developed under contract with IAI
- Mission concepts derived from stakeholder input, FAA Conops, etc.
- Missions developed by reviewing literature, talking to subject matter experts, and social-economic analysis.
- Aircraft takeoff/landing frequency, time of day of operation, and flight duration are mission dependent.
- Flight plan files are produced with varying volume to be used for denser forecasting scenarios.

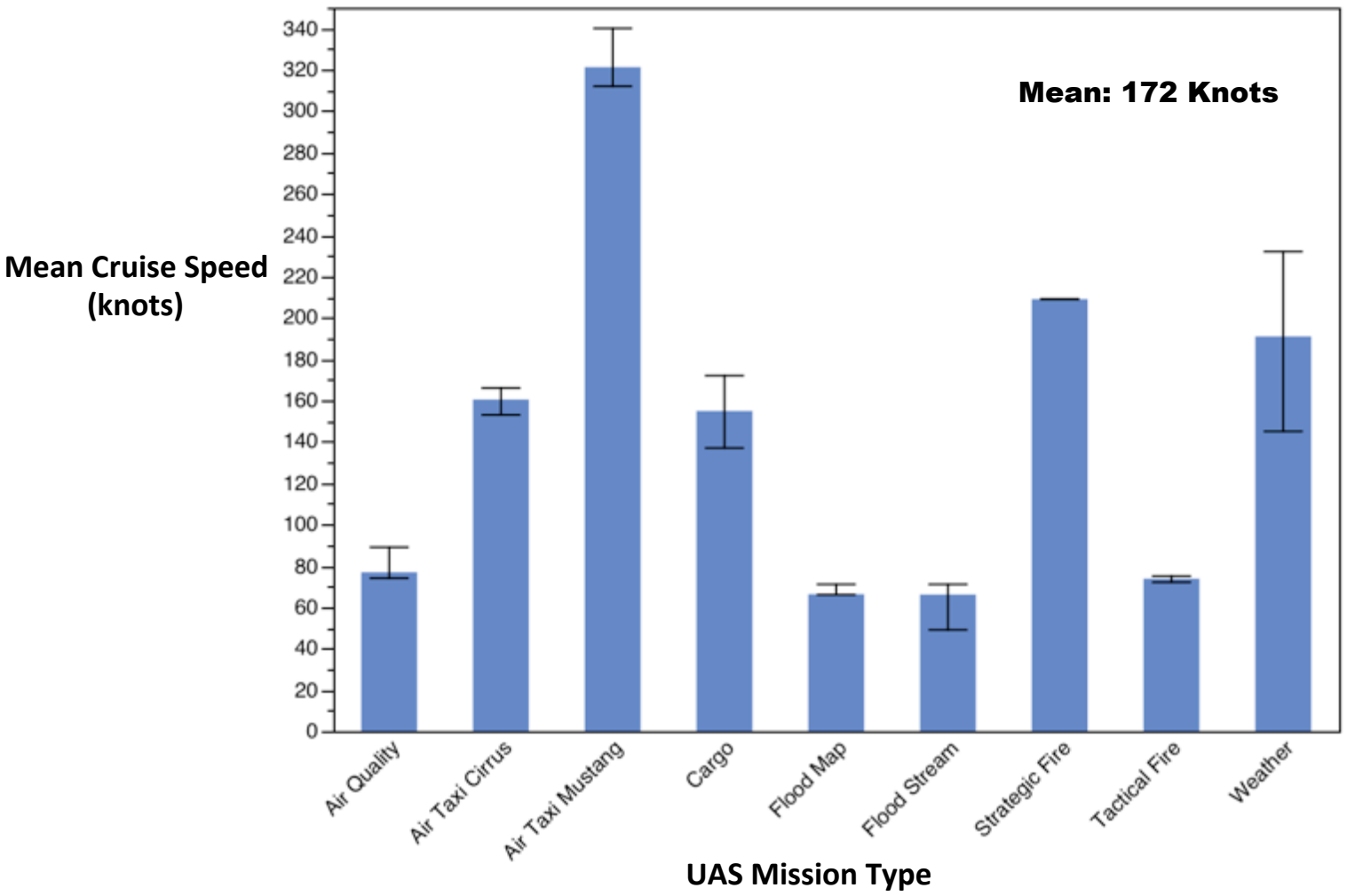
Mission Characteristics

	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

UAS Missions: Cruise Altitudes



UAS Mission: Cruise Speeds

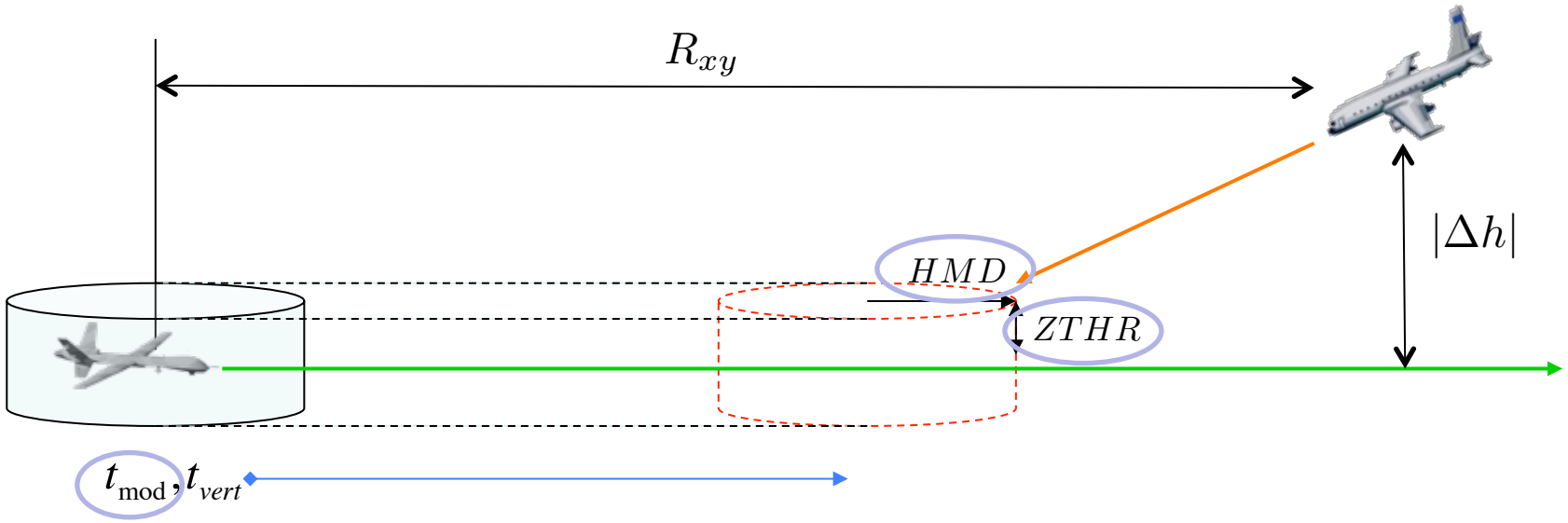


Simulation Configuration

- There are 23 different simulation runs (1 simulation run per traffic day)
- Each simulation had:
  - 9 Different Missions:
    - Different UAS vehicles
    - Different flight profiles
    - Different cruise altitudes and cruise speeds
    - Different durations and volumes of traffic (all missions ran for complete 24 hours)
  - Cooperative VFR Traffic
    - Days chosen with minimal delay (analyzed for IFR)
    - Varying volume of traffic (20-28k flights)
    - Days are spread over 4 seasons in 2012
  - No mitigation intervention
    - UAS vs. UAS conflicts ignored
    - No DAA system present
- Post Processing:
  - Each simulation run was post- processed independently and results were aggregated

Analysis 1

- Encounter Rates at the minimum tau values between aircraft pairs



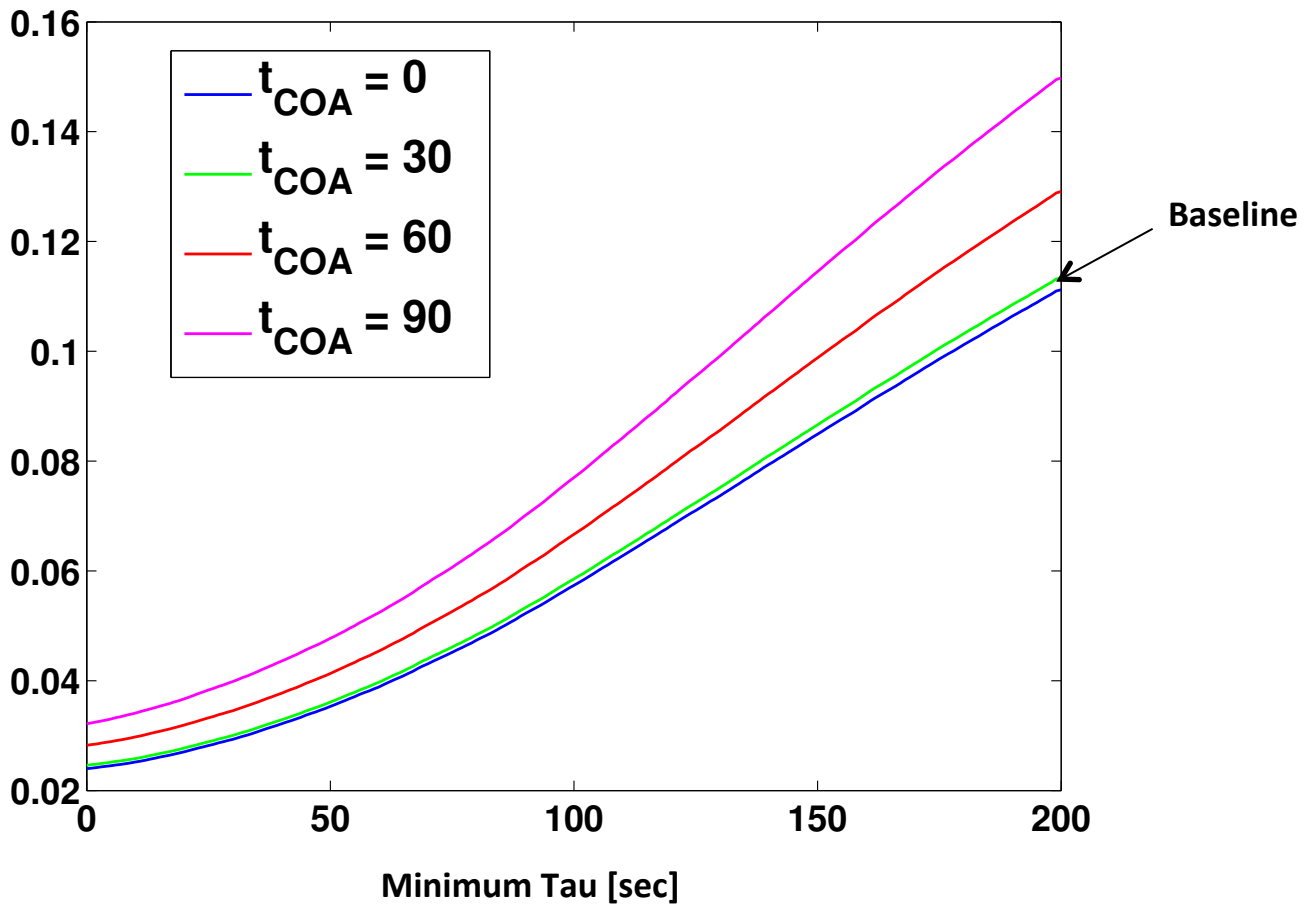
- Cost: $J = \left\{ \tau_{mod}^2 + \tau_{vert}^2 \right.$
- Constraints:

$$R_{xy}(t_{CPA}) \leq HMD, |\Delta(h)| \leq ZTHR \qquad \tau_{mod} \geq 0, \tau_{vert} \geq 0,$$

