Experiences from Modeling and Exploiting Data in Air Traffic Control

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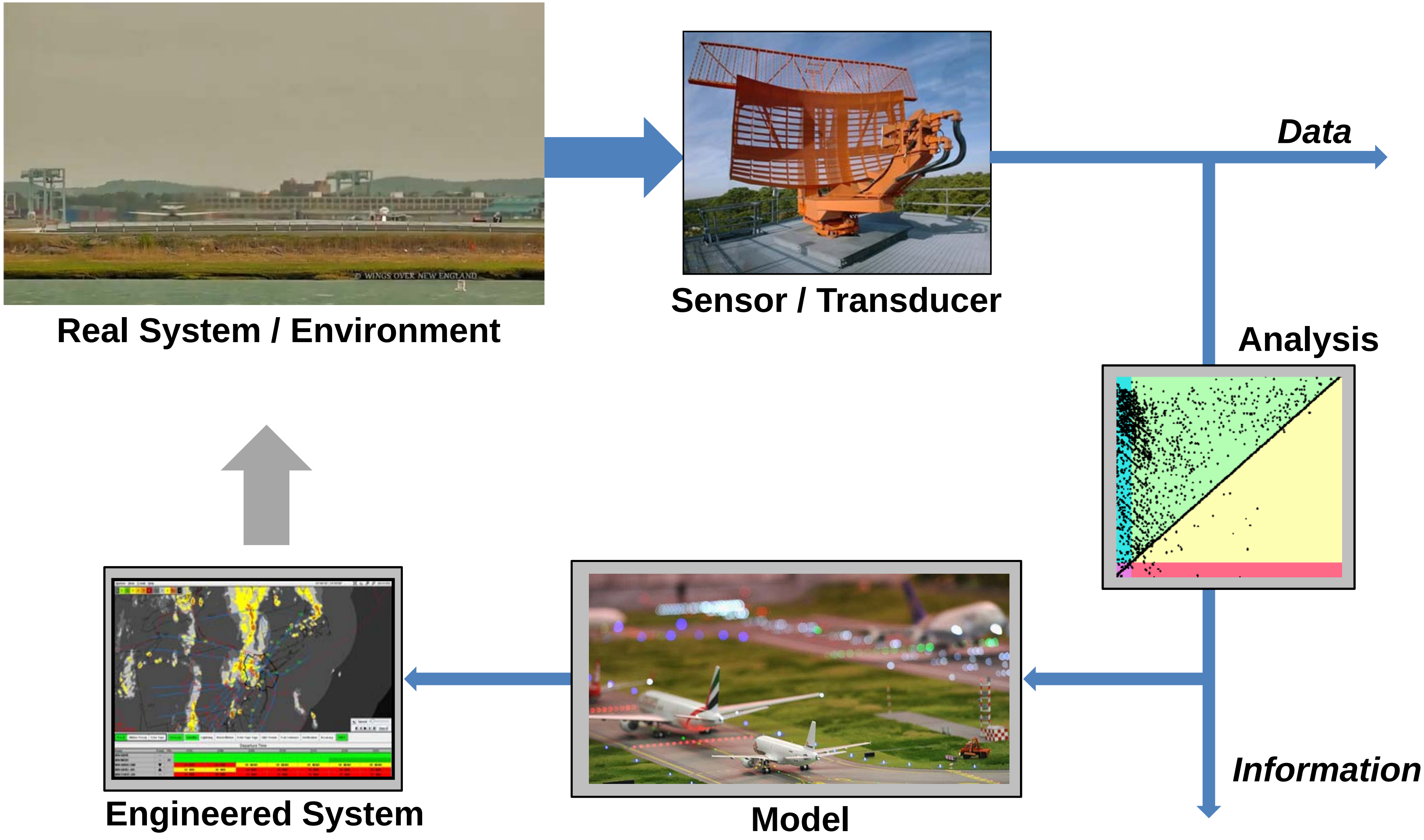
CIDU 2012: Intelligent Data Understanding

Bringing Data and Models Together



Real System / Environment

Sensor / Transducer

Data

Analysis

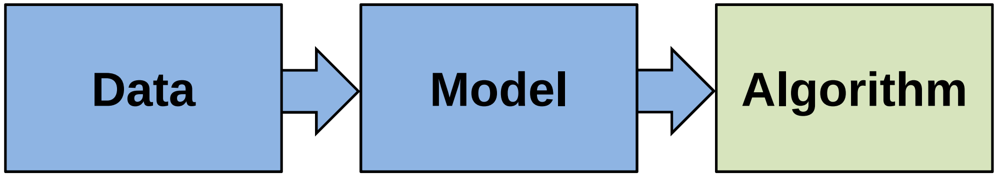
Information

Model

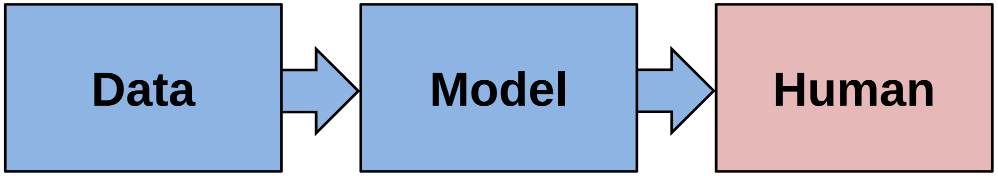
Engineered System

Two Vignettes

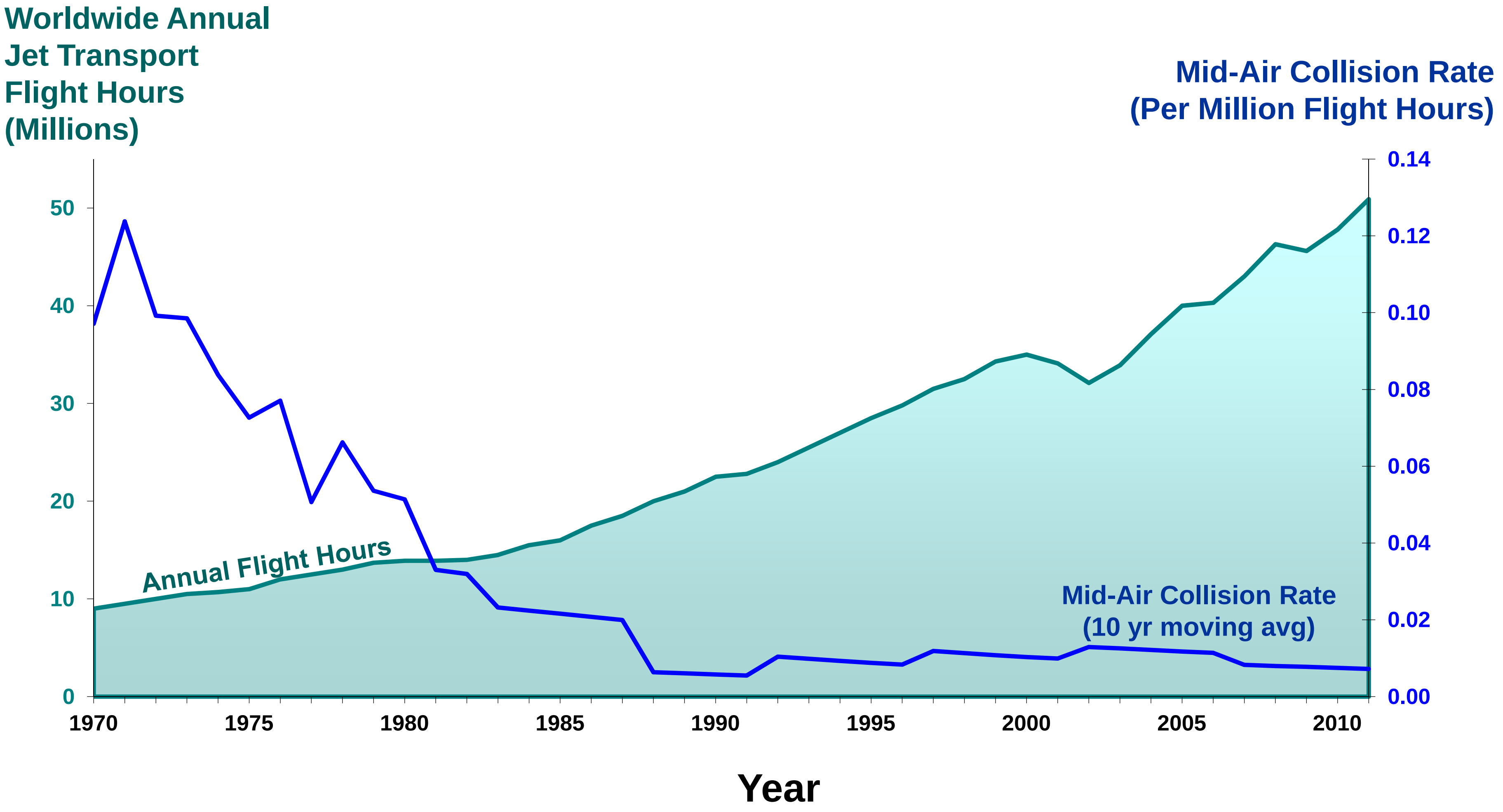
→ 1: Collision avoidance



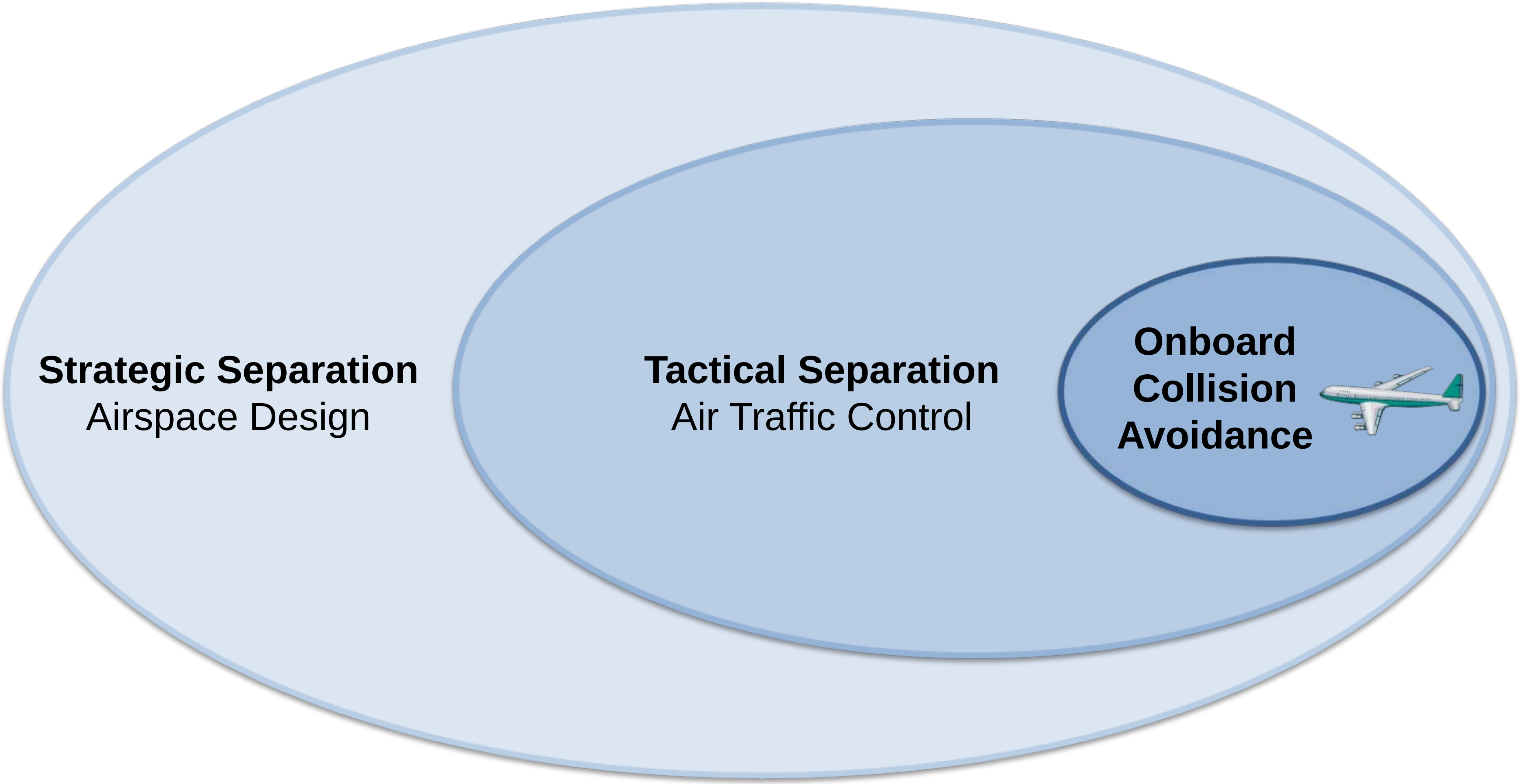
2: Airport departure management



Annual Flight Hours and Collision Rate



Collision Prevention Layers

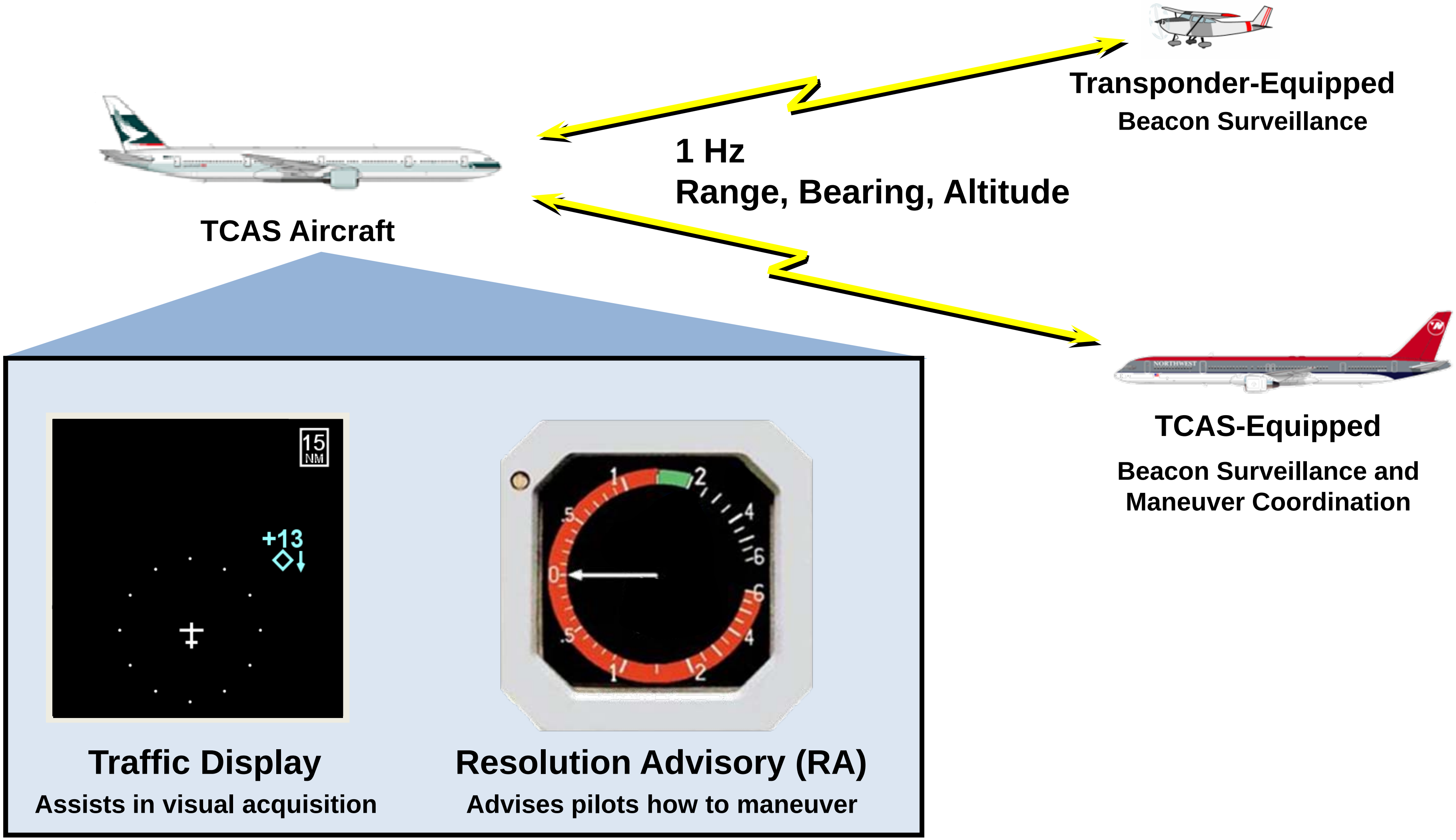


Strategic Separation
Airspace Design

Tactical Separation
Air Traffic Control

Onboard Collision Avoidance

Traffic Alert and Collision Avoidance System (TCAS)



Transponder-Equipped

Beacon Surveillance

1 Hz
Range, Bearing, Altitude

TCAS Aircraft

TCAS-Equipped

Beacon Surveillance and Maneuver Coordination

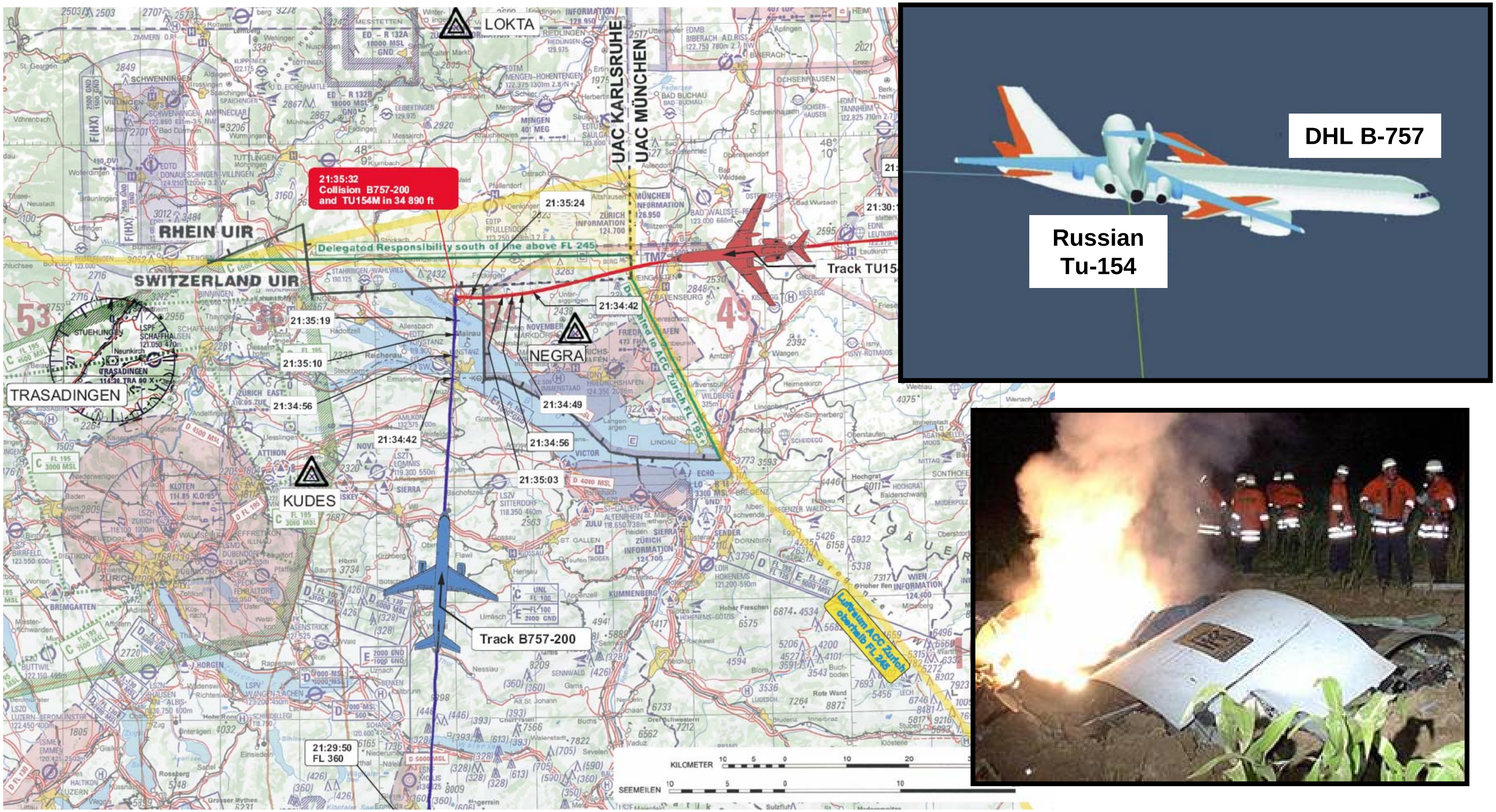
Traffic Display

Assists in visual acquisition

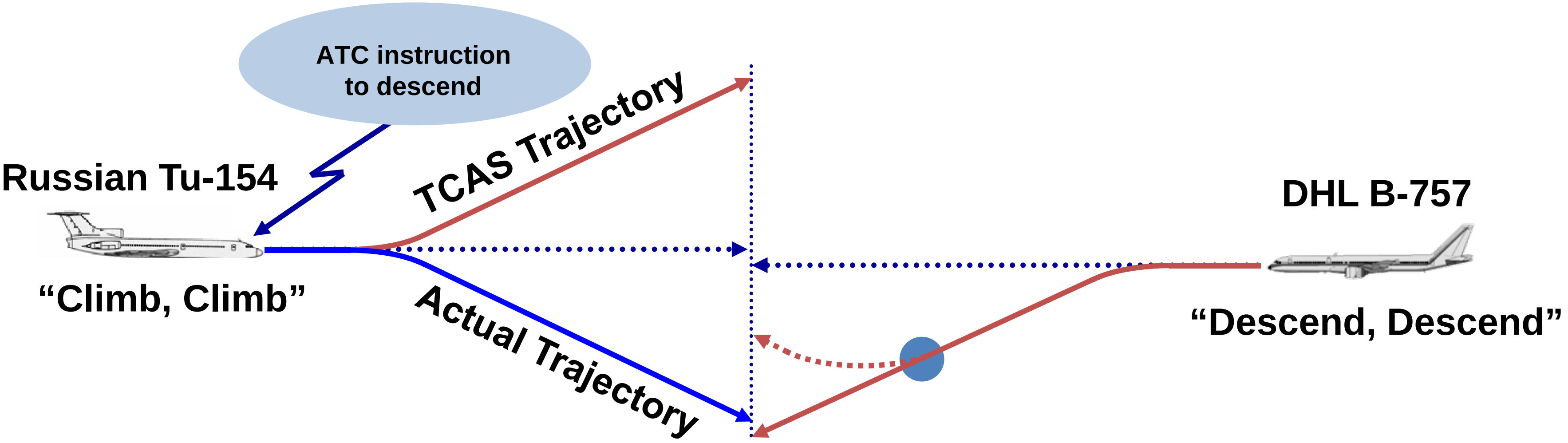
Resolution Advisory (RA)

