



Encounter Modeling for Sense and Avoid Development

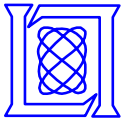
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MIT Lincoln Laboratory**

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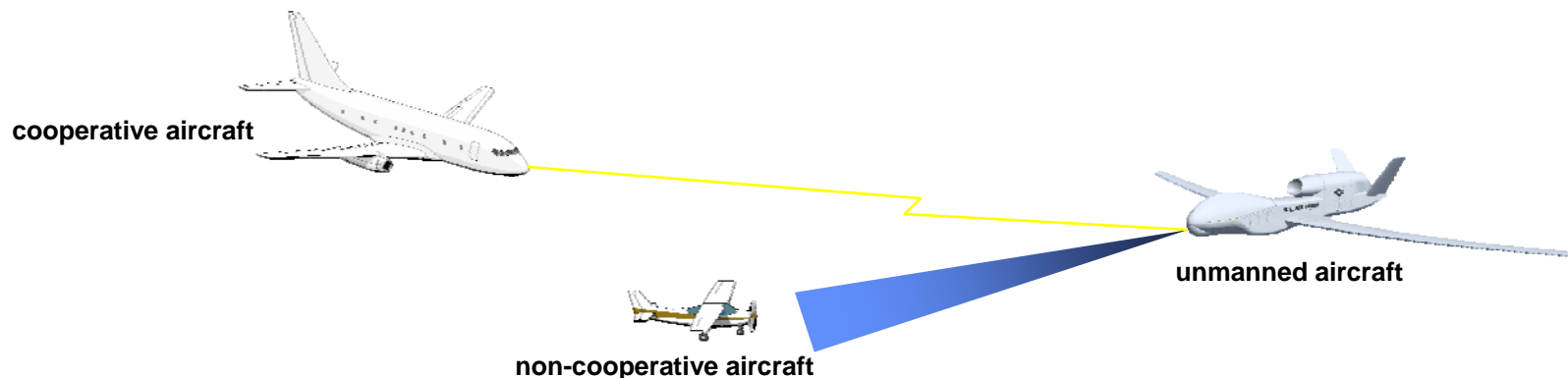
Future Needs for Collision Avoidance

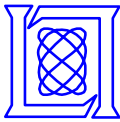
Collision avoidance systems have an important role in the future of aviation

- Integration of unmanned aircraft into the airspace will require sense and avoid capability with proven level of safety
- Next generation of air traffic control concepts will require enhancement of existing collision avoidance systems onboard manned aircraft

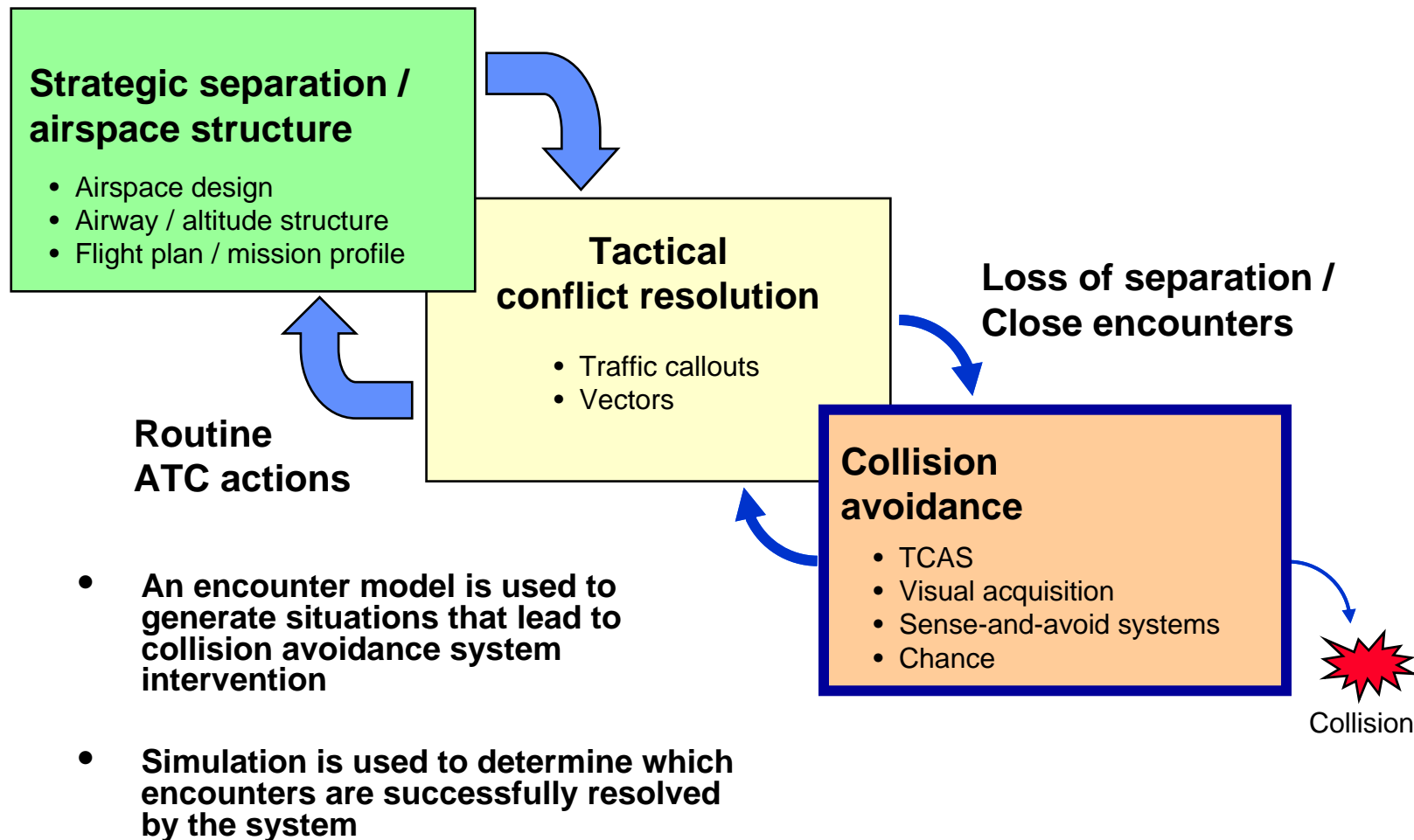
Before deployment of new systems, rigorous safety analysis is required

