

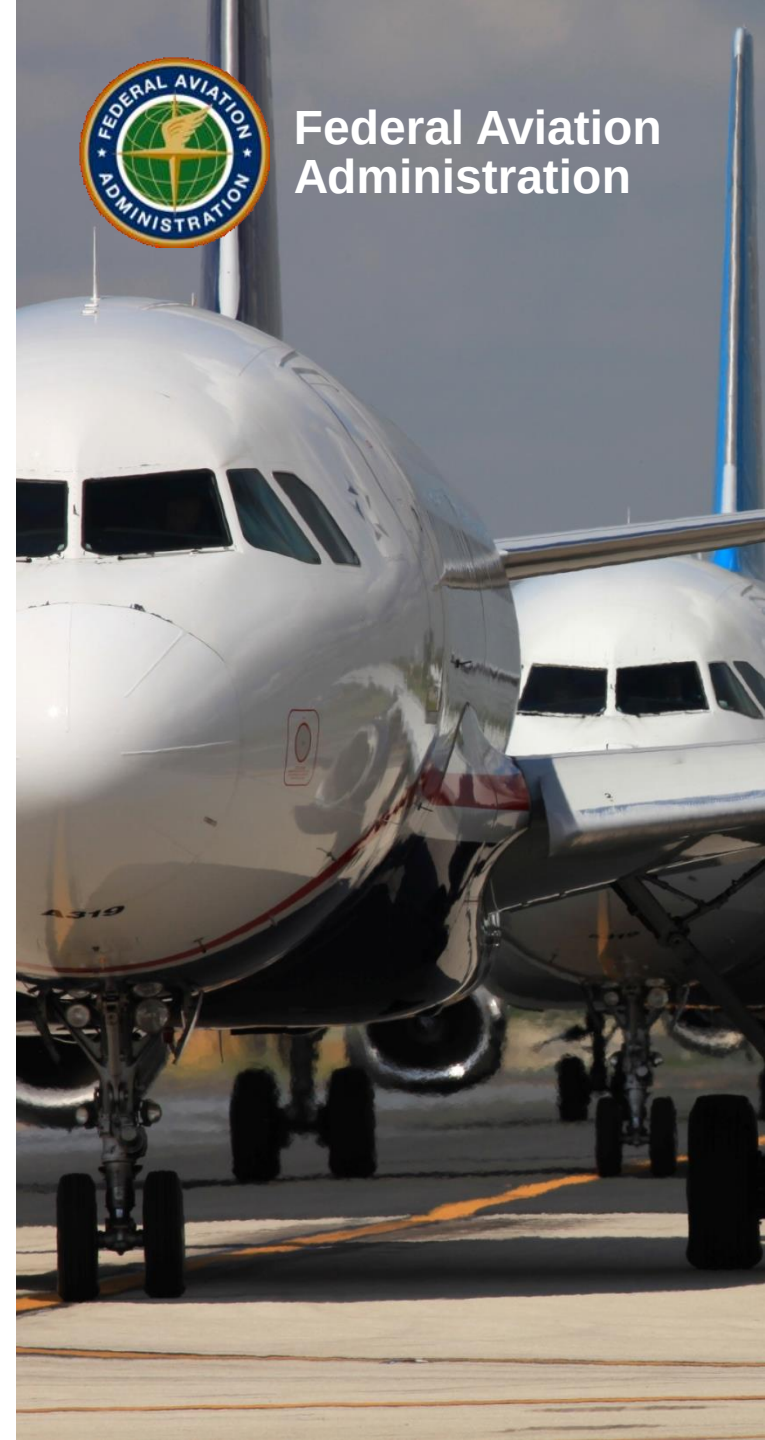
A Bayesian Network Model of Pilot Response to TCAS RAs

Robert Moss & Ted Londner
MIT Lincoln Laboratory

ATM R&D Seminar — June 28, 2017



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Outline



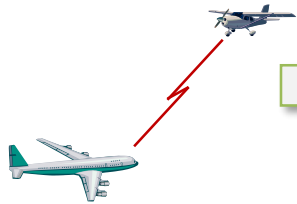
- **Introduction and Motivation**
- **Methodology**
- **Parametric Pilot Response Model**
- **Safety Simulations**
- **Conclusion**



Background—TCAS

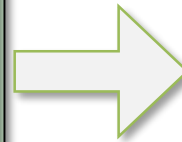
Traffic Alert and Collision Avoidance System

*Sensor
Measurements*



```
IF (ITF.A LT G.ZTHR)
THEN IF (ABS(ITF.VMD)
LT G.ZTHR)
THEN SET ZHIT;
ELSE CLEAR ZHIT;
ELSE IF (ITF.ADOT GE
P.ZDTHR)
THEN CLEAR ZHIT
ELSE
ITF.TAUV = -
ITF.A/ITF.ADOT;
```

*Resolution
Advisories*



Climb... Climb

*Advisory Display,
Annunciation*



Surveillance

- 1030/1090 MHz
- Intruder detection
- Position tracking

Advisory Criteria

- Alert criteria
- Time to CPA (tau) based
- Resolution advisory selection
- Pilot response assumptions

Display

- Intruder range and bearing
- Aural annunciation
- Advisory display

Pilot Response

- Pilots nominally directed to comply with all advisories
- Radar data shows pilots oftentimes do not respond



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TCAS Resolution Advisories

Maneuvers Available to TCAS' Advisory Logic (Version 7.1)

Sense	Resolution Advisory	Type	Target Vertical Rate (fpm)
Up	Do not Descend	Preventive	>0, -500, -1000, or -2000
	Maintain Vertical Speed	Preventive	Current Rate
	Level off	Corrective	0
	Climb	Corrective	1500
	Increase Climb	Corrective	2500
Down	Do not Climb	Preventive	<0, 500, 1000, or 2000
	Maintain Vertical Speed	Preventive	Current Rate
	Level off	Corrective	0
	Descend	Corrective	-1500
	Increase Descend	Corrective	-2500
Multi	Do not Climb or Descend	Preventive	0
	Level off	Corrective	0
N/A	Clear of Conflict	N/A	No restrictions

This analysis focuses on 1500 fpm TCAS *climb* and *descend* advisories



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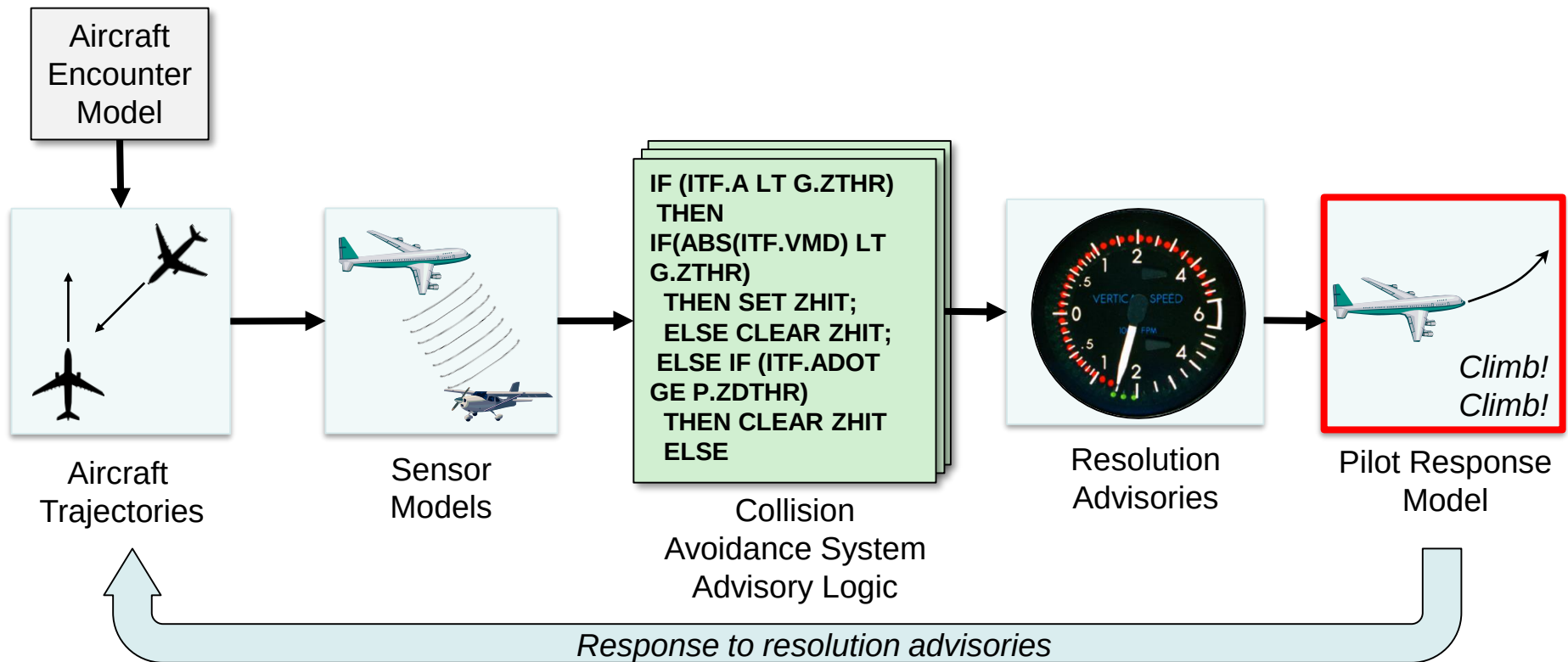
Pilot Response to TCAS Advisories