Advises pilots how to maneuver

Überlingen, Germany, 1 July 2002



Überlingen, Germany, 1 July 2002



Russian followed ATC instruction to descend

DHL followed TCAS RA to descend

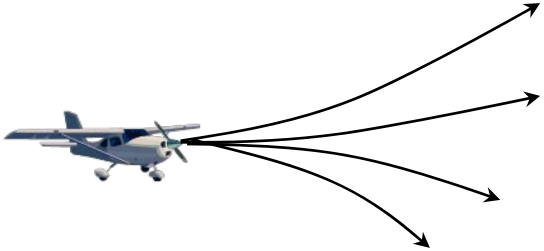
Led to changes in TCAS algorithms to improve reversal performance

Challenges for Decision Making

State Uncertainty

Imperfect sensor information leads to uncertainty in position and velocity of aircraft

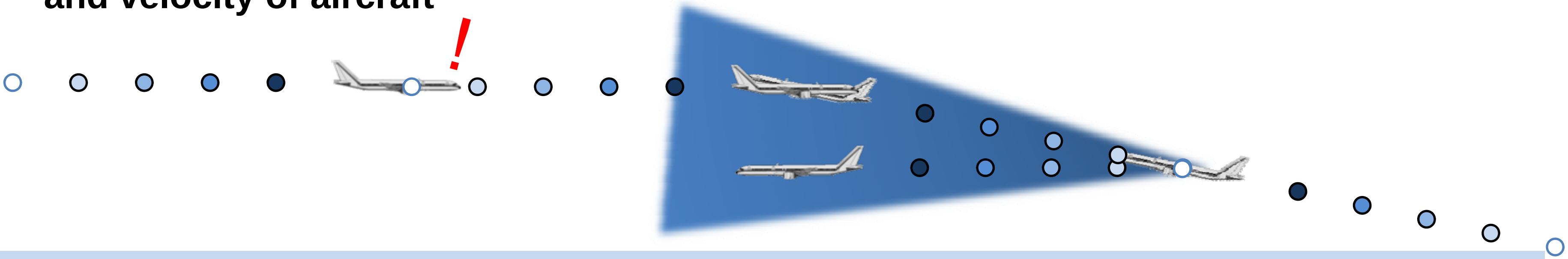
Dynamic Uncertainty



Variability makes it difficult to predict future trajectories of aircraft

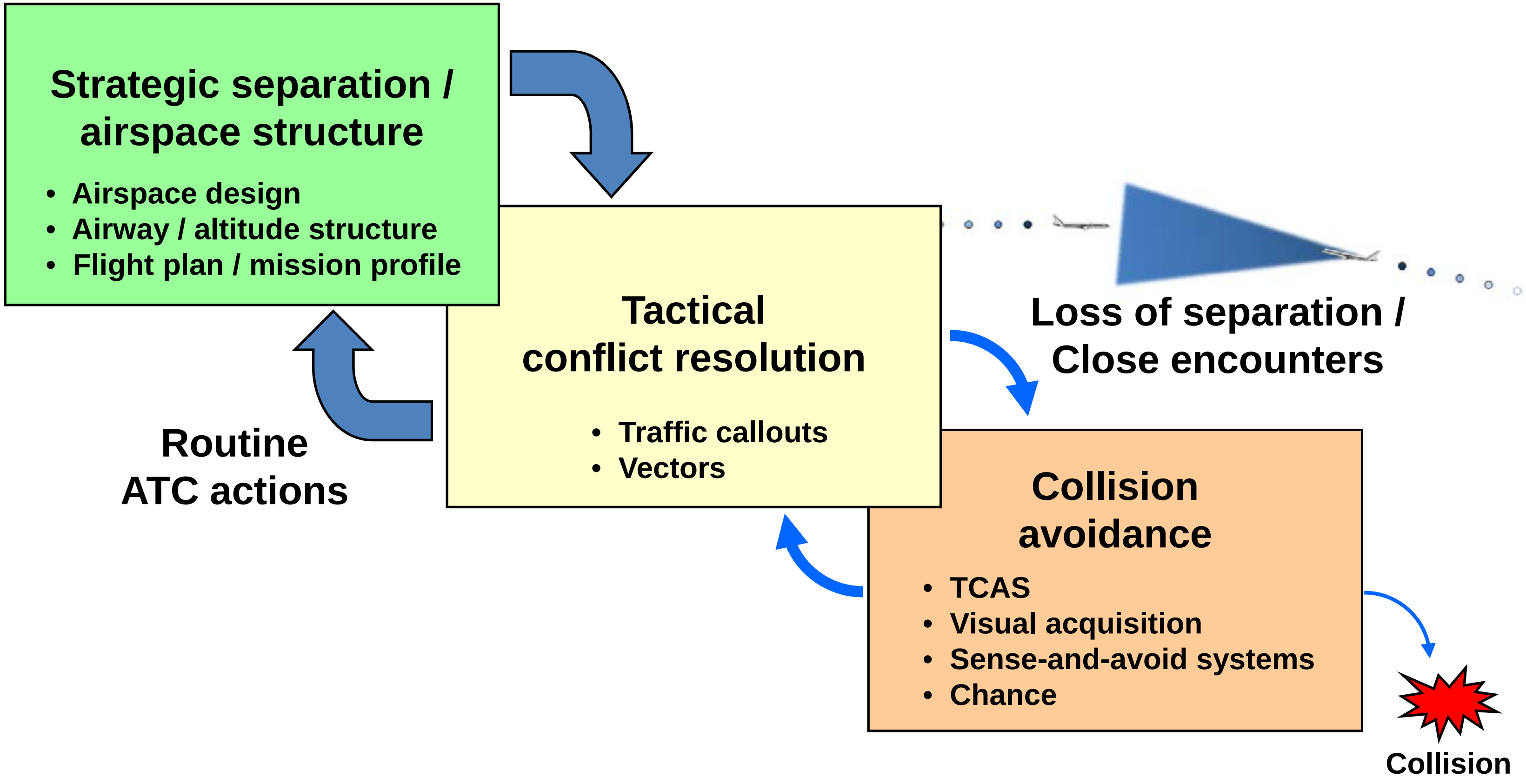
Multiple Objectives

System must carefully balance both safety and operational considerations



Alerting logic model needs to be matched to encounter characteristics

Collision Avoidance Chain



Strategic separation / airspace structure

- Airspace design
- Airway / altitude structure
- Flight plan / mission profile

Tactical conflict resolution

- Traffic callouts
- Vectors

Routine ATC actions

Loss of separation / Close encounters

Collision avoidance

- TCAS
- Visual acquisition
- Sense-and-avoid systems
- Chance

Collision

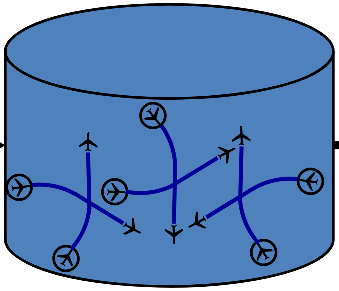
Traditional Development Process

Alerting Algorithm

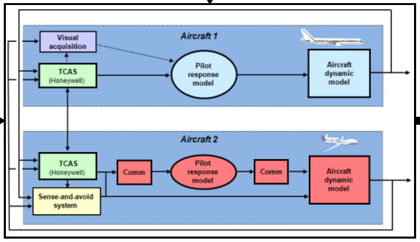
```
IF (OWNTENT(7) EQ $FALSE)
.    THEN   ZDGOAL = MAX(MIN(G.ZDOWN, P.MAXDRATE), P.CLMRT);
.    ELSE   ZDGOAL = MIN(MAX(G.ZDOWN, P.MINDRATE), P.DESRT);
CALL PROJECT_VERTICAL_GIVEN_ZDGOAL
.    IN ((G.TCUR - G.TPOSRA), G.ZTV, G.ZDTV, ZDGOAL, P.TV1, P.VACCEL)
.    OUT (ZPROJ, ZDPROJ);
IF   (((OWNTENT(7) EQ $FALSE AND ZPROJ GT G.ZOWN AND
.    (G.ZDOWN GE G.ZDTV - P.MODEL_ZD)) OR
.    (OWNTENT(7) EQ $TRUE AND ZPROJ LT G.ZOWN AND
.    (G.ZDOWN LE G.ZDTV + P.MODEL_ZD))) AND
.    G.TCUR – G.TPOSRA LT P.MODEL_T)
.    THEN   Z = ZPROJ;
.    .    .      ZD = ZDPROJ;
CALL MODEL_SEP
.    IN (DELAY, ZDGOAL, Z, ZD, P.VACCEL, OWNTENT(7),
.    .    ITF.ZINT, ITF.ZDINT, ITF entry)
.    OUT (NOMINAL_SEP);
```

Adjustments

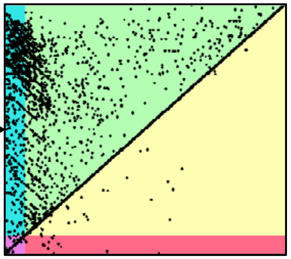
Operational Data



Encounter Model

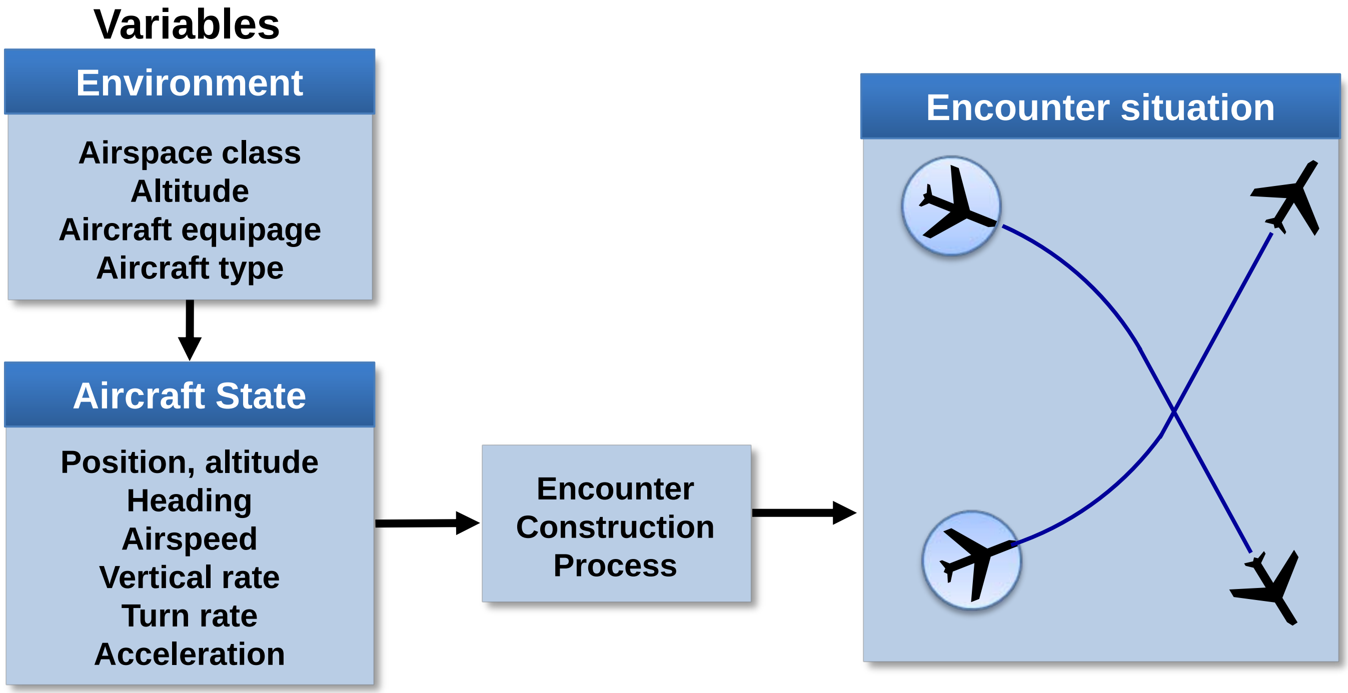


Dynamic Simulation



Observed Performance

Encounter Model Components



Variables

Environment

Airspace class
Altitude
Aircraft equipage
Aircraft type

Aircraft State

Position, altitude
Heading
Airspeed
Vertical rate
Turn rate
Acceleration

Encounter
Construction
Process

Encounter situation

Requirements

- Statistically representative geometries
- Physically realistic behavior
- Manageable size and execution time

Challenges

- Limited observed data to build model
- Selection of variables for model
- ID relationships between variables

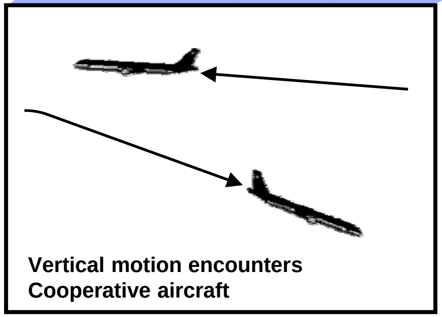
Encounter Model Development History

TCAS Mandate (U.S.)

TCAS Mandate (Worldwide)

1980	1985	1990	1995	2000	2005	2010

MITRE
(US)

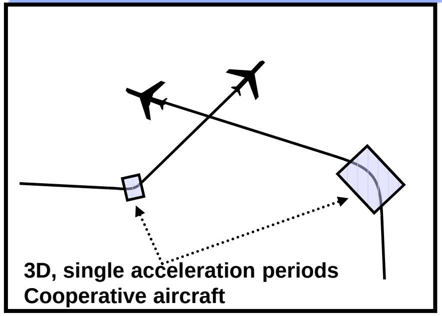


Vertical motion encounters
Cooperative aircraft

12 radar sites
1,683 encounters

Intl. Civil Aviation Org. (ICAO)
(US & Europe)

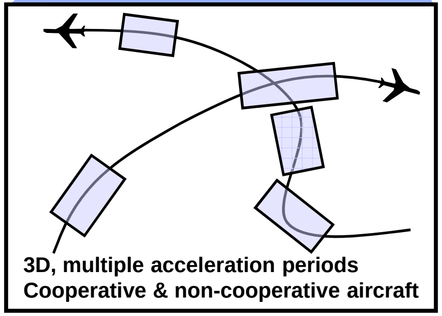
Eurocontrol
(Europe)



3D, single acceleration periods
Cooperative aircraft

6 radar sites
2,387 encounters

FAA / Lincoln Laboratory
(US)

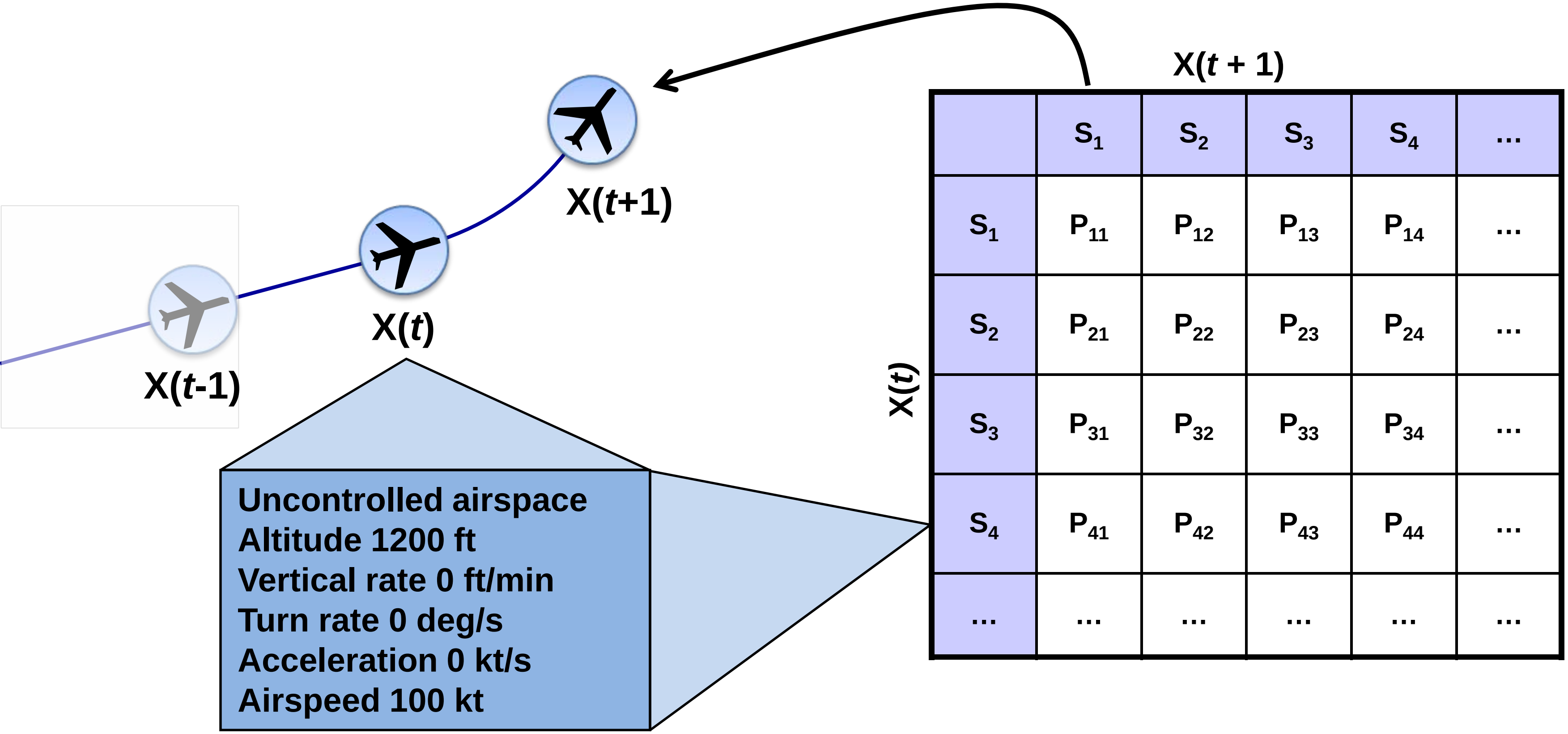


3D, multiple acceleration periods
Cooperative & non-cooperative aircraft

134 radar sites
411,867 encounters

M. J. Kochenderfer, M. W. M. Edwards, L. P. Espindle, J. K. Kuchar, and J. D. Griffith, "Airspace Encounter Models for Estimating Collision Risk," Journal of Guidance, Control, and Dynamics, vol. 33, iss. 2, pp. 487-499, 2010.