- Determine required surveillance performance and procedures
- Evaluation of performance through flight test and simulation
- Assessment of interoperability with existing systems

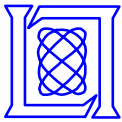




Collision Avoidance Chain

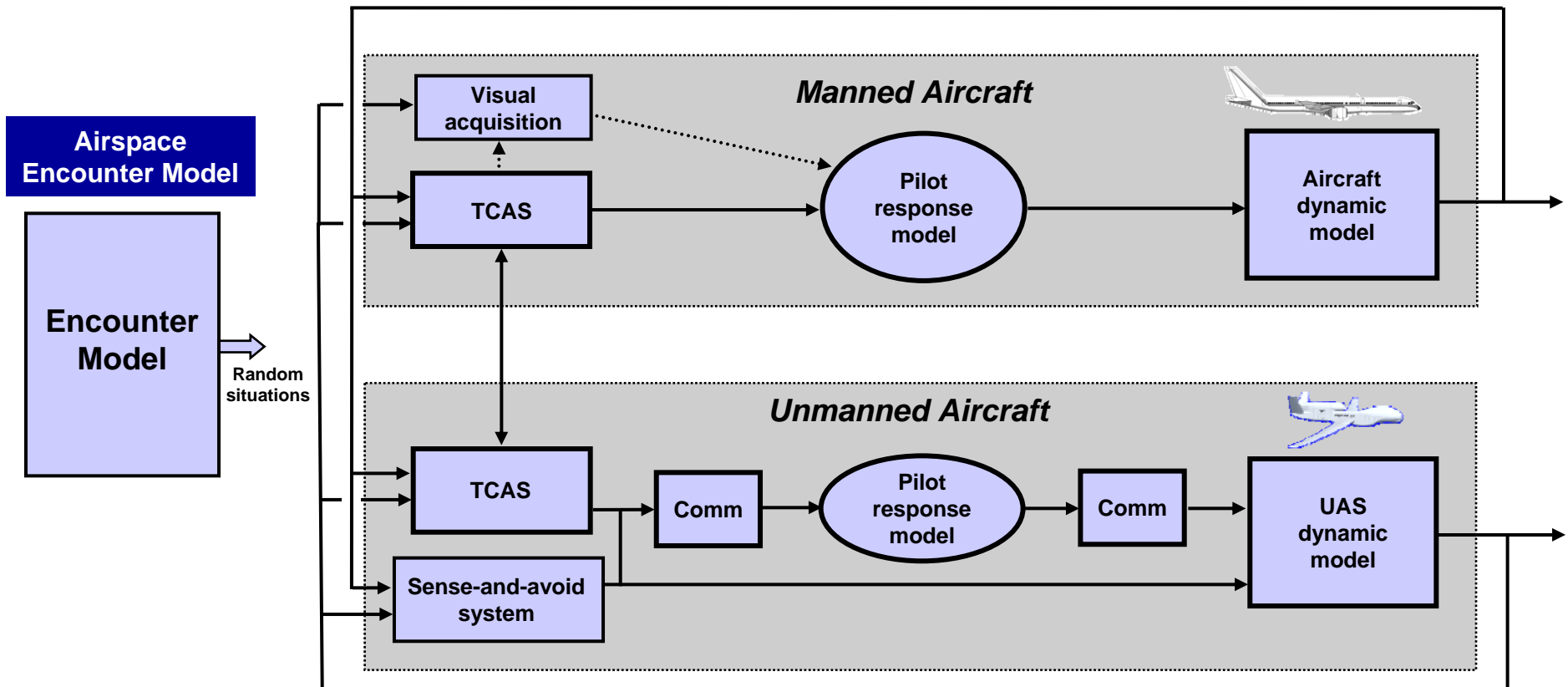


TCAS = Traffic Alert and Collision Avoidance System



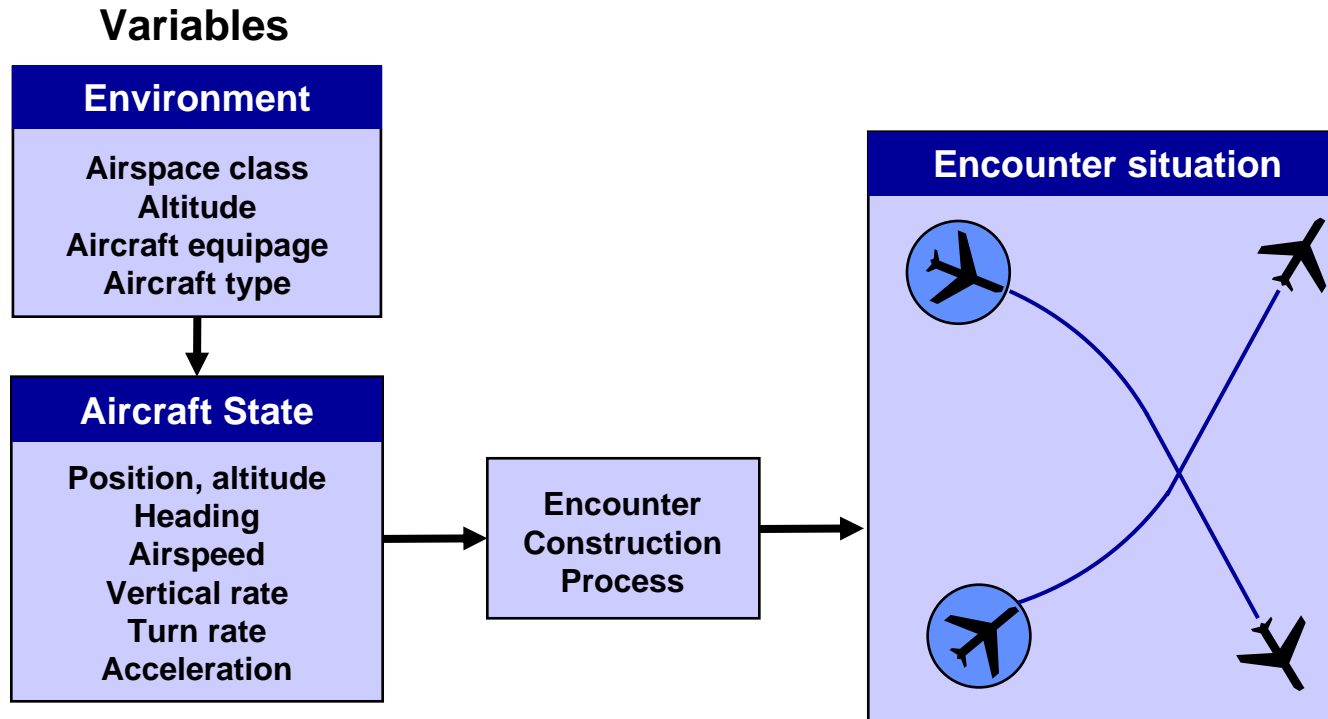
Monte Carlo Simulation Framework

Dynamic Simulation Model



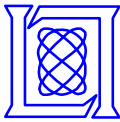


Encounter Model Components

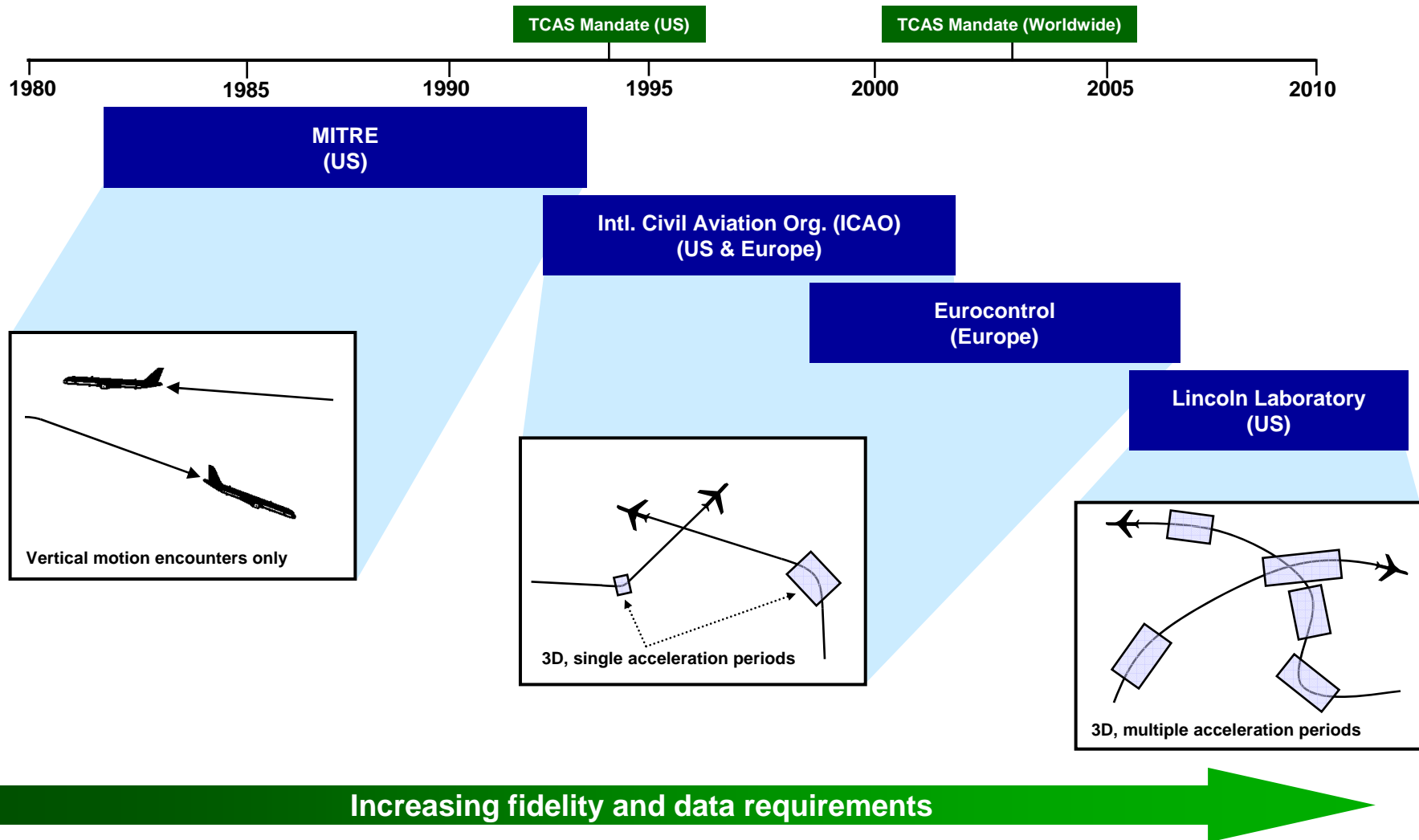


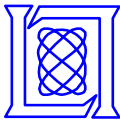
- **Challenges**
 - Limited observed data to build model
 - Choosing the variables defining the model
 - Identifying relationships between variables

Validity of analysis depends on validity of encounter model



Encounter Modeling Timeline





Encounter Model Categories

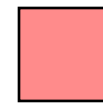


Aircraft of interest



Intruder aircraft

	Discrete code	1200/VFR
Discrete code	Correlated (cooperative)	Correlated (cooperative)
1200/VFR	Correlated (cooperative)	Uncorrelated 1200-code (non-cooperative surrogate)