- In United States, response instructions outlined in FAA AC 120-55C
- Pilots nominally directed to comply with all TCAS advisories
- **May choose to not respond when:**
 - Doing so would compromise safety
 - Safe separation can be assured through visual acquisition of intruder causing alert
- US radar data shows that pilot compliance with *climb* and *descend* RAs is between 50-60%
- **Pilot response is highly situational**
 - Influences include current vertical rate, visual acquisition of intruder, airspace operation
 - For example, response rate is especially low during approaches to parallel runways



Collision Avoidance System Evaluation

Fast-Time Monte Carlo Modeling and Simulation



Pilot response models are a crucial element of fast-time simulation of aircraft encounters: the primary method of evaluating collision avoidance systems



Motivation

Gaps in Current Pilot Response Models

- **Current models are *encounter-agnostic***
 - Naïve models assume perfect (100%) response
 - Other models assume fixed response probability (e.g., 80%) based on aggregate statistics
 - In both cases, response probabilities are applied identically to all encounters
- **Potential consequences of encounter-agnostic models:**
 - Inaccurate estimation of safety benefit
 - Masking of undesired system behavior
- **Current model variables:**
 - Probability of response, response delay, vertical acceleration
- **Standard response model (assumed by TCAS logic):**
 - Initial advisory: 5 seconds delay, 0.25g vertical acceleration
 - Subsequent advisories: 2.5 seconds, 0.35g
 - Assumed by TCAS logic; commonly used in CAS safety simulations

This work introduces a new pilot response model that is based on the parameters of individual encounters



Objectives

- **Construct a *parametric pilot response model* in which pilot response probability is a function of encounter parameters**
 - Example encounter parameters: RA issued, aircraft vertical rate, airspace operation
 - Construct model from US operational radar data using Bayesian network techniques
- **Quantify the sensitivity of TCAS safety benefit to pilot response model assumptions**
 - Employ parametric model in fast-time simulation of aircraft encounters with TCAS
 - Analyze resulting probability of near mid-air collision (NMAC)
 - Compare to results obtained from encounter-agnostic pilot response models



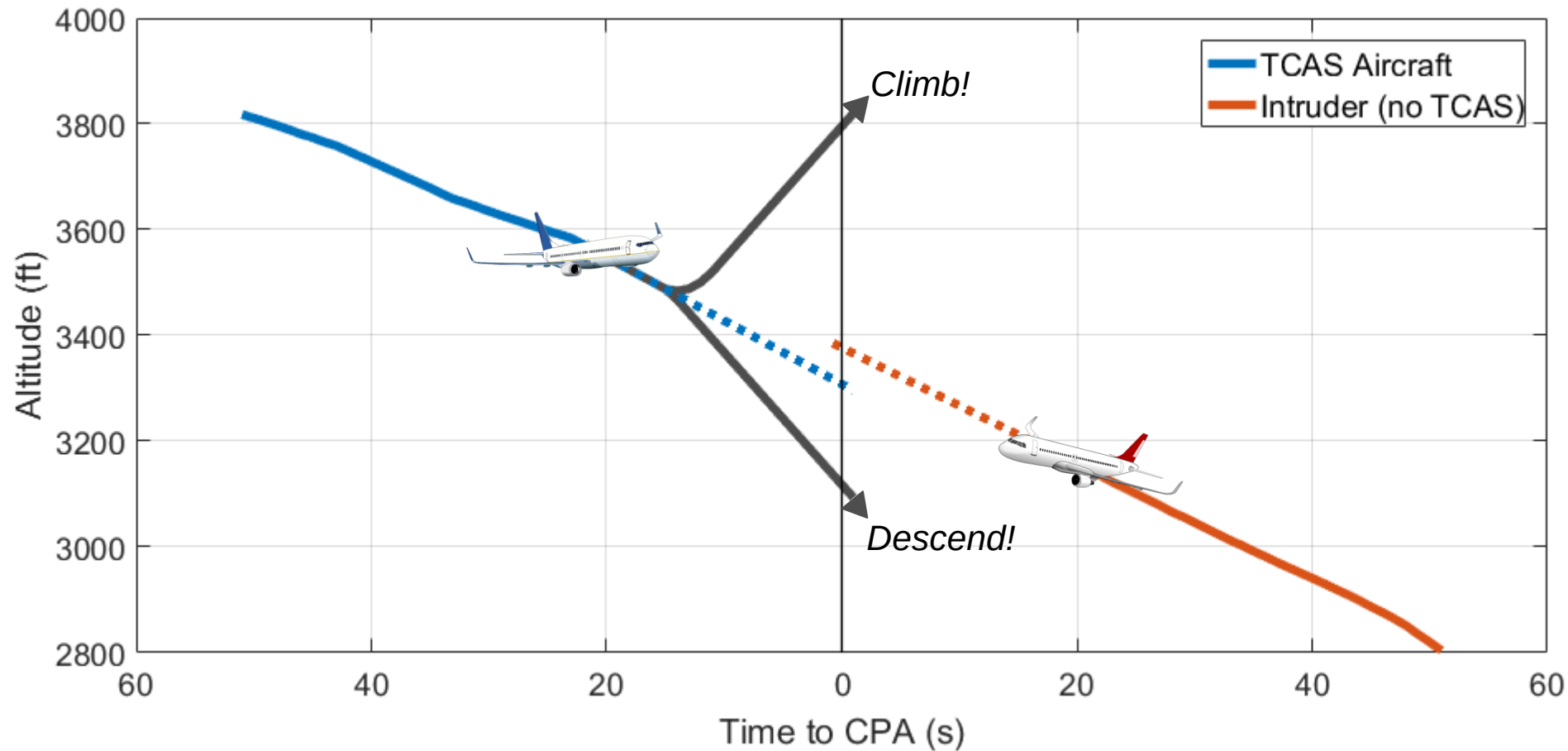
Parametric Pilot Response Model

- Pilot response probability calculated for each encounter
- Response probability a function of encounter parameters
- Encounter parameters affecting pilot response probability identified using Bayesian network
 - Similar technique used to build Lincoln Laboratory Correlated Encounter Model
- Data source is radar recordings of TCAS encounters in US collected through TCAS RA Monitoring System (TRAMS)
- *Climb and Descend RAs only*
 - Due to limitations of TRAMS data source
- Pilot response definition
 - RA compliance considered only
 - No consideration of response delay or acceleration



Notional Encounter

Potential TCAS Advisories



A parametric response model defines probability of pilot response to each potential TCAS advisory based on the specific parameters of this encounter



Outline

- Introduction and Motivation
- ➔ • Methodology
- Parametric Pilot Response Model
- Safety Simulations
- Conclusion



Methodology

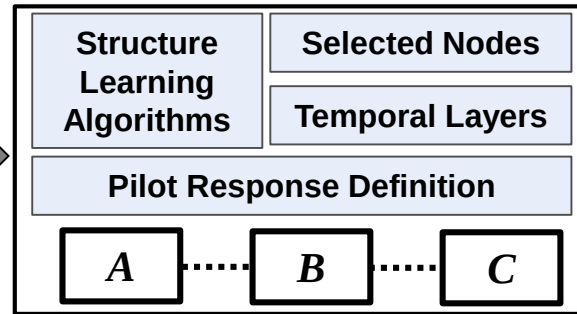
Schematic

Recorded TRAMS Encounters

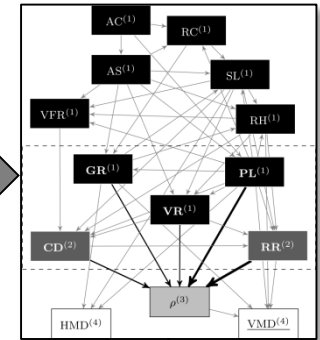


Feature
Extraction

Bayesian Network Structure Learning

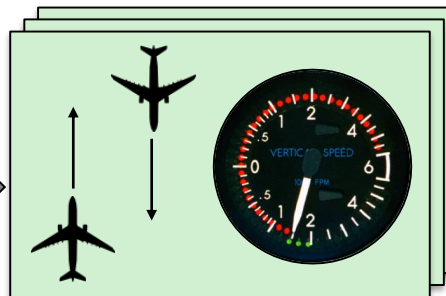


Parametric Pilot
Response Model

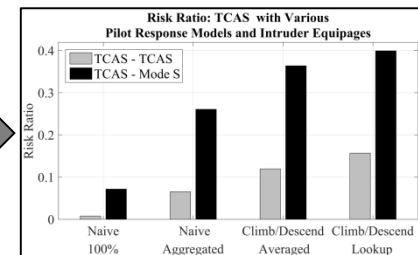


Parametric Pilot
Response Model

Alternate Pilot
Response Models



Fast-Time Encounter
Simulation With TCAS



Safety Metrics

Simulations with a parametric pilot response model capture the effect of encounter parameters on pilot response, which in turn affects collision risk

