Optimal Aircraft Rerouting During Commercial Space Launches

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Motivation

Problem:

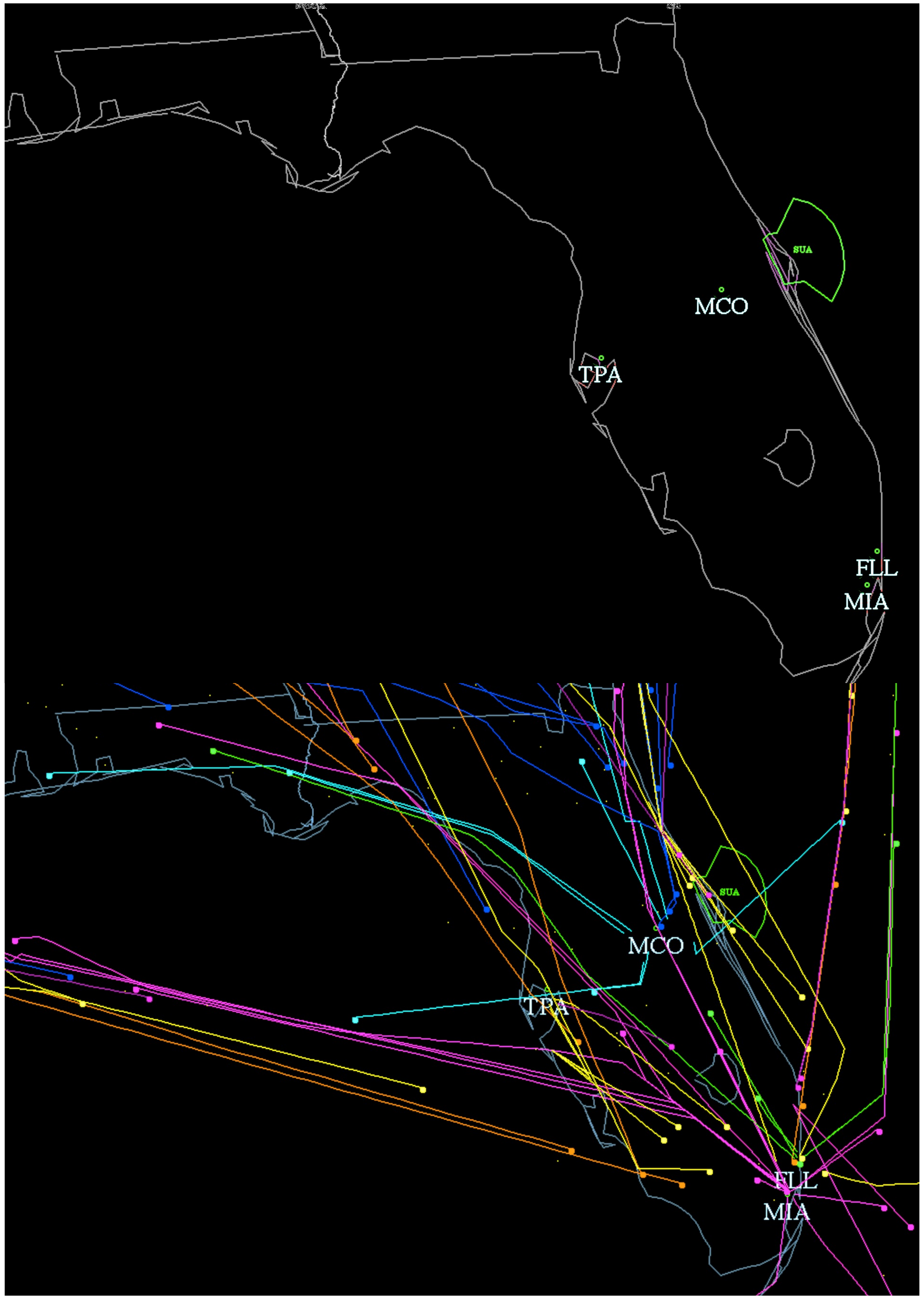
- Launch vehicle anomaly can lead to 10,000+ pieces of debris
- Projected increase in commercial space launches

Current process: FAA shuts down large column of airspace

- Airspace shut for hours causing many aircraft reroutes

Research area: FAA is investigating methods to reduce airspace disruptions while maintaining airspace safety

Motivation Continued



Dynamic restrictions would:

- Allow safety zones to change throughout launch trajectory and launch vehicle health
- Account for uncertainties
- Adapt to any anomalies
- Promote efficiency
- Ensure safety

Proposed solution:

Model problem as a Markov Decision Process and solve for optimal policy

Outline

- Commercial Space Launch Scenario
- Problem Formulation
- Results
- Conclusions

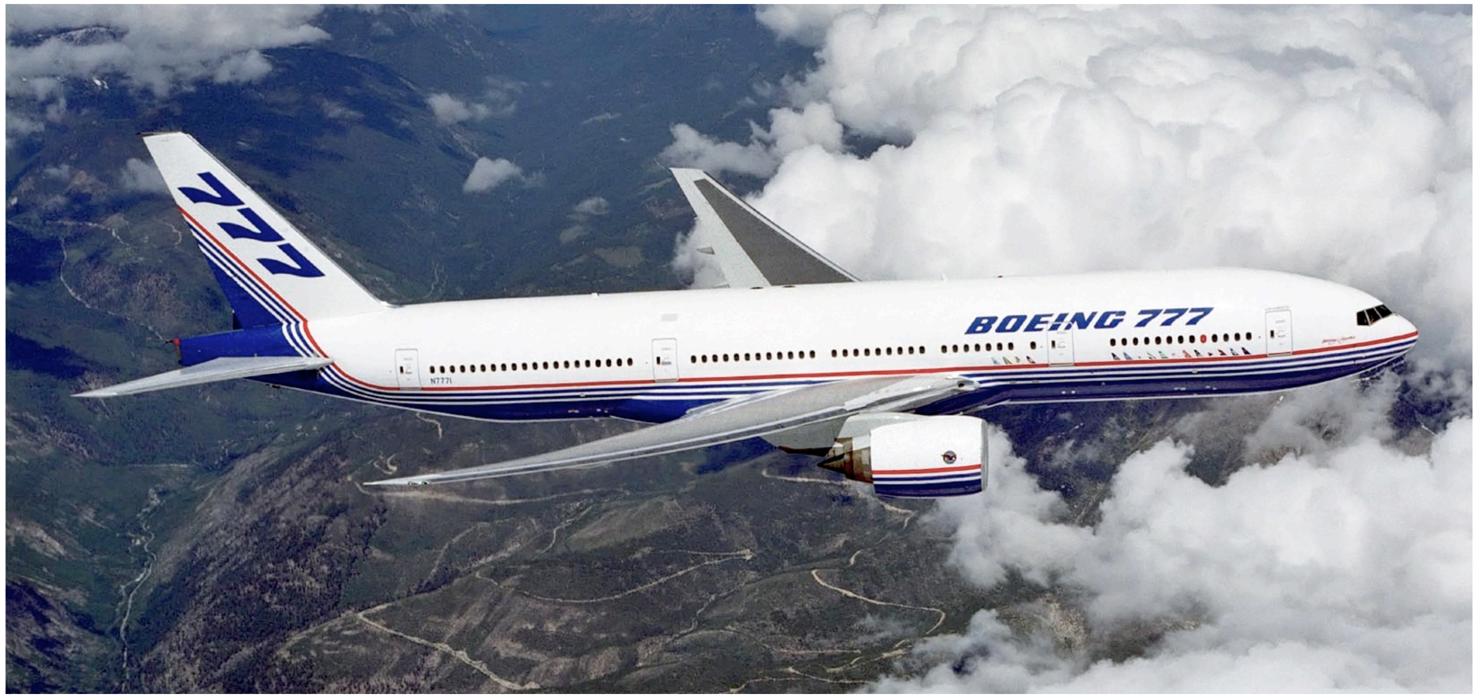
Scenario

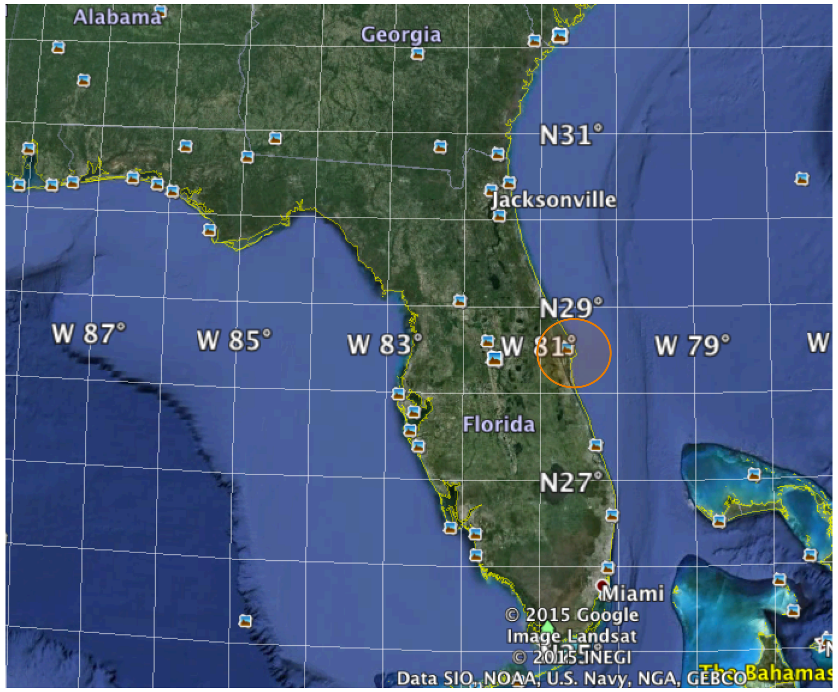
Launch Environment

- Cape Canaveral
- October