Non-cooperative Conventional	Uncorrelated 1200-code (non-cooperative surrogate)	Uncorrelated 1200-code (non-cooperative surrogate)
Non-cooperative Unconventional	Uncorrelated (unconventional aircraft)	Uncorrelated (unconventional aircraft)



Correlated (cooperative)

- Existing U.S. model needs to be updated, does not capture RVSM
- Assumes ATC involvement
- Funded by FAA



Uncorrelated 1200-code (non-cooperative surrogate)

- First model to capture encounters between VFR aircraft
- Assumes no ATC involvement
- Funded by Air Force



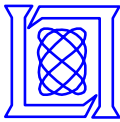
Uncorrelated (unconventional aircraft)

- Models balloons, gliders, ultralights
- Assumes no ATC involvement
- Funded by DHS



Outline

- Introduction
- • **Encounter Model Structure**
- Data processing
- Status and Applications
- Summary



Markov Models

- Well-studied category of dynamic model that fits many natural processes (Markov, 1906)
- Next state is determined probabilistically from the current state
- Can be constructed from observed data

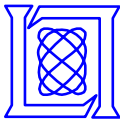
State at $t + 1$

	S1	S2	S3	S4	...
S1	P11	P12	P13	P14	...
S2	P21	P22	P23	P24	...
S3	P31	P32	P33	P34	...
S4	P41	P42	P43	P44	...
...