- Find Minimum Tau

$$min(J)$$

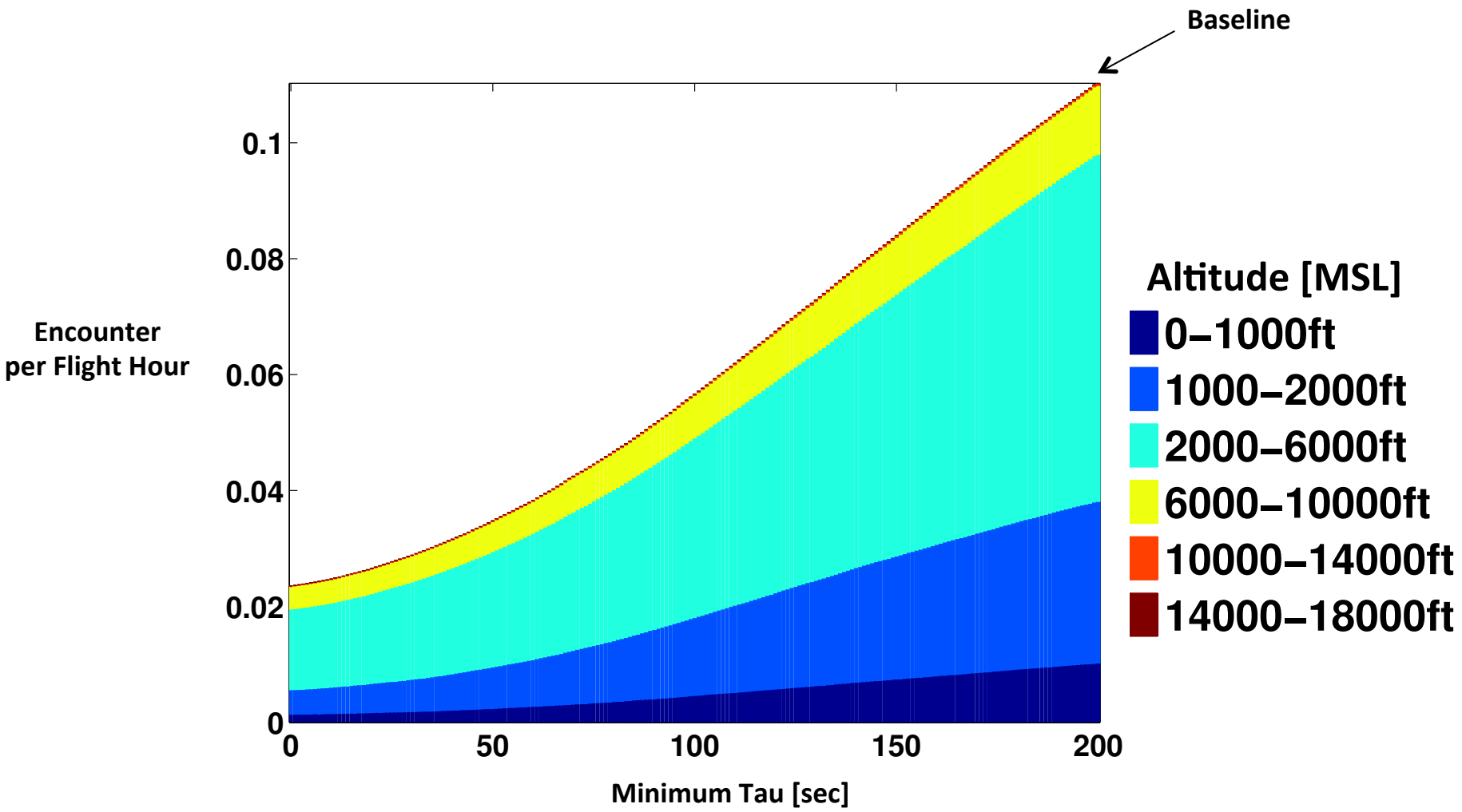
Encounter Rate vs. Time Threshold



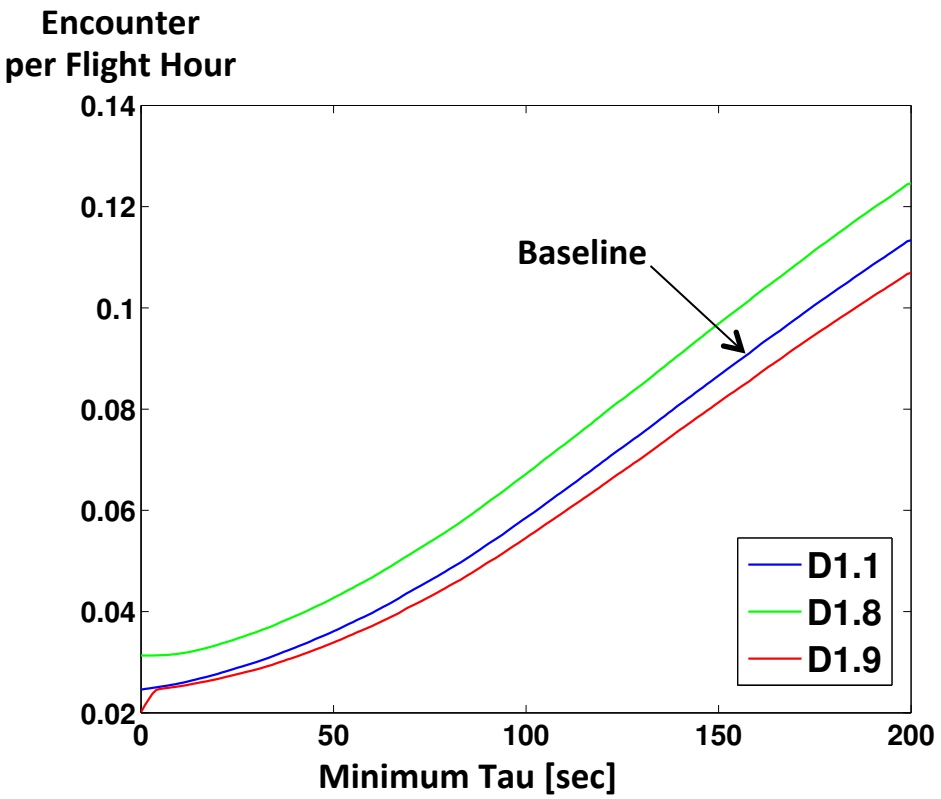
TCAS Sensitivity Level 6
(Used as Baseline for Analysis 1)

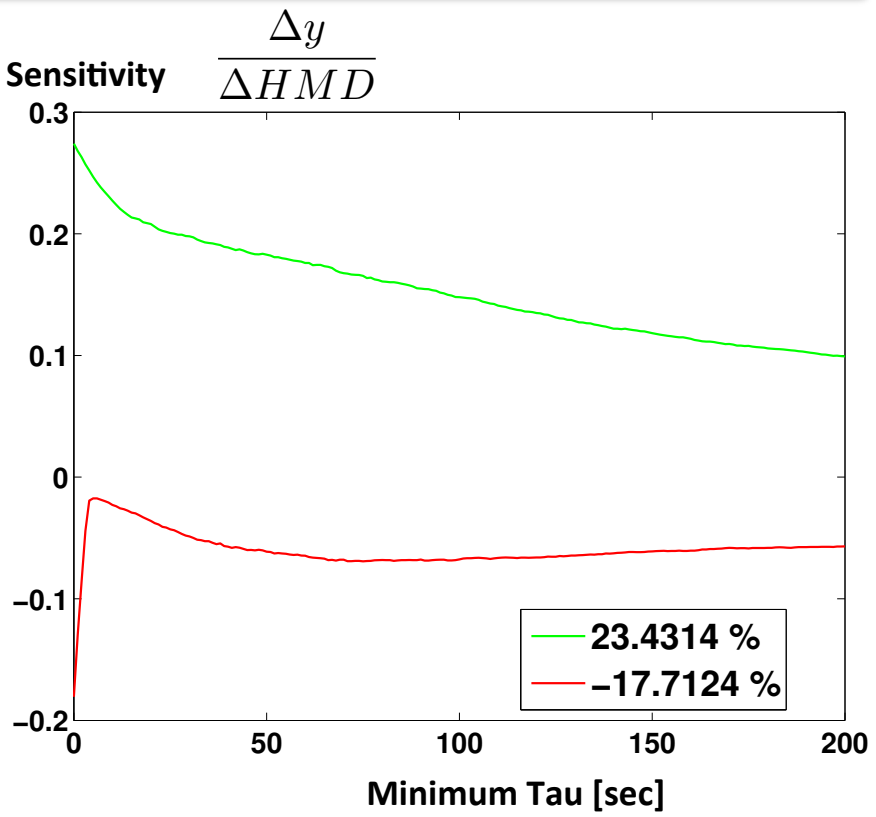
Configuration	DMOD [nmi]	HMD [ft]	ZTHR [ft]	Tcoa [sec]
D1.1	0.80	4861	600	30

Relative Altitude Contribution to Encounter Rate



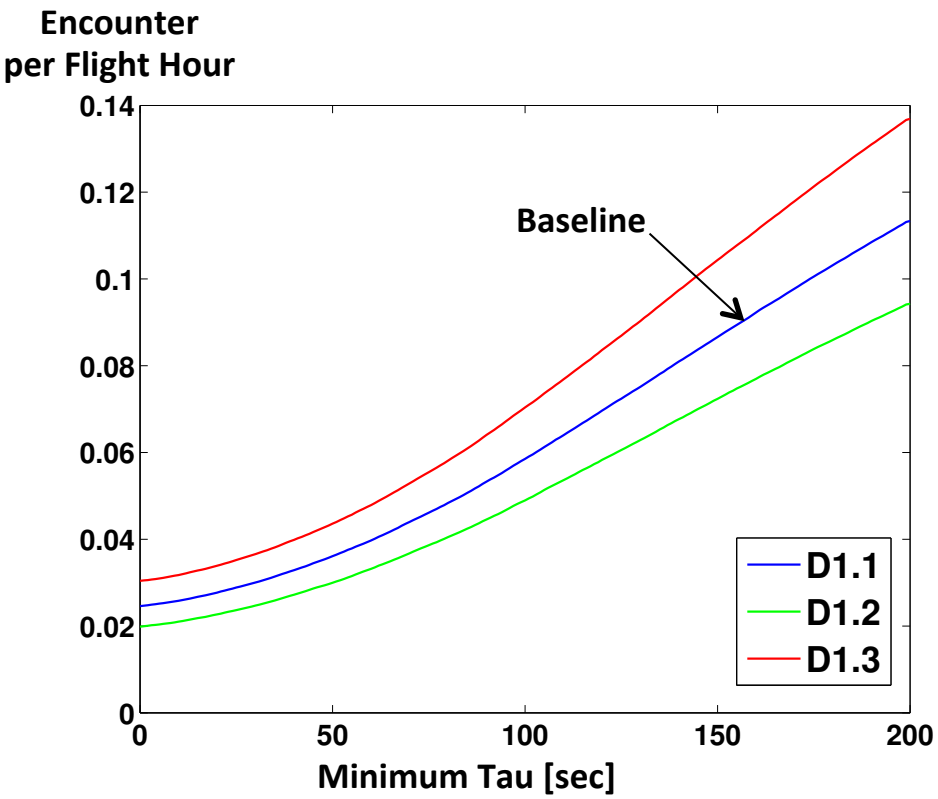
Effect of HMD

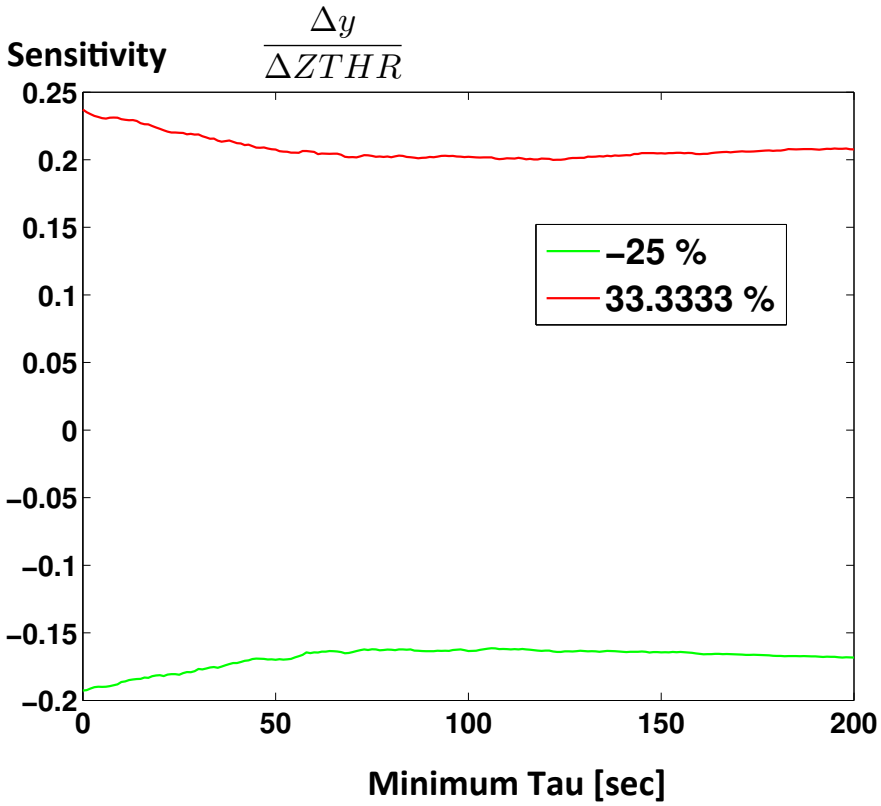




Configuration	DMOD [nmi]	HMD [ft]	ZTHR [ft]	Tcoa [sec]
D1.1	0.80	4861	600	30
D1.8	0.80	6000	600	30
D1.9	0.80	4000	600	30