Aircraft: Boeing 777 – 200

- Cruise Speed at 35,000 ft (10.7 km): 0.84 Mach
- Turn Rate: standard rate (3° per second) and half standard rate (1.5° per second)



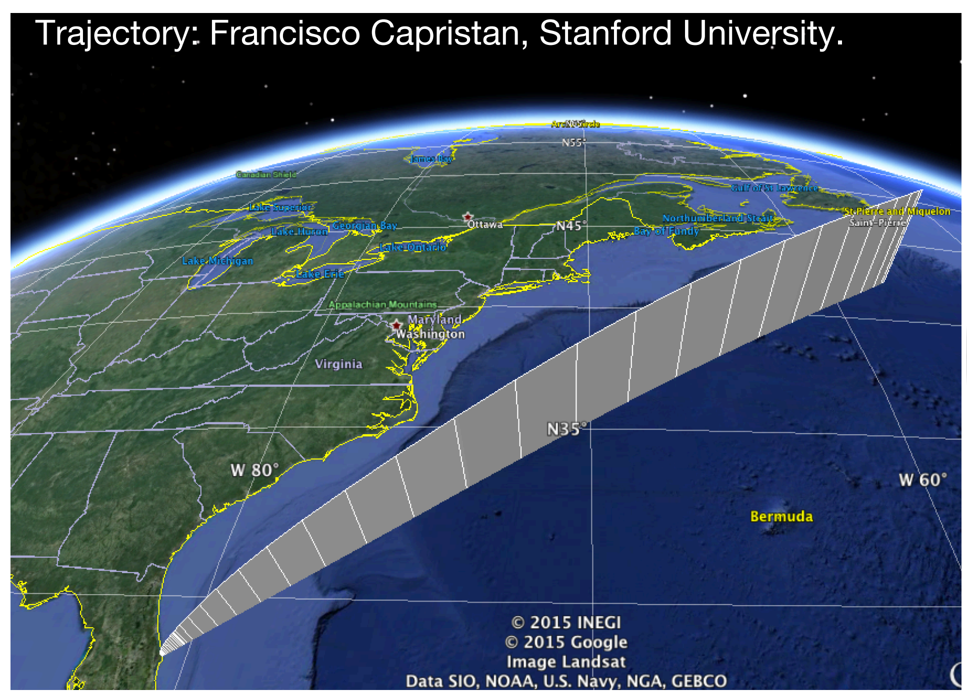


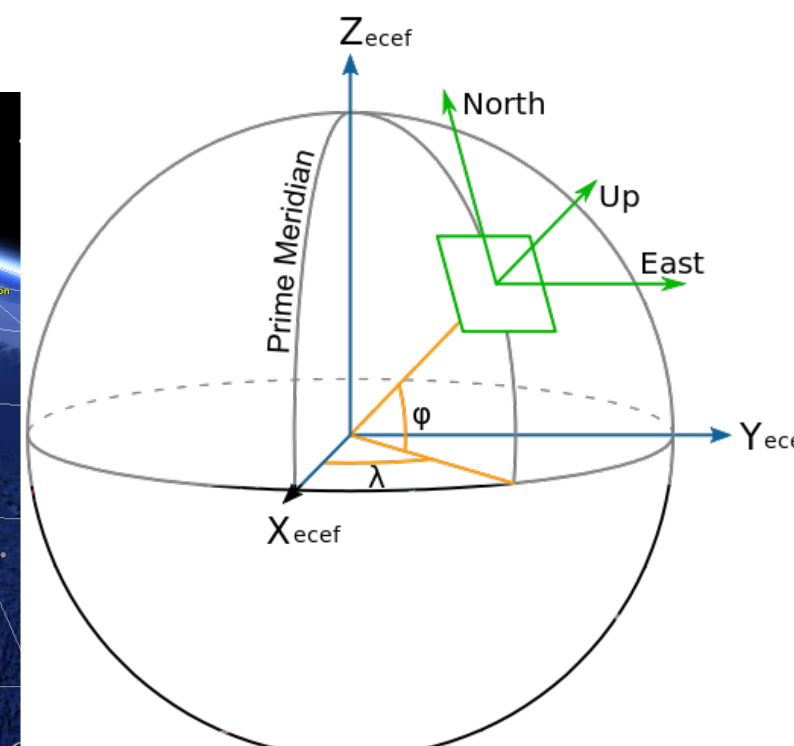
Launch Vehicle

Vehicle: Two-stage-to-orbit rocket

Trajectory:

- Derived longitude latitude altitude position
- Modeled as a 2D trajectory using east and north coordinates of the east north up reference frame





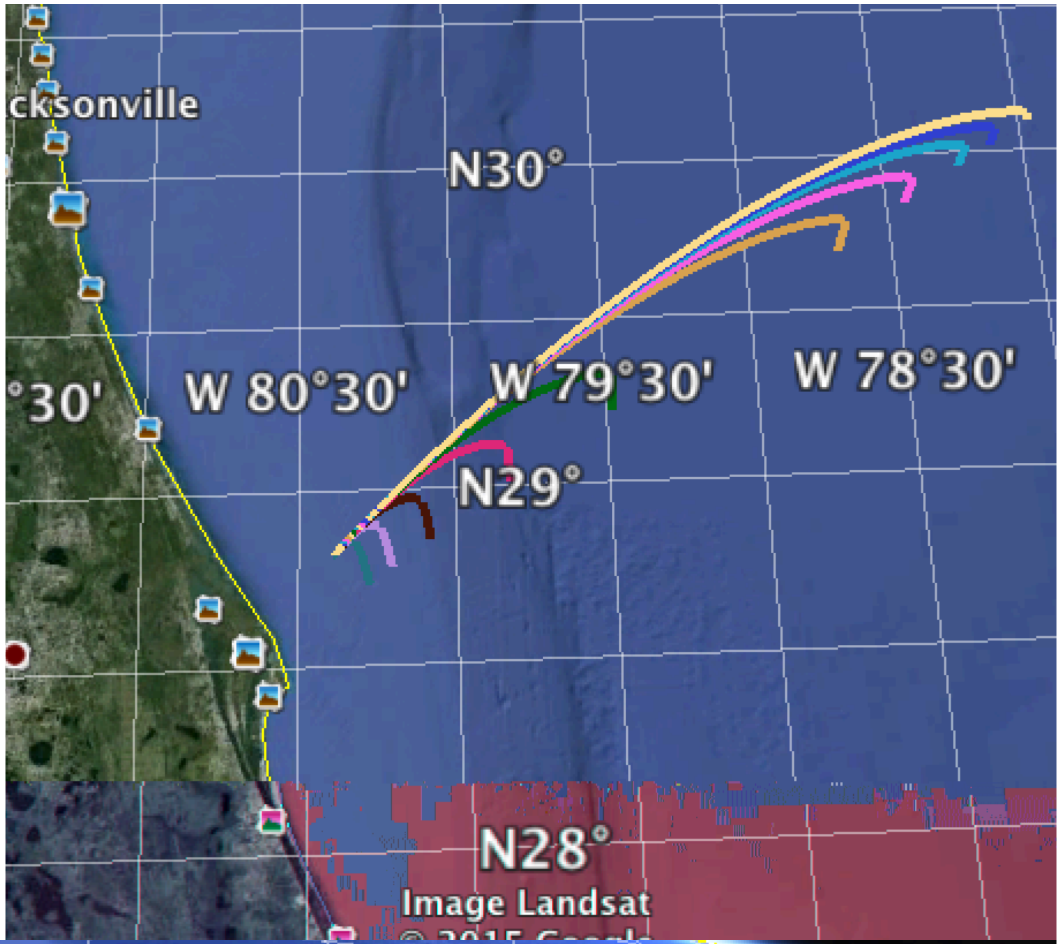
Debris Model

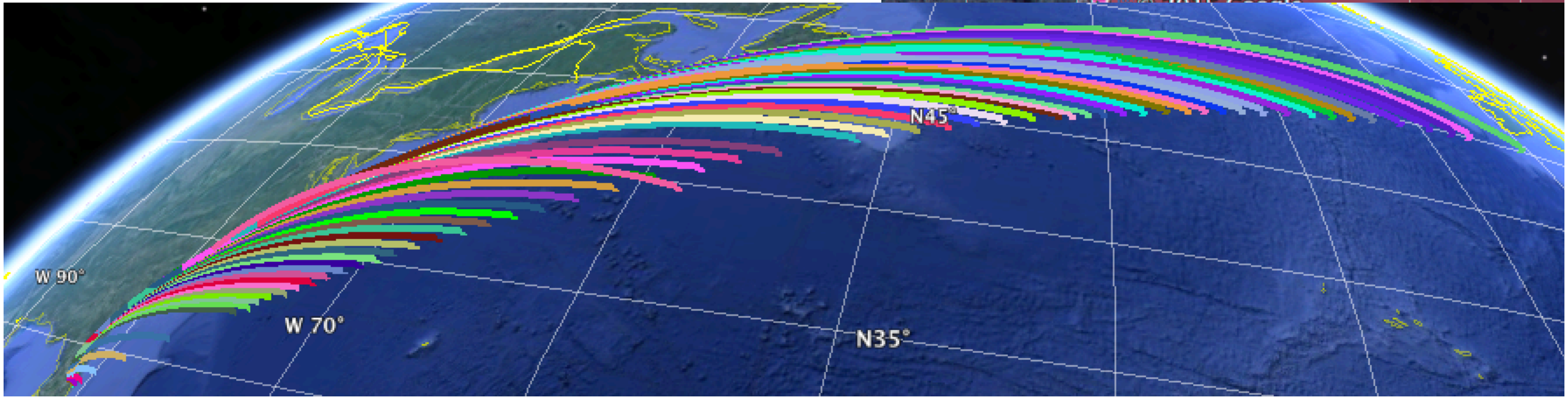
Look at 11 types of debris

- Ballistic coefficient, size, weight

Update trajectory at every time step

- Launch vehicle state vector as the initial state
- Trajectory found with RSAT





RSAT Weather Inputs

Model: Global Forecast System

Location: Kennedy Space Center

Range: 1 to 25 km

Inputs at each Height:

- Latitude and longitude position of measurement
- Mean density