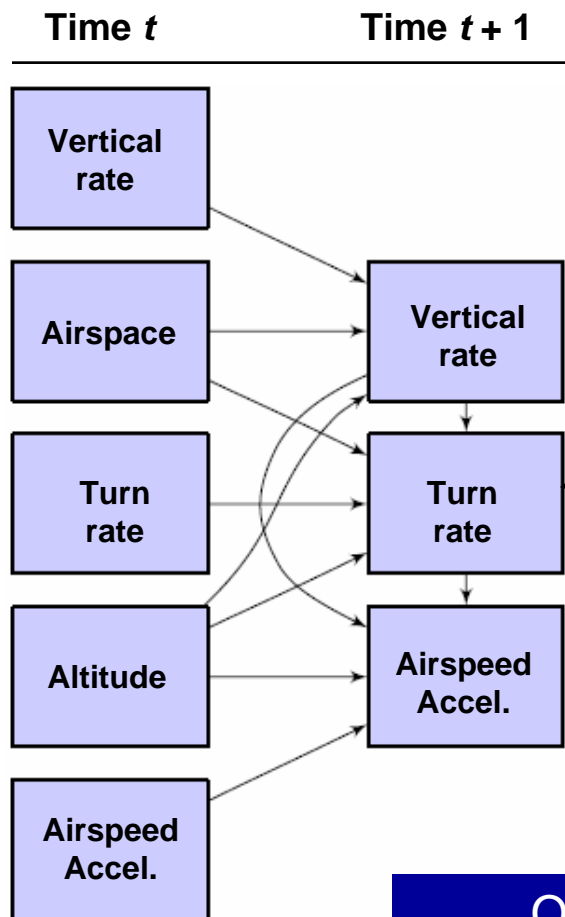
State at t

Uncontrolled airspace
Altitude 1200 ft
Vertical rate 0 ft/min
Turn rate 0 deg/s
Acceleration 0 kt/s
Airspeed 100 kt

A complete state transition matrix has 983 million parameters, making this approach impractical



Dynamic Bayesian Networks



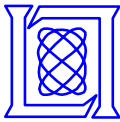
Dynamic Bayesian networks compactly represent Markov models (Dean & Kanazawa, 1989; Murphy, 2002)

Conditional Probability Table
 $P(\text{Turn}(t+1) \mid \text{Turn}(t), \text{Vertical}(t+1), \text{Airspace}(t), \text{Alt}(t))$

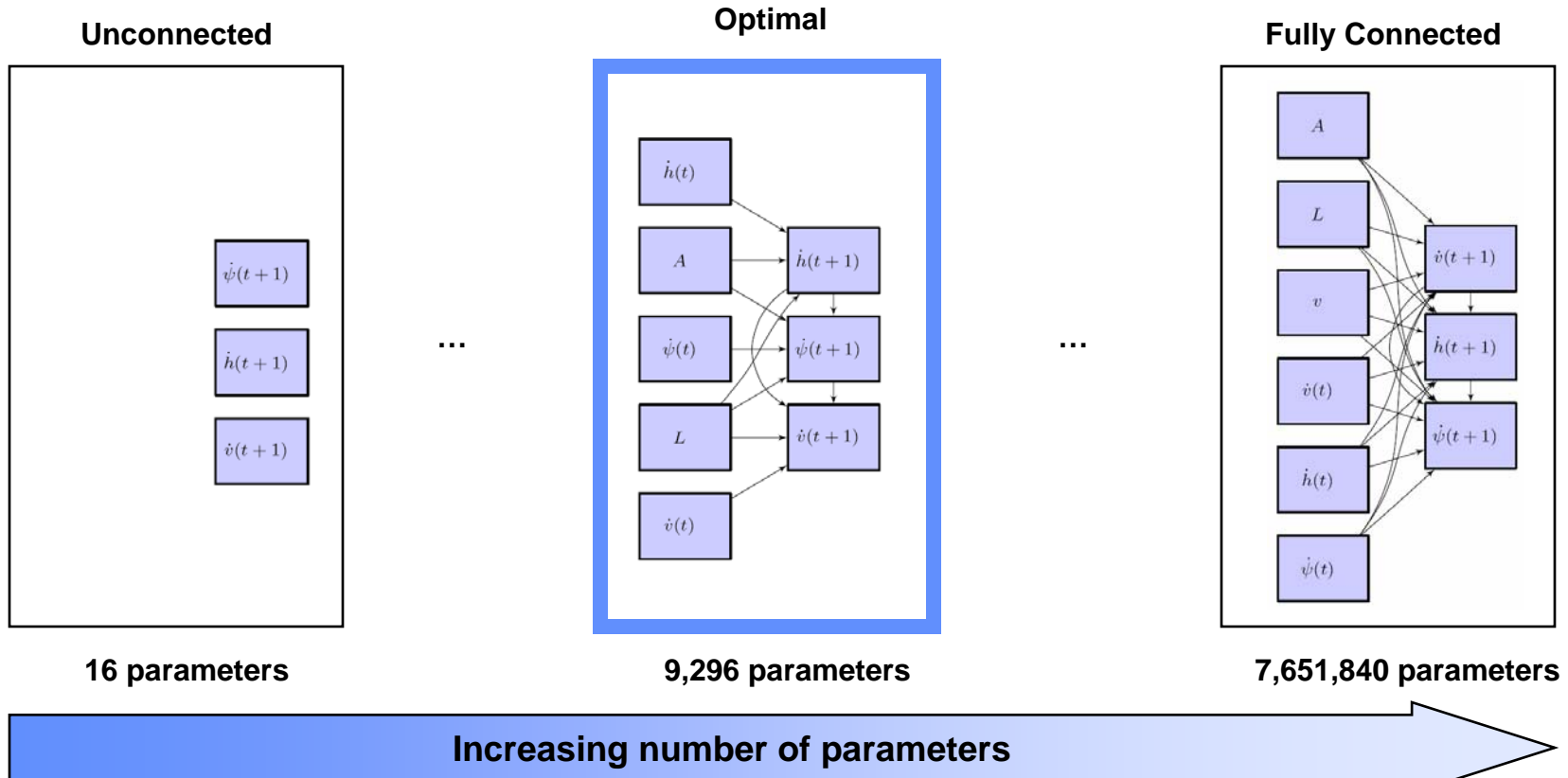
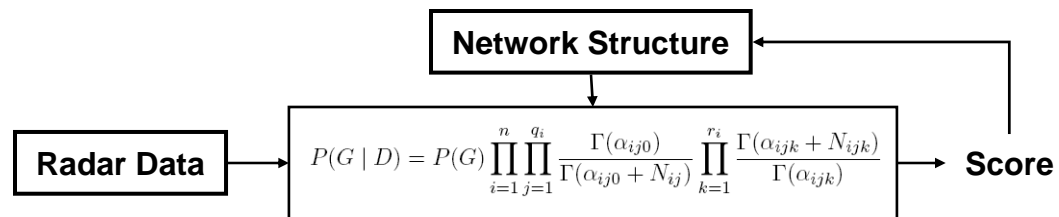
A	L	$\psi(t)$	$\hat{h}(t+1)$	$\psi(t+1)$			
				[-8, -6]	[-6, -4.5]	[-4.5, -1.5]	[-1.5, 1.5]
B	[3000, ∞]	[-8, -6]	[-250, 250]	5346	306	0	0
C	[3000, ∞]	[-8, -6]	[-250, 250]	90	7	0	0
D	[3000, ∞]	[-8, -6]	[-250, 250]	0	0	0	0
O	[3000, ∞]	[-8, -6]	[-250, 250]	49439	2562	0	0
B	[0, 1200]	[-6, -4.5]	[-250, 250]	86	1268	123	0
C	[0, 1200]	[-6, -4.5]	[-250, 250]	306	4440	399	0
D	[0, 1200]	[-6, -4.5]	[-250, 250]	3903	99413	7637	0
O	[0, 1200]	[-6, -4.5]	[-250, 250]	10139	244892	19790	0
B	[1200, 3000]	[-6, -4.5]	[-250, 250]	35	806	79	0
C	[1200, 3000]	[-6, -4.5]	[-250, 250]	50	1782	140	0
D	[1200, 3000]	[-6, -4.5]	[-250, 250]	538	12316	1113	0
O	[1200, 3000]	[-6, -4.5]	[-250, 250]	4457	106791	9795	0
B	[3000, ∞]	[-6, -4.5]	[-250, 250]	279	4657	597	0
C	[3000, ∞]	[-6, -4.5]	[-250, 250]	7	87	11	0