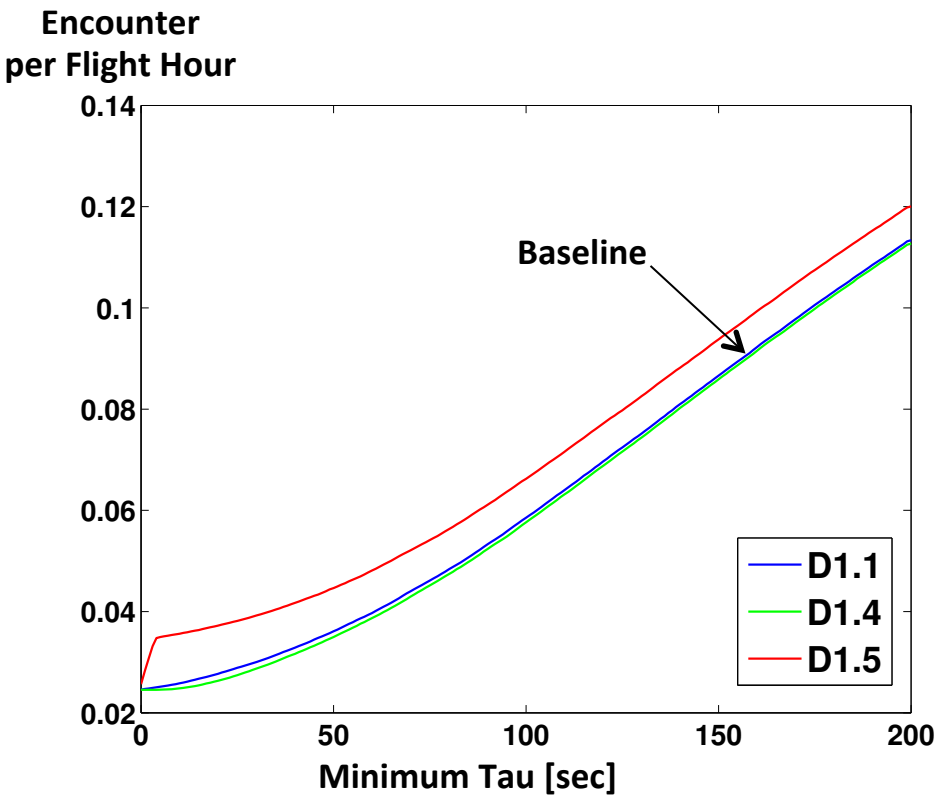
Effect of ZTHR

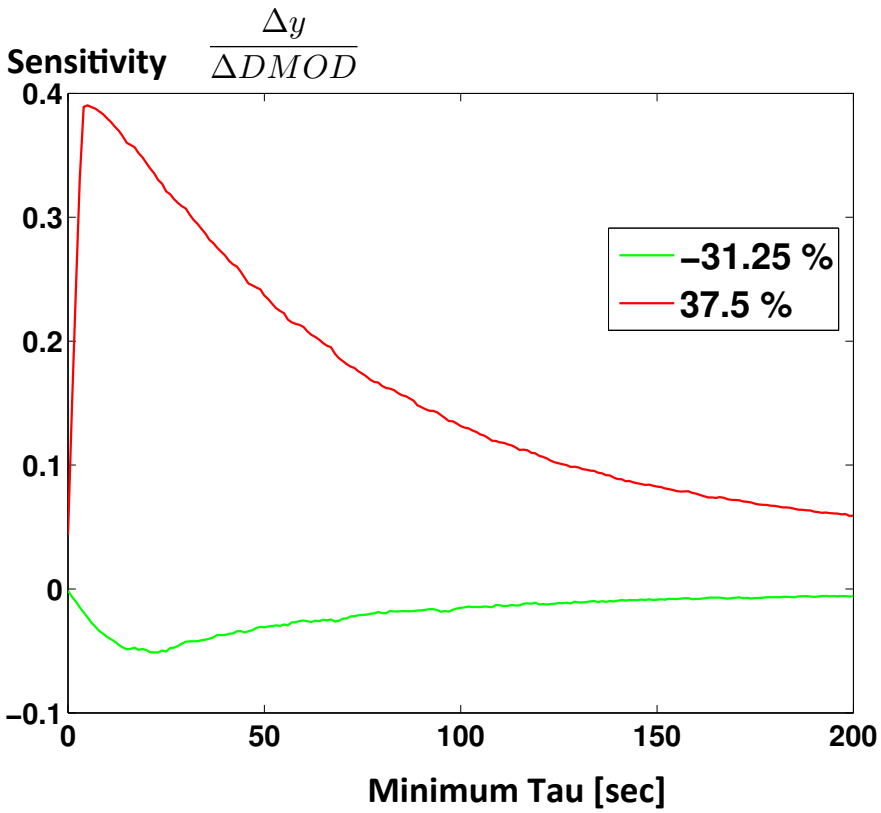




Configuration	DMOD [nmi]	HMD [ft]	ZTHR [ft]	Tcoa [sec]
D1.1	0.80	4861	600	30
D1.2	0.80	4861	450	30
D1.3	0.80	4861	800	30

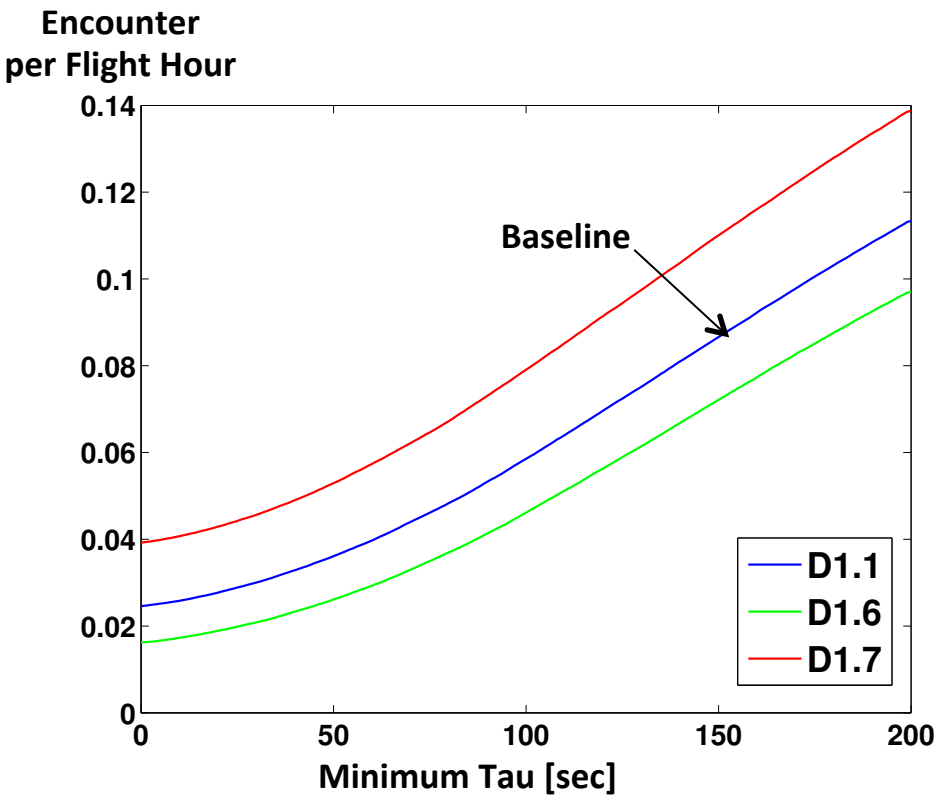
Effect of DMOD

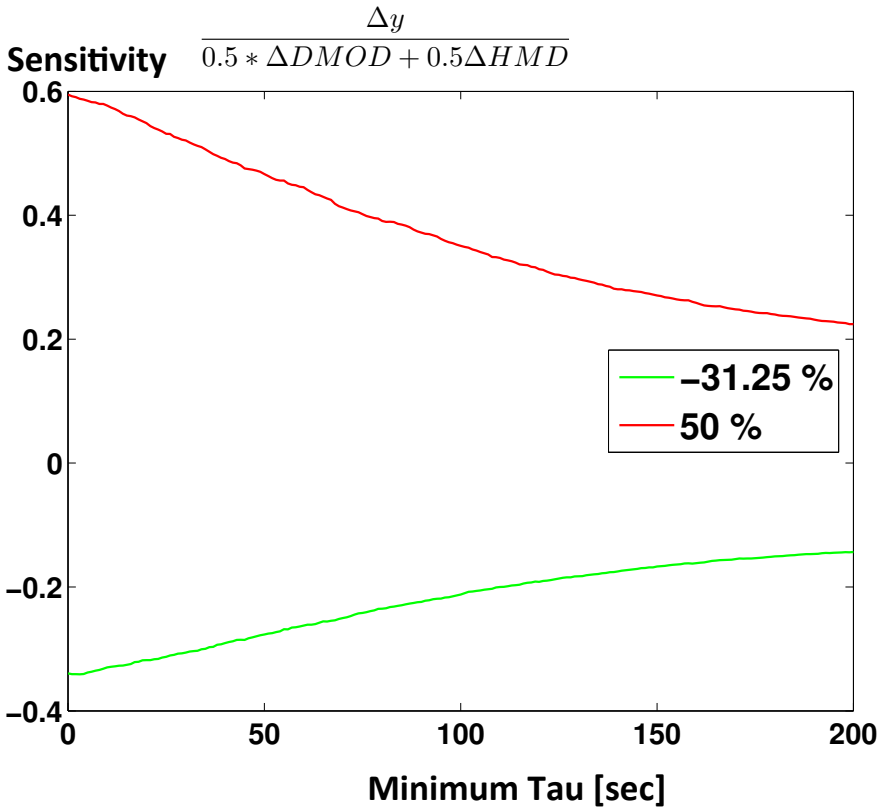




Configuration	DMOD [nmi]	HMD [ft]	ZTHR [ft]	Tcoa [sec]
D1.1	0.80	4861	600	30
D1.4	0.55	4861	600	30
D1.5	1.1	4861	600	30

Effect of DMOD and HMD

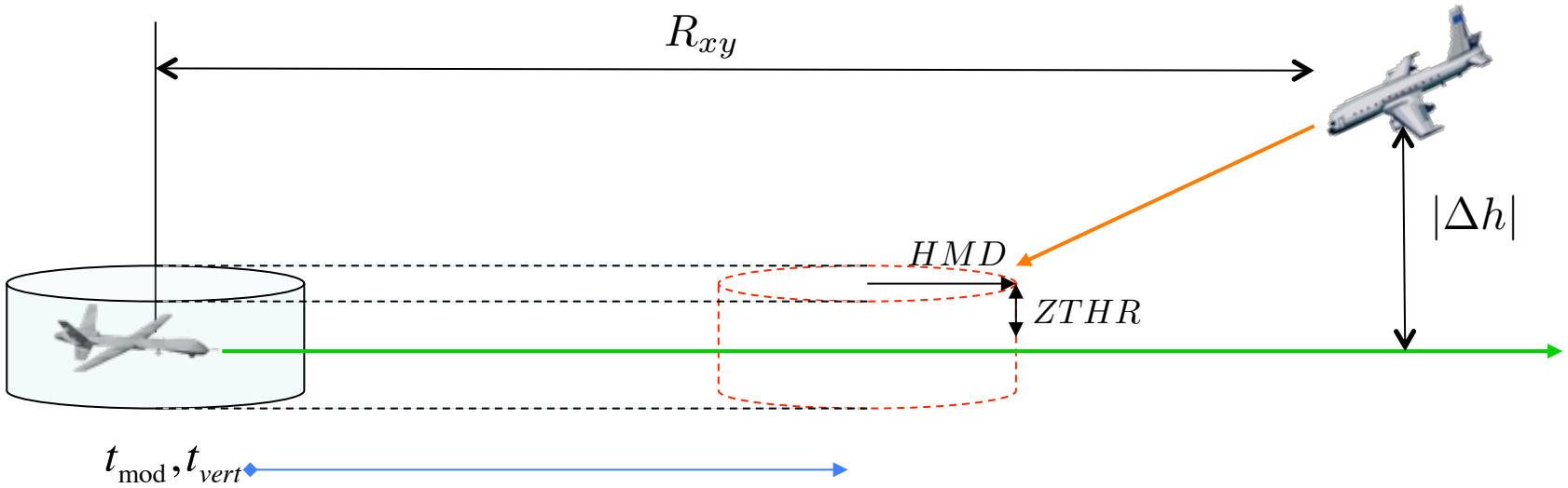




Configuration	DMOD [nmi]	HMD [ft]	ZTHR [ft]	Tcoa [sec]
D1.1	0.80	4861	600	30
D1.6	0.55	3342	600	30
D1.7	1.2	7292	600	30

Analysis 2: Definition of Well Clear

- Evaluating characteristics at a well clear violation

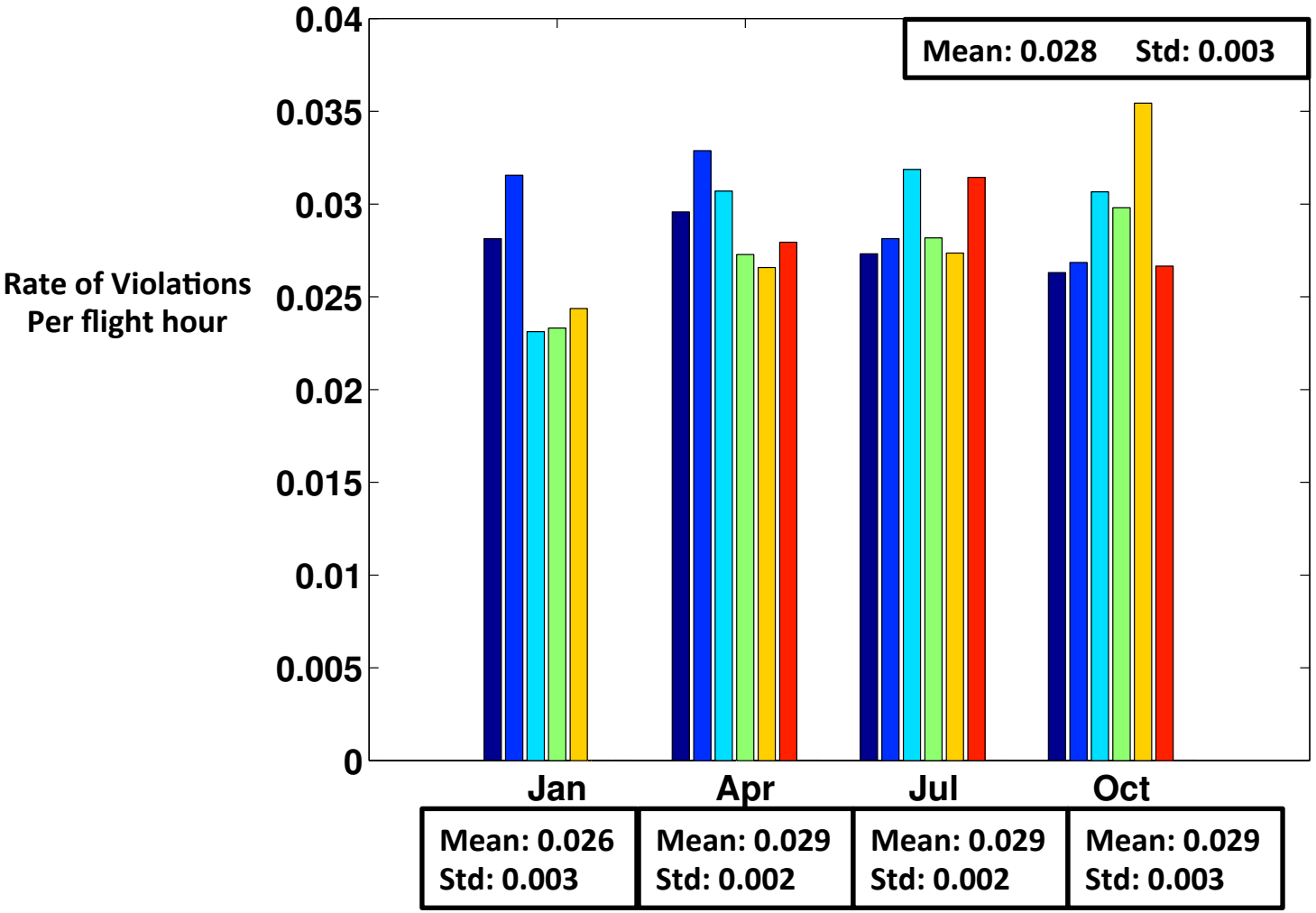


- Horizontal Criteria (H1): $0 \leq \tau_{mod} \leq \tau^*_{mod} \quad and \quad R_{xy}(t_{CPA}) \leq HMD$
- Vertical Criteria (V1): $0 \leq \tau_{vert} \leq \tau^*_{vert} \quad or \quad |\Delta h| \leq ZTHR$
- Well Clear Definition (WCV): $WCV: \quad H1 = true \quad and \quad V1 = true$