Markov Model Representation

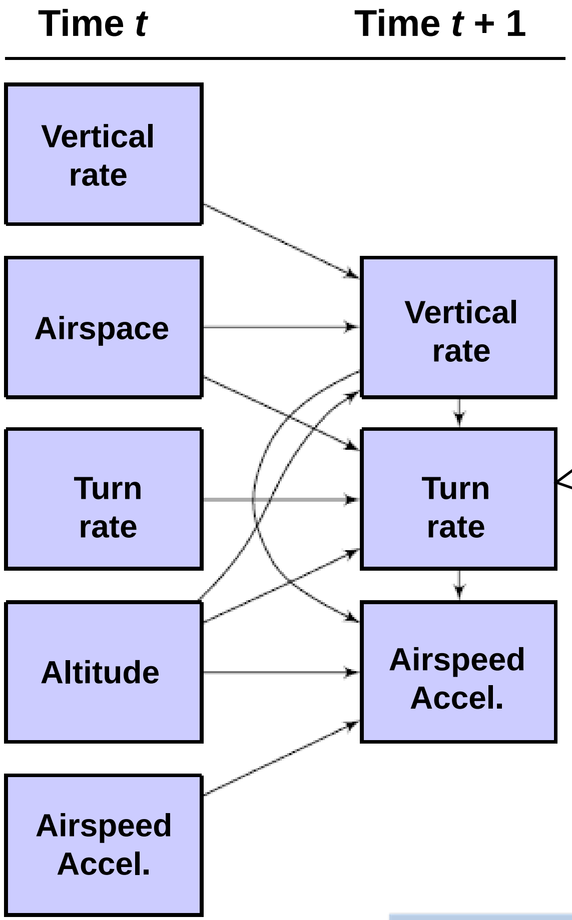


Uncontrolled airspace
Altitude 1200 ft
Vertical rate 0 ft/min
Turn rate 0 deg/s
Acceleration 0 kt/s
Airspeed 100 kt

	S_1	S_2	S_3	S_4	…
S_1	P_{11}	P_{12}	P_{13}	P_{14}	…
S_2	P_{21}	P_{22}	P_{23}	P_{24}	…
S_3	P_{31}	P_{32}	P_{33}	P_{34}	…
S_4	P_{41}	P_{42}	P_{43}	P_{44}	…
…	…	…	…	…	…

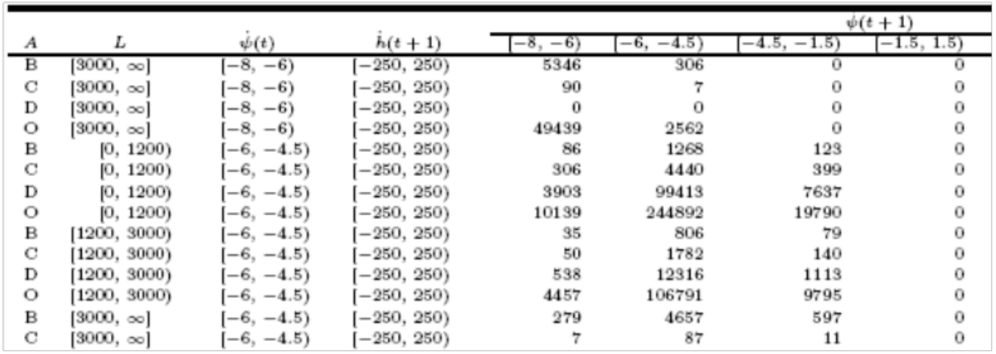
A complete state transition matrix can have ~1 billion parameters, making this approach impractical

Dynamic Bayesian Networks



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

Conditional Probability Table
P(Turn(*t* + 1) | Turn(*t*), Vertical(*t* + 1), Airspace(*t*), Alt(*t*))

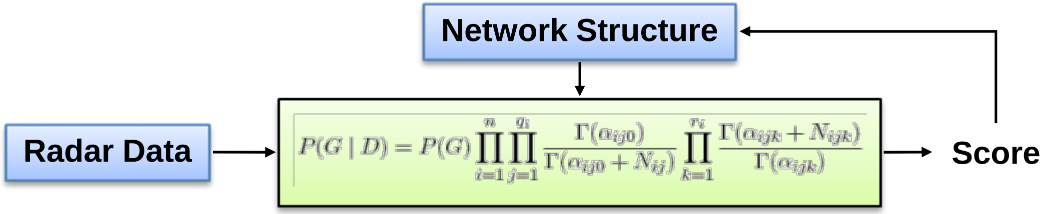


A	L	$\dot{\psi}(t)$	$\dot{h}(t+1)$	$\dot{\psi}(t+1)$			
				$[-8, -6)$	$[-6, -4.5)$	$[-4.5, -1.5)$	$[-1.5, 1.5)$
B	$[3000, \infty]$	$[-8, -6)$	$[-250, 250)$	5346	306	0	0
C	$[3000, \infty]$	$[-8, -6)$	$[-250, 250)$	90	7	0	0
D	$[3000, \infty]$	$[-8, -6)$	$[-250, 250)$	0	0	0	0
O	$[3000, \infty]$	$[-8, -6)$	$[-250, 250)$	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	$[3000, \infty]$	$[-6, -4.5)$	$[-250, 250)$	279	4657	597	0
C	$[3000, \infty]$	$[-6, -4.5)$	$[-250, 250)$	7	87	11	0

…

Only ~9,000 independent parameters required

Bayesian Network Structure Learning



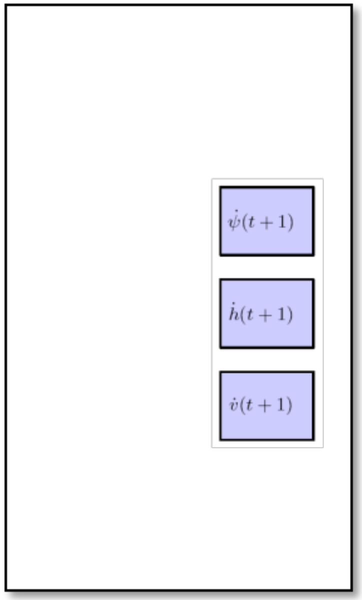
Network Structure

Radar Data

$$P(G \mid D) = P(G)\prod_{i=1}^{n}\prod_{j=1}^{q_i}\frac{\Gamma(\alpha_{ij0})}{\Gamma(\alpha_{ij0}+N_{ij})}\prod_{k=1}^{r_i}\frac{\Gamma(\alpha_{ijk}+N_{ijk})}{\Gamma(\alpha_{ijk})}$$

Score

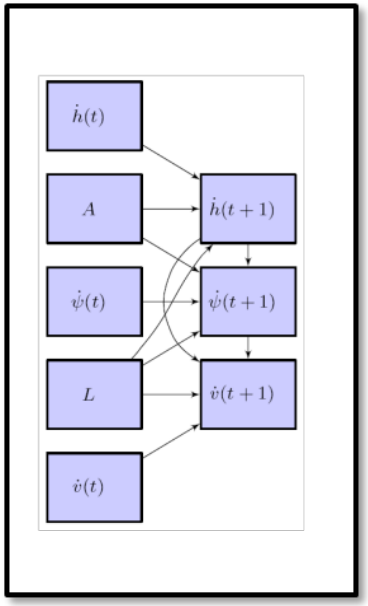
Unconnected



16 parameters

…

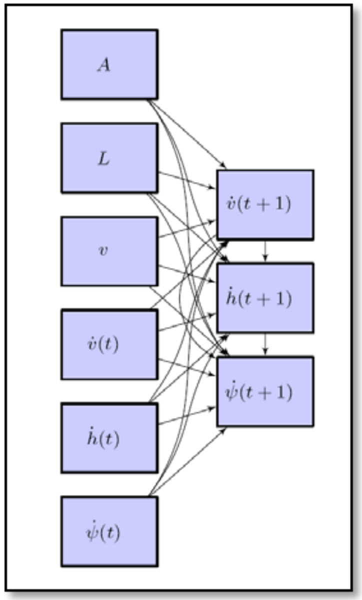
Optimal



9,296 parameters

…

Fully Connected



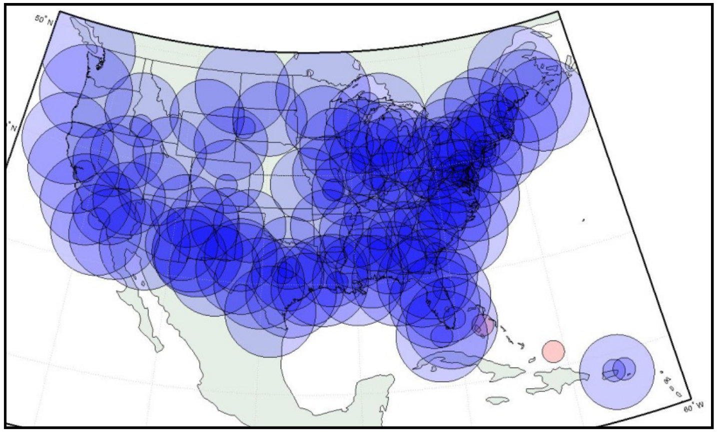
7,651,840 parameters

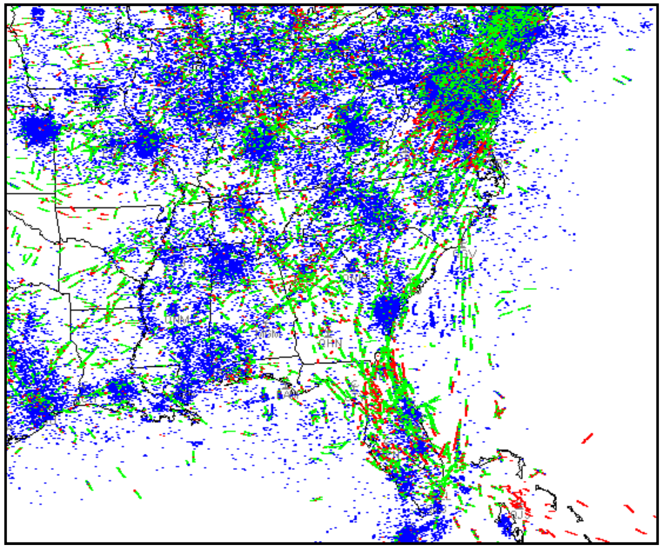
Increasing number of parameters

New US Airspace Models
National Radar Data Feeds

- **Data gathered at Eastern / Western Air Defense Sectors, transmitted to 84th Radar Evaluation Squadron (RADES), thence to Lincoln Lab**

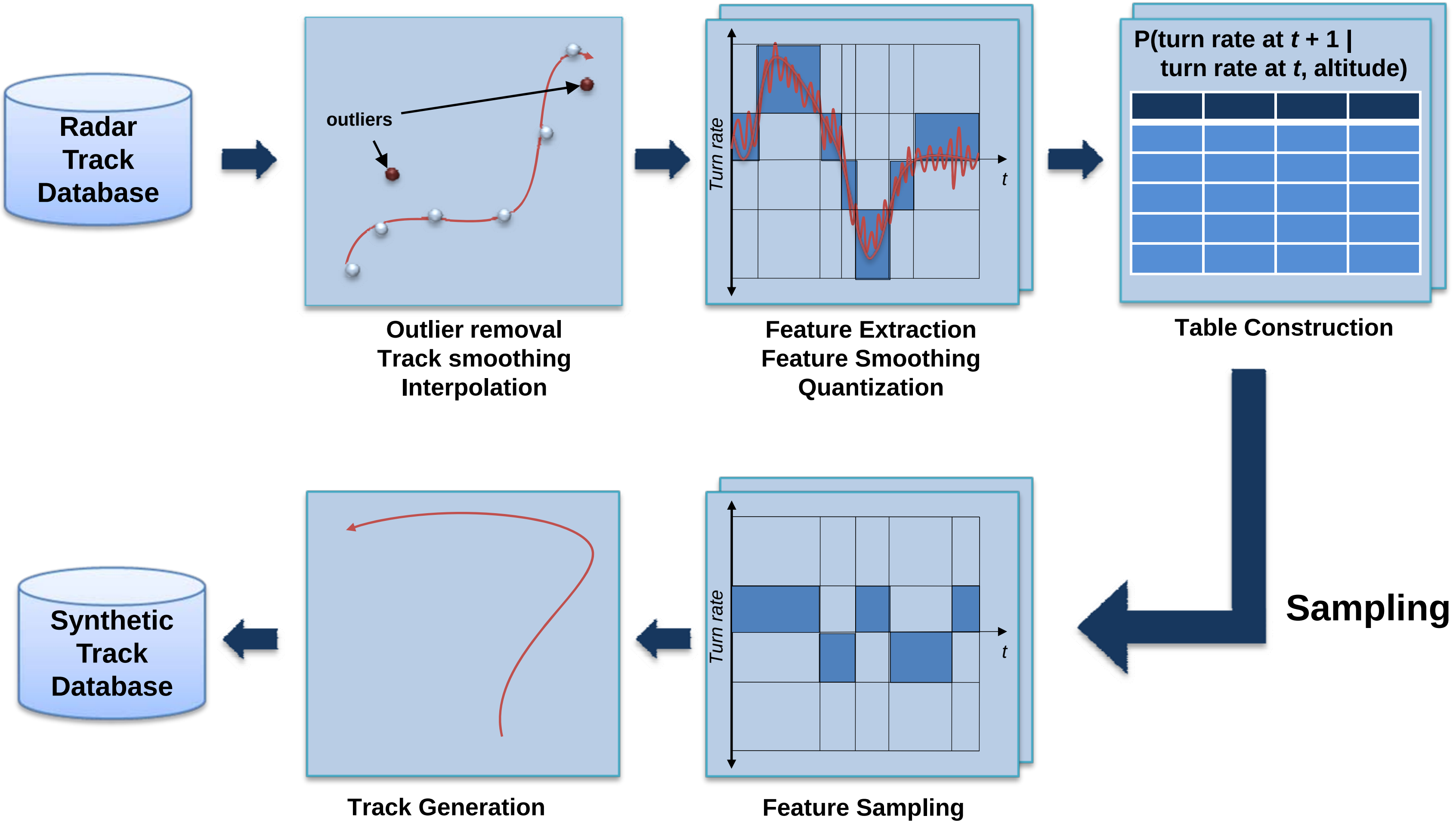
- **Raw sensor data**
  - **134 sensors including CONUS and littoral / offshore coverage**
  - **Not affected by filtering or tracking**
  - **Primary and secondary radar returns**
  - **8 radar types (including long-range ARSR-4, short-range ASR-8 -9 -11)**
  - **Includes height measurements for some sensors (e.g., ARSR-4)**
  - **~ 10 GB of data / day**





Primary-only **Beacon-only** **Reinforced**

Track Processing and Synthesis



Outlier removal
Track smoothing
Interpolation

Feature Extraction
Feature Smoothing
Quantization

Table Construction

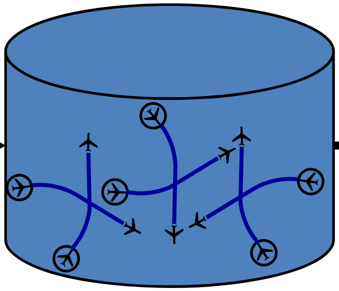
Feature Sampling

Track Generation

Results validated by comparison to other operational data

Traditional Development Process

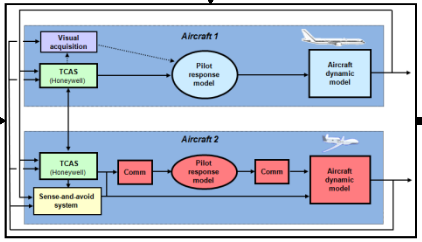
Operational
Data



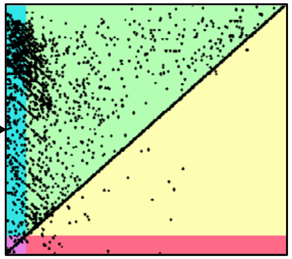
Encounter
Model

Alerting Algorithm

```
IF (OWNTENT(7) EQ $FALSE)
.     THEN   ZDGOAL = MAX(MIN(G.ZDOWN, P.MAXDRATE), P.CLMRT);
.     ELSE    ZDGOAL = MIN(MAX(G.ZDOWN, P.MINDRATE), P.DESRT);
CALL PROJECT_VERTICAL_GIVEN_ZDGOAL
.     IN ((G.TCUR - G.TPOSRA), G.ZTV, G.ZDTV, ZDGOAL, P.TV1, P.VACCEL)
.     OUT (ZPROJ, ZDPROJ);
IF    (((OWNTENT(7) EQ $FALSE AND ZPROJ GT G.ZOWN AND
.     (G.ZDOWN GE G.ZDTV - P.MODEL_ZD)) OR
.     (OWNTENT(7) EQ $TRUE AND ZPROJ LT G.ZOWN AND
.     (G.ZDOWN LE G.ZDTV + P.MODEL_ZD))) AND
.     G.TCUR – G.TPOSRA LT P.MODEL_T)
.     THEN   Z = ZPROJ;
.     .     .     ZD = ZDPROJ;
CALL MODEL_SEP
.     IN (DELAY, ZDGOAL, Z, ZD, P.VACCEL, OWNTENT(7),
.     .     ITF.ZINT, ITF.ZDINT, ITF entry)
.     OUT (NOMINAL_SEP);
```



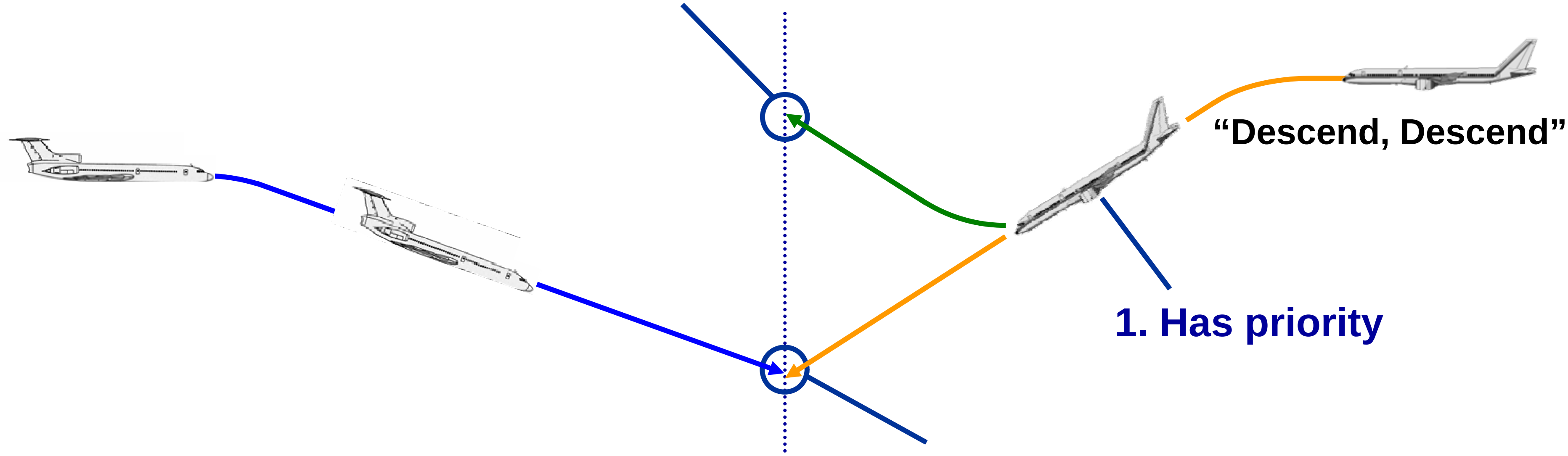
Dynamic
Simulation



Observed
Performance

Adjustments

TCAS V7.0 Sense Reversal Criteria



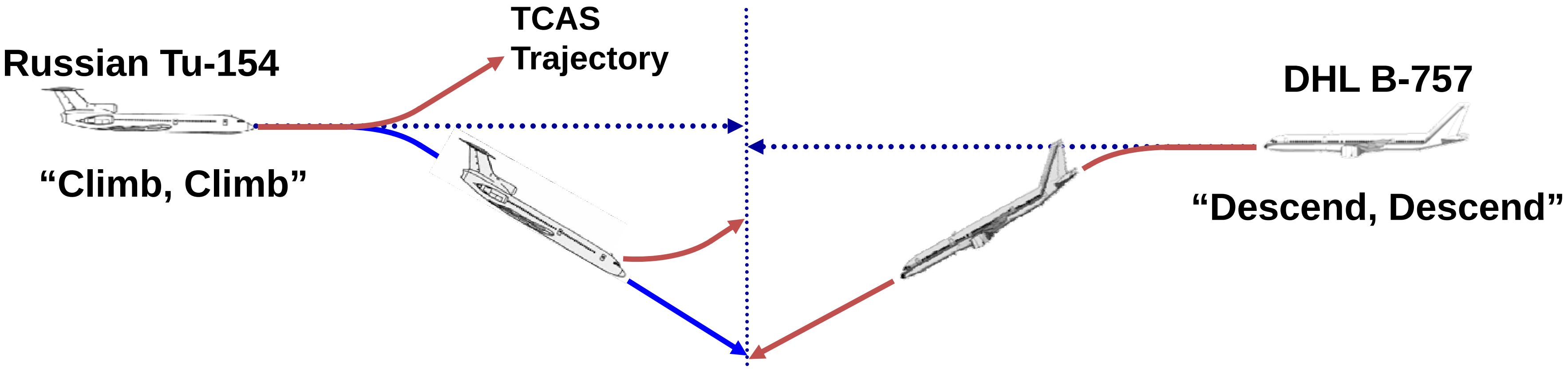
3. Reversed RA is adequate

“Descend, Descend”

1. Has priority

2. Current RA is not adequate

Sense Reversal Behavior at Überlingen



Russian aircraft

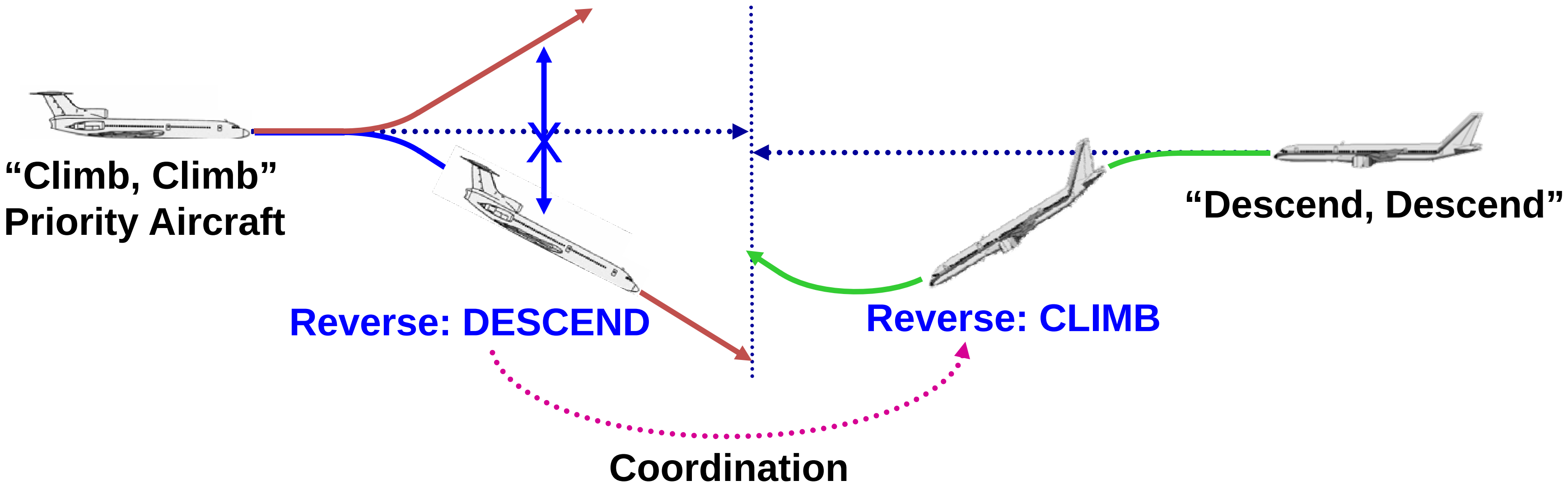
- Had priority
- Climb RA provides adequate separation: No reversal