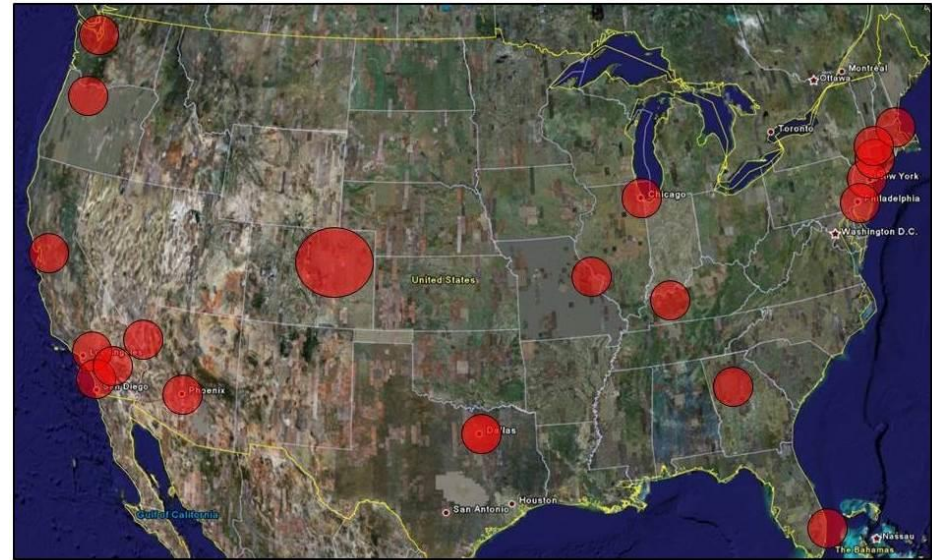


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TCAS RA Monitoring System (TRAMS)

Data Source

- **Recordings of TCAS RA encounters**
 - RAs issued
 - Aircraft tracks
 - 550,000+ encounters since 2008
- **20 secondary-surveillance terminal radars:**
 - 60 nautical mile range
 - 4.6 second rotation period
- **RA information downlinked by aircraft transponders**
 - Content depend on versions of TCAS and aircraft transponder
 - Older formats do not capture details of *Adjust Vertical Speed, Level Off* RAs



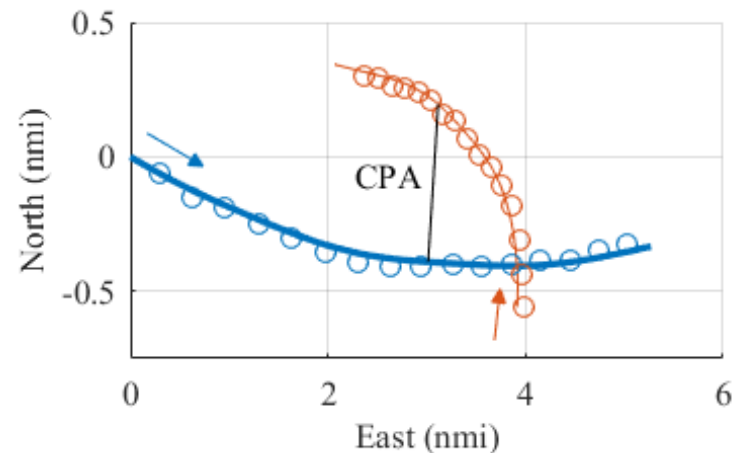
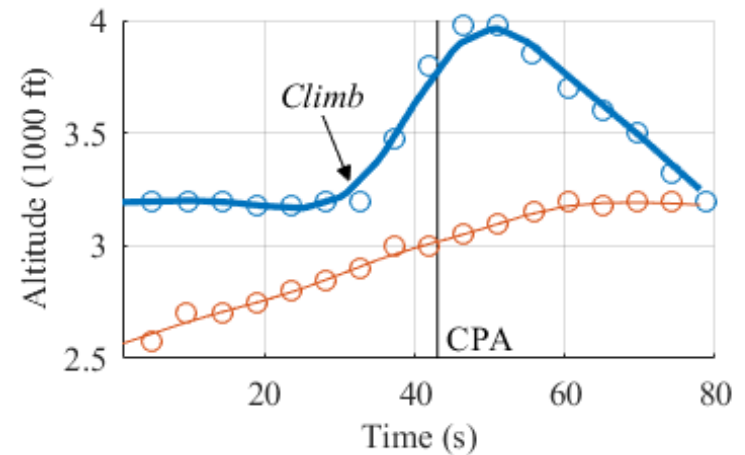
TRAMS radar coverage



Methodology

Data Collection

- **Dataset: 80,955 TRAMS encounters recorded between 2008 and 2016**
- **Geometric variables calculated based on smoothed, interpolated trajectories**
- **Filtering parameters**
 - First RA *climb* or *descend*
 - No RA reversals
 - Not formation or military flight
 - Recording longer than 10 seconds
 - Terminal radars only



- Blue: TCAS; Red: Unequipped
- Lines: Smoothed; Circles: recording



Methodology

Definition of Pilot Response

- **Based on observed compliance as seen in TRAMS**
 - *Climb and descend* RAs only
- **Pilot complies with (responds to) RA if aircraft achieves 400 fpm in appropriate direction within 15 seconds of RA**
 - *Climb and descend* RAs advise 1500 fpm
- **Constrained by TRAMS data source**
- **No consideration of response delay, strength, acceleration**
 - Requires data source with finer resolution than TRAMS

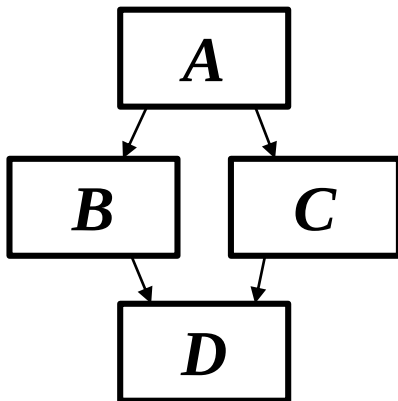
Pilot compliance with RAs is determined based on aircraft vertical rate after the RA is issued



Bayesian Networks

Analysis Framework

- Compact representation of joint probability distributions
- Variables represented as *nodes*
- Arrows connect *parent* to *child* nodes, represent statistical correlations
- Each node's probability distribution:
 - Fully defined by values of parent nodes
 - Based on frequencies of node values observed in dataset



- Statistical correlations exist among A, B, C, D
- A is the parent of B and C ; B and C are the parents of D
- Probability distribution of D depends solely on value of parents B and C
 - D is conditionally independent of A given knowledge of B and C

This study identifies the encounter parameters that influence probability of pilot response—that is, the *parent nodes* of pilot response probability

Methodology

Node Selection

- **Nodes selected based on:**
 1. Subject matter expert perception of factors affecting pilot response
 2. Contents of TRAMS data
- **Four temporal layers enforce causality between nodes**
 - Children of a node must be in same or lower temporal layer (i.e., bigger number)

(1) Aircraft Parameters, Encounter Geometry		(2) RA Parameters	
AC	Aircraft Category	RR	Rate Reversal
AS	Airspace	CD	Climb or Descend RA
SL	TCAS Sensitivity Level	(3) Response	
VFR	Intruder Beacon Category	ρ	Pilot Response Probability
PL	Parallel Approach Encounter	(4) Encounter Outcome	
RC	Relative Course	VMD	Vertical Miss Distance
RH	Relative Altitude	HMD	Horizontal Miss Distance
VR	Ownship Vertical Rate		
GR	Ground Range		