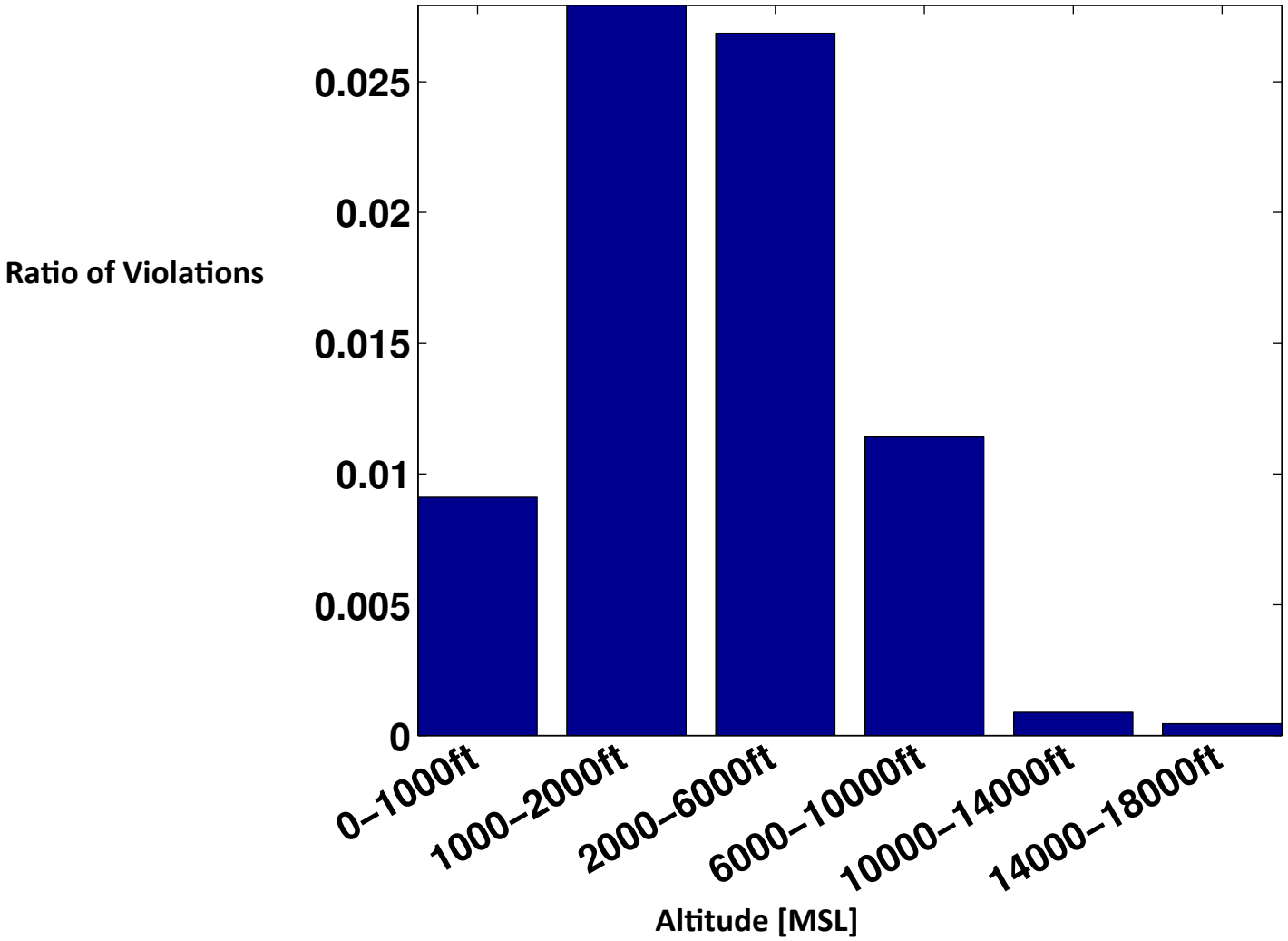
SARP Recommended Definition →

Tau [sec]	Tcoa [sec]	DMOD [nmi]	HMD [ft]	ZTHR [ft]
35	0	1.1	4000	700

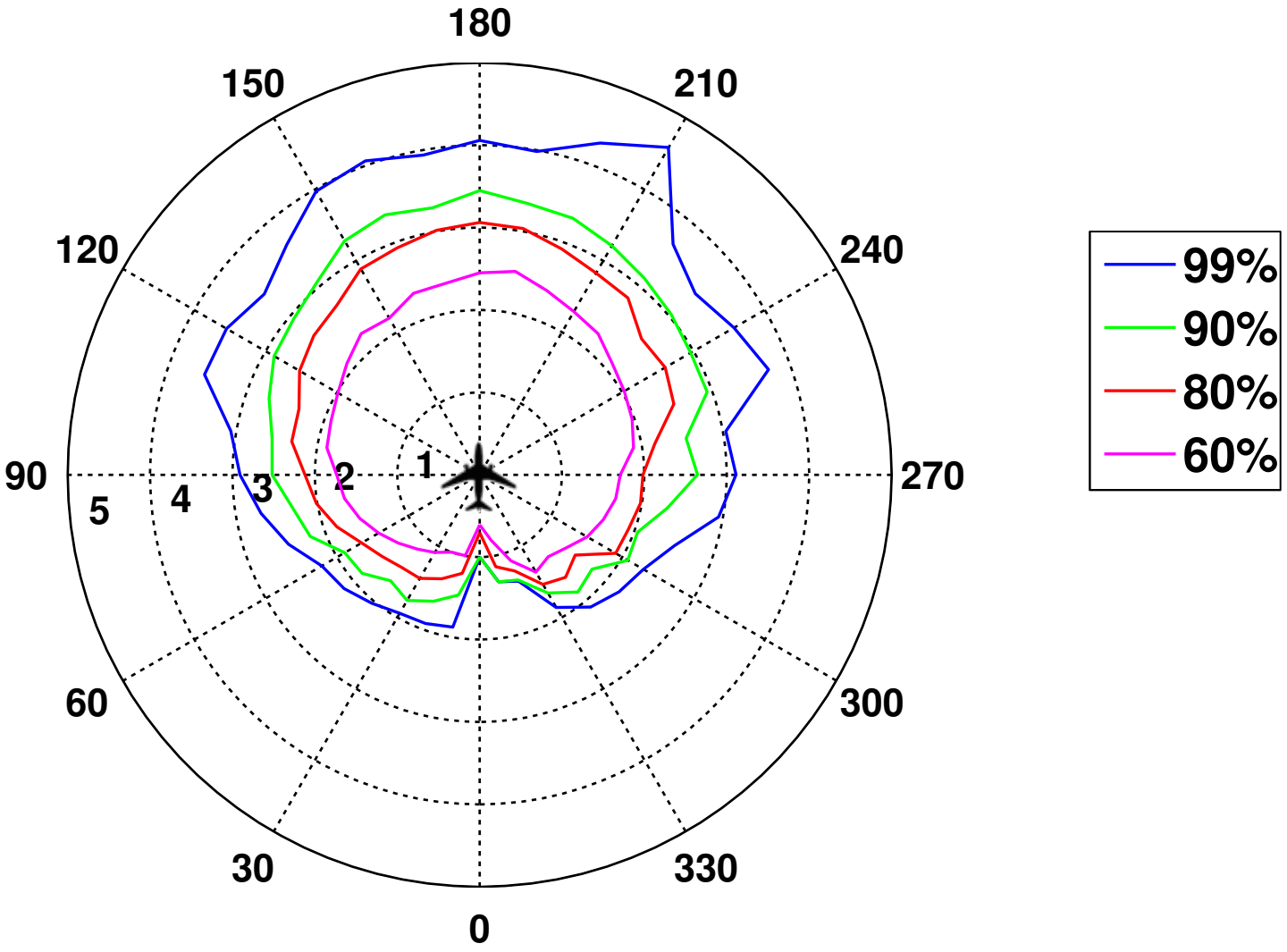
Rate of Well Clear Violations



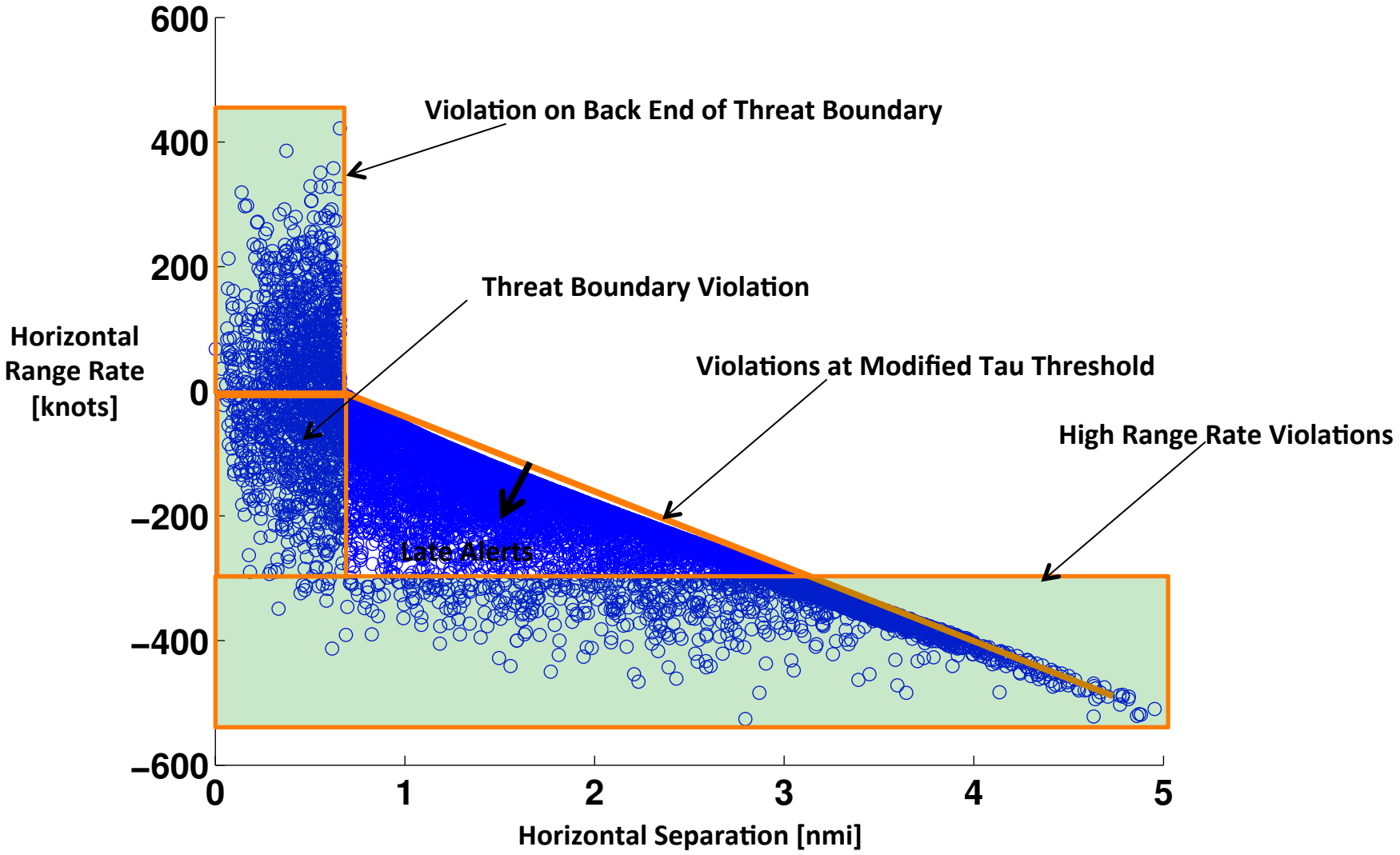
Encounter Rate by Altitude



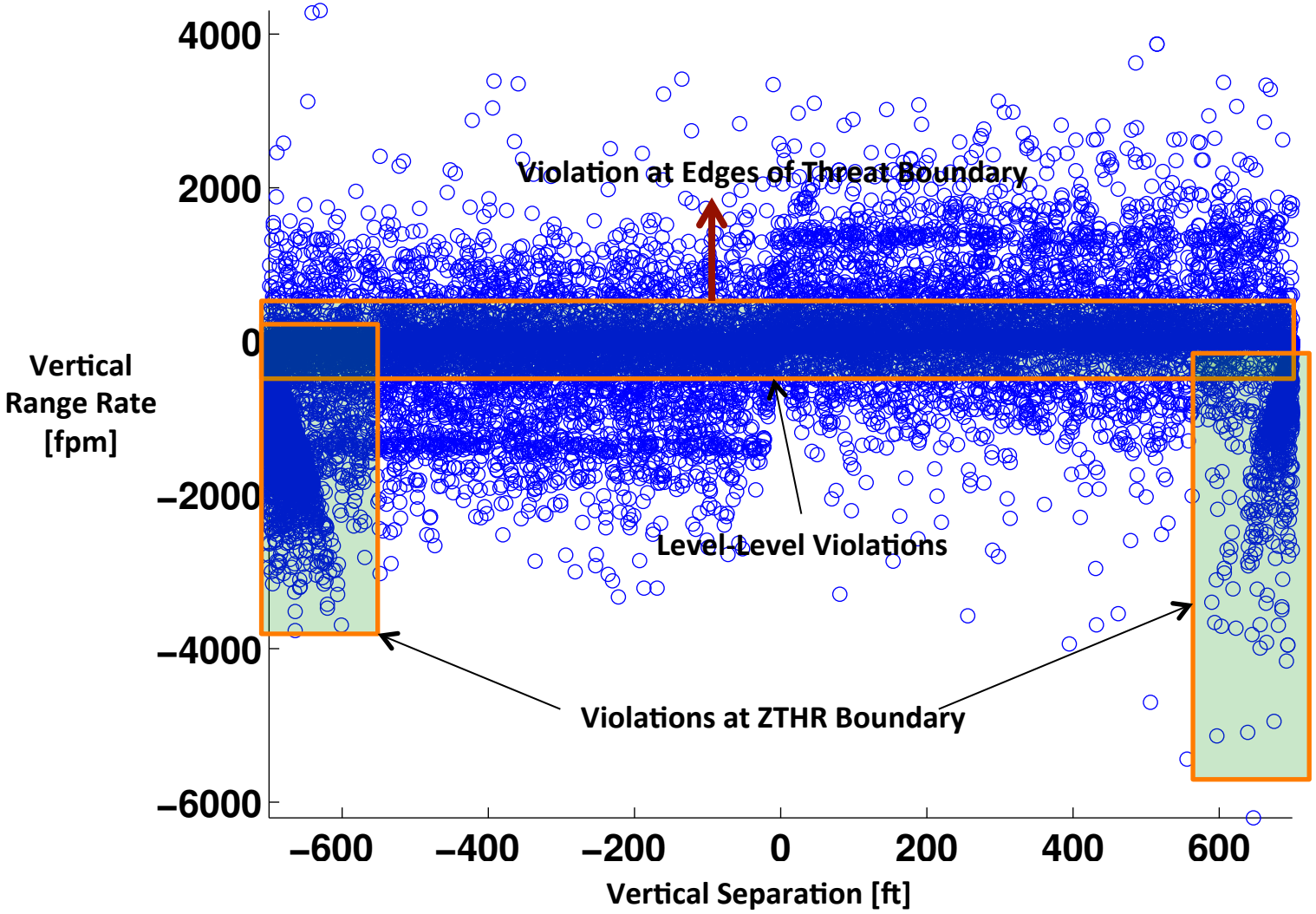
Statistics at WCV: Relative Heading



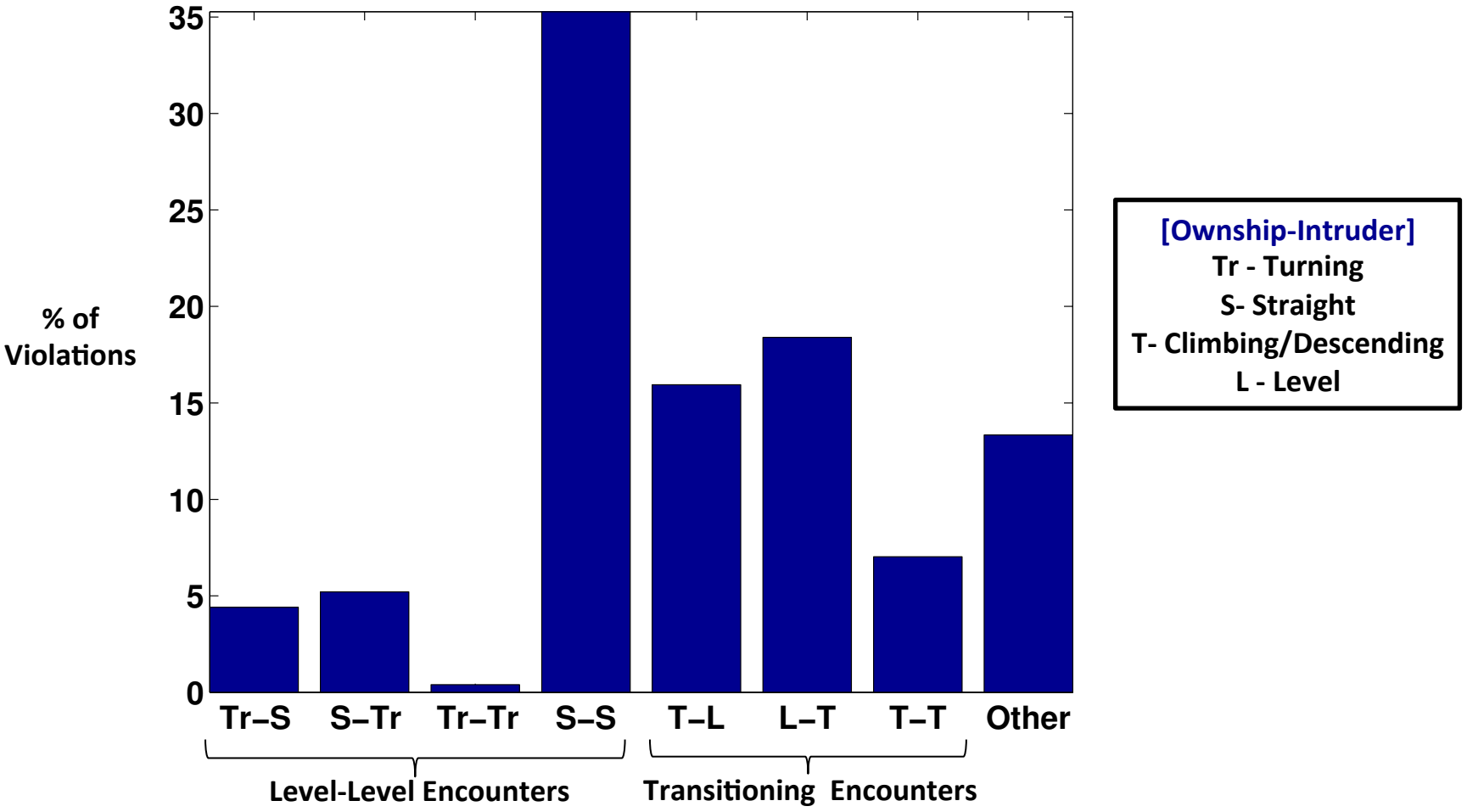