Algorithm relied on invalid assumption that own aircraft was following its RA

V7.1 Logic Change Proposal*

Test whether own aircraft is following its RA

Coordination ensures compatible reversals



"Climb, Climb"
Priority Aircraft

"Descend, Descend"

Reverse: DESCEND

Reverse: CLIMB

Coordination

Provides the aircraft that is following its RA an escape path

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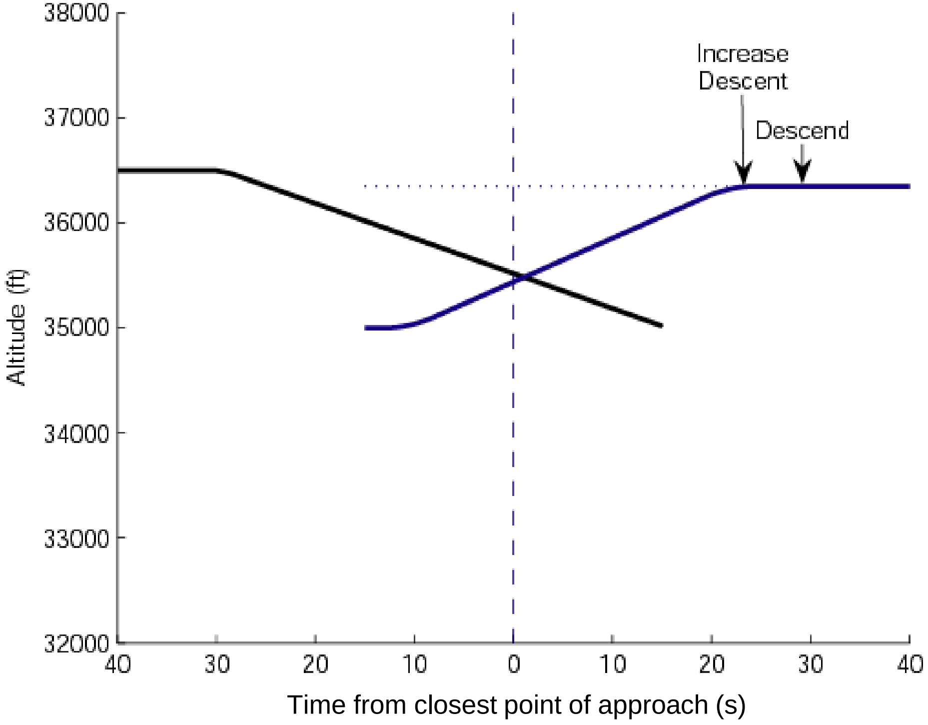
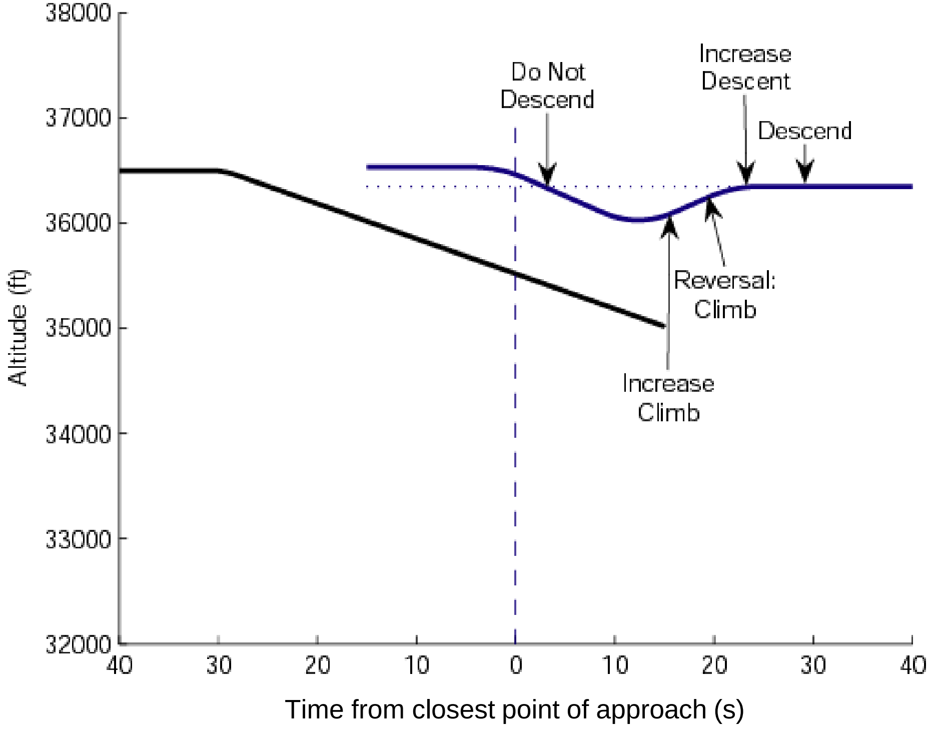
* Other significant improvements are included as well

Simulation of Überlingen Geometry

Encounter with TCAS V7.0

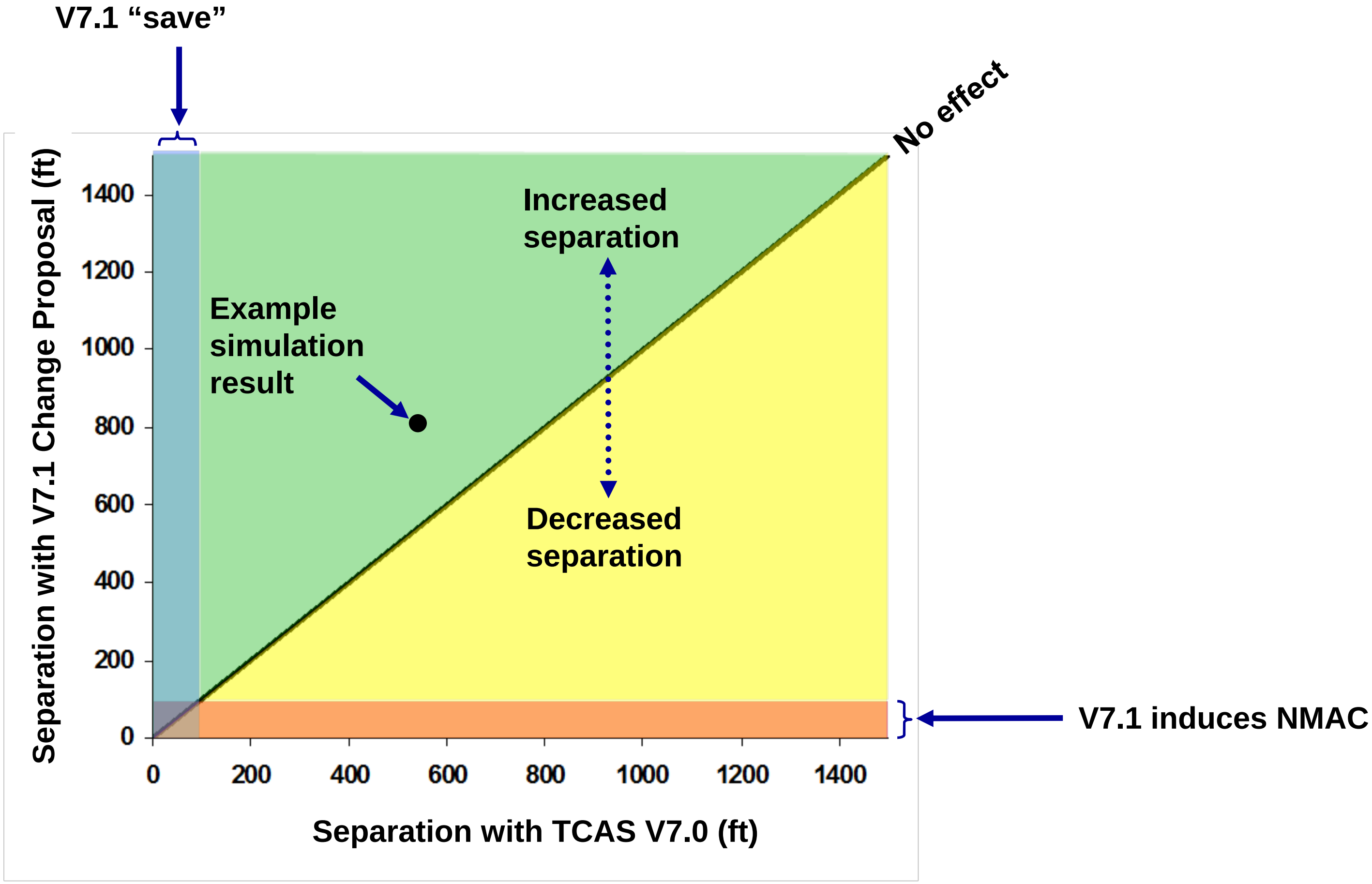


Encounter with TCAS V7.1



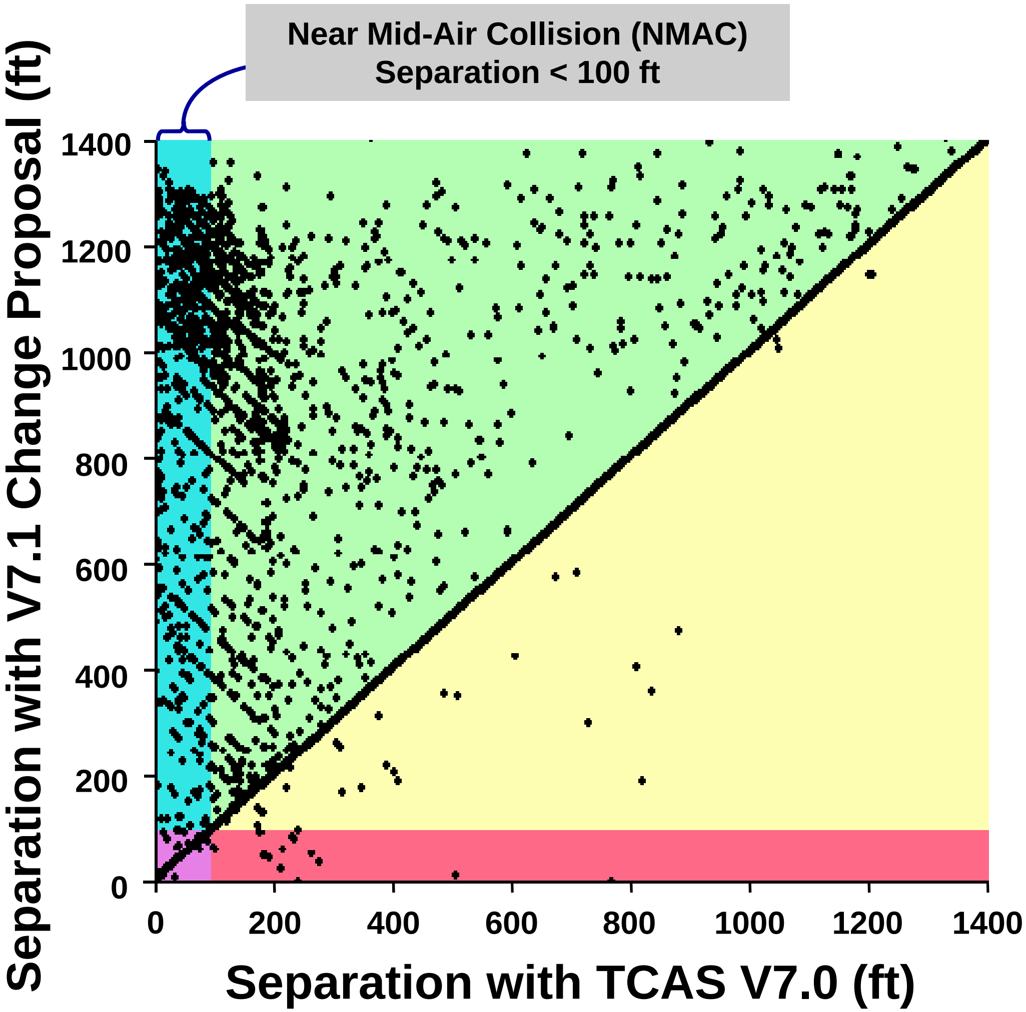
TCAS V7.1 successfully reverses the RA sense

Performance Robustness Comparison



Near Mid-Air Collision (NMAC): separation < 100 ft

Example Monte Carlo Results:
Vertical Separation When One Aircraft Ignores RAs



- Change proposal affects 0.05% of runs
- 92% of changes involve separation gains
- 22% of changes are saves
- 2% of changes are induced NMACs
- 3% of changes are unresolved NMACs

Impact: European Adoption

IFALPA

The Global Voice of Pilots

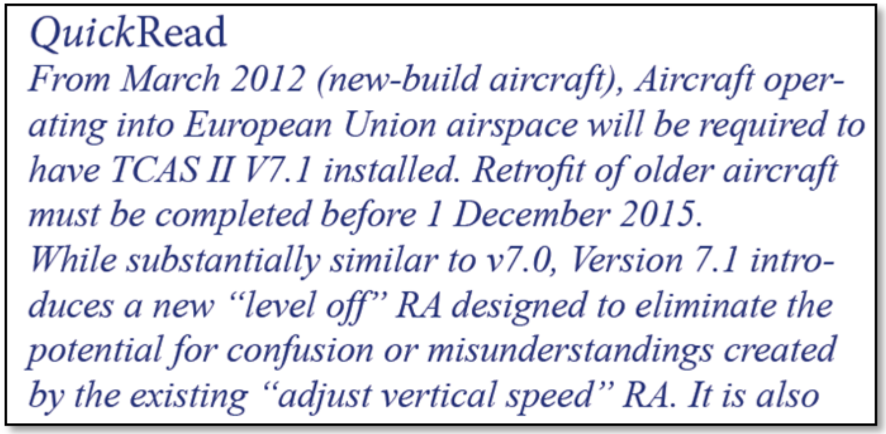
Air Traffic Services

Briefing Leaflet

12ATSBL09

February 2012

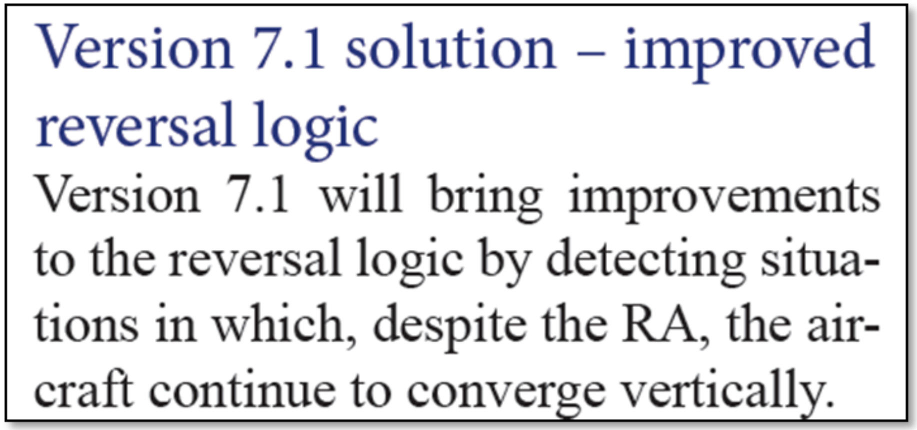
TCAS version 7.1: Coming to a cockpit near you soon...



QuickRead

From March 2012 (new-build aircraft), Aircraft operating into European Union airspace will be required to have TCAS II V7.1 installed. Retrofit of older aircraft must be completed before 1 December 2015.

While substantially similar to v7.0, Version 7.1 introduces a new "level off" RA designed to eliminate the potential for confusion or misunderstandings created by the existing "adjust vertical speed" RA. It is also

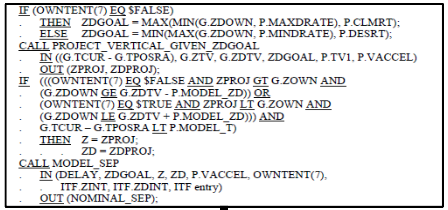


Version 7.1 solution – improved reversal logic

Version 7.1 will bring improvements to the reversal logic by detecting situations in which, despite the RA, the aircraft continue to converge vertically.

Problems with the Traditional Development Process

Alerting Algorithm



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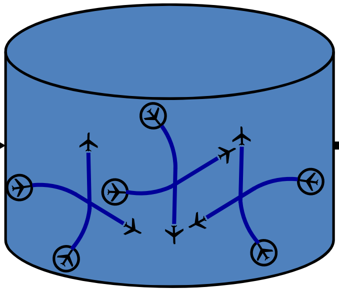
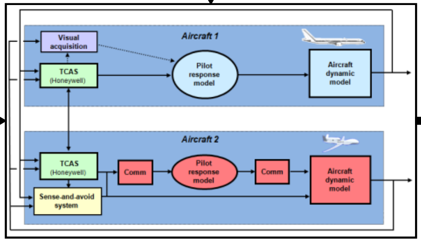
CALL PROJECT_VERTICAL_GIVEN_ZDGOAL
.    IN ((G.TCUR - G.TPOSRA), G.ZTV, G.ZDTV, ZDGOAL, P.TV1, P.VACCEL)
.    OUT (ZPROJ, ZDPROJ);
IF   (((OWNTENT(7) EQ $FALSE AND ZPROJ GT G.ZOWN AND
.    (G.ZDOWN GE G.ZDTV - P.MODEL_ZD)) OR
.    (OWNTENT(7) EQ $TRUE AND ZPROJ LT G.ZOWN AND
.    (G.ZDOWN LE G.ZDTV + P.MODEL_ZD))) AND
.    G.TCUR – G.TPOSRA LT P.MODEL_T)
.    THEN   Z = ZPROJ;
.    .    .    ZD = ZDPROJ;
CALL MODEL_SEP
.    IN (DELAY, ZDGOAL, Z, ZD, P.VACCEL, OWNTENT(7),
.    .    ITF.ZINT, ITF.ZDINT, ITF entry)
.    OUT (NOMINAL_SEP);
```

Changes

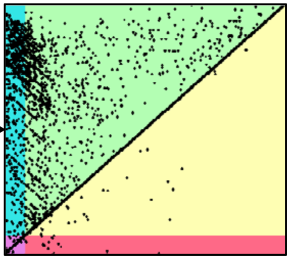
Operational Data



Encounter Model



Dynamic Simulation

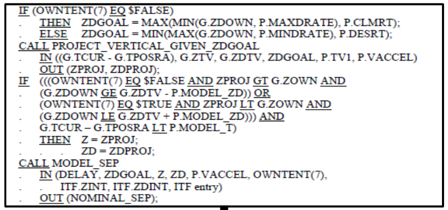


Observed Performance

Traditional V7.1 upgrade process involved trial-and-error and spanned several years

A Direct Approach:
Decision Theoretic Design

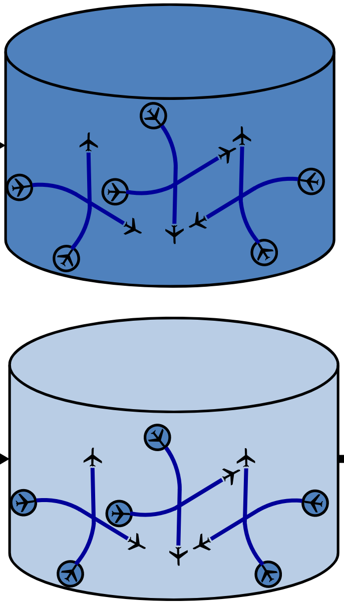
Alerting Algorithm



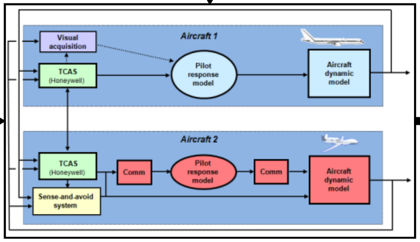
```
IF (OWNTENT(7) EQ $FALSE)
.      THEN   ZDGOAL = MAX(MIN(G.ZDOWN, P.MAXDRATE), P.CLMRT);
.      ELSE    ZDGOAL = MIN(MAX(G.ZDOWN, P.MINDRATE), P.DESRT);
CALL PROJECT_VERTICAL_GIVEN_ZDGOAL
.      IN ((G.TCUR - G.TPOSRA), G.ZTV, G.ZDTV, ZDGOAL, P.TV1, P.VACCEL)
.      OUT (ZPROJ, ZDPROJ);
IF     (((OWNTENT(7) EQ $FALSE AND ZPROJ GT G.ZOWN AND
.      (G.ZDOWN GE G.ZDTV - P.MODEL_ZD)) OR
.      (OWNTENT(7) EQ $TRUE AND ZPROJ LT G.ZOWN AND
.      (G.ZDOWN LE G.ZDTV + P.MODEL_ZD))) AND
.      G.TCUR – G.TPOSRA LT P.MODEL_T)
.      THEN   Z = ZPROJ;
.      .      .      ZD = ZDPROJ;
CALL MODEL_SEP
.      IN (DELAY, ZDGOAL, Z, ZD, P.VACCEL, OWNTENT(7),
.      .      ITF.ZINT, ITF.ZDINT, ITF entry)
.      OUT (NOMINAL_SEP);
```

Decision Theoretic Design

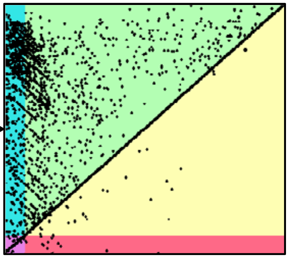
Operational Data



Encounter Models

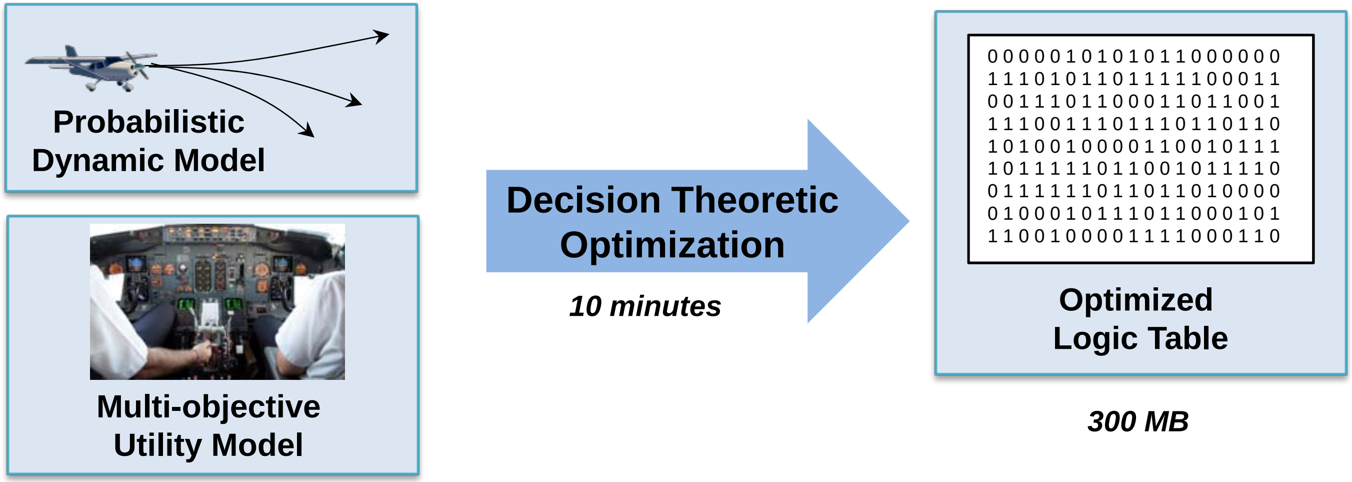


Dynamic Simulation



Observed Performance

Next-Generation TCAS
Logic Development: ACAS X



Probabilistic Dynamic Model

Multi-objective Utility Model

Decision Theoretic Optimization

10 minutes