Bayesian Network Nodes and Temporal Layers



Methodology

Structure Learning

- **Structure Learning** is the algorithmic process of drawing the arrows between nodes
 - Establishes parent/child relationships
 - Defines the encounter parameters that influence pilot response probability (parent nodes)
- **Structure learning algorithms:**
 - *Bayesian Search* and *Greedy Thick Thinning* employed
 - GeNIe software package, University of Pittsburgh
- **Bayesian score** measures how well network structure represents data used to build it
- **Desired network features:**
 - High Bayesian score
 - Simplicity
 - Ease of simulation



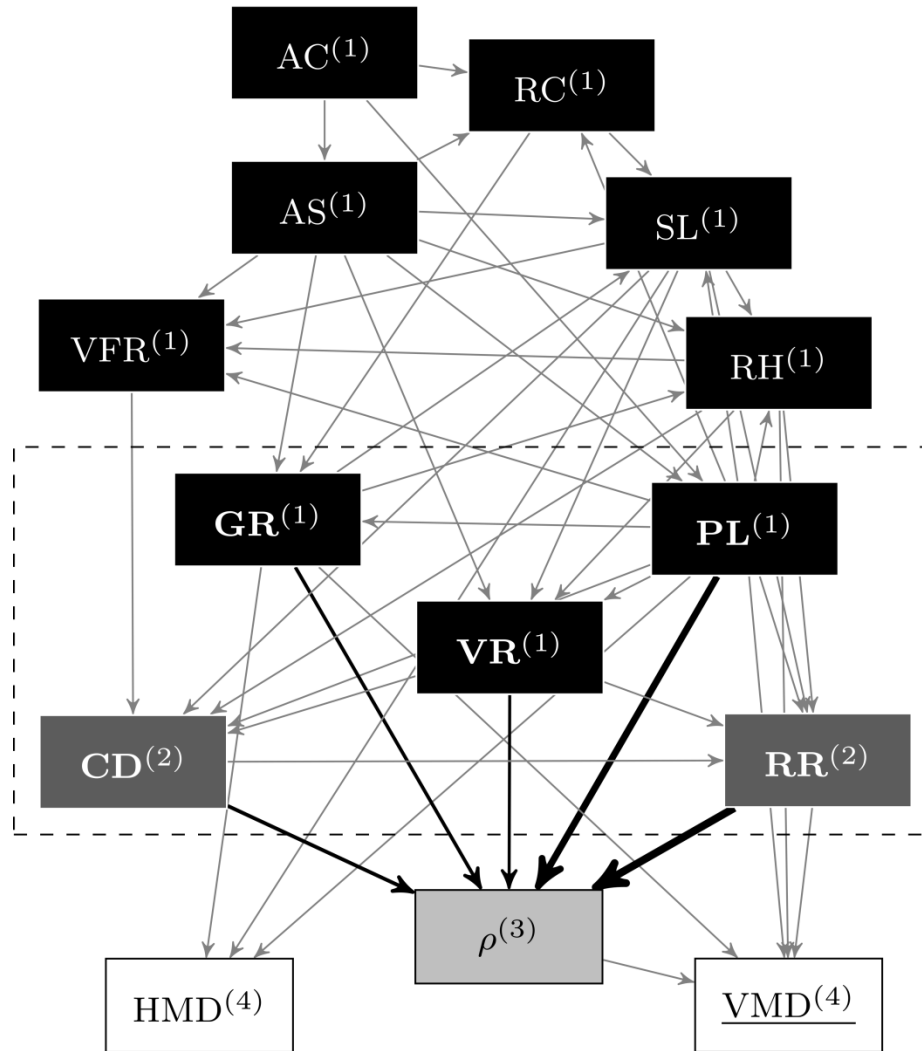
Outline

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Selected Network

Structure



- Aircraft Category AC
- Airspace AS
- TCAS Sensitivity Level SL
- Intruder Beacon Category VFR
- Relative Course RC
- Relative Altitude RH
- *Parallel Approach Encounter PL
- *Vertical Rate VR
- *Ground Range GR
- *Rate Reversal RR
- *Climb/Descend CD
- Pilot Response ρ
- Vertical Miss Distance VMD
- Horizontal Miss Distance HMD



Selected Network

Lookup Table

- **From structure learning: pilot response probability is a function of five encounter parameters**
 - Parameters are parent nodes, defined by network structure
 - *Parallel Approach Encounter, Vertical Rate, Ground Range, Rate Reversal, RA Type (Climb or Descend)*
- **Lookup table is used to determine pilot response probability for individual encounters**
 - Each row of lookup table corresponds to a unique combination of parent node values
 - Response probability equals rate of pilot compliance with TCAS RAs for the corresponding parent node values, as observed in TRAMS recordings

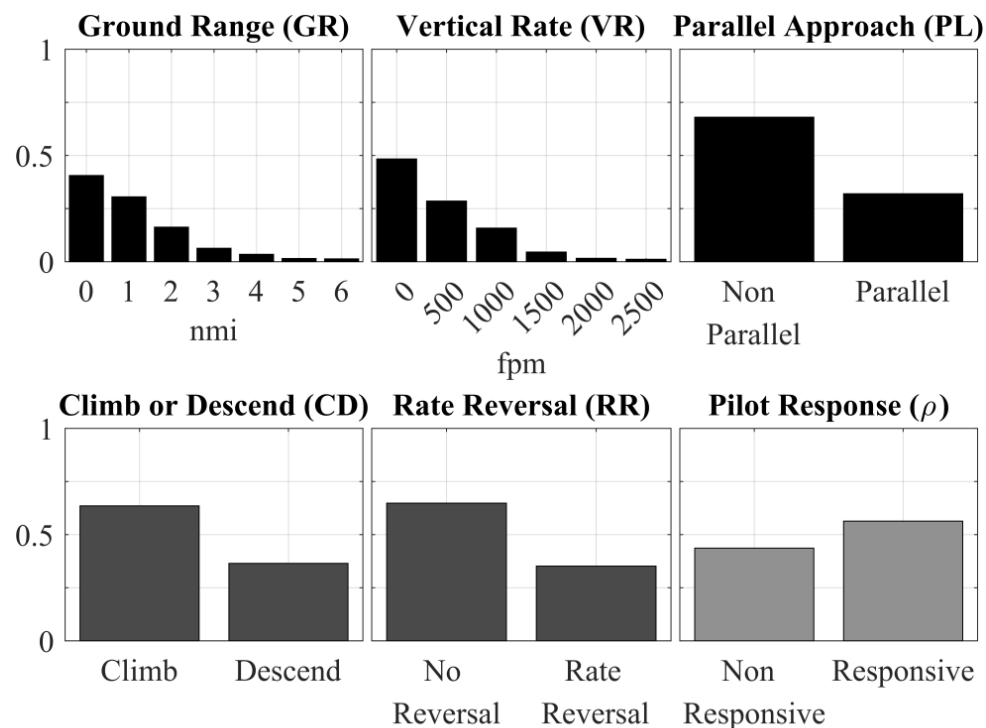
Rate Reversal	RA Type	Parallel Approach	Ground Range (nmi)	Vertical Rate (fpm)	Probability of Pilot Response (p)
No	Climb	No	<1	[0, 500)	0.389
Yes	Climb	No	<1	[0, 500)	0.310
No	Descend	No	<1	[0, 500)	0.421
Yes	Descend	No	<1	[0, 500)	0.423
No	Climb	Yes	<1	[0, 500)	0.098
Yes	Climb	Yes	<1	[0, 500)	0.051
No	Descend	Yes	<1	[0, 500)	0.736
Yes	Descend	Yes	<1	[0, 500)	0.600
No	Climb	No	[1, 2)	[0, 500)	0.572
Yes	Climb	No	[1, 2)	[0, 500)	0.478

First 10 (of 336) Rows of Lookup Table



Pilot Response and Parent Nodes Statistics

- **Strength of Influence** analysis is used to determine sensitivity of pilot response probability to each parent node
- Response probability is most sensitive to rate reversals and parallel approach encounters
- Relative strengths of each parent node (sums to 1):
 - Rate Reversal **RR**: 0.31
 - Parallel Approach **PL**: 0.27
 - Climb/Descend **CD**: 0.15
 - Ground Range **GR**: 0.14
 - Vertical Rate **VR**: 0.12
- Overall pilot response probability: **56%**
 - Non-parallel approaches: **62%**
 - Climb RAs: **58%**
 - Descend RAs: **69%**
 - Results agree with previous studies



Probability distributions of pilot response and its parent nodes in the dataset

Pilot response probability is most sensitive to the presence of a *rate reversal* and whether or not the RA occurred during an approach to parallel runways



Pilot Response and Parent Nodes

Discussion

- **Rate Reversals:**

- Lower probability of pilot response
- Associated with *climb* RAs
- *Pilots less likely to respond to RAs in opposition to current flight path*