...

Only 9,296 independent parameters required
 (0.0009% of what exhaustive approach requires)



Bayesian Network Structure Learning





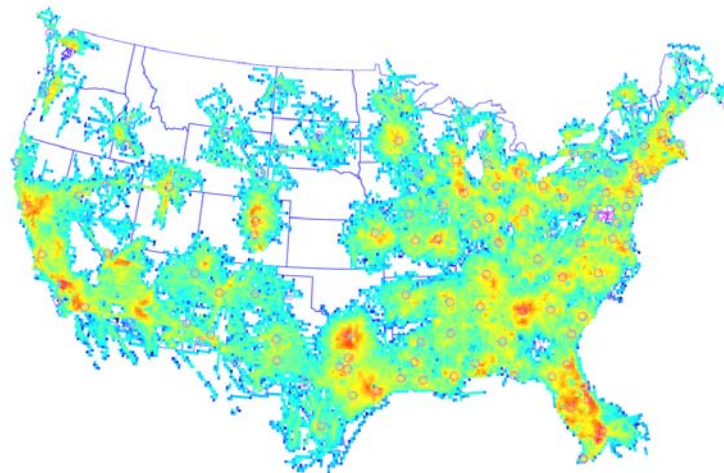
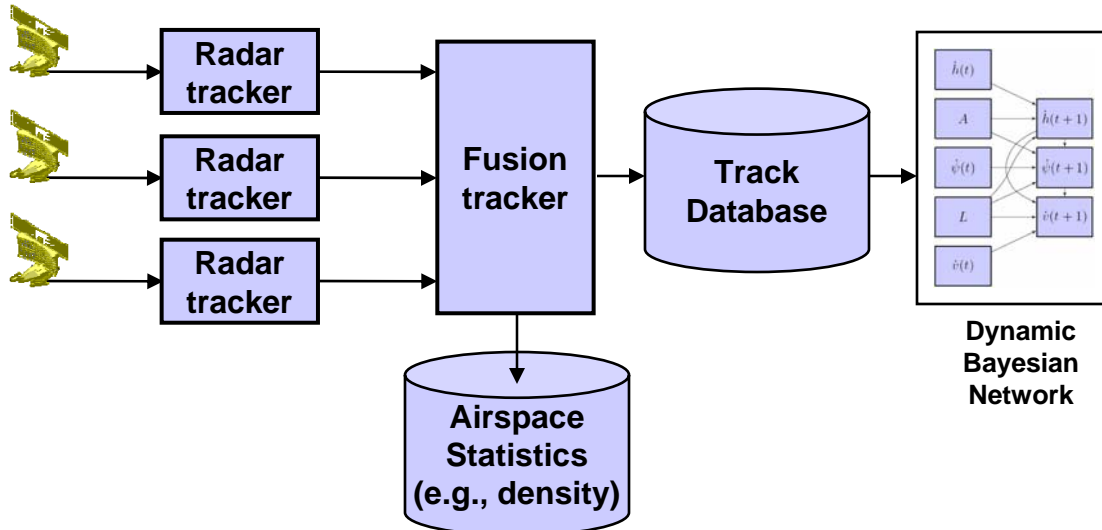
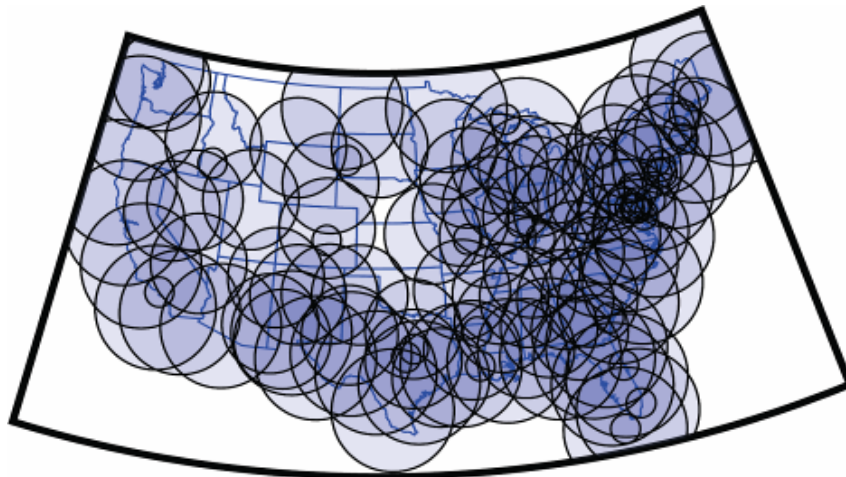
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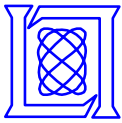