```
0 0 0 0 0 1 0 1 0 1 0 1 1 0 0 0 0 0 0
1 1 1 0 1 0 1 1 0 1 1 1 1 1 0 0 0 1 1
0 0 1 1 1 0 1 1 0 0 0 1 1 0 1 1 0 0 1
1 1 1 0 0 1 1 1 0 1 1 1 0 1 1 0 1 1 0
1 0 1 0 0 1 0 0 0 0 1 1 0 0 1 0 1 1 1
1 0 1 1 1 1 1 0 1 1 0 0 1 0 1 1 1 1 0
0 1 1 1 1 1 1 0 1 1 0 1 1 0 1 0 0 0 0
0 1 0 0 0 1 0 1 1 1 0 1 1 0 0 0 1 0 1
1 1 0 0 1 0 0 0 0 1 1 1 1 0 0 0 1 1 0
```

Optimized Logic Table

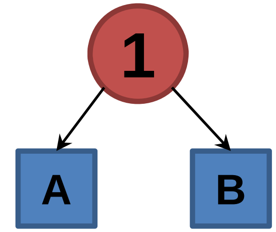
300 MB

- **Logic complexity is represented using numeric table instead of rules**
- **Table is standardized and given to system manufacturers**
- **Updates can be made to the system by uploading a new table**

Markov Decision Process (MDP)

MDPs are a general framework for formulating sequential decision problems

- State space
  - Set of all possible states

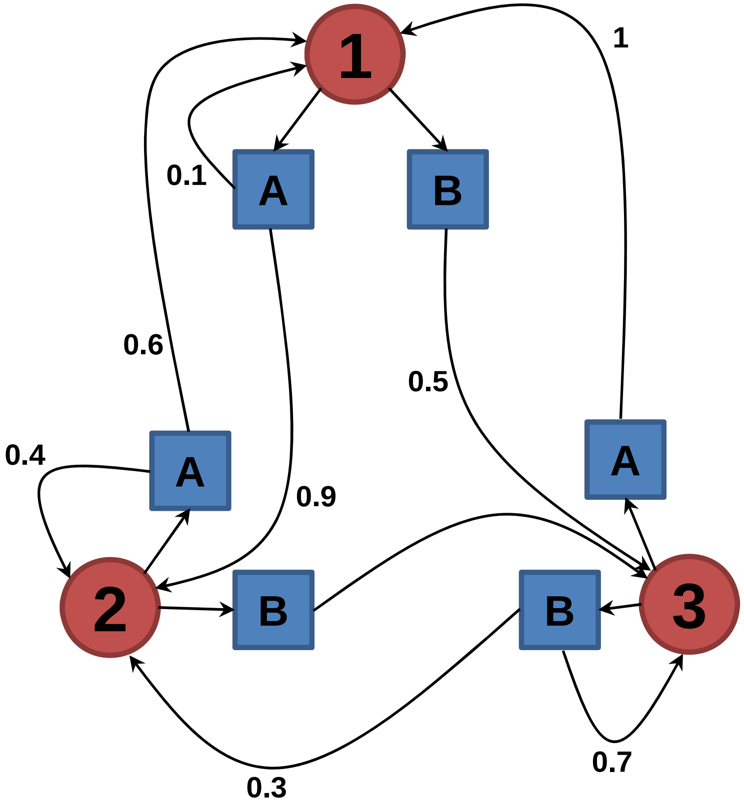


- Action space
  - Set of all possible actions

Markov Decision Process (MDP)

MDPs are a general framework for formulating sequential decision problems

- State space
  - Set of all possible states
- Action space
  - Set of all possible actions
- Dynamic model
  - State transition probabilities

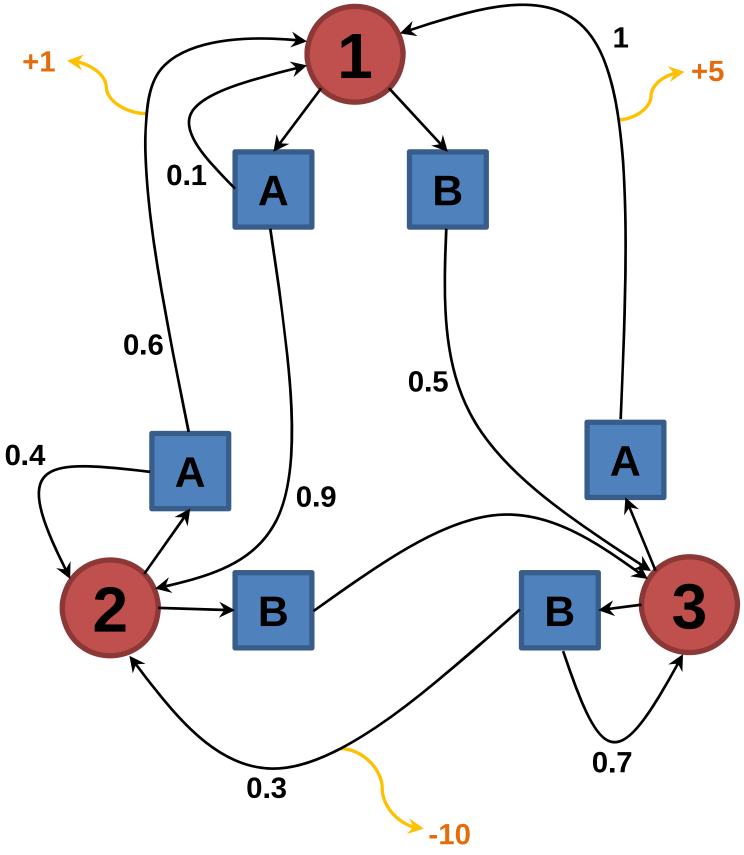


Markov Decision Process (MDP)

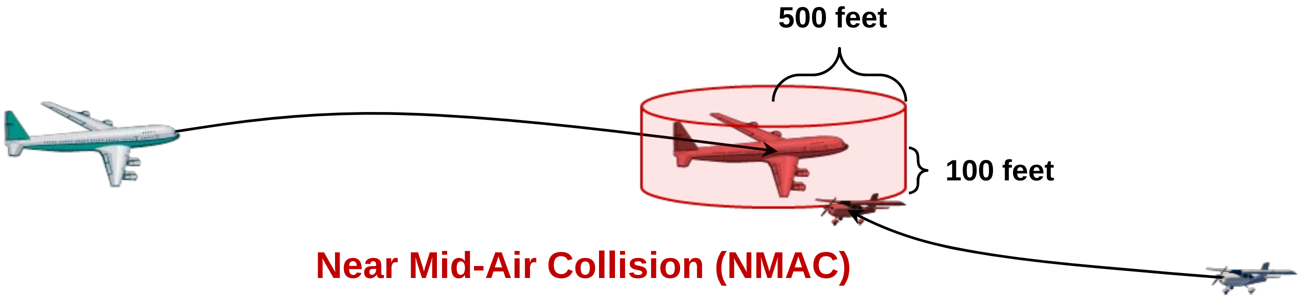
MDPs are a general framework for formulating sequential decision problems

- **State space**
  - **Set of all possible states**
- **Action space**
  - **Set of all possible actions**
- **Dynamic model**
  - **State transition probabilities**
- **Reward model**
  - **Reward for making transition**

Objective is to maximize reward



Collision Avoidance MDP



Near Mid-Air Collision (NMAC)

State space	Action space
Relative altitude Own vertical rate Intruder vertical rate Time to lateral NMAC State of advisory	Clear of conflict Climb > 1500 ft/min Climb > 2500 ft/min Descend > 1500 ft/min Descend > 2500 ft/min
Dynamic model	**Reward model**
Head-on, constant closure Random vertical acceleration Pilot response delay (5 s) Pilot response strength (1/4 g) State of advisory	NMAC (-1) Alert (-0.01) Reversal (-0.01) Strengthen (-0.009) Clear of conflict (0.0001)

M. J. Kochenderfer and J. P. Chryssanthacopoulos, "A Decision-Theoretic Approach to Developing Robust Collision Avoidance Logic," in IEEE International Conference on Intelligent Transportation Systems, Madeira Island, Portugal, 2010.

Dynamic Programming (DP)

DP is an efficient way to solve an MDP

Expected value