- **Parallel Approaches:**

- Lower probability of pilot response
- *During parallel approaches when pilot did not respond to RA, RA was a climb 92% of the time (would result in go-around)*

- **Climb/Descend:**

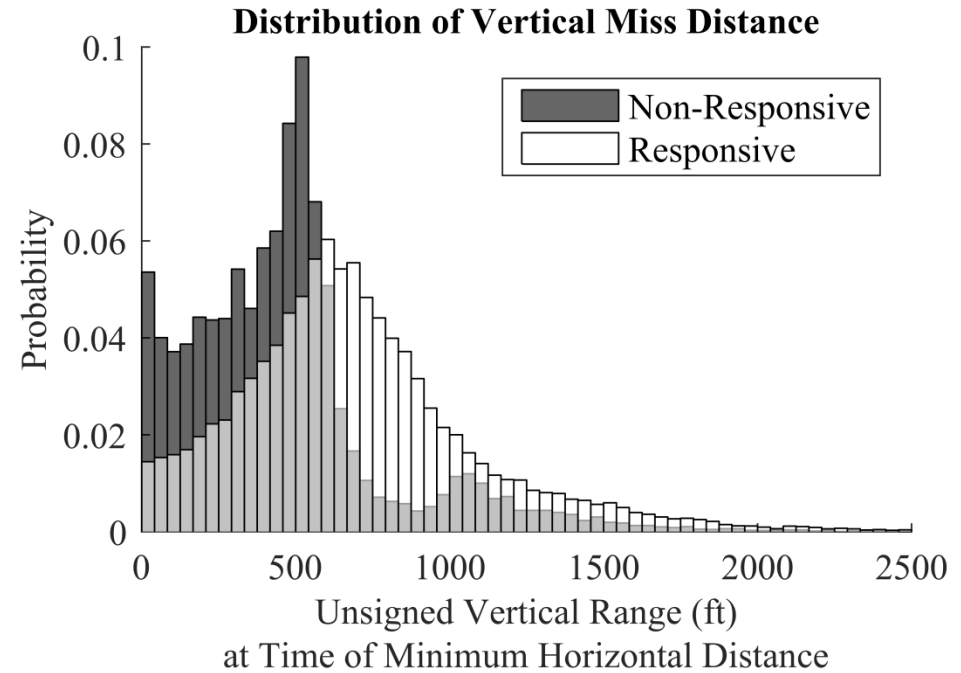
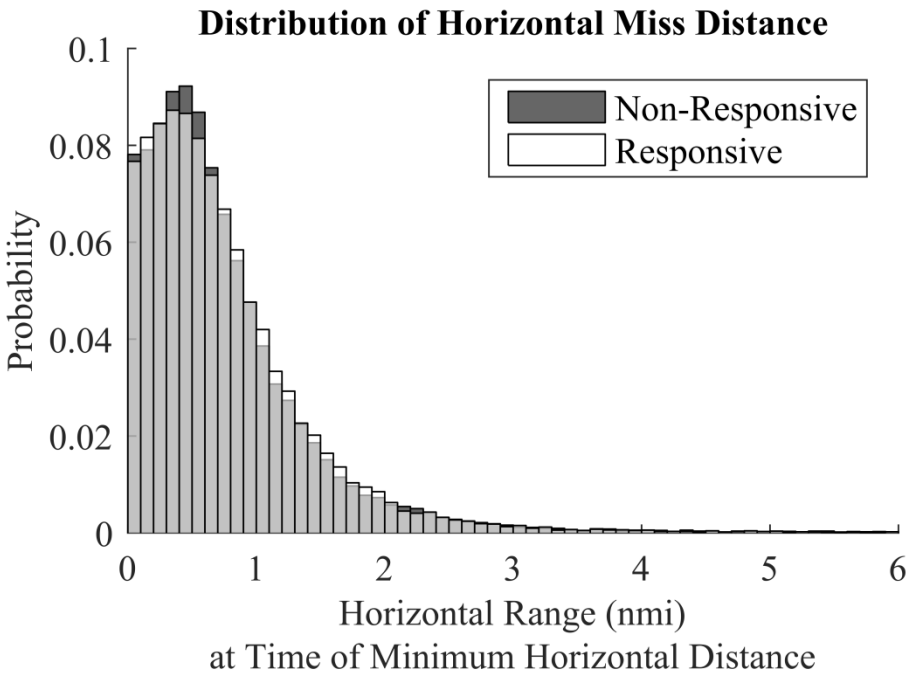
- Pilots less likely to respond to *climb* RAs than *descend* RAs

Condition	Pilot Response Probability (ρ)	Proportion of Dataset
Full Dataset	56%	100.0%
Encounters with rate reversal	29%	35.2%
Encounters with parallel approach	45%	32.0%
Encounters without parallel approach	62%	68.0%
Encounters with <i>climb</i> RAs	44%	63.5%
Encounters with <i>descend</i> RAs	77%	36.5%



Vertical and Horizontal Miss Distance

Distributions when Pilot Does or Does Not Respond to RA



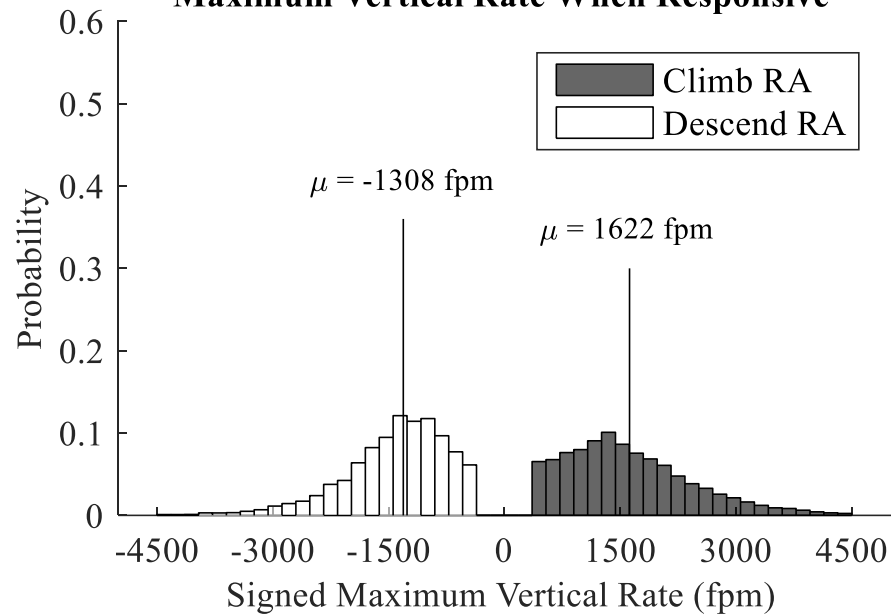
Pilot response correlates with an increase in VMD and has no effect on HMD



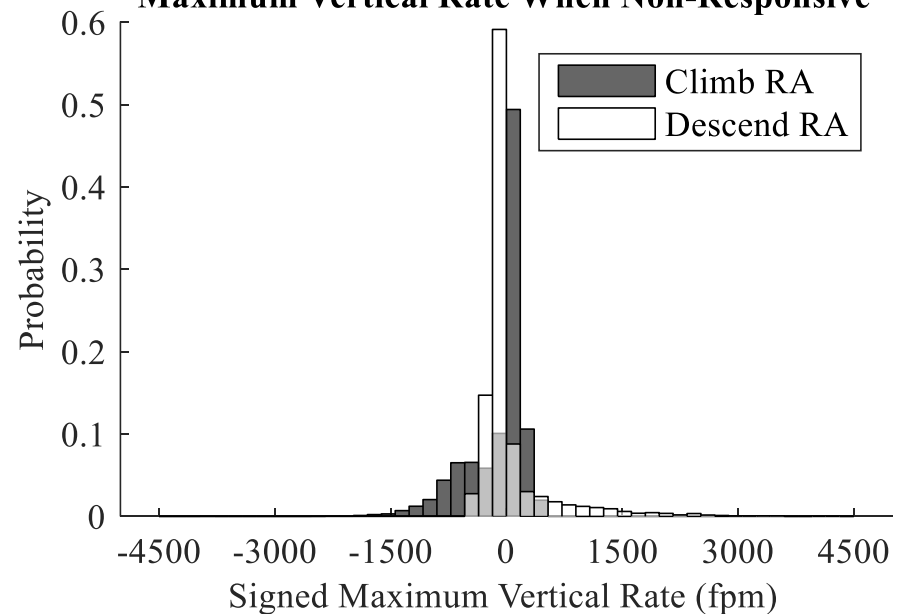
Aircraft Vertical Rate

Distributions when Pilot Does or Does Not Respond to RA

Maximum Vertical Rate When Responsive



Maximum Vertical Rate When Non-Responsive



Distributions of vertical rate strongly reflect pilot responsiveness to TCAS RAs.