Radar Feed Overview

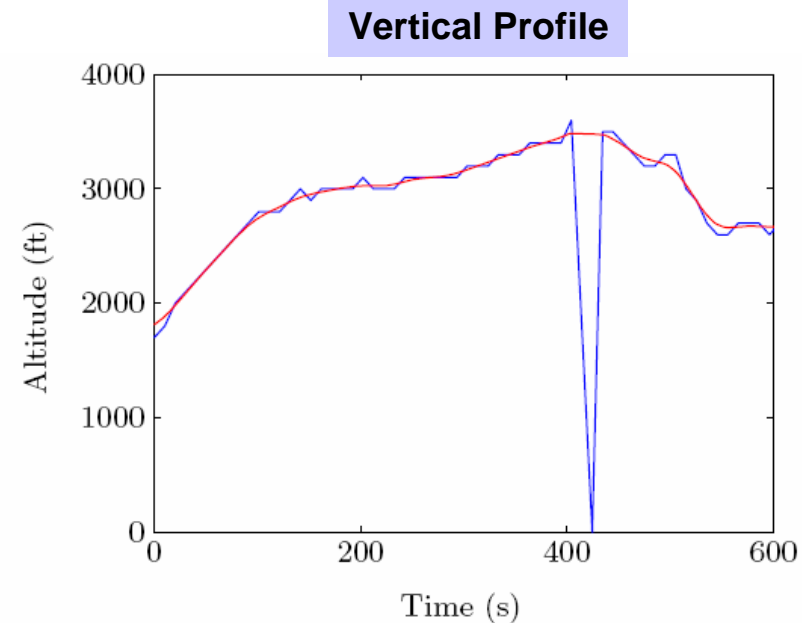
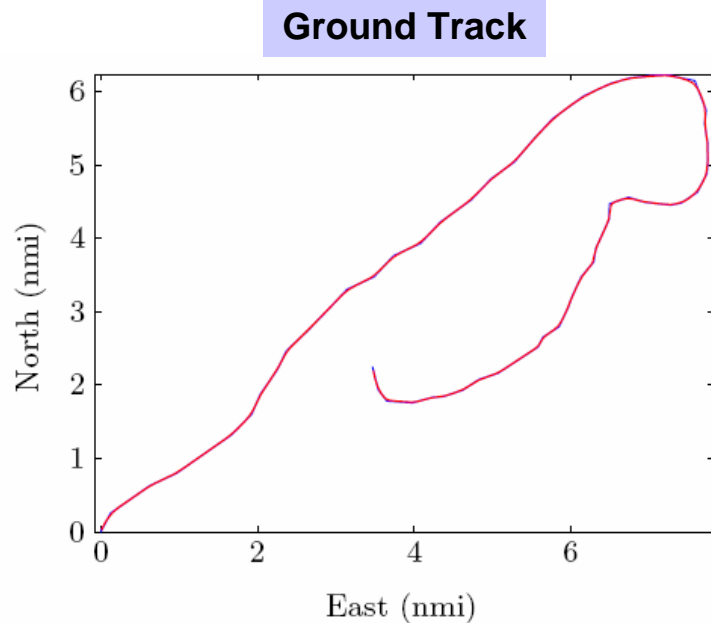
- Data gathered at Eastern / Western Air Defense Sectors, transmitted to Hill AFB, then to Lincoln
- Raw sensor data
 - 121 (reliable) sensors
 - 8 radar types (including long-range ARSR-4, short-range ASR-8-9-11)
 - ~ 10 GB / day



VFR Traffic Density



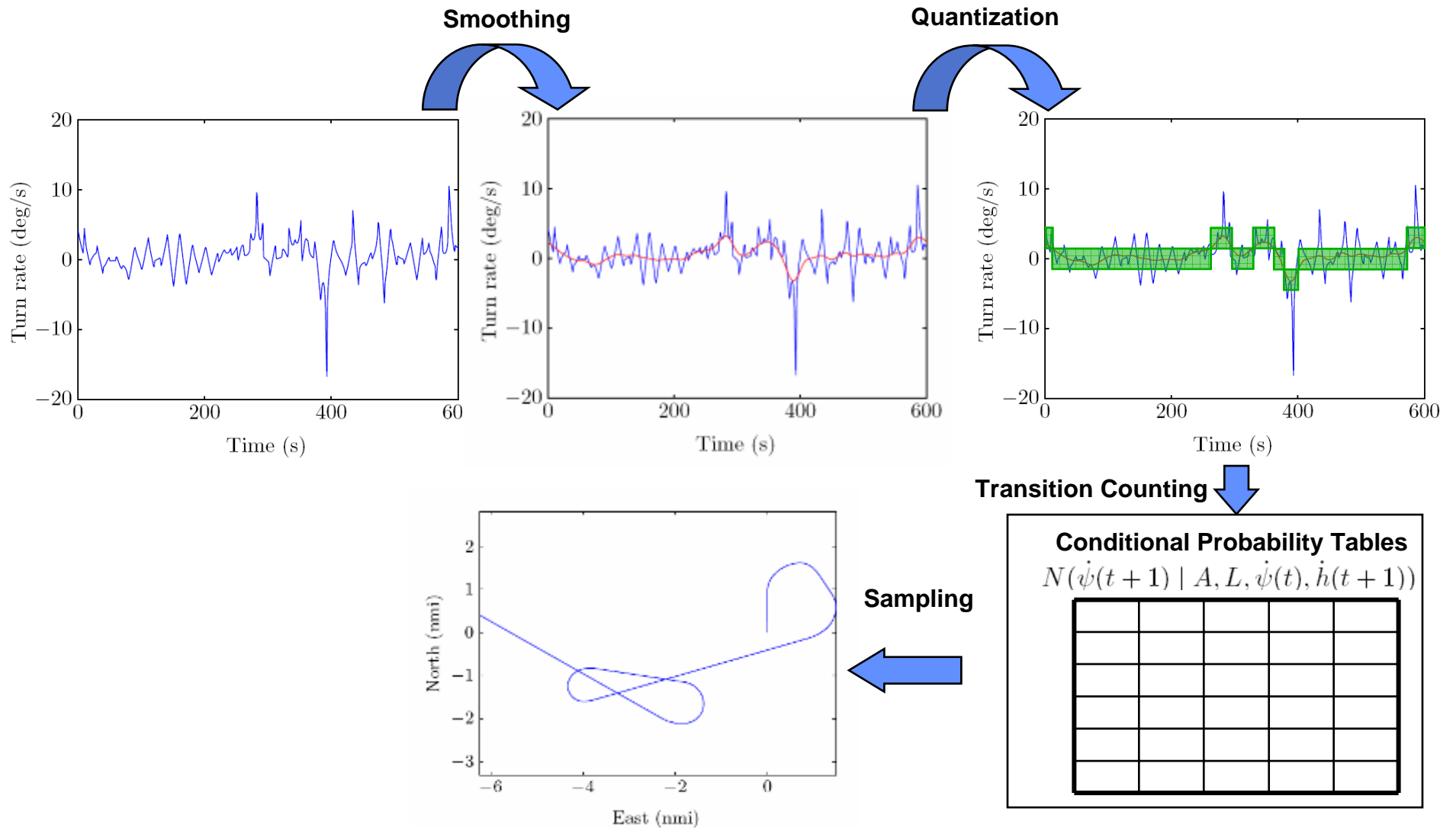
Outlier Detection, Smoothing, and Interpolation