$$Q(s,a) = R(s,a) + \sum_{s'} P(s' | s,a) V(s')$$

$$V(s) = \max_{a} Q(s,a)$$

- **DP is an iterative process for computing the expected value when starting from each state**
- **Best action can be derived directly from expected value**

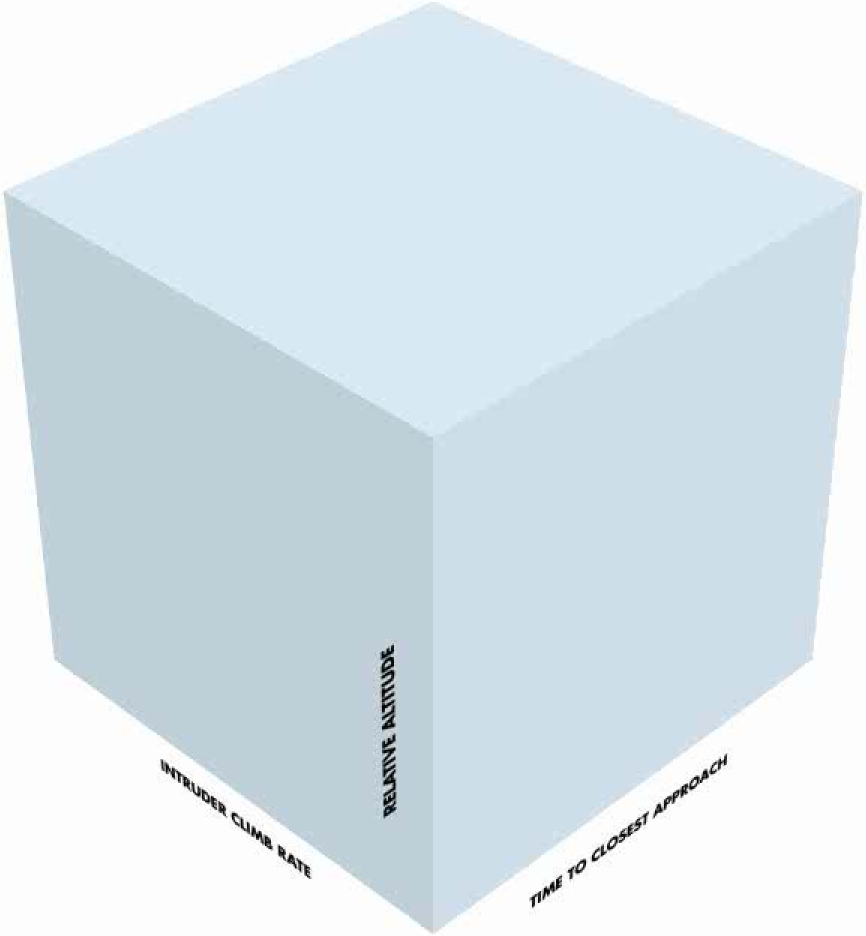
Dynamic Programming (DP)

Notional Expected Value Table

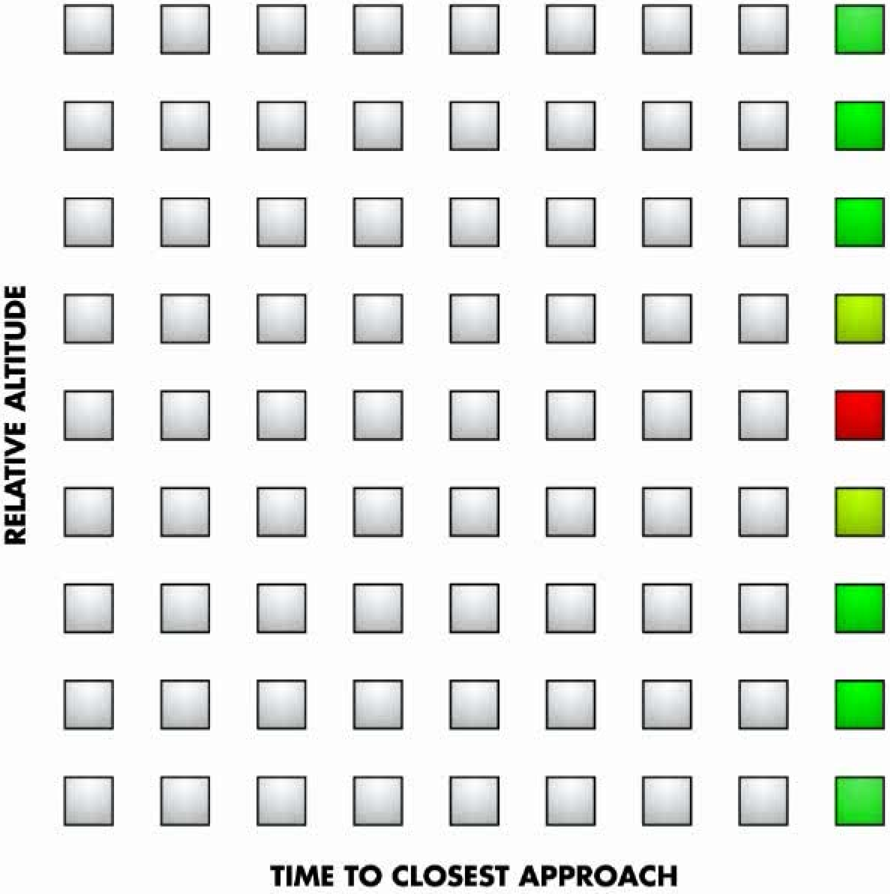
State					Expected Value		
Relative altitude	Time to go	Own vert. spd.	Intruder vert. spd.	Advisory state	No alert	Climb	Descend
100	19	1500	-1000	None	**-0.0144**	-0.4215	-0.0190
200	20	0	0	None	-0.0449	**-0.0339**	-0.4251
…	…	…	…	…	…	…	…

- **Rows correspond to different discrete states**
- **Table queried in real time on aircraft to select optimal action**

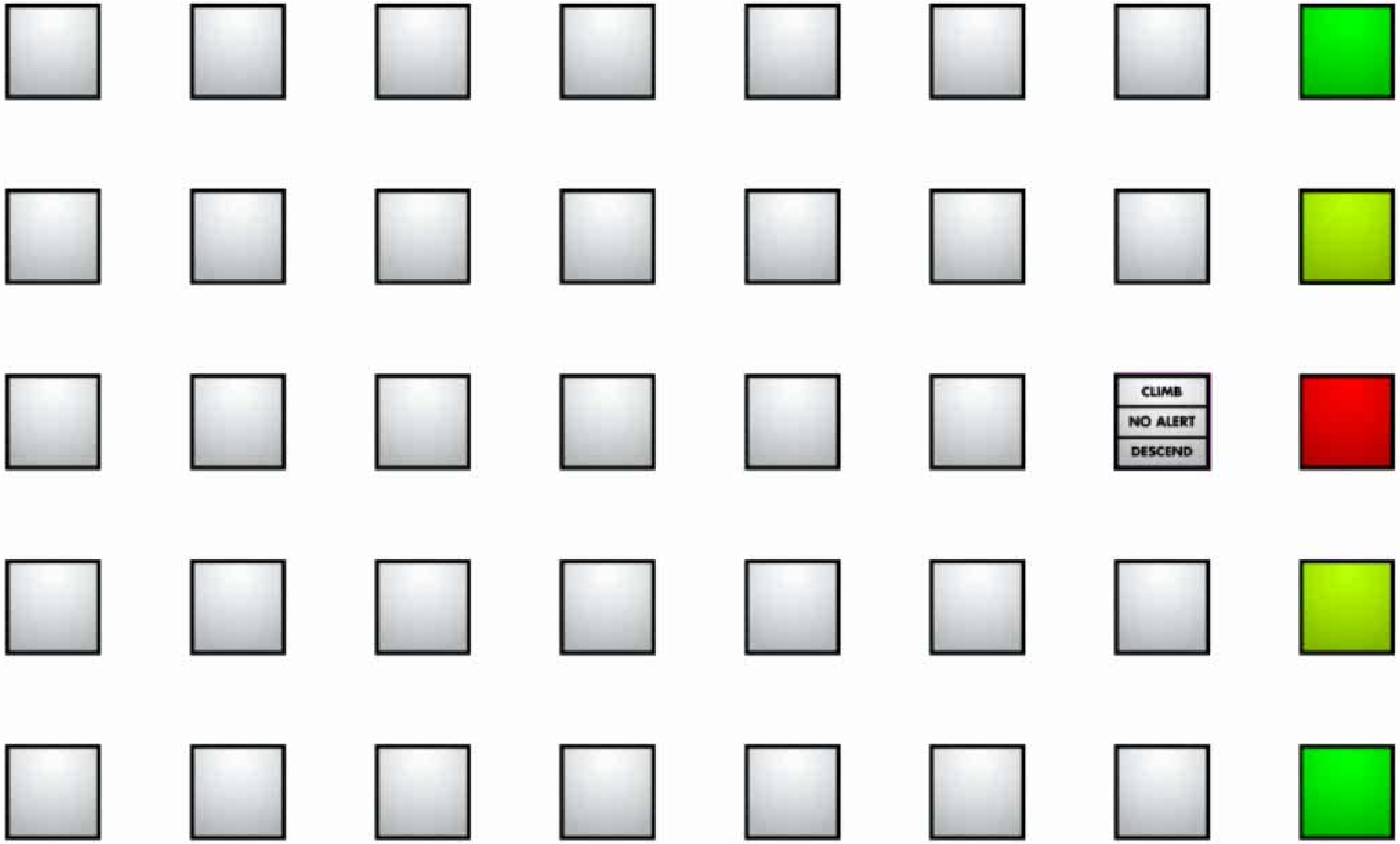
Dynamic Programming (DP)



Dynamic Programming (DP)

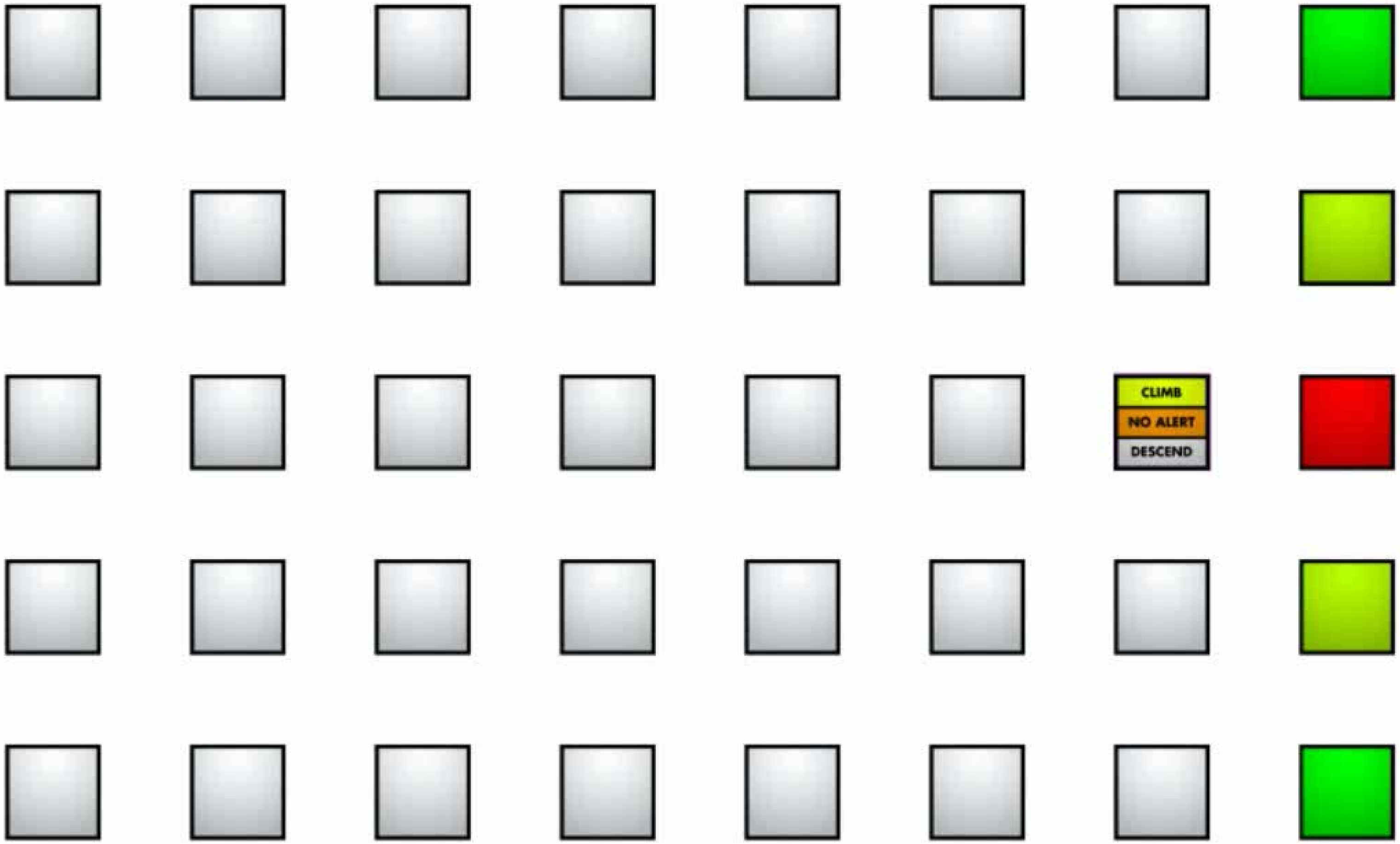


Dynamic Programming (DP)

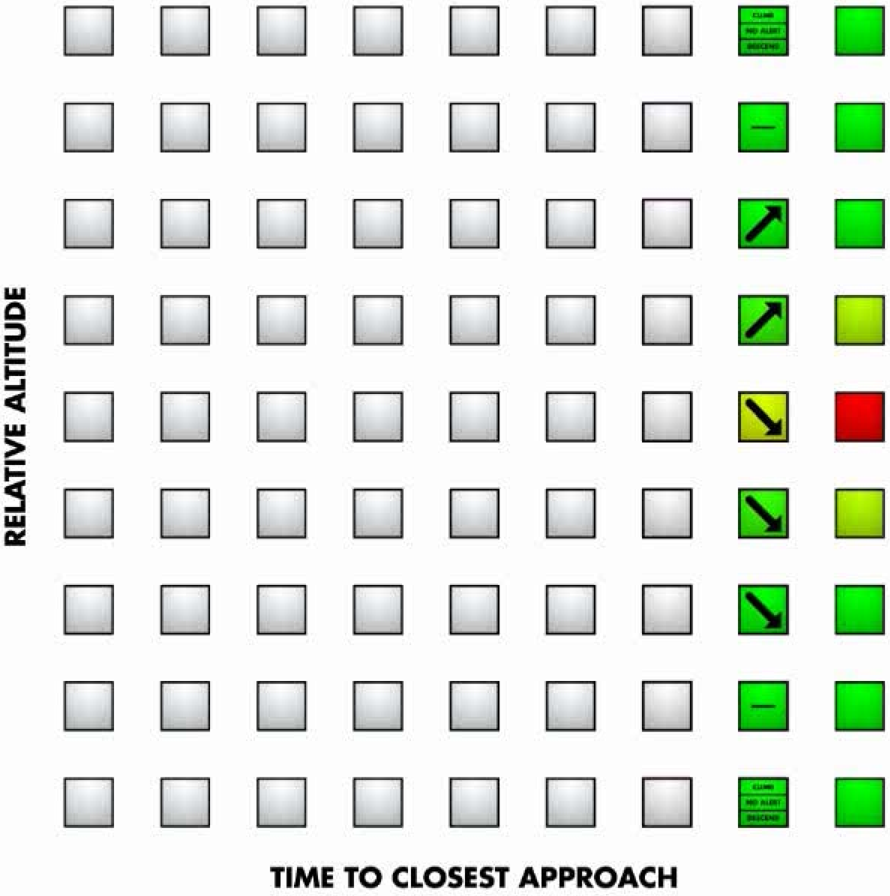


Dynamic Programming (DP)

Dynamic Programming (DP)

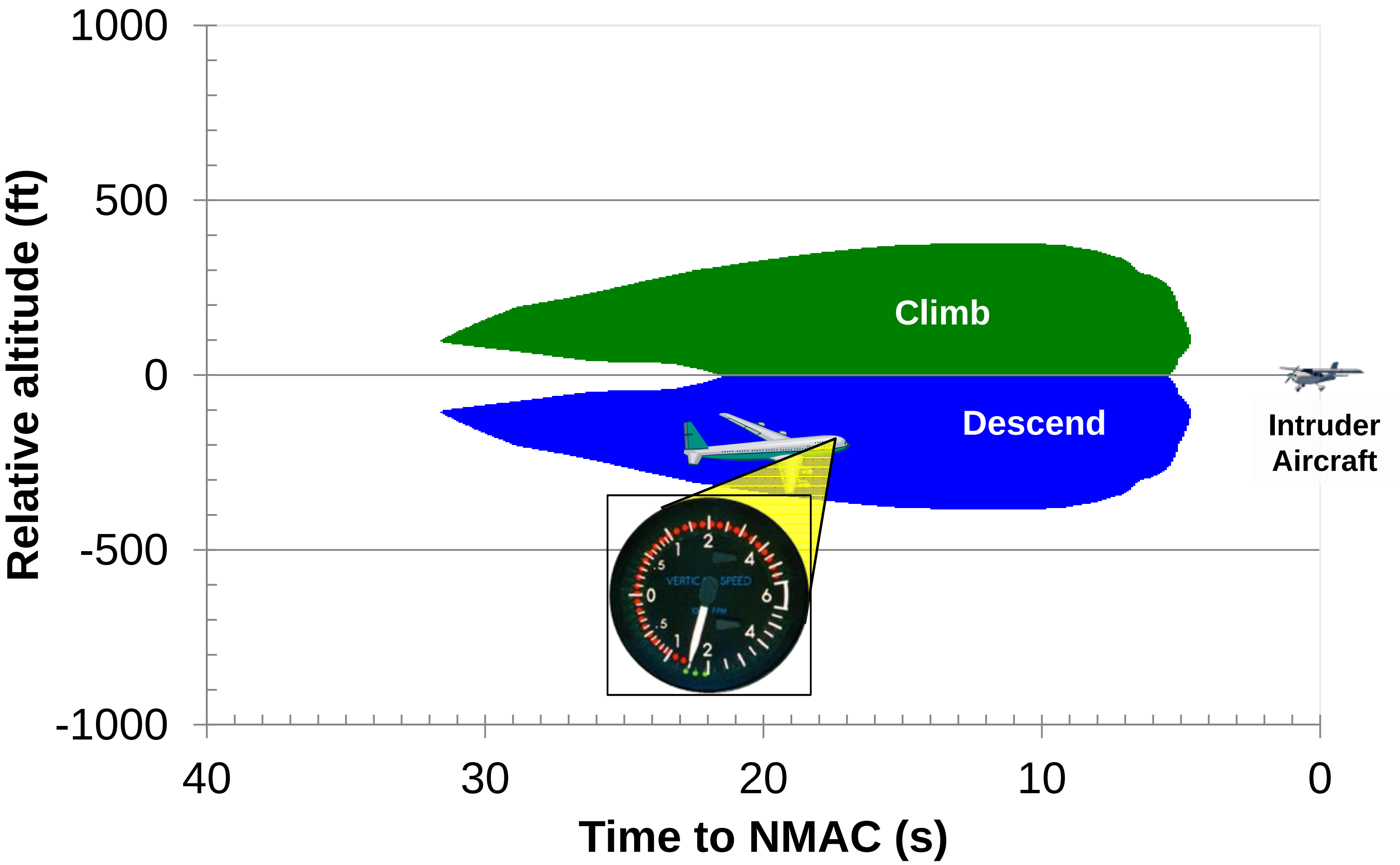


Dynamic Programming (DP)



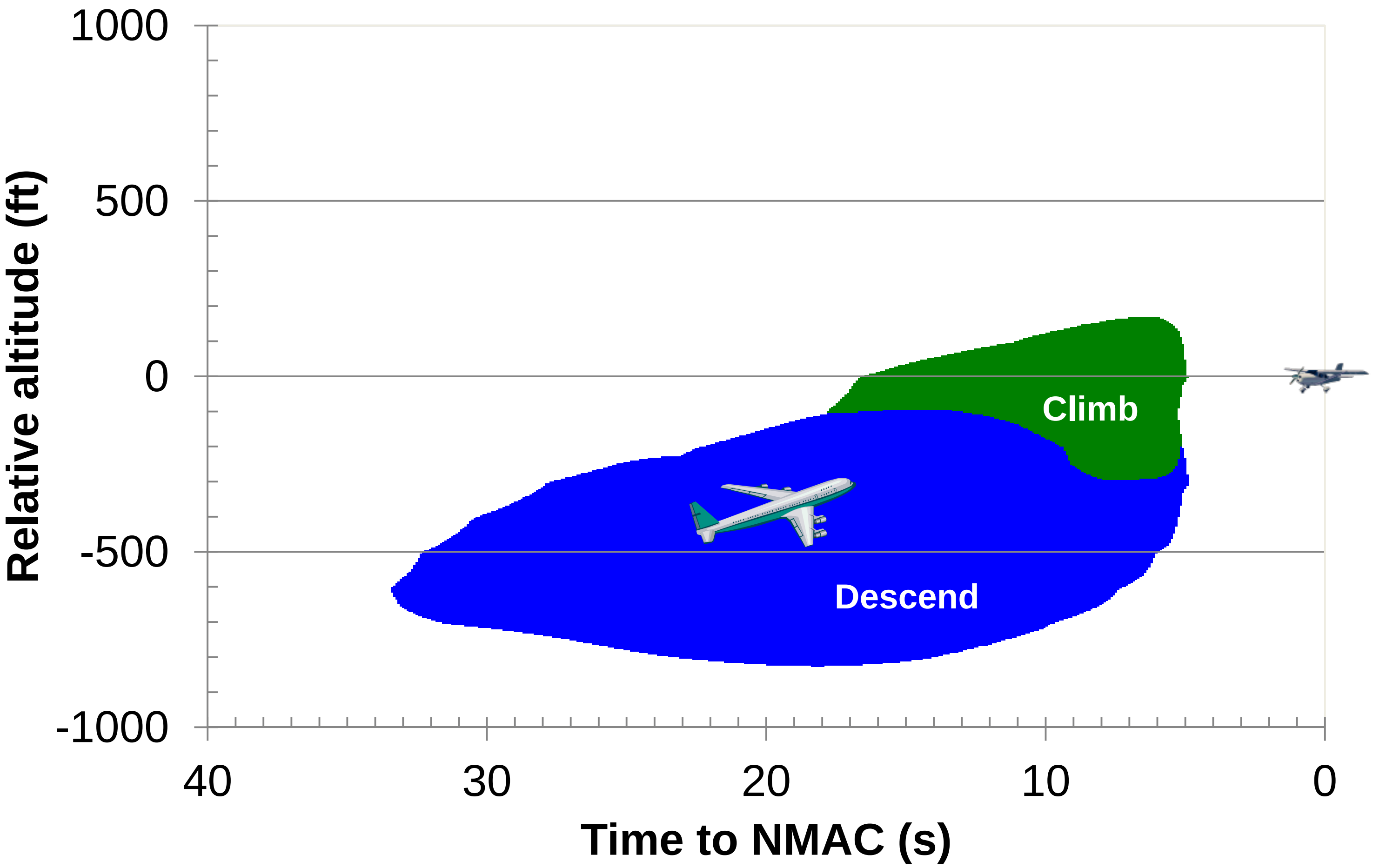
Optimized Logic

Both Own and Intruder Level

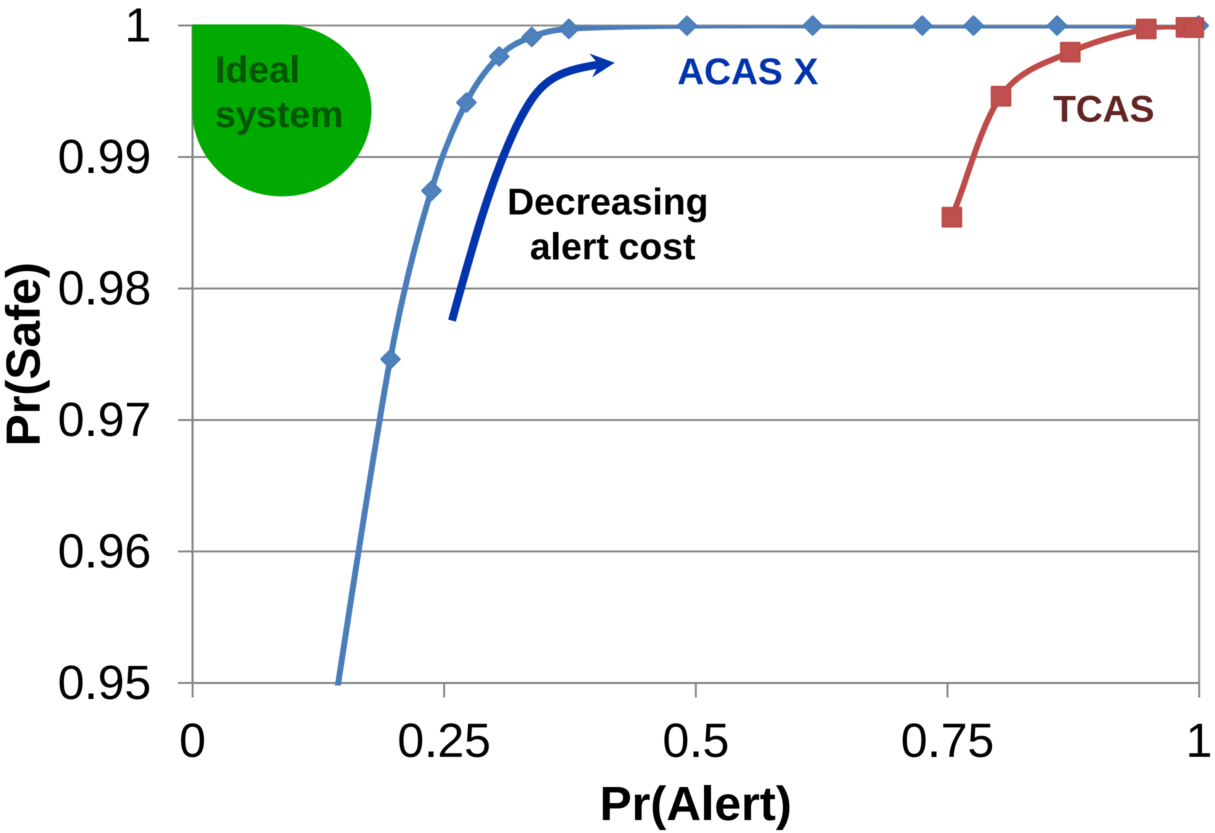


Optimized Logic

Own Climbing 1500 ft/min, Intruder Level



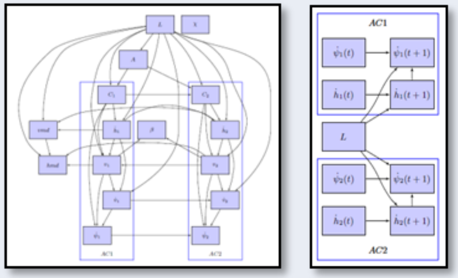
Safety Curve



Pr(Safe) = 1-Pr(NMAC)

Performance Validation

Airspace Encounter Models

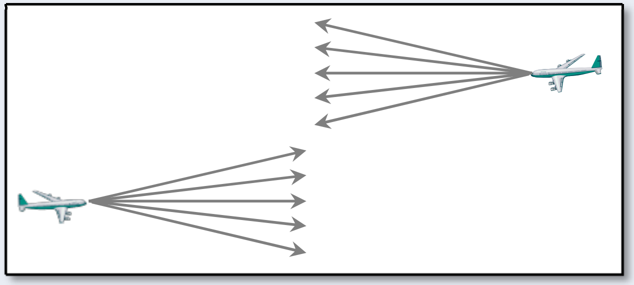


Generate many encounters
representative of airspace

Recorded Radar Tracks

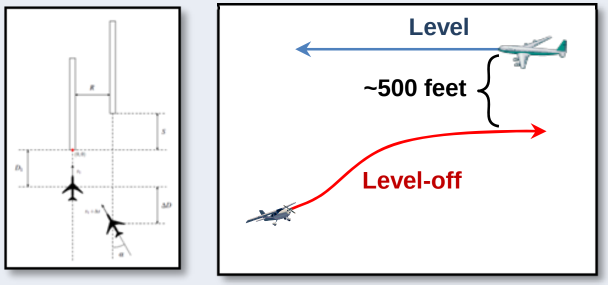
Recorded radar tracks with
known TCAS intervention

Stress Testing



Exhaustive variations
of certain classes of encounters

Scenario Specific Mini-Models



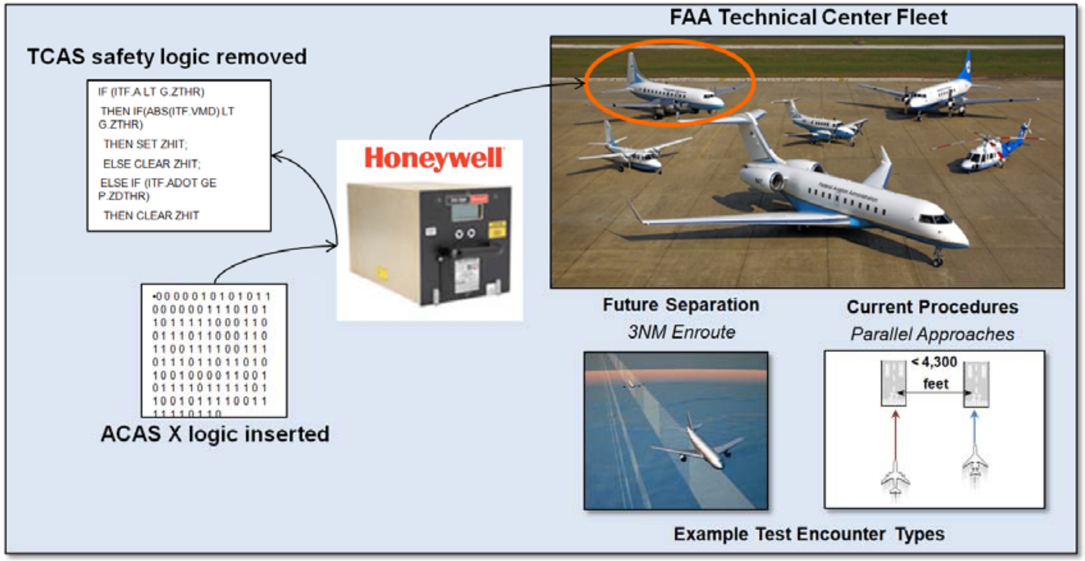
Focused models constructed
from expert knowledge and data

M. J. Kochenderfer, J. E. Holland, and J. P. Chryssanthacopoulos, "Next generation airborne collision avoidance system," *Lincoln Laboratory Journal*, Vol. 19, No. 1, pp. 17-33, 2012.

Future of ACAS X

- **Performance validation continues, initial results positive**
  - **Reduced nuisance alert rate: 63% fewer alerts**
  - **Complex reversal / crossing alerts reduced by 52%-68%**

- **Operational flight tests starting in 2013**



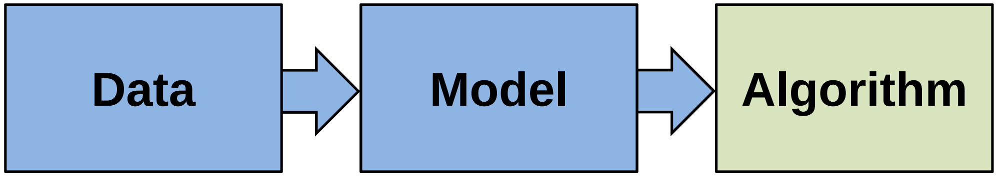
```
IF (ITF.A LT G.ZTHR)
 THEN IF(ABS(ITF.VMD) LT
G.ZTHR)
  THEN SET ZHIT;
  ELSE CLEAR ZHIT;
 ELSE IF (ITF.ADOT GE
P.ZDTHR)
  THEN CLEAR ZHIT
```