Closure Rate vs. Miss Distance (Horizontal)



Closure Rate vs. Miss Distance (Vertical)

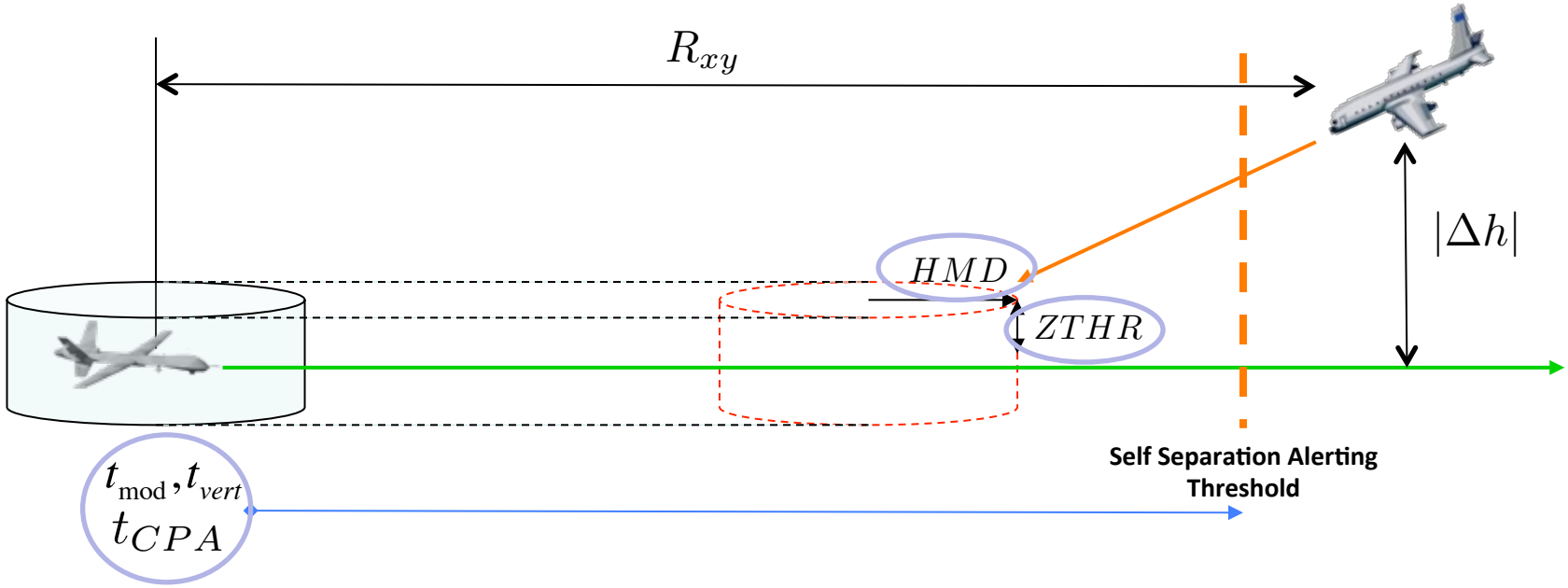


Type of Violation



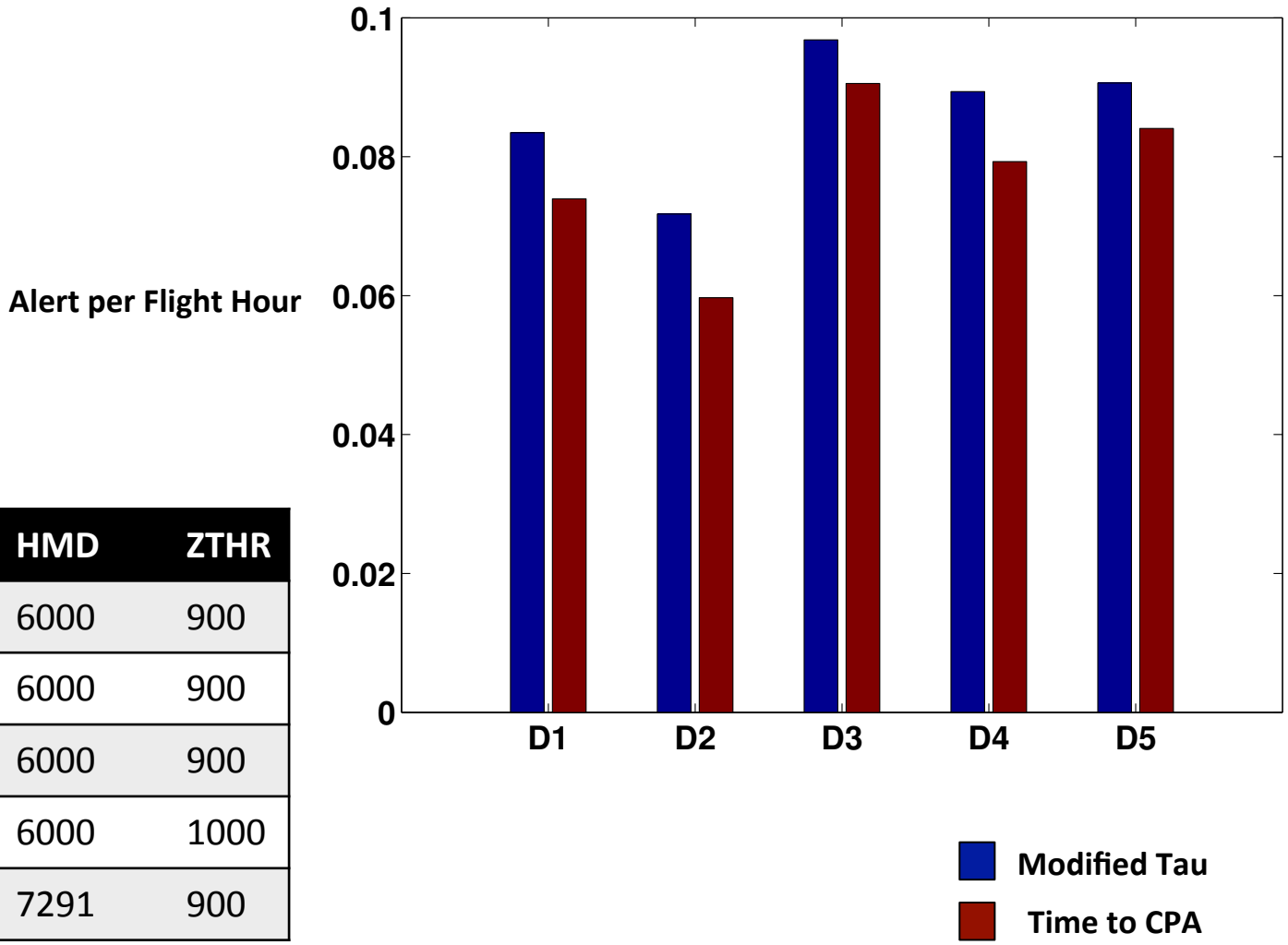
Analysis 3

- Characteristics about the Self Separation Threshold
  - Analysis uses Well Clear Definition plus buffers for alerting
  - Also looks at time to CPA calculation