Outline

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Simulation Parameters



Parameter	Aircraft 1	Aircraft 2
CAS Equipage	TCAS v7.1	TCAS v7.1 or <i>Mode S only</i>
Master/Slave Relationship	Master	Slave (when TCAS equipped)
Pilot Response Delay, Acceleration	Standard TCAS Assumptions (Initial: 5 sec, 0.25g; Subsequent: 2.5 sec, 0.35g)	
Surveillance	Standard TCAS surveillance noise models	
Encounter Set	Lincoln Laboratory Correlated Encounter Model: 3,976,080 encounters (all non-parallel approaches)	
Pilot Response Model	Four models, including Bayesian network model	



Pilot Response Models

Model	Pilot Response Probability		# of Encounter Parameters
	Climb/Descend Encounters	Other Encounters	
1. Naive 100%	100%	100%	0
2. Naive Aggregated	86%	86%	0
3. Climb/Descend Averaged	66%	100%	1: RA Type
4. Bayesian Network	Encounter-specific	100%	5: Parent Nodes

More encounter parameters incorporated

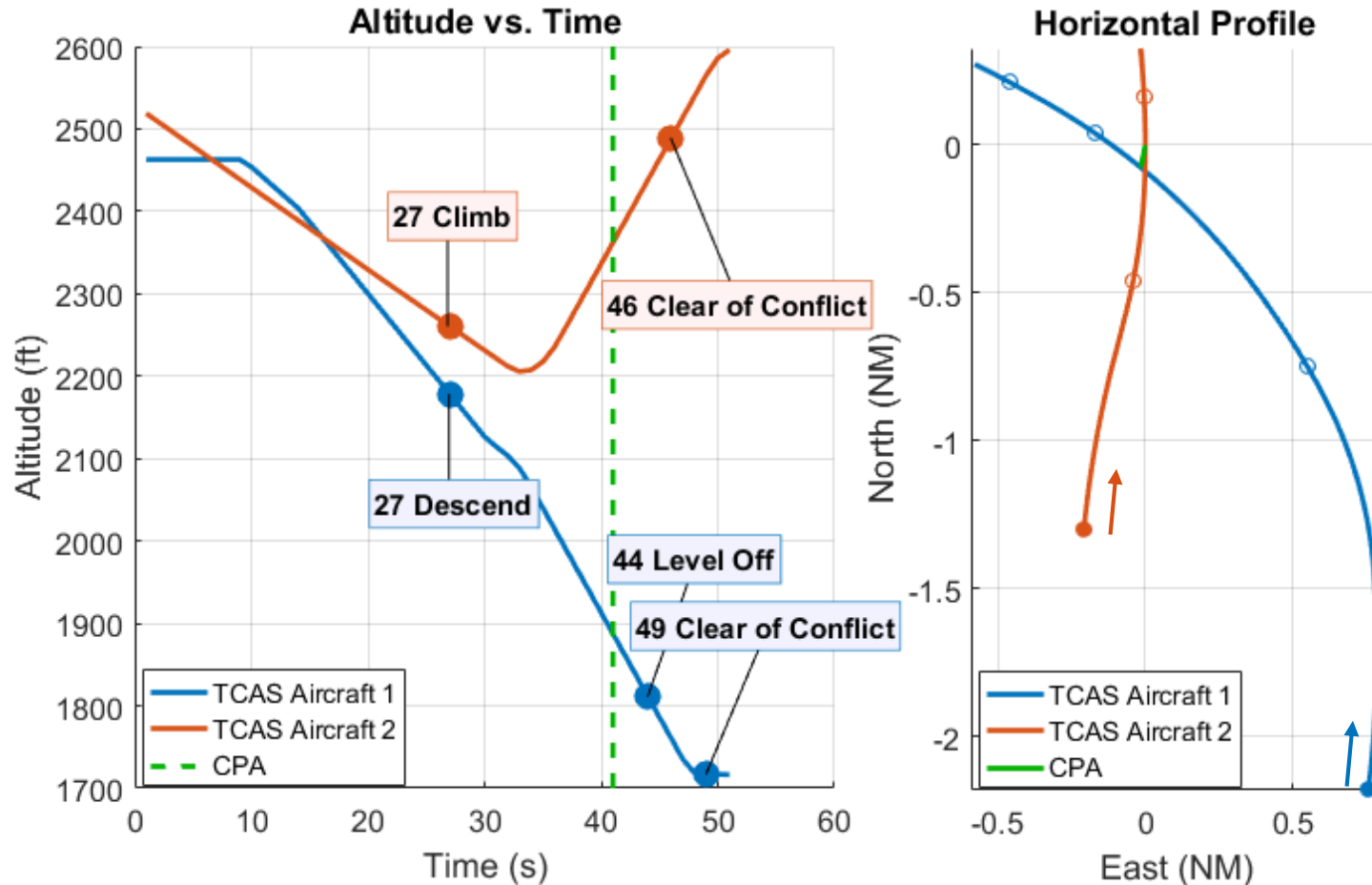


- **Four pilot response models simulated (separately)**
- **86% and 66% figures are averages of the individual encounter pilot response probabilities obtained from the Bayesian network**
 - 66% is the average response probability for *climb* and *descend* encounters only
 - 86% is a combination of 66% for *climb/descend* encounters and 100% for other encounters

Response probabilities for Models 2–4 come from the Bayesian network
These models differ in how these probabilities are averaged across encounter parameters



Example Encounter



Aircraft 1: $\rho = 99.7\%$

- **CD:** Descend RA
- **PL:** Non-parallel
- **VR:** -1000 fpm
- **GR:** 0.7 nmi
- **RR:** No rate reversal

Aircraft 2: $\rho = 21.2\%$

- **CD:** Climb RA
- **PL:** Non-parallel
- **VR:** -500 fpm
- **GR:** 0.7 nmi
- **RR:** Rate reversal

Note: VR and GR are quantized

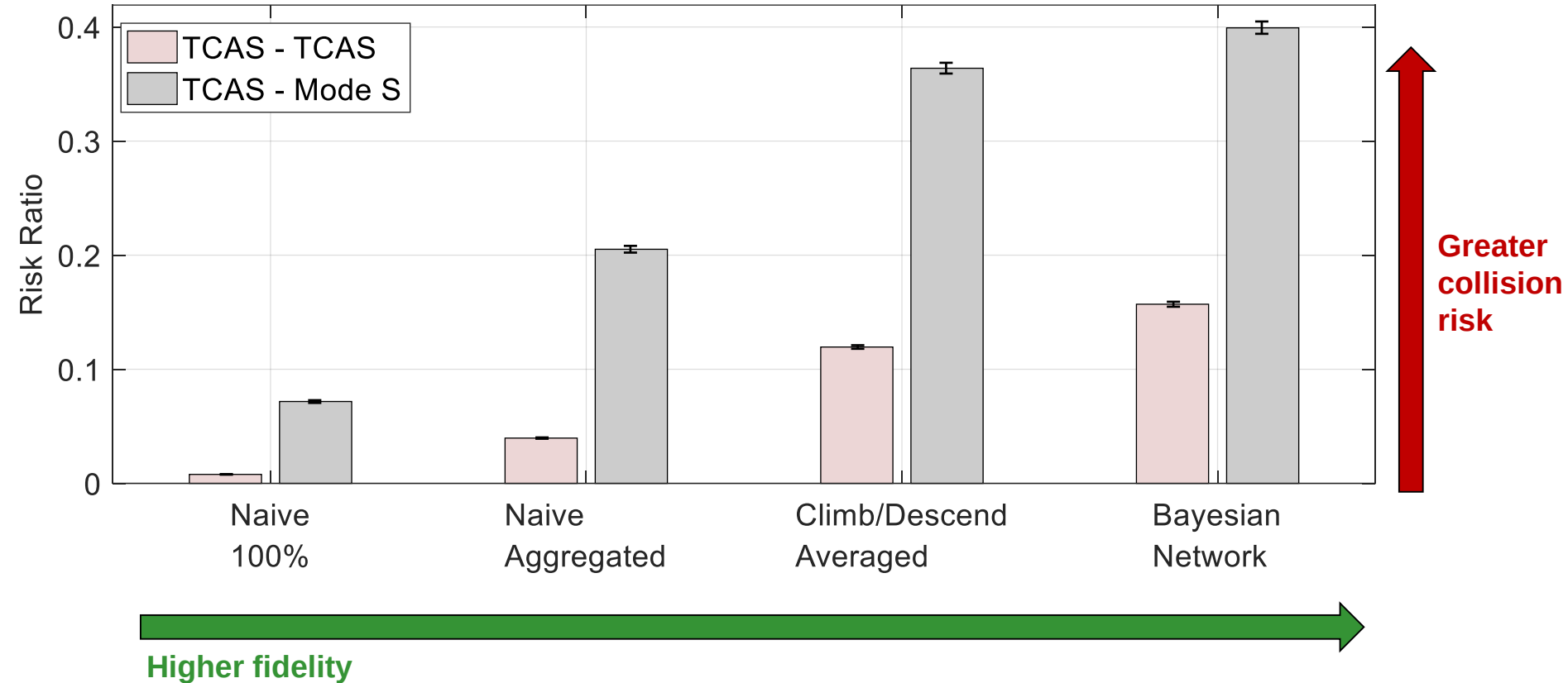
In this simulated encounter, the two TCAS aircraft receive RAs with widely diverging probabilities of response (ρ), obtained from the Bayesian network



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Evaluation of Pilot Response Models

$$\text{Risk Ratio: } \frac{P(\text{NMAC})_{\text{with TCAS}}}{P(\text{NMAC})_{\text{without TCAS}}}$$



These results suggest that higher fidelity pilot response models that are sensitive to encounter parameters can result in higher estimates of collision risk.