- **Outlier Detection**
 - Remove points and altitude reports from consideration when there are excessive vertical rates or airspeeds
- **Smoothing**
 - Locally-weighted smoothing function removes noise
- **Interpolation**
 - Interpolate to 1 second intervals using piecewise cubic functions



Feature Extraction and Sampling





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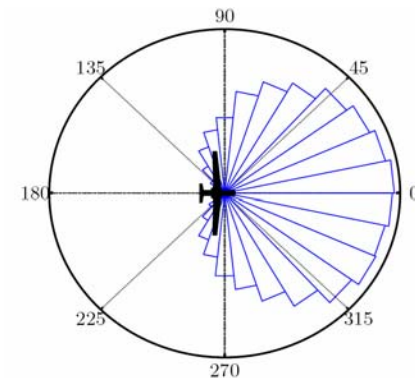
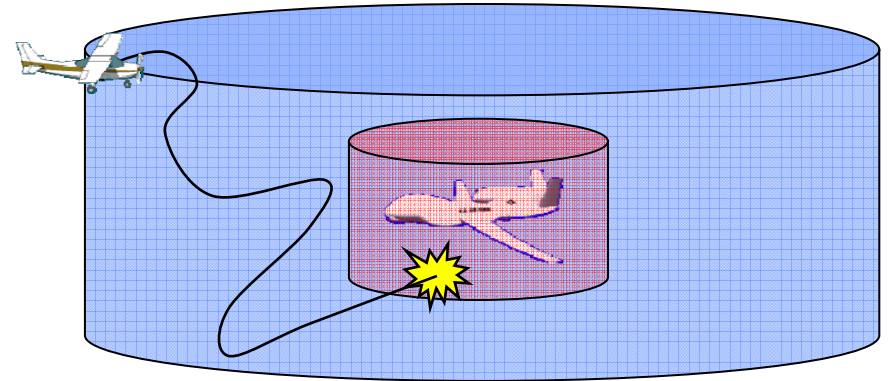
Status and Applications

- **Models under development**
 - Final models based on 9-12 months of national radar data
 - Final models to be delivered to the community in September
 - Validation by comparing statistics of generated encounters against observed data
 - Vetting the model with RTCA SC-147, interacting with SC-203, and plan to work with SC-218
- **Applications**
 - Sensor design trade studies
 - Evaluation of Northrop Grumman sense and avoid system for Global Hawk
 - Analysis of TCAS for FAA
 - Development of advanced collision avoidance algorithms



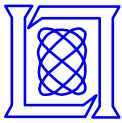
Example Parametric Analysis of UAV Sensors

- **Components**
 - **Own aircraft**
Global Hawk model based on radar tracks and performance characteristics
 - **Intruder aircraft**
VFR model based on 30 million 1200-code reports
 - **Sensor model**
- **Simulation**
 - **Intruder randomly initialized on encounter cylinder**
 - **Uncorrelated encounter model used to propagate intruder**



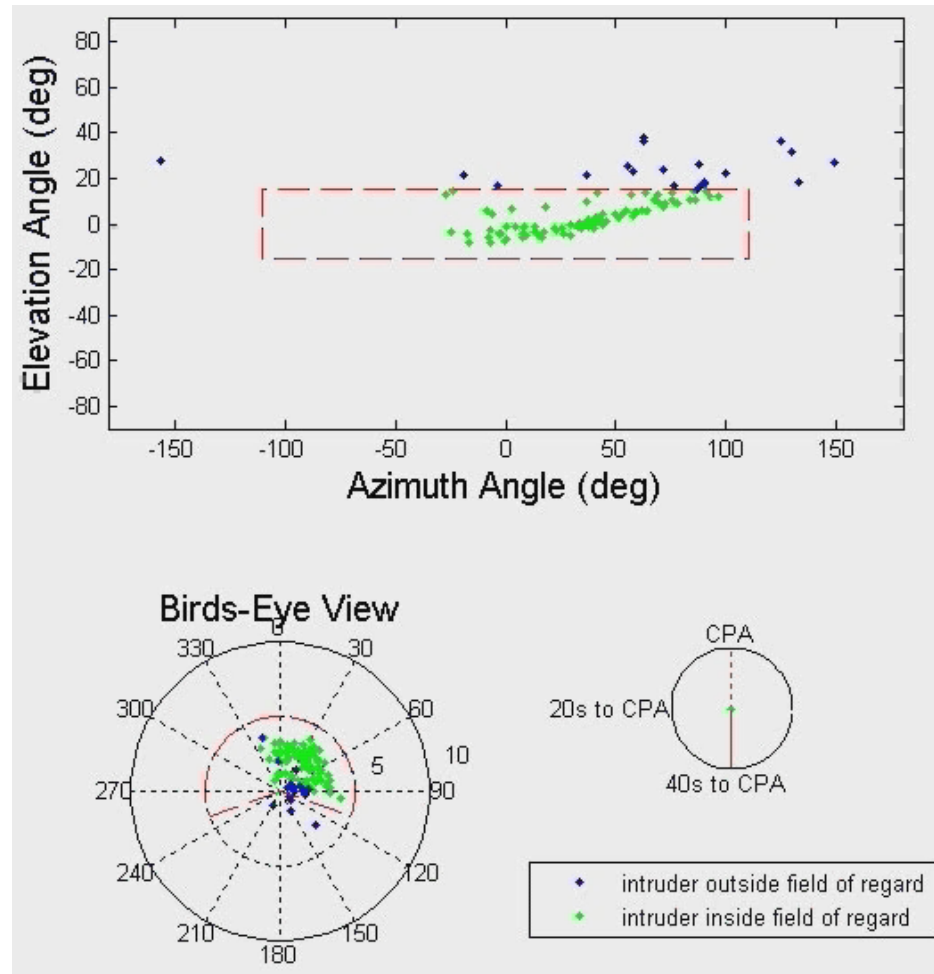
Approach angle distribution

Run 1 million encounters in parallel computing environment to provide sufficient data