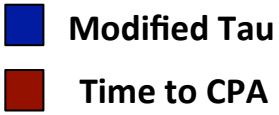
Rate of Self Separation Alerts

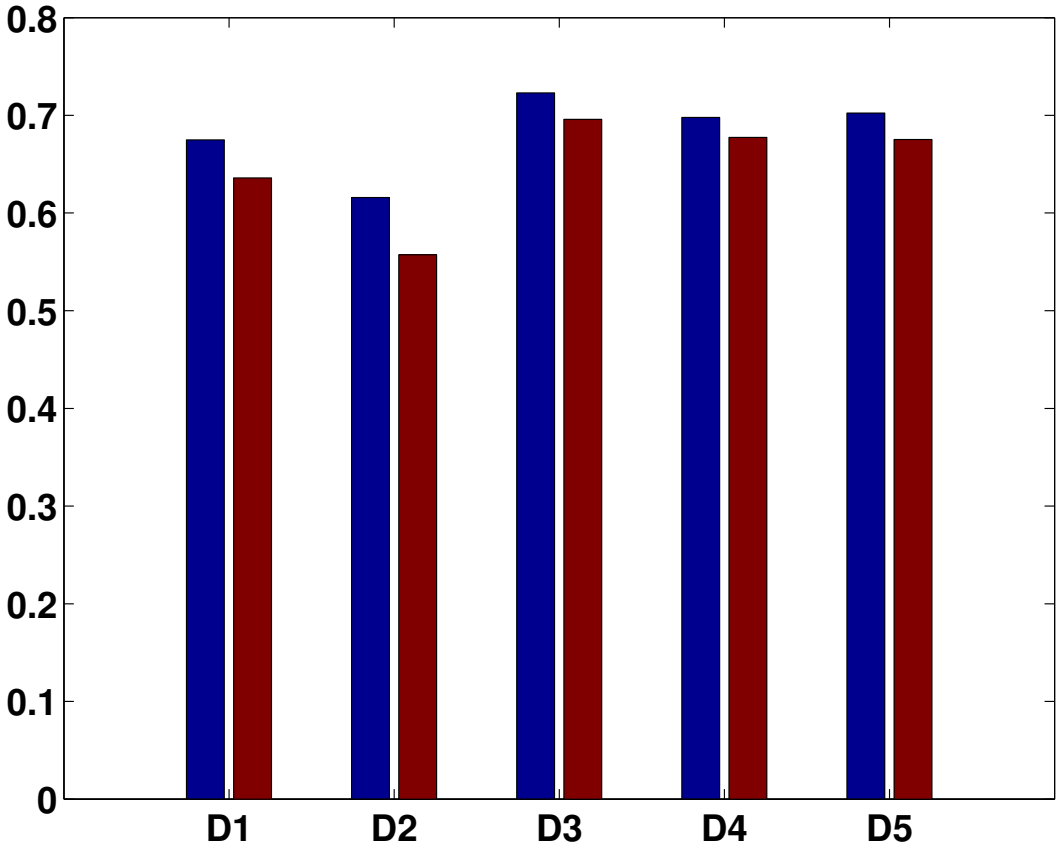
	Tau	T_CPA	HMD	ZTHR
D1	90	90	6000	900
D2	70	70	6000	900
D3	110	110	6000	900
D4	90	90	6000	1000
D5	90	90	7291	900



Alerts with no WCVs

Ratio of alerts
that did not result in WCV



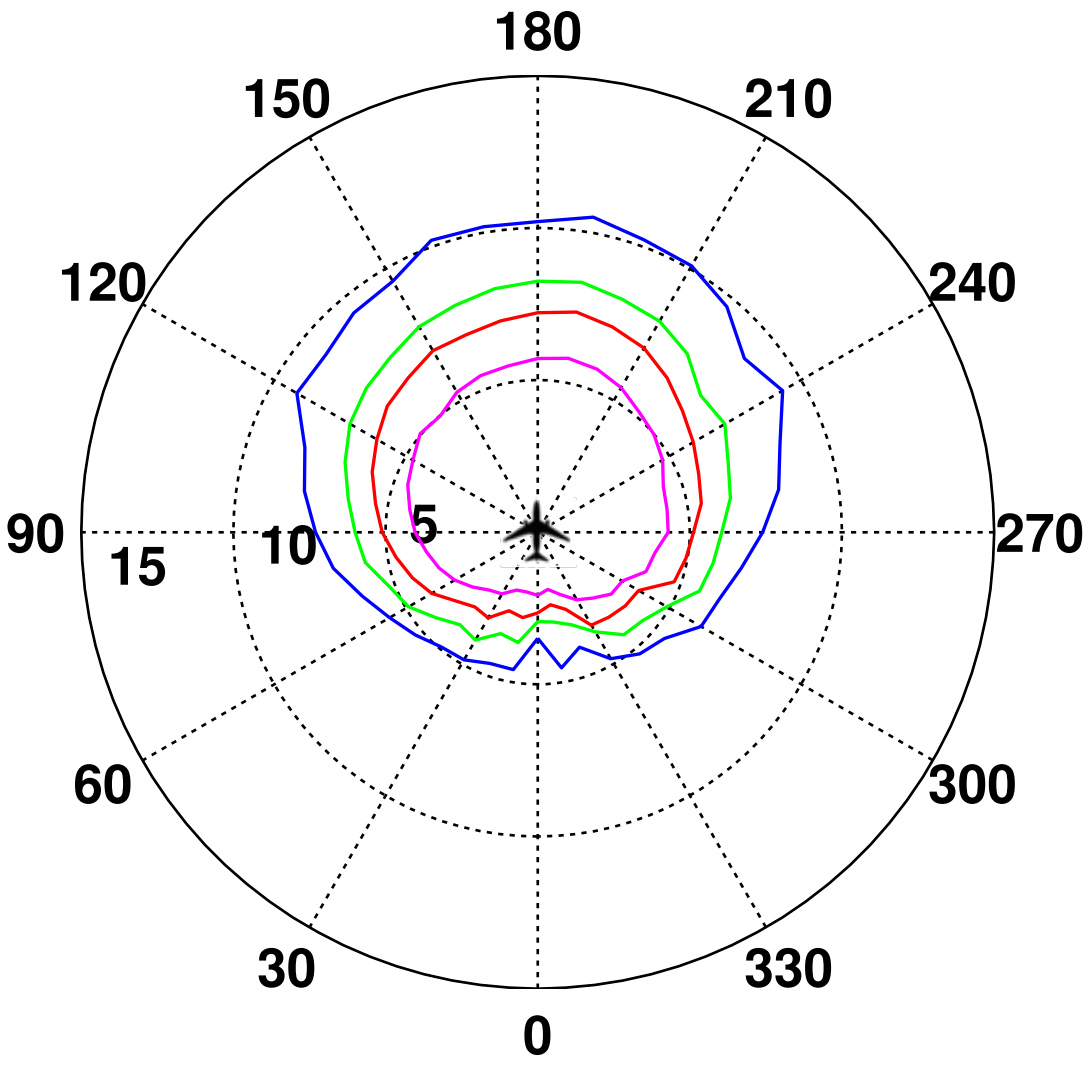


	Tau	T_CPA	HMD	ZTHR
D1	90	90	6000	900
D2	70	70	6000	900
D3	110	110	6000	900
D4	90	90	6000	1000
D5	90	90	7291	900

Well Clear Definition

Tau [sec]	Tcoa [sec]	DMOD [nmi]	HMD [ft]	ZTHR [ft]
35	0	1.1	4000	700

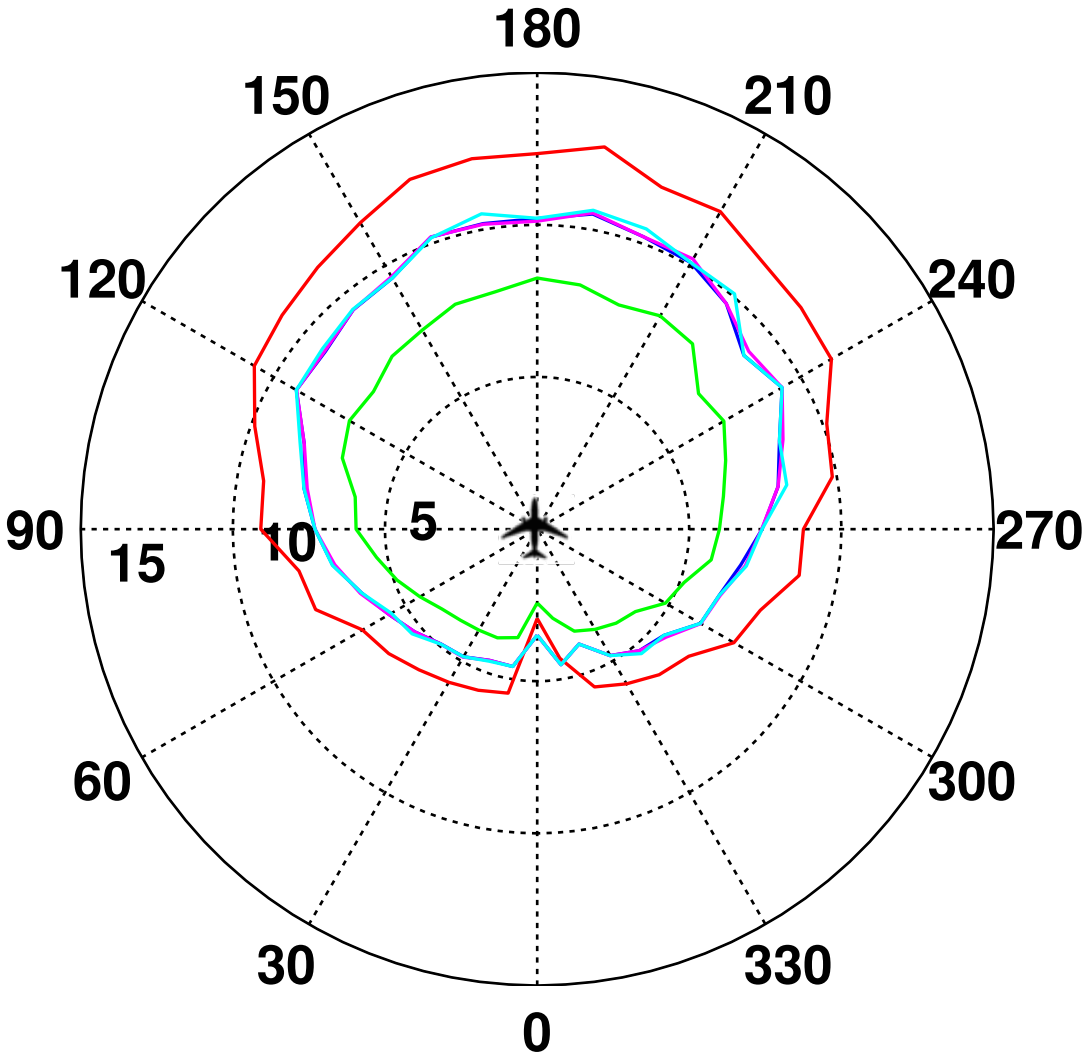
Statistics at Alert: Relative Heading



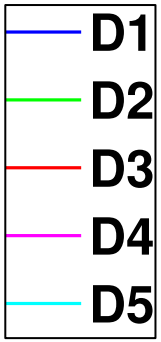
	Tau	HMD	ZTHR
D1	90	6000	900

99%
90%
80%
60%

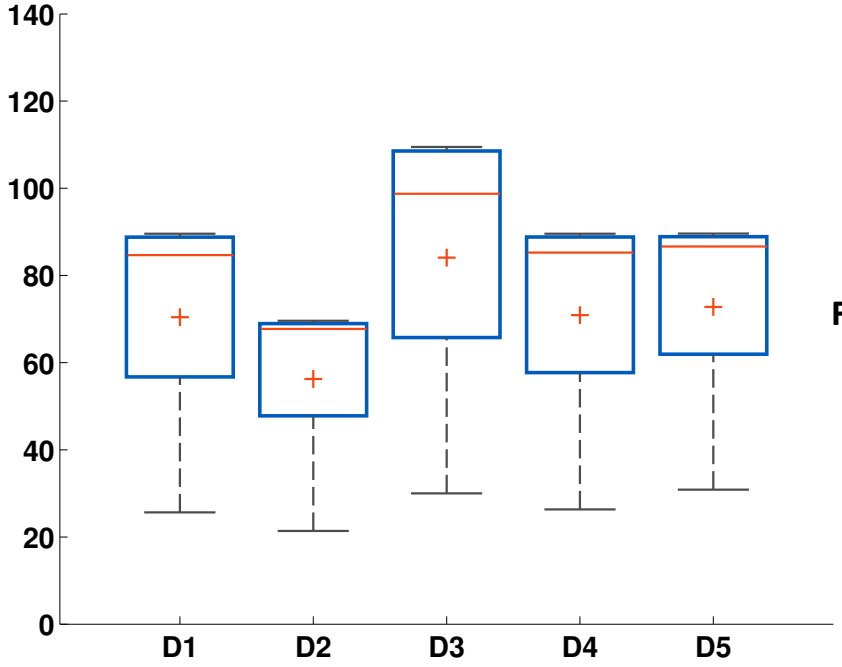
Statistics at Alert: Relative Heading



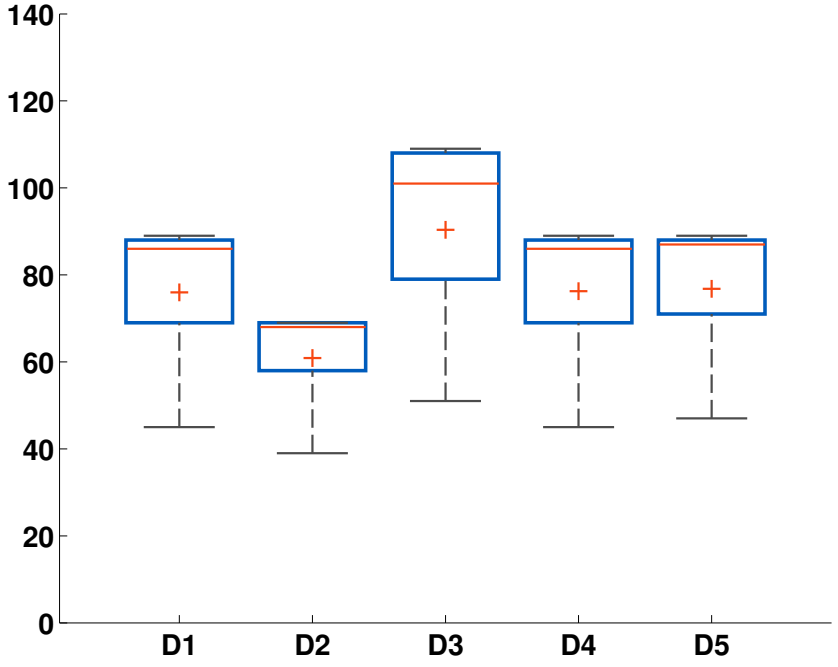
	Tau	HMD	ZTHR
D1	90	6000	900
D2	70	6000	900
D3	110	6000	900
D4	90	6000	1000
D5	90	7291	900



Statistics at Alert: Time at First Alert



Time to First Alert [sec]