```
•0 0 0 0 0 1 0 1 0 1 0 1 1
0 0 0 0 0 0 1 1 1 0 1 0 1
1 0 1 1 1 1 1 0 0 0 1 1 0
0 1 1 1 0 1 1 0 0 0 1 1 0
1 1 0 0 1 1 1 1 0 0 1 1 1
0 1 1 1 0 1 1 0 1 1 0 1 0
1 0 0 1 0 0 0 0 1 1 0 0 1
0 1 1 1 1 0 1 1 1 1 1 0 1
1 0 0 1 0 1 1 1 1 0 0 1 1
1 1 1 1 0 1 1 0
```

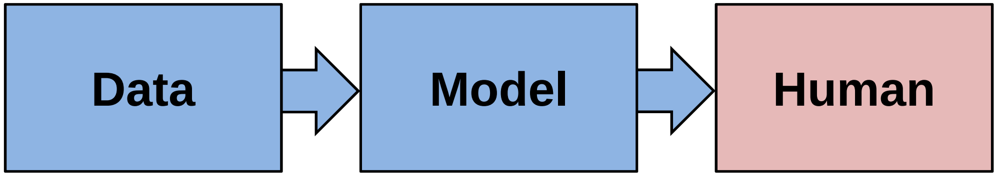
Final performance requirements and additional tuning will be vetted through a government / industry standards-making group

Two Vignettes

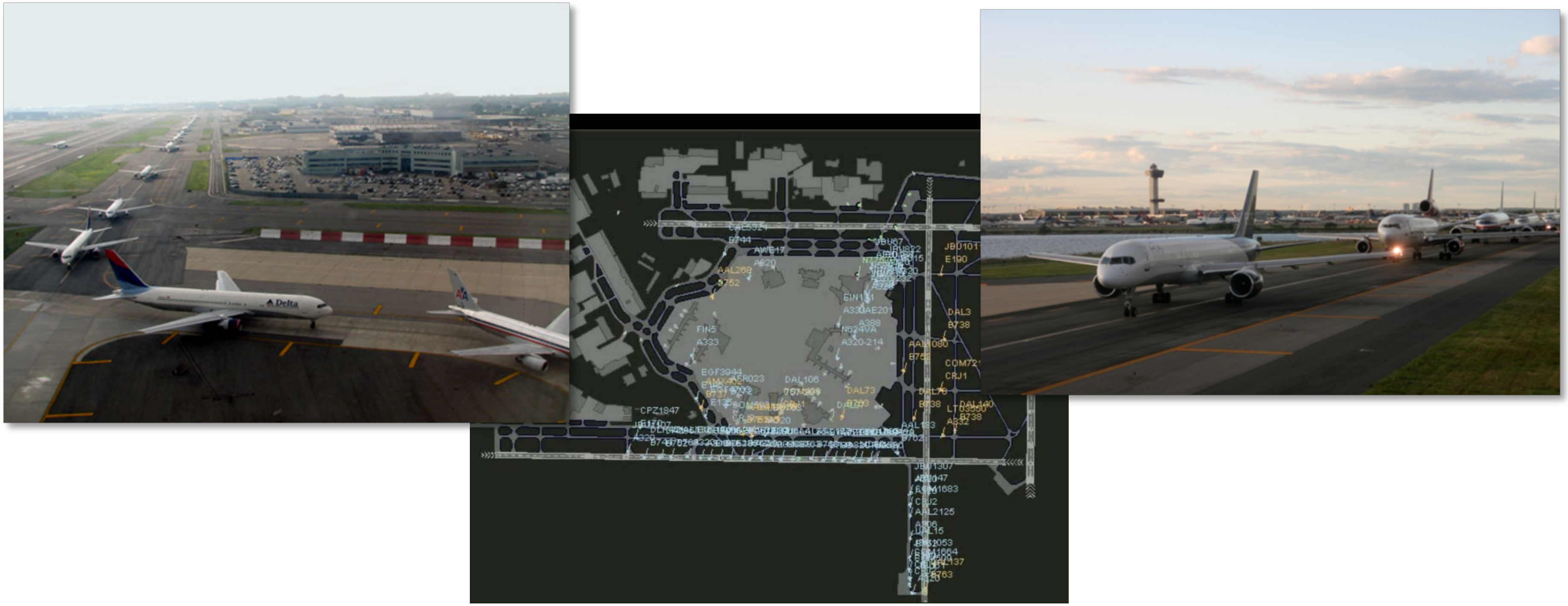
1: Collision avoidance



2: Airport departure management

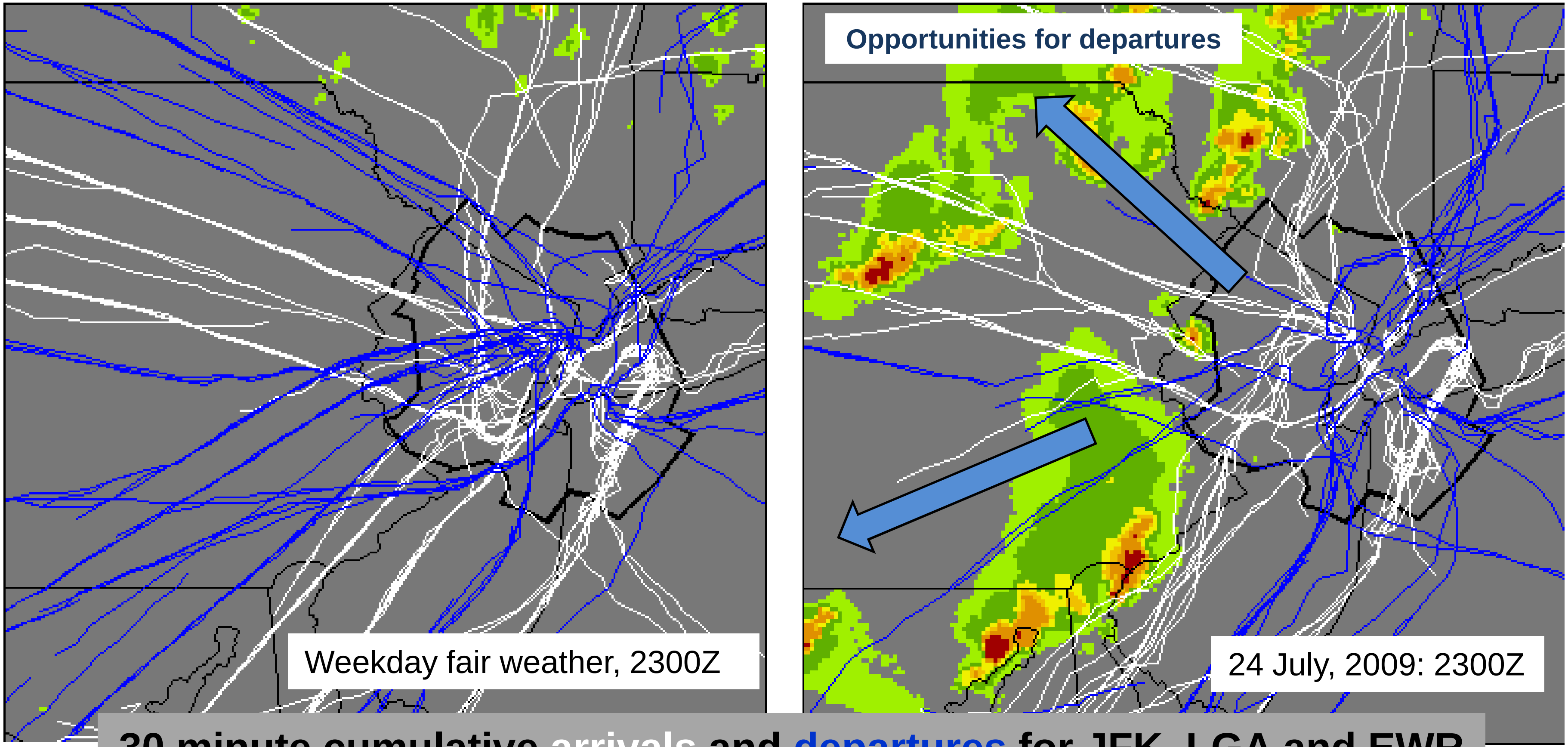


Motivation for Improving Departure Management



- **Estimated 75% of all US air traffic delays related to NY airports or airspace**
- **Severe Weather Avoidance Programs (SWAP) for convective weather in place 60-80 days per year in NY**

Missed Departure Opportunities



Weekday fair weather, 2300Z

Opportunities for departures

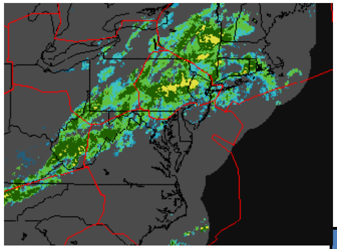
24 July, 2009: 2300Z

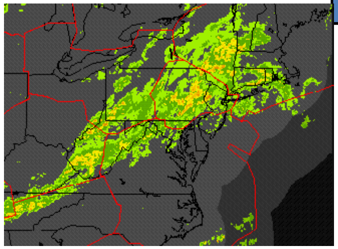
30 minute cumulative arrivals and departures for JFK, LGA and EWR

- **Many factors contribute toward missed opportunities**
- **Example of ‘difficult decision making’: time pressure, ambiguous information, significant consequences**

Route Availability Planning Tool (RAPT)

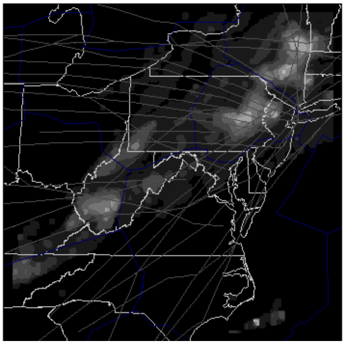
CIWS echo top forecast



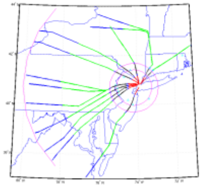


CIWS VIL forecast

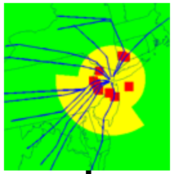
Weather Avoidance Field (WAF)



Departure route database

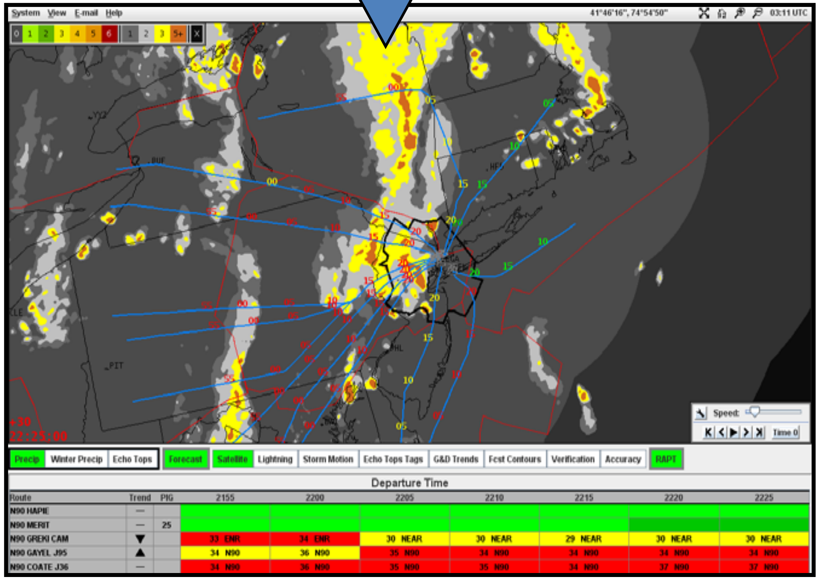


Deviation sensitivity field



RAPT

**Blockage calculation,
status threshold + timeline analysis**

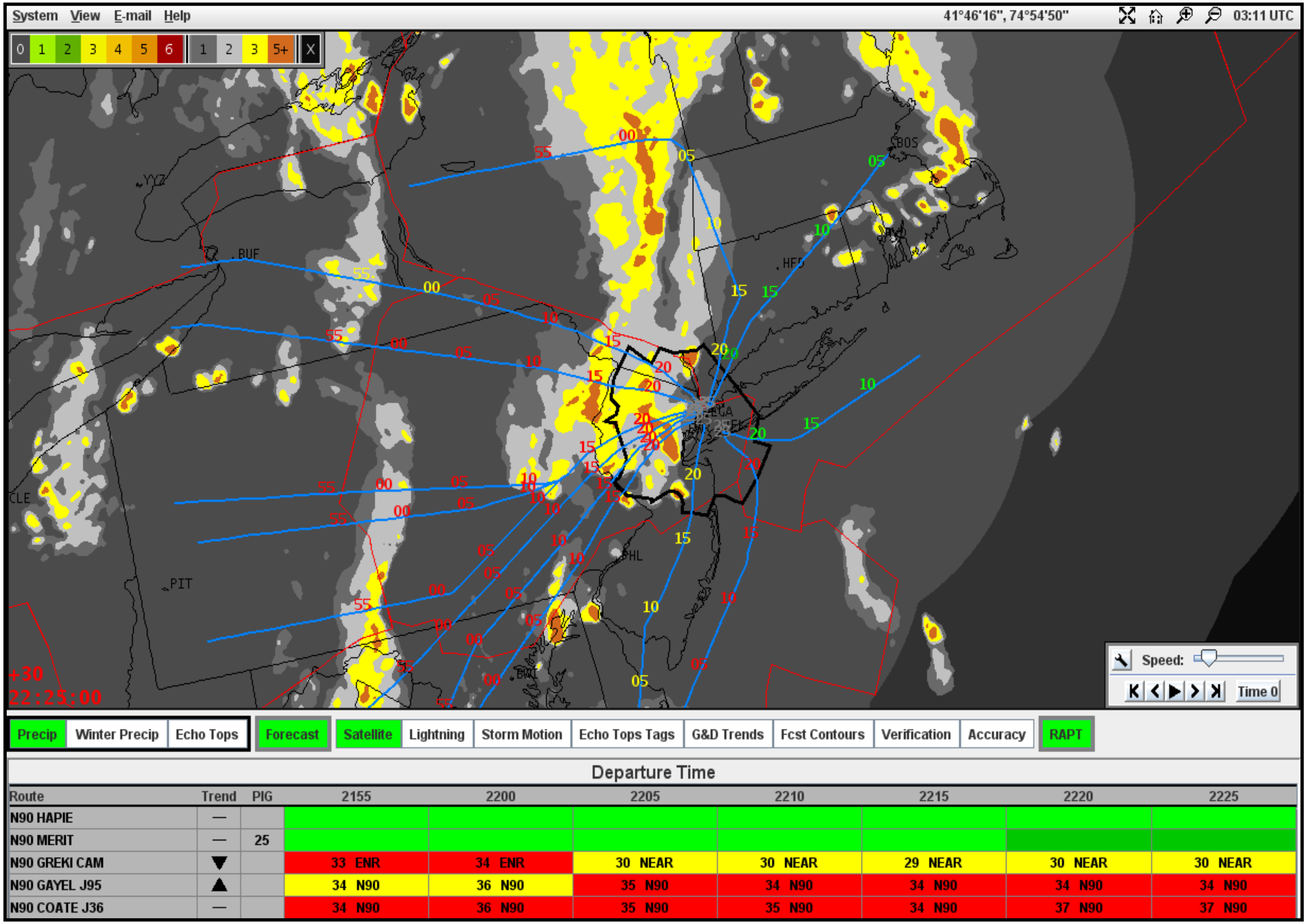


Departure Time

Route	Trend	PIG	2155	2200	2205	2210	2215	2220	2225
N90 HAPIE	—								
N90 MERIT	—	25							
N90 GREKI CAM	▼		33 ENR	34 ENR	30 NEAR	30 NEAR	29 NEAR	30 NEAR	30 NEAR
N90 GAYEL J95	▲		34 N90	36 N90	35 N90	34 N90	34 N90	34 N90	34 N90
N90 COATE J36	—		34 N90	36 N90	35 N90	35 N90	34 N90	37 N90	37 N90

RAPT provides 30 minute forecast of departure route impacts via dedicated and web-based displays deployed to FAA and airline facilities

RAPT User Interface

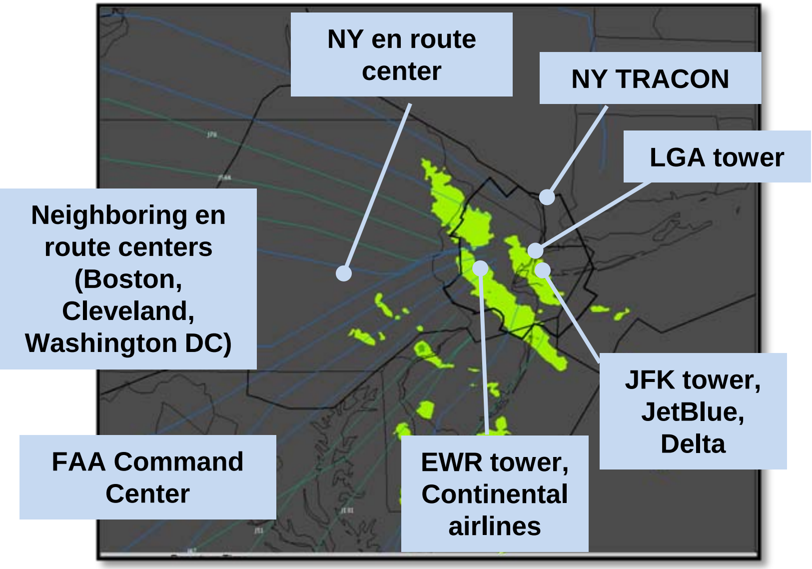


Departure Time

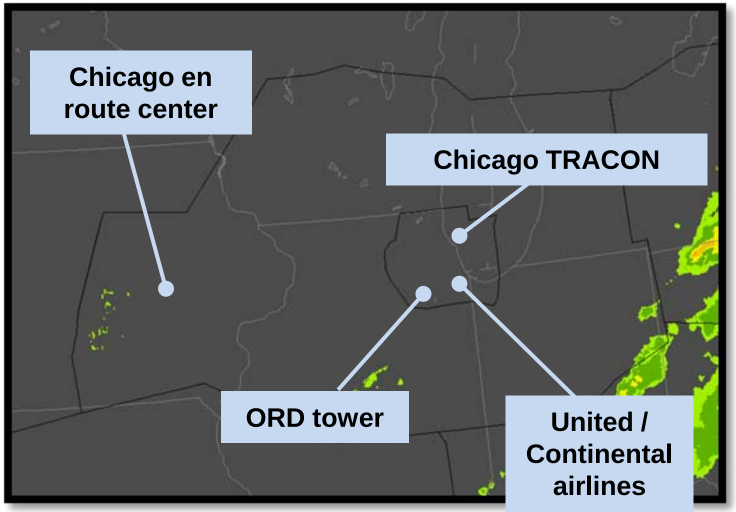
Route	Trend	PIG	2155	2200	2205	2210	2215	2220	2225
N90 HAPIE	—		🟩	🟩	🟩	🟩	🟩	🟩	🟩
N90 MERIT	—	25	🟩	🟩	🟩	🟩	🟩	🟩	🟩
N90 GREKI CAM	▼		33 ENR	34 ENR	30 NEAR	30 NEAR	29 NEAR	30 NEAR	30 NEAR
N90 GAYEL J95	▲		34 N90	36 N90	35 N90	34 N90	34 N90	34 N90	34 N90
N90 COATE J36	—		34 N90	36 N90	35 N90	35 N90	34 N90	37 N90	37 N90

RAPT Evaluations

New York



Chicago

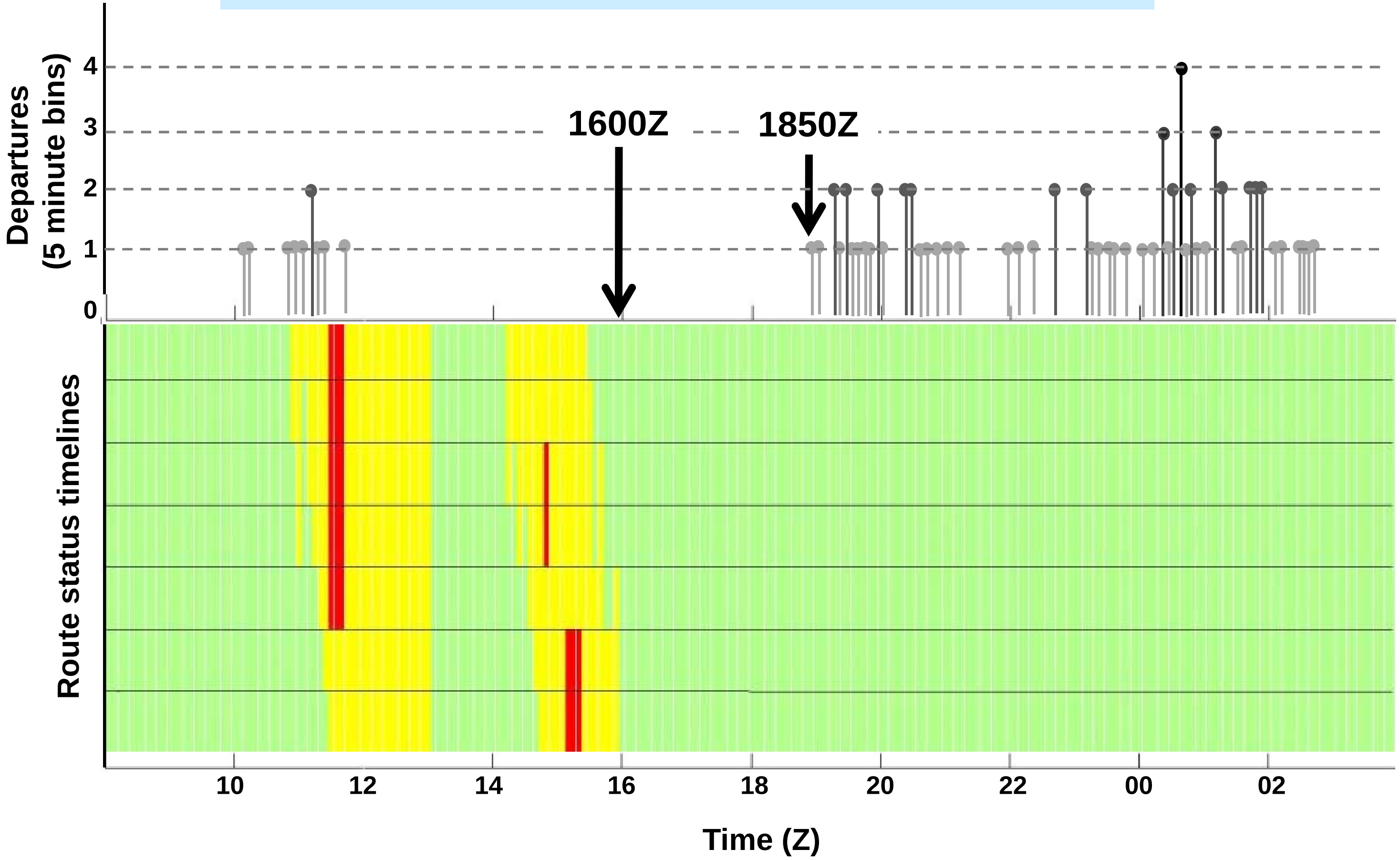


- **Deployment included annual training, user group meetings, and operational evaluations**
  - **NY (2007–2009): concept development, investment decision**
  - **Chicago (2010, 2012): extension of concept, site adaptation**

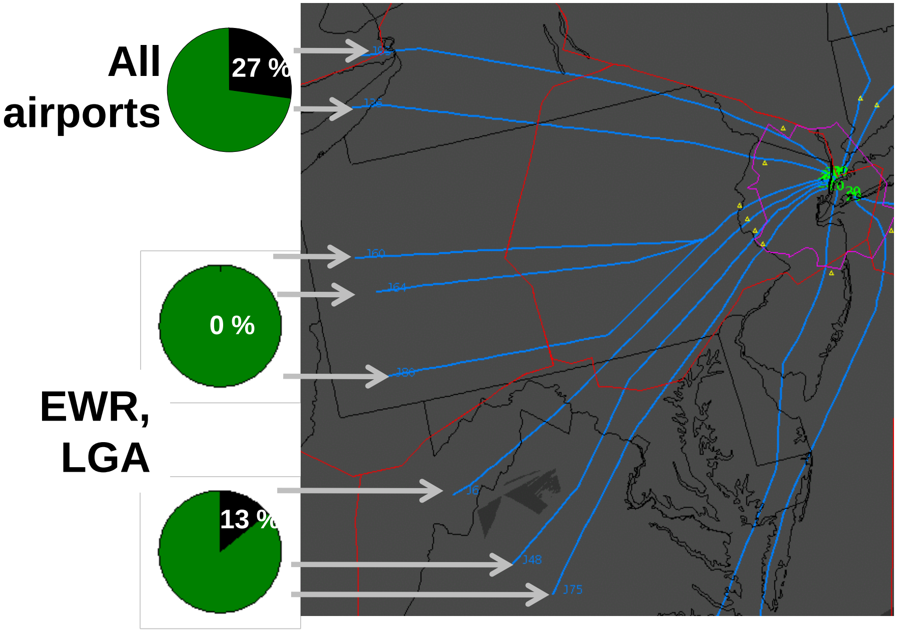
- **Evaluations combined simultaneous observations at all operational facilities with data analysis from several thunderstorm events**