Impact of Bayesian Network Model

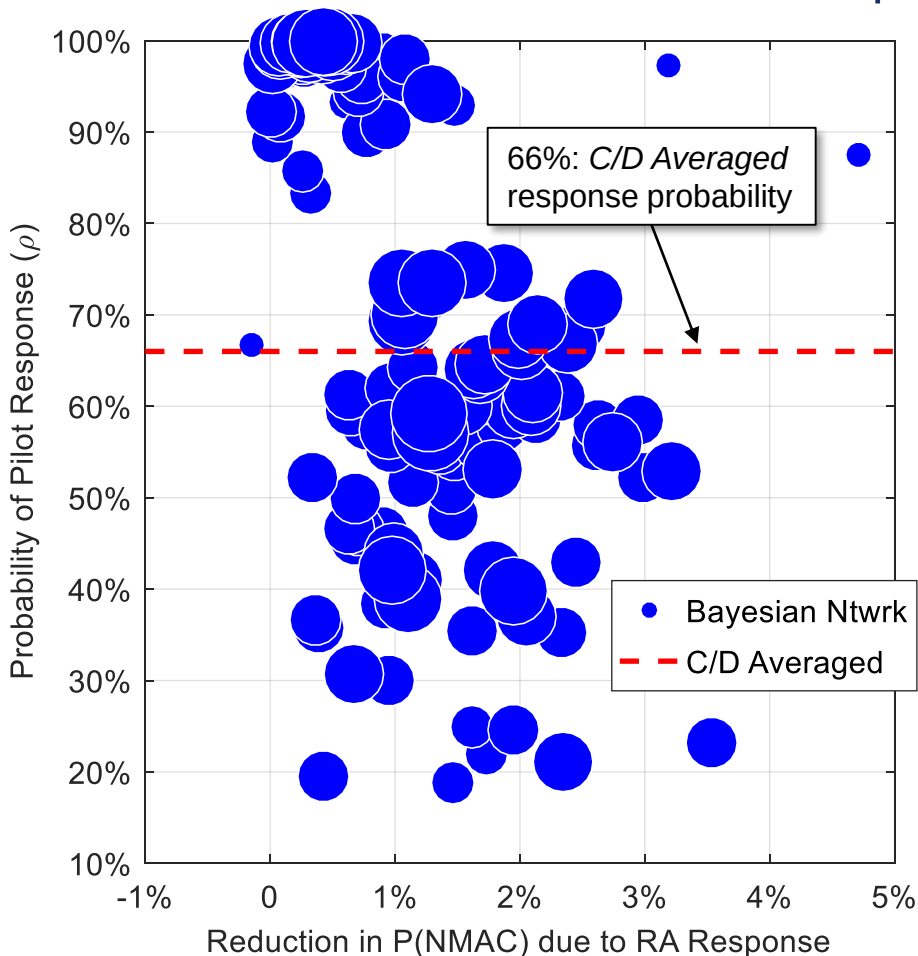
Importance of Calculating Pilot Response for Individual Encounters

- ***Bayesian Network*** model calculates probability of RA response for individual *climb/descend* encounters
- ***Climb/Descend Averaged*** model applies a single average probability of response to all *climb/descend* encounters
 - Average is based on probabilities calculated from Bayesian network
- Simulated collision risk is higher for ***Bayesian Network*** model than for ***Climb/Descend Averaged*** model
- Suggests that using an averaged probability of response results in a lower estimate of collision risk
- Suggests importance of incorporating encounter parameters in a pilot response model



Impact of Bayesian Network Model

Description of Results



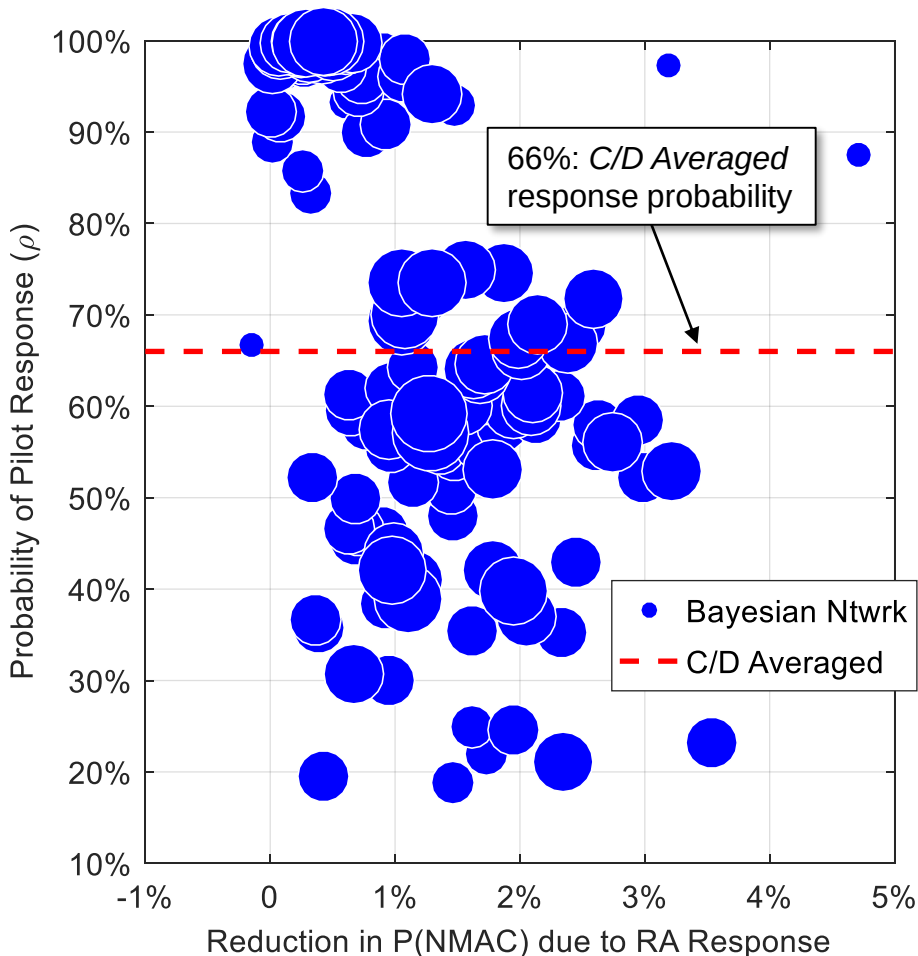
- Graph addresses *Climb/Descend Averaged* and *Bayesian Network* models
- Y-axis: probability of pilot response
- X-axis: reduction in P(NMAC) due to RA response
 - Example: if P(NMAC) is 25%, a reduction of 5% makes it 20%
 - Represents “benefit” of responding to TCAS RAs
 - Encounters with *Climb* or *Descend* RA (~20% of encounters)
 - One aircraft equipped with TCAS, intruder unequipped
- Circle size represents likelihood in simulated data
- Average P(NMAC) without RA response is 1.2%
 - Most encounters do not end in NMAC regardless of TCAS
- Observations:
 - RA response reduced P(NMAC) by <5% in >99.99% of encounters

RA response reduced P(NMAC) by <5% in the vast majority of simulated encounters



Impact of Bayesian Network Model

Discussion of Results



- **Correlation :**

- As reduction in P(NMAC) due to RA response increases, probability of pilot response decreases
- Encounter-agnostic *Climb/Descend Averaged* model overestimates pilot response probability during encounters where responding to RAs has greater effect

- **Impact:**

- Encounter-agnostic *Climb/Descend Averaged* model underestimates overall collision risk

- **Explains why *Climb/Descend Averaged* risk ratio is less than *Bayesian Network* risk ratio**

- Aggregate effect of small differences in individual encounters

Encounter-agnostic pilot response models can underestimate collision risk by overestimating probability of pilot response

Summary and Conclusions

- Created and investigated safety impact of pilot response model parameterized to encounter variables
- Bayesian network model created from TRAMS data, applied to pilot compliance with *climb* and *descend* RAs
- Encounter parameters influencing pilot response: parallel approach, rate reversal, vertical rate, RA type, ground range
- Estimates of TCAS collision risk higher with encounter-specific Bayesian model
- Safety simulations demonstrated that encounter-agnostic pilot response models can underestimate collision risk by overestimating pilot response probability. Differences quantified by this analysis



Potential Follow On Work

- Pilot response model created for this network limited by TRAMS
- Model incorporating other variables requires data source with finer resolution and more complete information than TRAMS
- Encounter parameters of interest: traffic alert timing, ATC interaction, etc.
- Model features of interest: response delay, response acceleration, level off RAs, etc.
- UAV model of response to Detect and Avoid (DAA) alerting





Thank you for your attention!