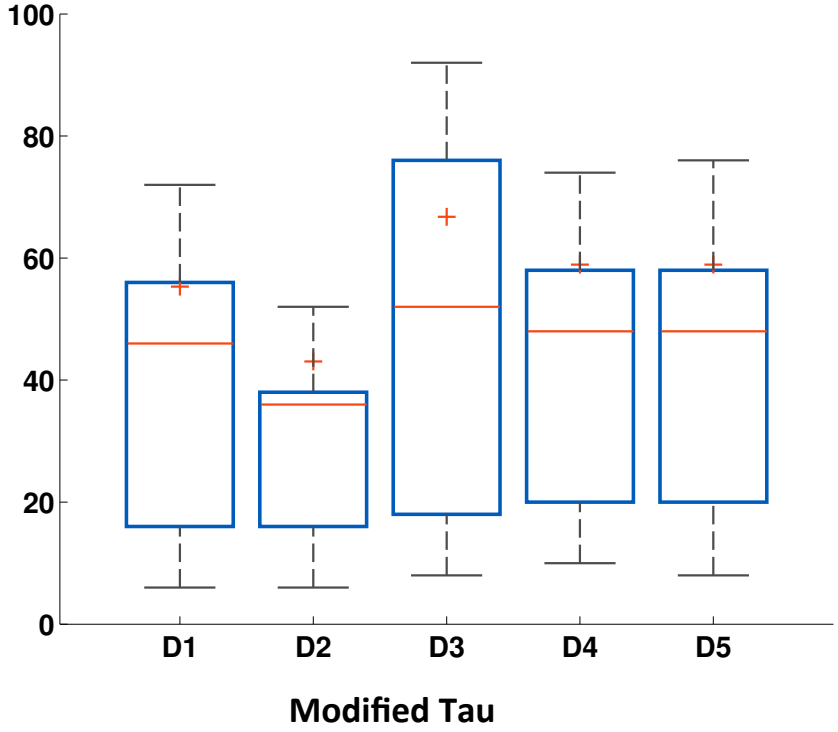
Modified Tau

	Tau	T_CPA	HMD	ZTHR
D1	90	90	6000	900
D2	70	70	6000	900
D3	110	110	6000	900
D4	90	90	6000	1000
D5	90	90	7291	900

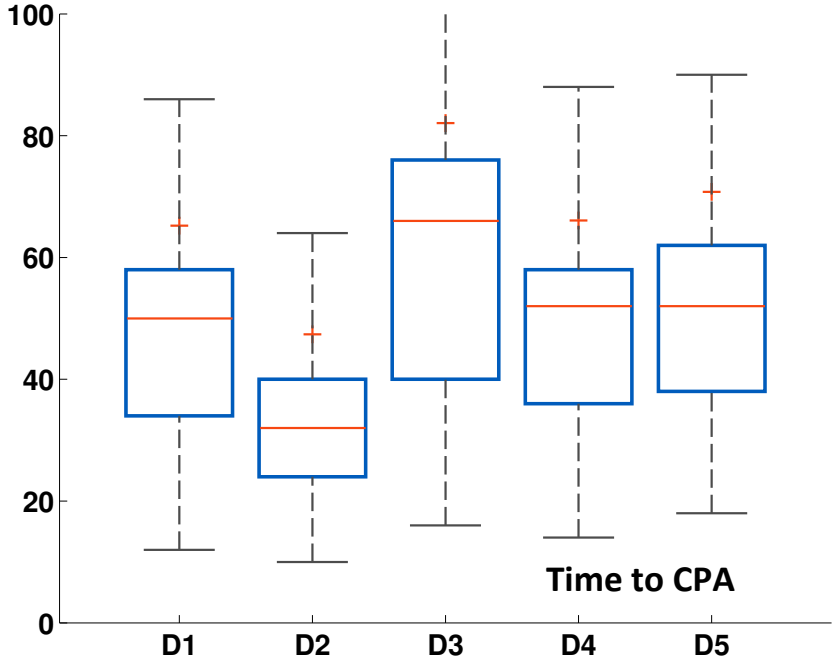
Time to CPA

Median
μ
25%–75%
9%–91%

Statistics at Alert: Time to Violation



Time to WCV [sec]



Median
μ
25%–75%
9%–91%

Well Clear Definition

Tau [sec]	Tcoa [sec]	DMOD [nmi]	HMD [ft]	ZTHR [ft]
35	0	1.1	4000	700

	Tau	T_CPA	HMD	ZTHR
D1	90	90	6000	900
D2	70	70	6000	900
D3	110	110	6000	900
D4	90	90	6000	1000
D5	90	90	7291	900

Conclusions

- Three analysis were conducted against 23 days of recorded VFR traffic.
- 9 UAS missions were used in each simulation
- Results indicate:
  - A minimum 5 nmi range to avoid missed detections
  - 99% of the alerts lie with 10 nmi with a 90 second modified tau alerting threshold (Analysis 3, D1 configuration)
  - HMD and ZTHR will have the largest impact on encounter rates and the closer two aircraft are the more sensitive the encounter rate is to these parameters.
  - ~70% of alerts generated using modified tau or time to co-attitude criteria did not lead to a WCV.
- Follow-on experiment will look at non-cooperative and cooperative VFR traffic with more UAS missions.

Questions

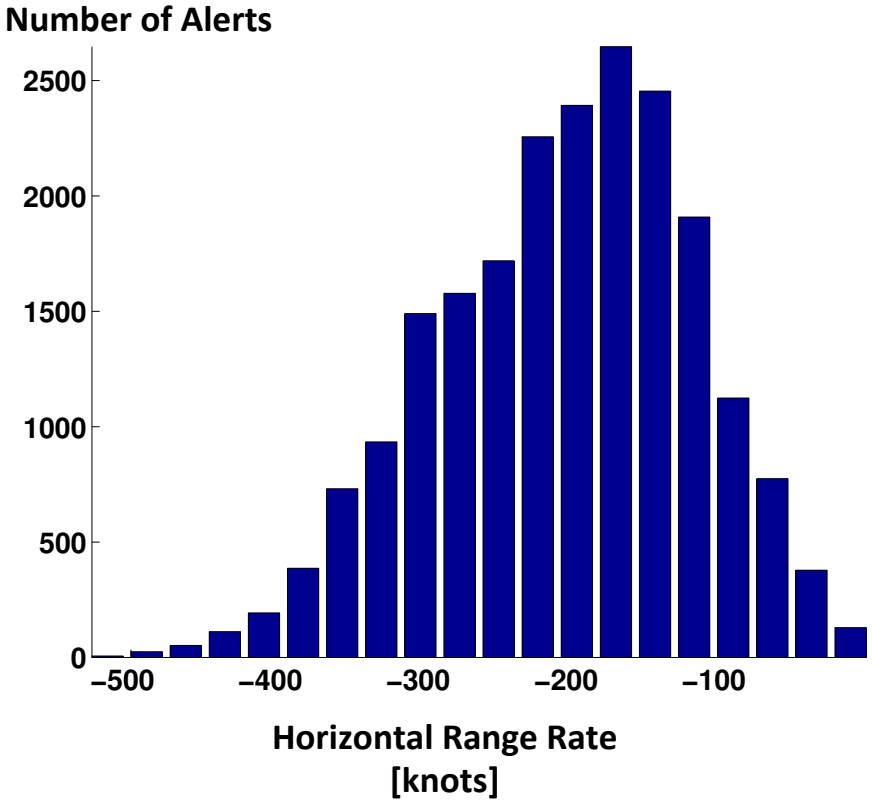


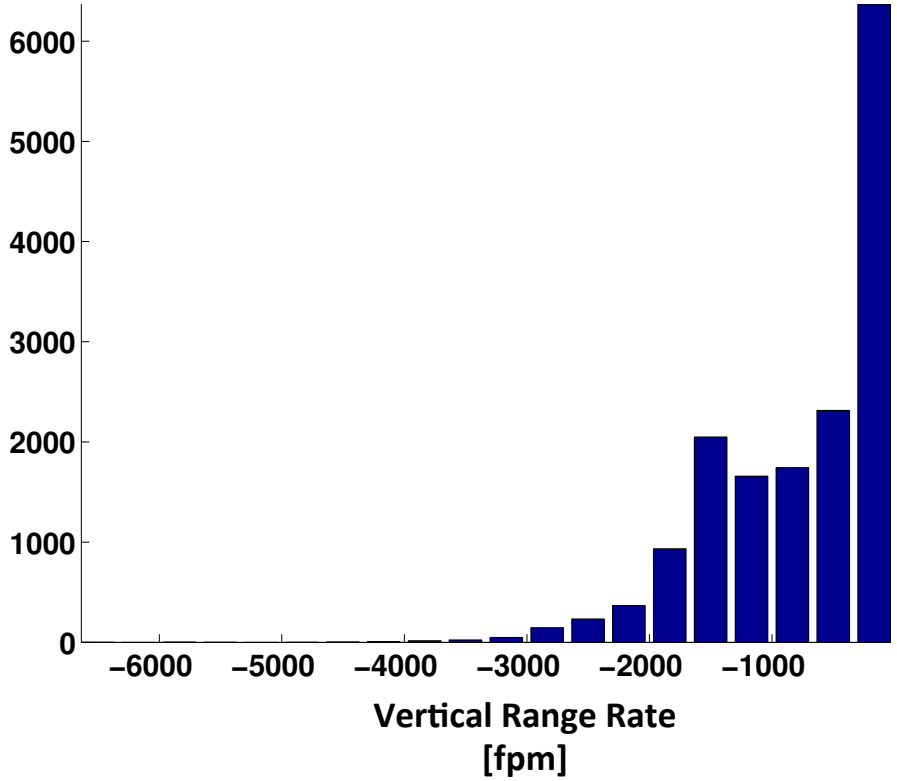
Marcus Johnson
marcus.johnson@nasa.gov

Backup Slides



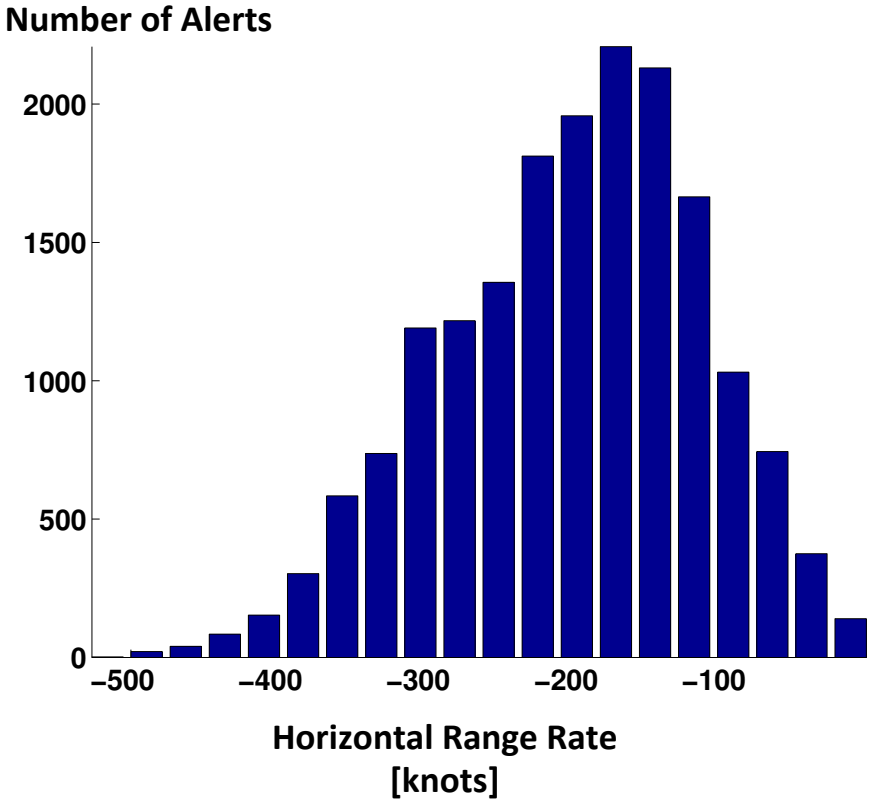
Statistics at Alert: Range Rates for 99% of alerts