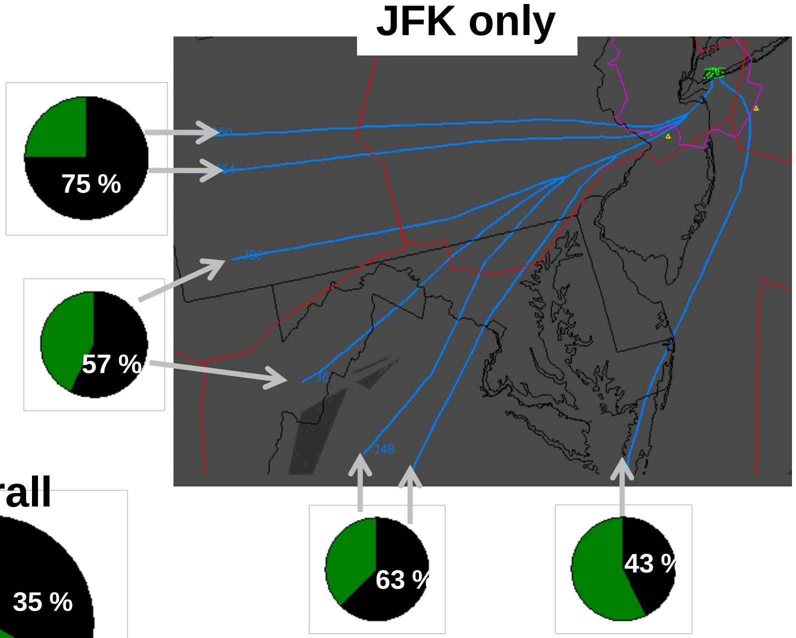
Example Post-impact Green Missed Opportunity

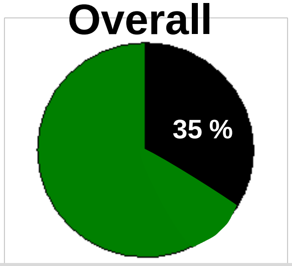
2 hour, 50 minute gap between end of weather impact and first departure



Missed Opportunities for Timely Route Reopening on Post-Impact Green







🟩 Efficient reopening
⬛ Missed opportunity

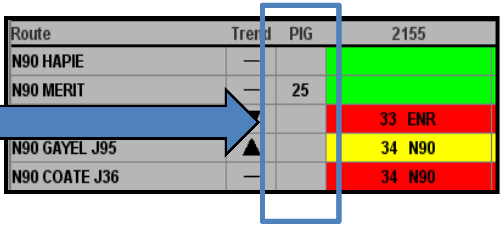
11 days studied (2008): 113 post-impact green opportunity events

Efficient reopening = departure within 15 minutes of Green
Missed opportunity = no departure within 15 minutes

Developments in Response

GREEN = GO

🟩🟩🟩🟩🟩🟩🟩



Route	Trend	PIG	2155
N90 HAPIE	—		🟩
N90 MERIT	—	25	🟩
	▼		🟥 33 ENR
N90 GAYEL J95	▲		🟨 34 N90
N90 COATE J36	—		🟥 34 N90

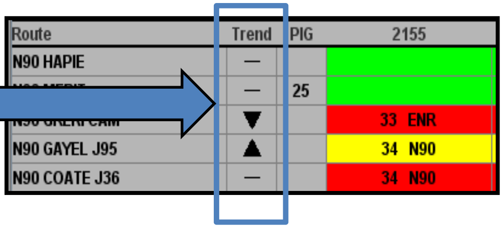
Post-impact Green timer

RED = PLAN REROUTE

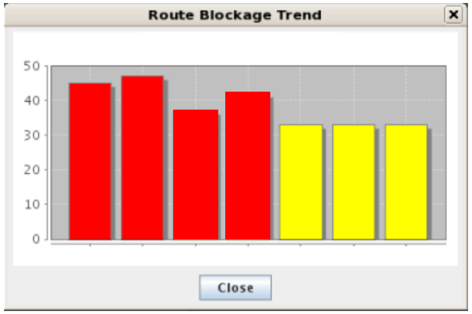
🟥🟥🟥🟥🟥🟥🟥

YELLOW = USE JUDGMENT (apply / reduce restrictions)

🟨🟨🟨🟨🟨🟨🟨



Route	Trend	PIG	2155
N90 HAPIE	—		🟩
	—	25	🟩
	▼		🟥 33 ENR
N90 GAYEL J95	▲		🟨 34 N90
N90 COATE J36	—		🟥 34 N90

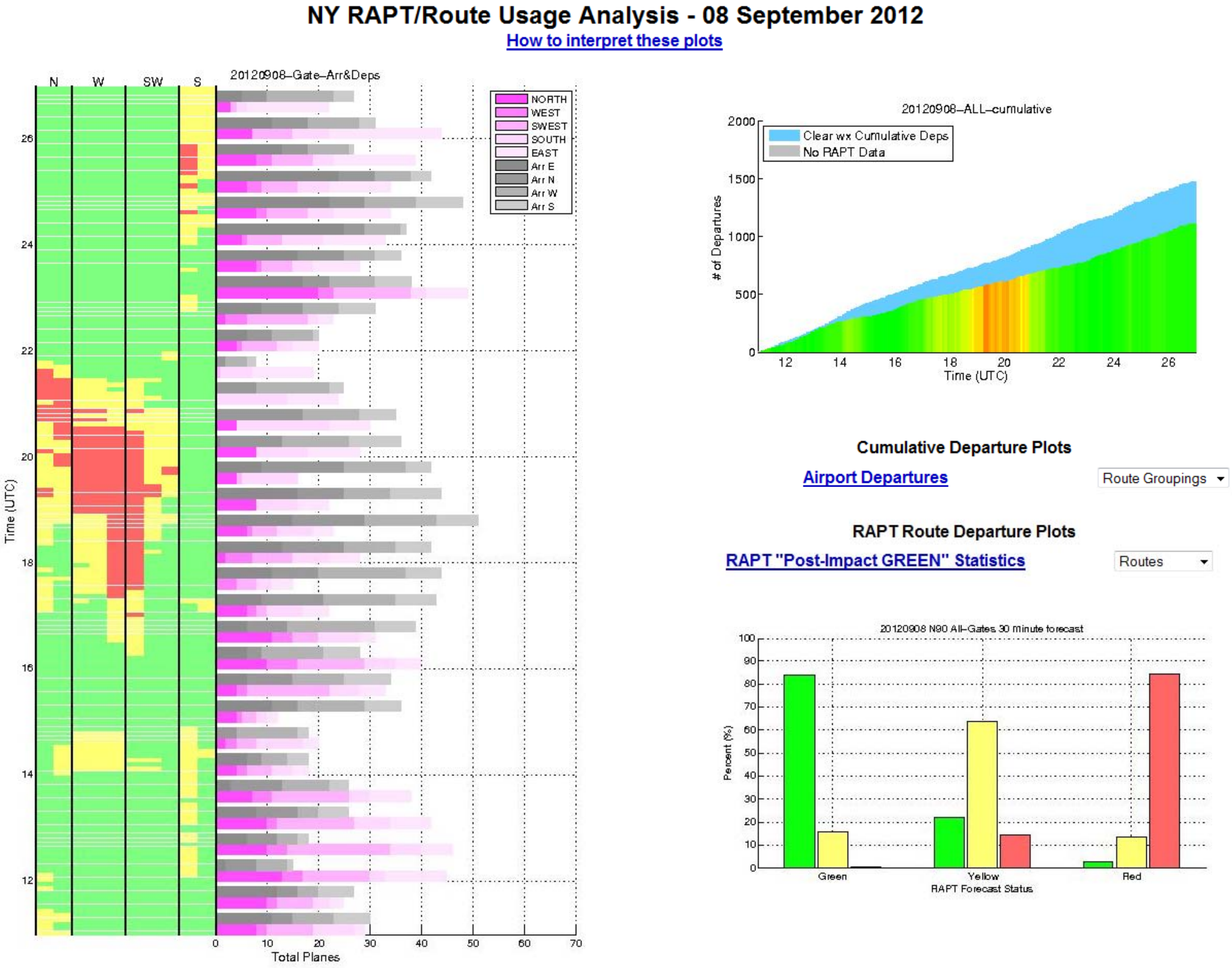


Past blockage and echo top trends

- **Refocus training, ConOps on high confidence, high value decisions**
- **Provide additional information where uncertainty is high**
- **Provide automated next-day analysis and performance metrics**

Additional Feedback to the User:

Daily performance summaries



NY RAPT/Route Usage Analysis - 08 September 2012

How to interpret these plots

Cumulative Departure Plots

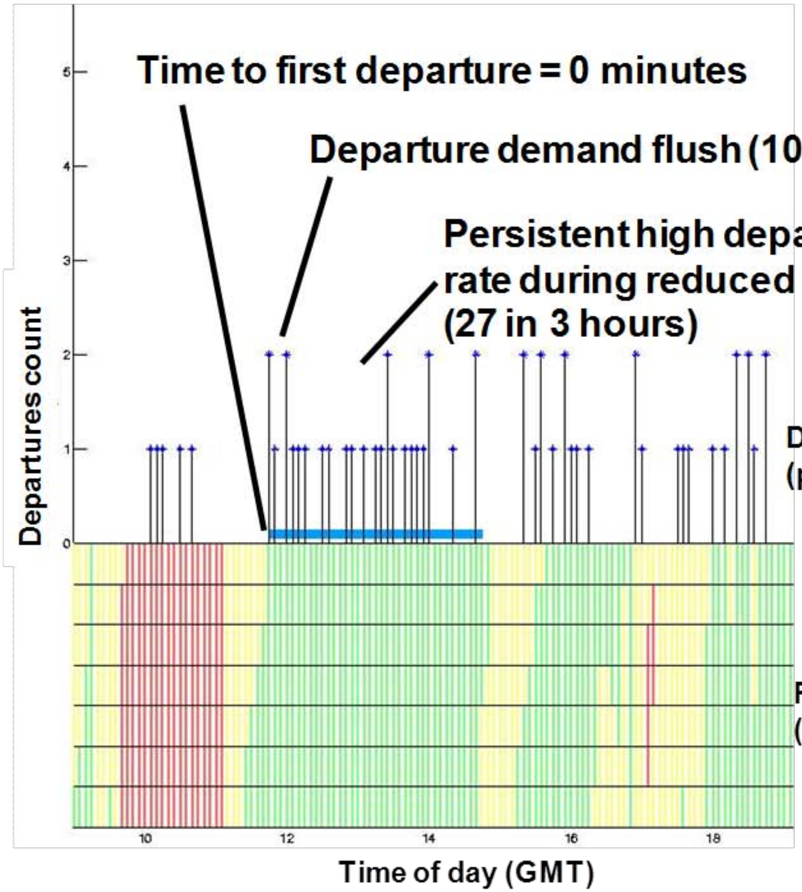
Airport Departures

RAPT Route Departure Plots

RAPT "Post-Impact GREEN" Statistics

Using RAPT to Proactively Reopen a Departure Route

July 29, 2010



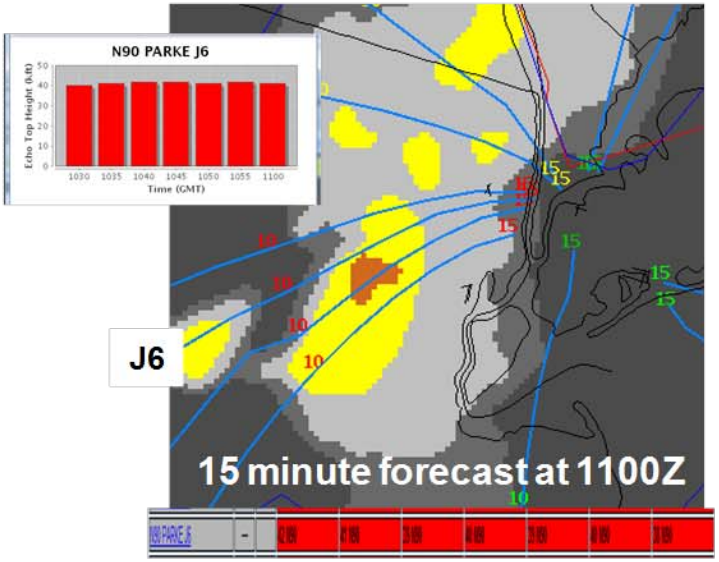
Time to first departure = 0 minutes

Departure demand flush (10 in the first hour)

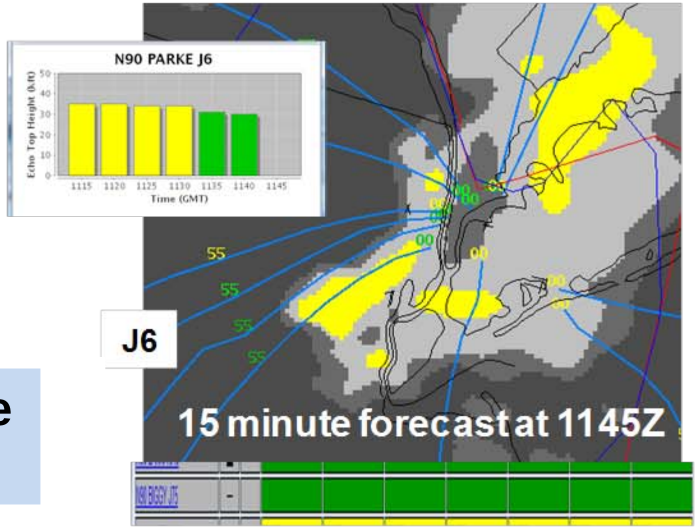
Persistent high departure rate during reduced impact (27 in 3 hours)

Departures on route (per 5 minute bin)

RAPT forecast timelines (5 minute updates)



15 minute forecast at 1100Z

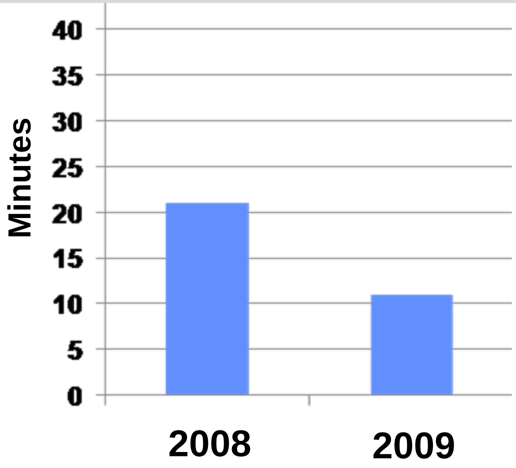


15 minute forecast at 1145Z

Proactive re-opening of closed route releases pent-up demand efficiently

Impacts

Post-impact Green: Mean Time to First Departure

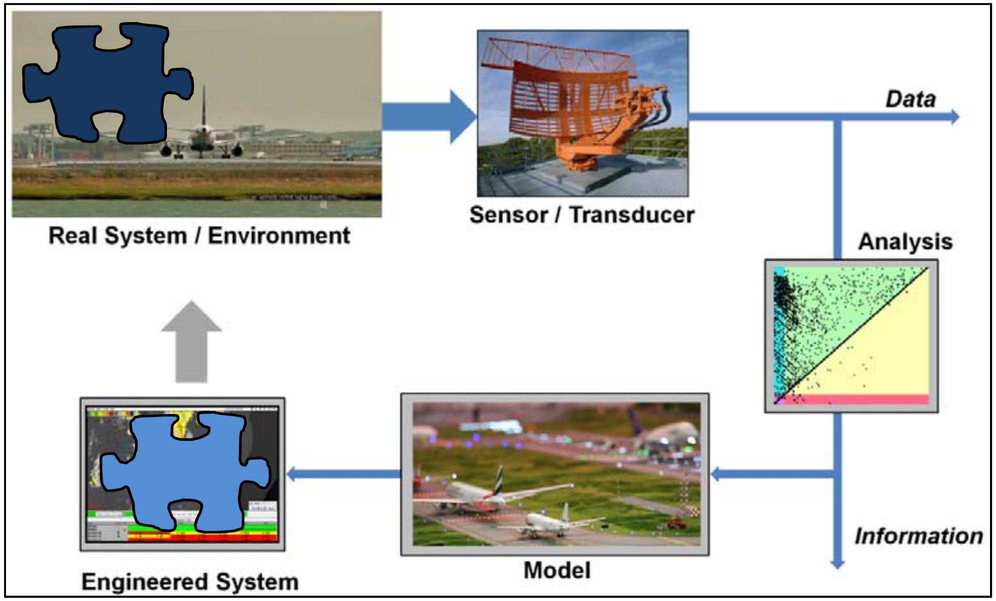


	Delay savings (hours)
2007 TOTAL	2,366
2008 TOTAL	2,618
2009 TOTAL	5,549

- Improved performance and evidence of procedural evolution
  - More rapid, higher-volume route re-opening
  - Reduced reliance on pathfinders to validate open routes
  - Proactive ‘open on Yellow’ in anticipation of Green
- RAPT slated for FAA deployment to Chicago, Philadelphia, Washington DC, New York

Summary

- **Models and algorithms need to be matched to actual operations via the available data**



- **Broad access to data, coupled with advanced techniques, are enabling new direct algorithmic design methods**
- **Many exciting challenges remain in Air Traffic Control**
  - **Extracting benefit from advances in Communications, Navigation, and Surveillance**
  - **Push toward more effective design and assessment methods**