Overlay of Intruder Positions Relative to Sensor Field of View

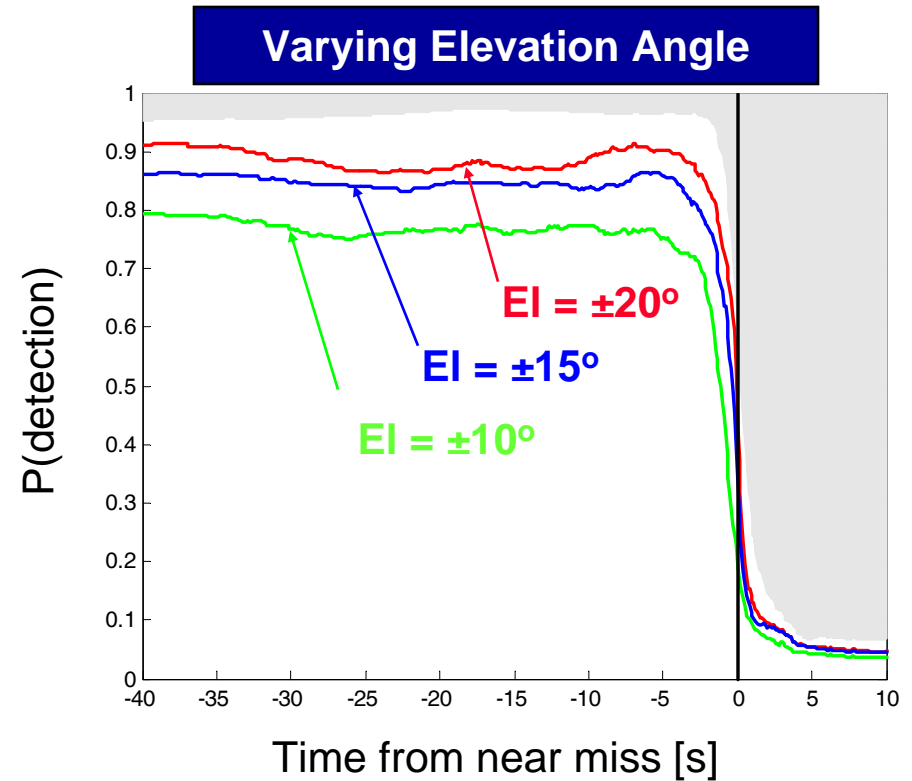
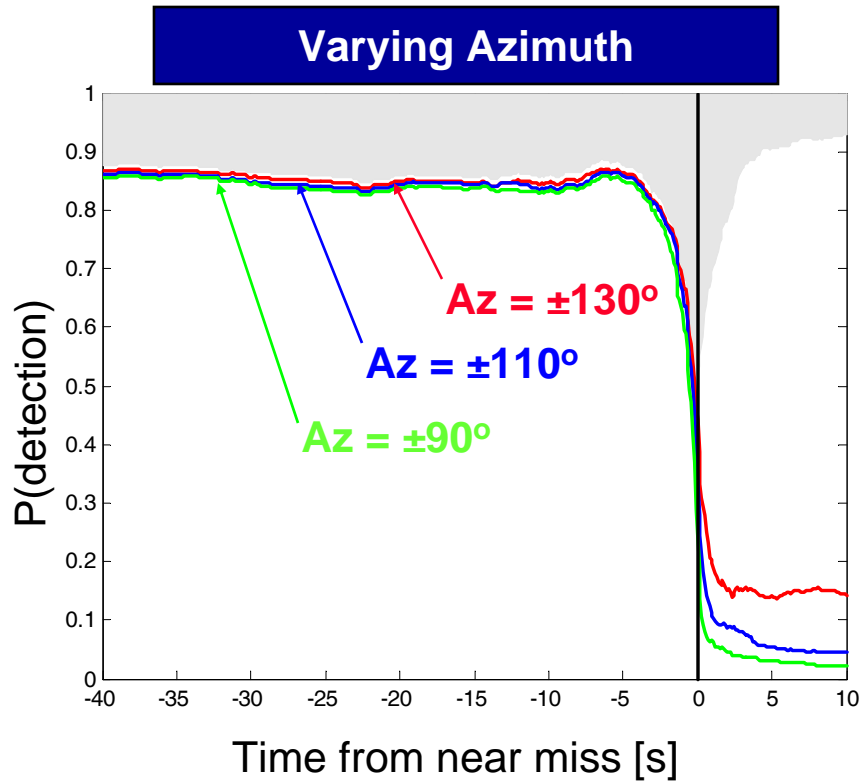
$\pm 110^\circ \times 15^\circ$ FOV
simple 5 NM detection range



- Global Hawk climbing turn departure procedure
- 100 NMAC-causing VFR intruders



Effect of Changing Azimuth Angle



- **Global Hawk intruders are concentrated towards 0° bearing**
 - Distribution of intruders is a function of own aircraft **airspeed**
- **Many intruders are above the FOV for the climb out radar profile**
 - Global Hawk is flying with a **bank angle** causing the FOV to dip



Summary

- **Encounter models are critical to collision avoidance safety analysis**
 - Must be representative of actual airspace
 - Existing models are out of date and do not reflect important characteristics of encounters
- **Dynamic Bayesian networks produce realistic models of encounters**
 - Compactly represent Markov models, reducing number of parameters
 - Statistical methods used to optimize model complexity based on ~1 year of National observed data
- **Status**
 - Models to be completed in September, delivered to community
 - Serves as National resource to support system development and certification