Robert Moss: robert.moss@ll.mit.edu

Ted Londner: elondner@ll.mit.edu



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Backup Slides



Minimum and Maximum Probability of Response

TABLE VII
PARENT NODE VALUES FOR MAXIMUM AND MINIMUM PROBABILITY OF
RESPONSE

	RR	PL	CD	GR	VR	ρ
Complete Dataset	False	True	Descend	0 nmi	−500 fpm	0.9998
	True	True	Climb	0 nmi	−500 fpm	0.0440
Non-Parallels	False	False	Descend	1 nmi	−500 fpm	0.9991
	True	False	Climb	0 nmi	−2000 fpm	0.1875

- **Minimum and maximum probability of response and associated parent node values**
 - Minimum probability of response (0.0440): *climb* RA while descending (rate reversal), ground range less than 1 nmi, parallel approach
 - Maximum probability of response (0.9998): *descend* RA while descending, ground range less than 1 nmi, parallel approach



Calculating Probability of NMAC

Incorporating Pilot Response Probability

- Goal: determine safety impact of pilot response model relative to other models
- Simulate encounter set, calculate $P(NMAC)$ based on pilot response probability ρ
- Equipped-Equipped (EE) and Equipped-Unequipped (EU)

EE: Simulate each encounter four times

1. AC1: respond 100%
AC2: respond 100%
 $P(NMAC)_{11}$

2. AC1: respond 100%
AC2: respond 0%
 $P(NMAC)_{10}$

3. AC1: respond 0%
AC2: respond 100%
 $P(NMAC)_{01}$

4. AC1: respond 0%
AC2: respond 0%
 $P(NMAC)_{00}$

$$P(NMAC) = \rho_1\rho_2P(NMAC)_{11} + \rho_1(1 - \rho_2)P(NMAC)_{10} + (1 - \rho_1)\rho_2P(NMAC)_{01} + (1 - \rho_1)(1 - \rho_2)P(NMAC)_{00}$$

EU: Simulate each encounter twice

1. AC1: Respond 100%
 $P(NMAC)_1$

2. AC1: Respond 0%
 $P(NMAC)_0$

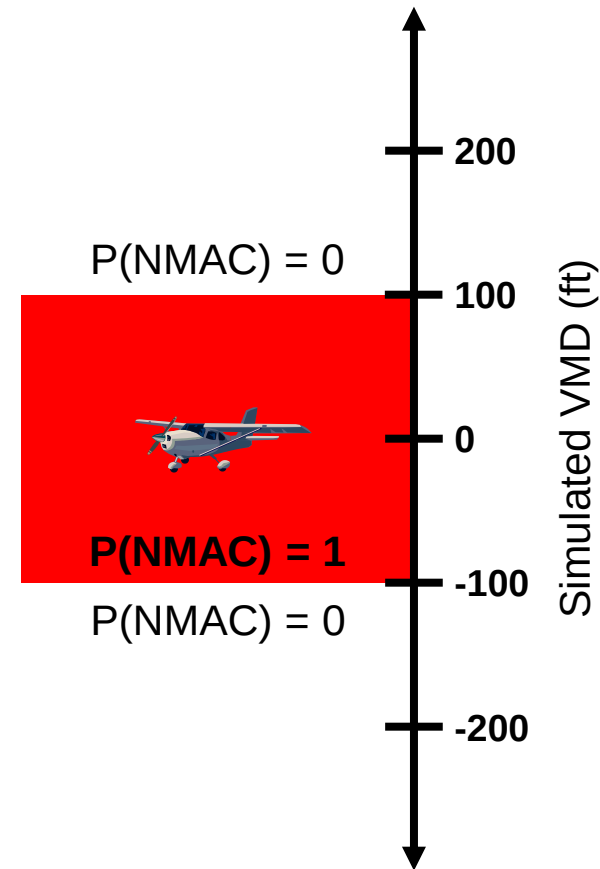
$$P(NMAC) = \rho_1P(NMAC)_1 + (1 - \rho_1)P(NMAC)_0$$



Calculating Probability of NMAC

Without Altimetry Error

- $P(\text{NMAC})$ either 0 or 1 for an individual encounter.
- $P(\text{NMAC}) = 0$ if an NMAC does not occur
- $P(\text{NMAC}) = 1$ if an NMAC does occur
- This method was not used to calculate $P(\text{NMAC})$ in this study



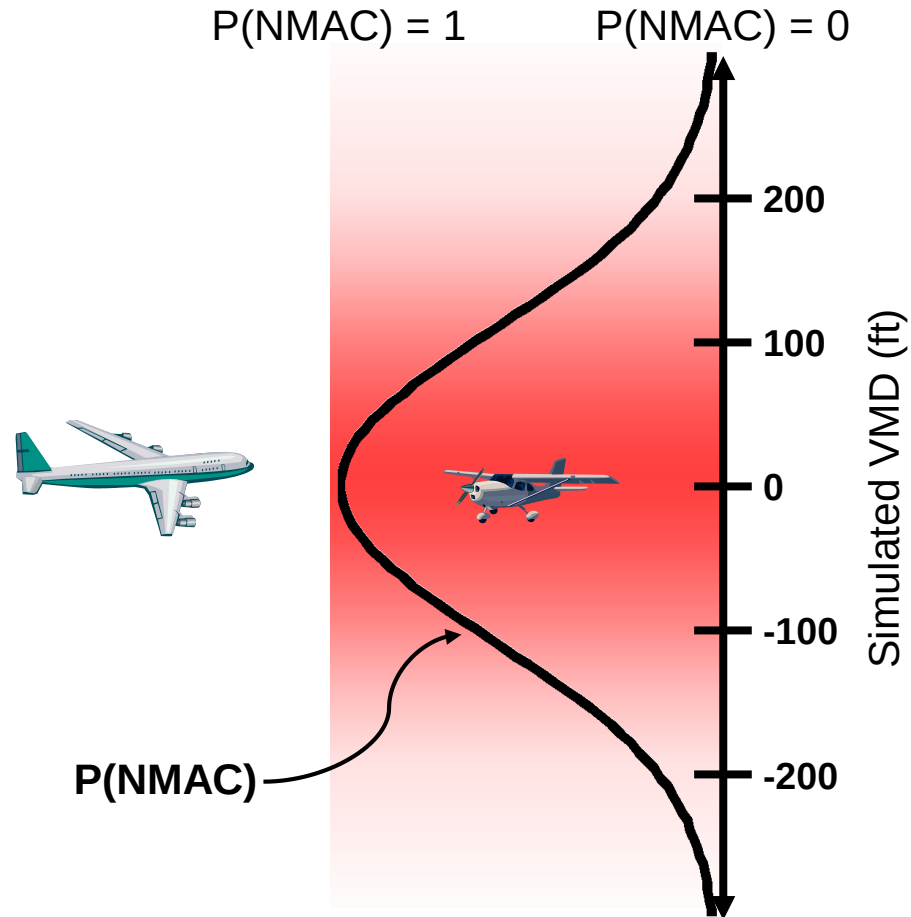
Assumes HMD < 500 feet



Calculating Probability of NMAC

With Altimetry Error

- Method used to calculate $P(\text{NMAC})$ in this study
- Function of minimum vertical separation during period when horizontal separation is less than 500 feet
 - If horizontal separation never less than 500 feet, $P(\text{NMAC}) = 0$
- ASARP's altitude error model used for ACAS X tuning
 - Altimetry error a function of aircraft CAS equipage and altitude



Assumes HMD < 500 feet
 $P(\text{NMAC})$ curve is drawn to scale