- Density standard deviation
- Wind velocity in up, west, and south directions
- Wind velocity standard deviations

For initial implementation, all inputs are the average of a month's worth of data

Safety Thresholds

Where

Location debris trajectory intersects 35,000 feet

Ellipse around location

- Minor axis = 500 feet
- Major axis = 1000 feet in direction of launch vehicle at time of anomaly

When

Time debris trajectory intersects 35,000 feet ± 20 sec

Anomaly is modeled for that time step ± 10 sec

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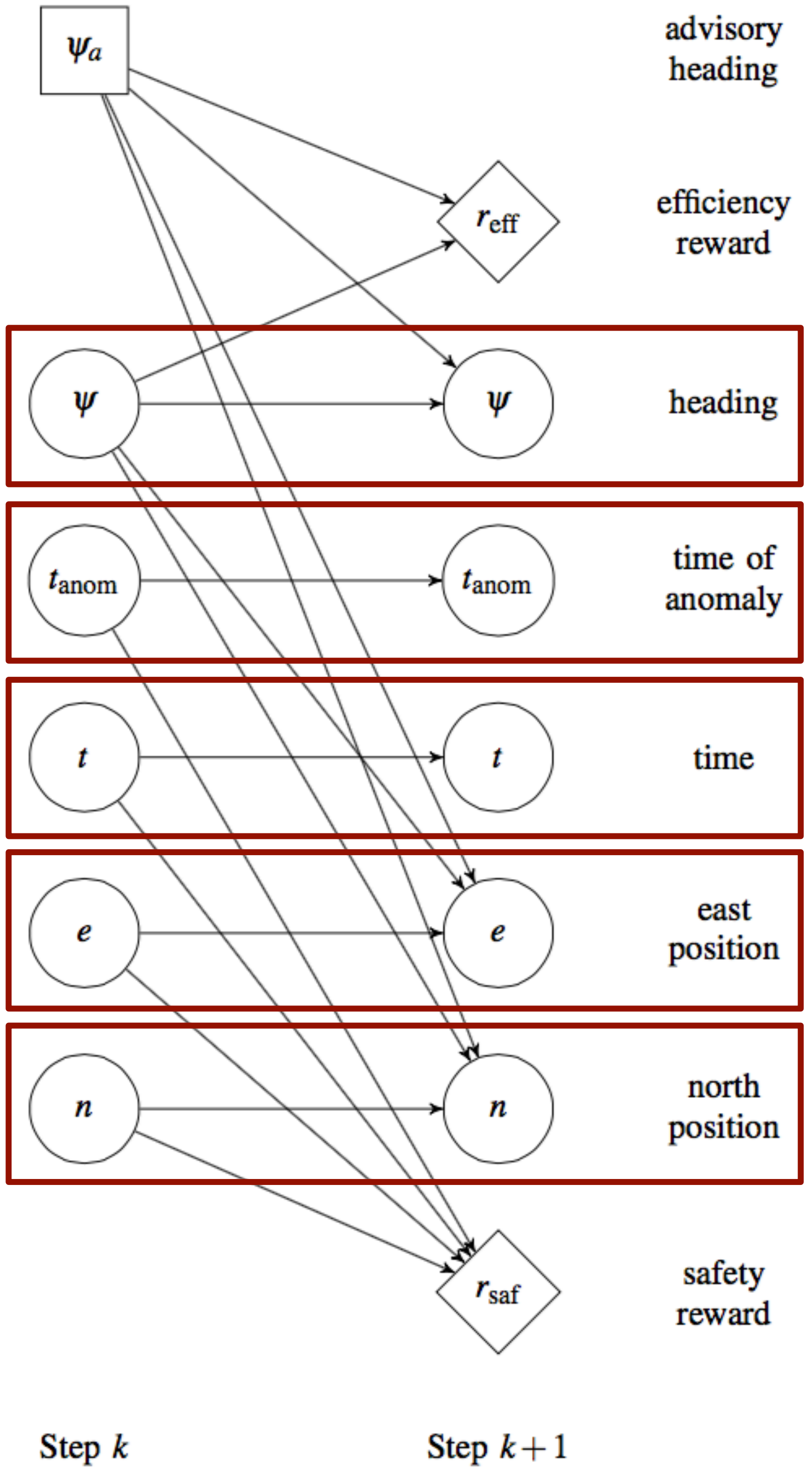
Markov Decision Process Overview