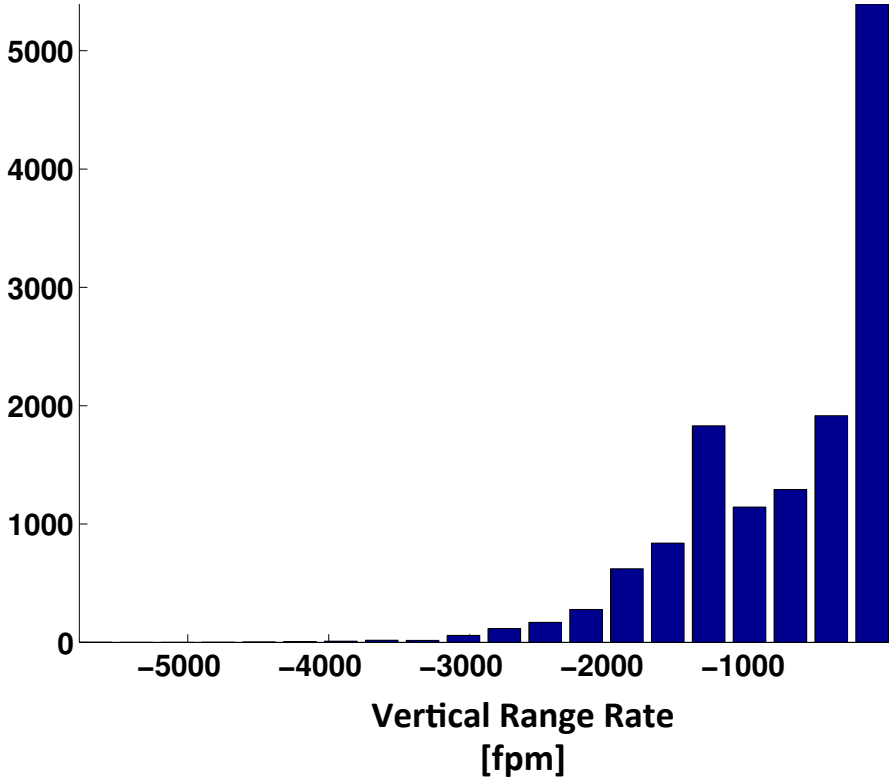




Configuration	Tau	HMD	ZTHR
D1	90	6000	900

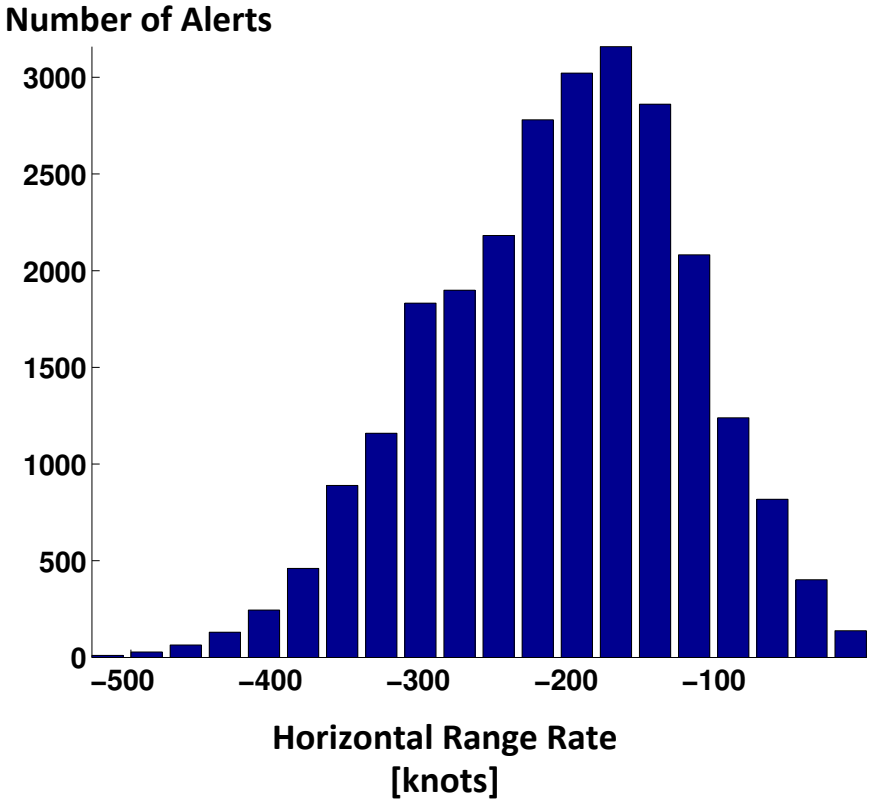
Statistics at Alert: Range Rates for 99% of alerts

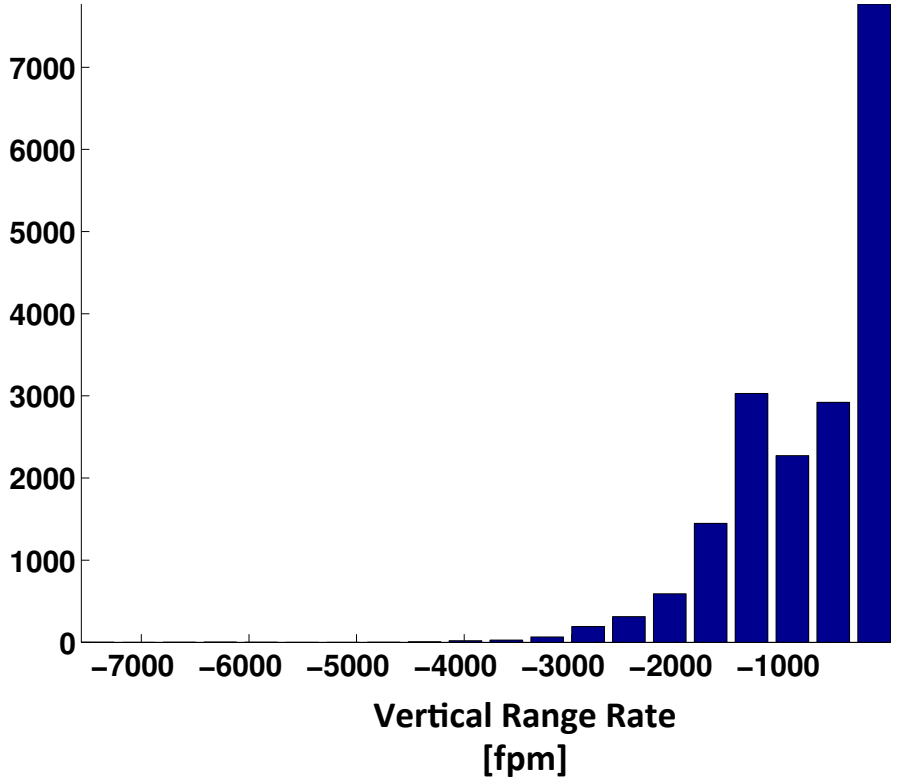




Configuration	Tau	HMD	ZTHR
D2	70	6000	900

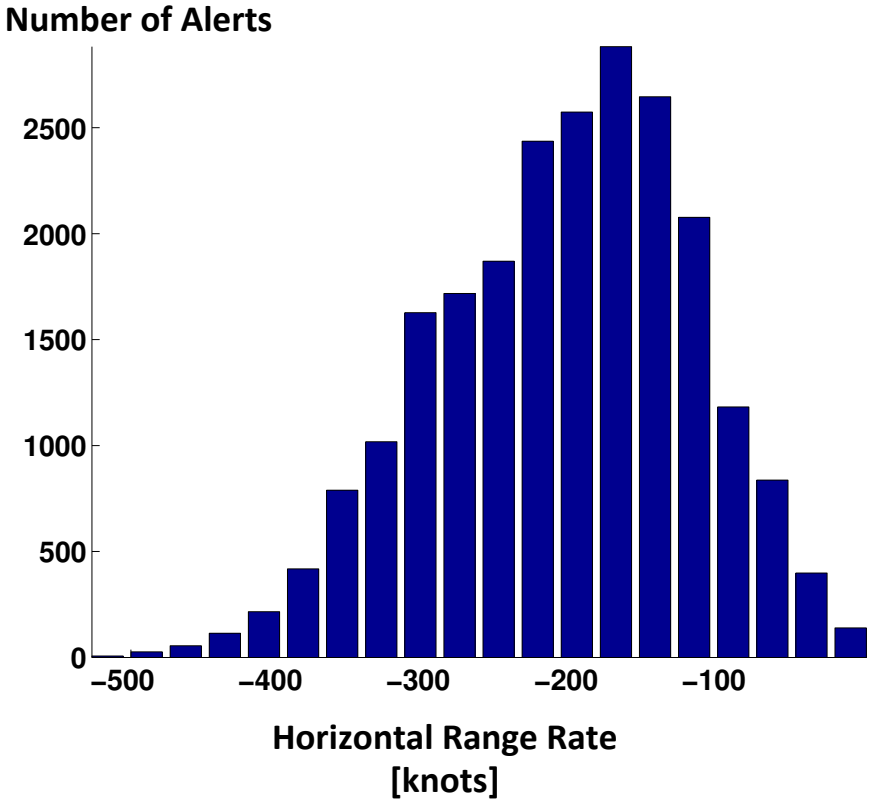
Statistics at Alert: Range Rates for 99% of alerts

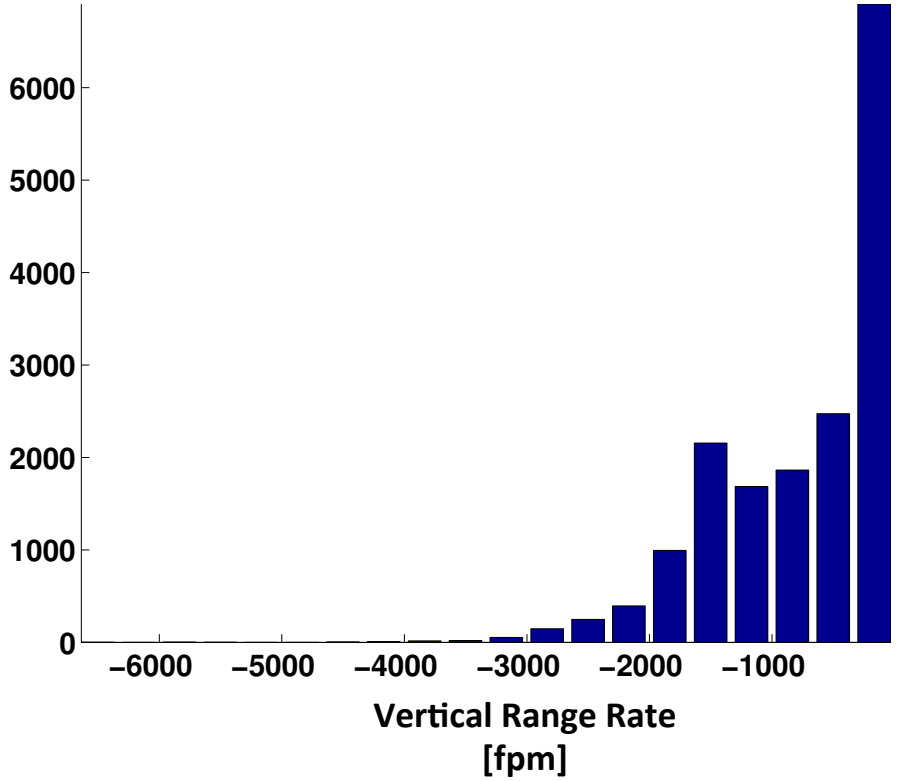




Configuration	Tau	HMD	ZTHR
D3	110	6000	900

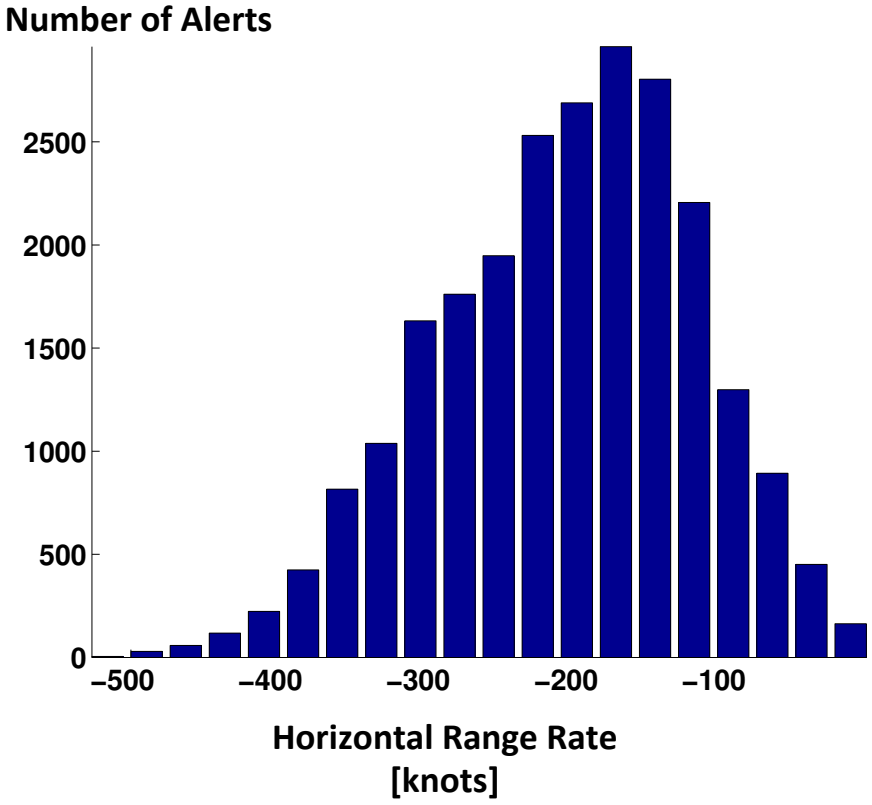
Statistics at Alert: Range Rates for 99% of alerts

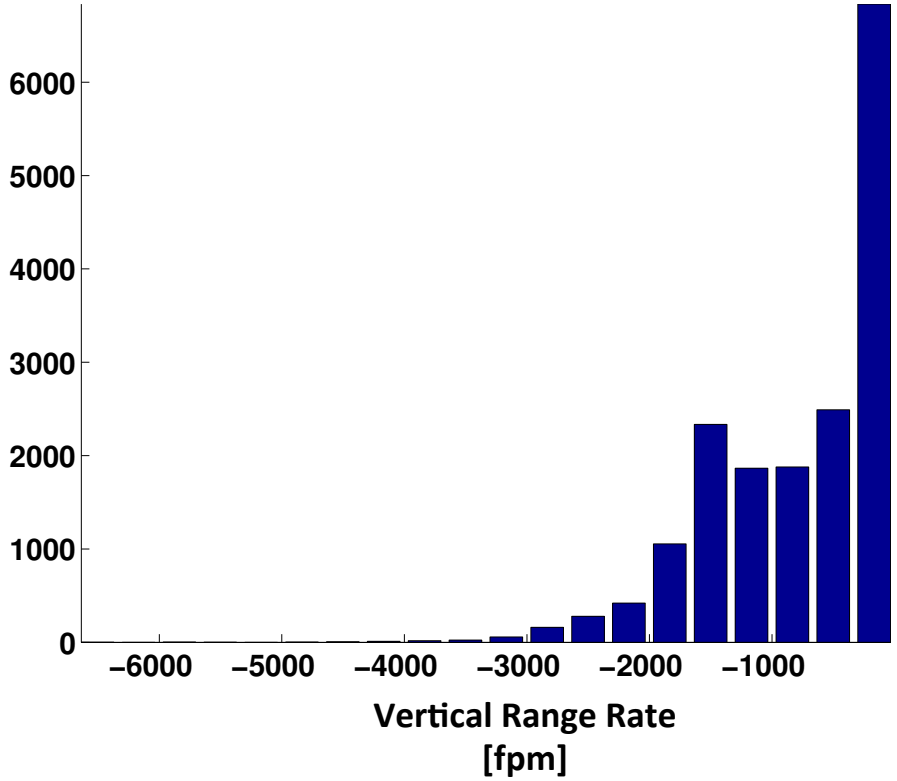




Configuration	Tau	HMD	ZTHR
D4	90	6000	1000

Statistics at Alert: Range Rates for 99% of alerts





Configuration	Tau	HMD	ZTHR
D5	90	7291	900