S is the **state space**: a set that contains all possible states

A state s ∈ S captures:

- Aircraft position
- Aircraft heading
- Time of anomaly
- Time since launch

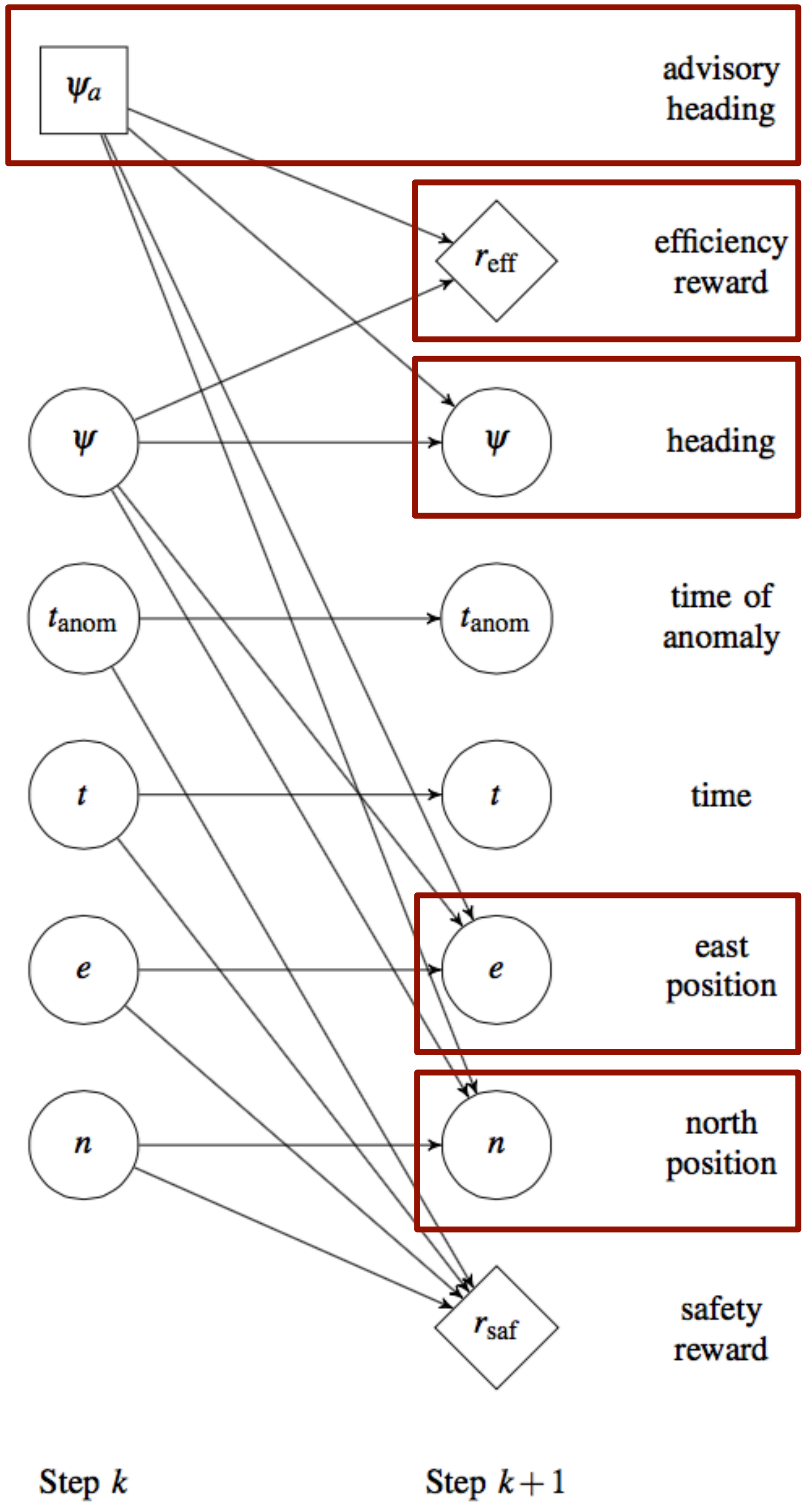


Markov Decision Process Overview

A is the **action space**: a set that contains all possible actions

An action a ∈ A corresponds to:

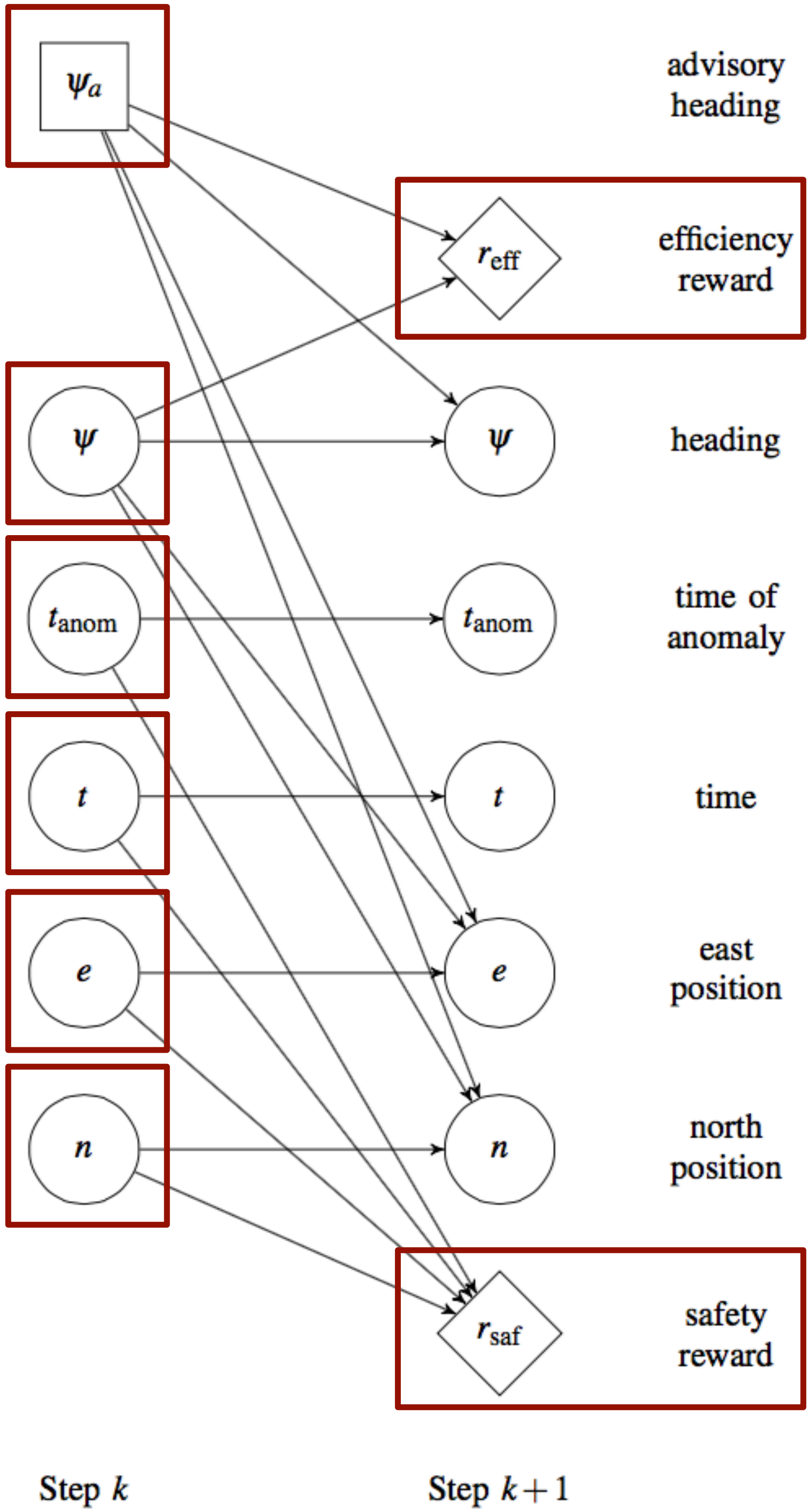
- heading change advisory



Markov Decision Process Overview

R is the **reward model**:

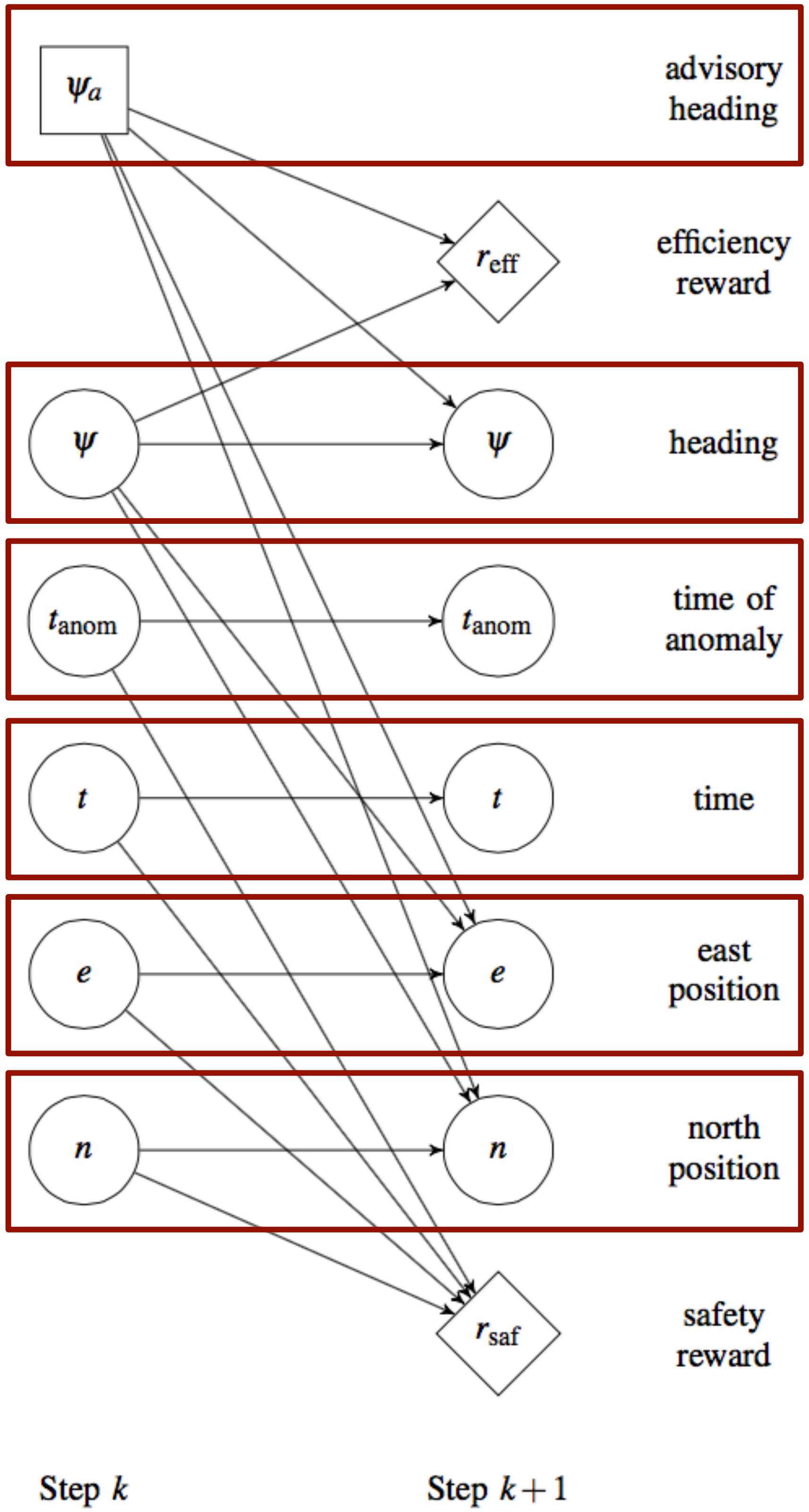
- Current state, s
- Action, a
- Immediate reward: R(s, a)
- Reward penalizes disruption and violations of safety thresholds



Markov Decision Process Overview

T is the **transition model**

- Current state, s
- Action, a
- New state, s′
- Probability of transitioning to s′: T(s′ | s, a)
- Captures uncertainty in the launch vehicle and aircraft trajectories



Aircraft State Space

Variable	Discretization	Units
e	$-25{,}000, -23{,}000, \ldots, 51{,}000$	meters
n	$-45{,}000, -43{,}000, \ldots, 65{,}000$	meters
ψ	$0, 15, \ldots, 360$	degrees
t_{anom}	NIL, $0, 10, \ldots, 110$	seconds
t	$0, 10, \ldots, 810$	seconds

Grid: State space modeled as a 5 dimensional grid with all possible combinations of the components

- 58,203,600 possible states

Action Space

Possible Actions

- 15° heading changes (for 10 second intervals) from 0° to 360°
- An additional aircraft action, NIL

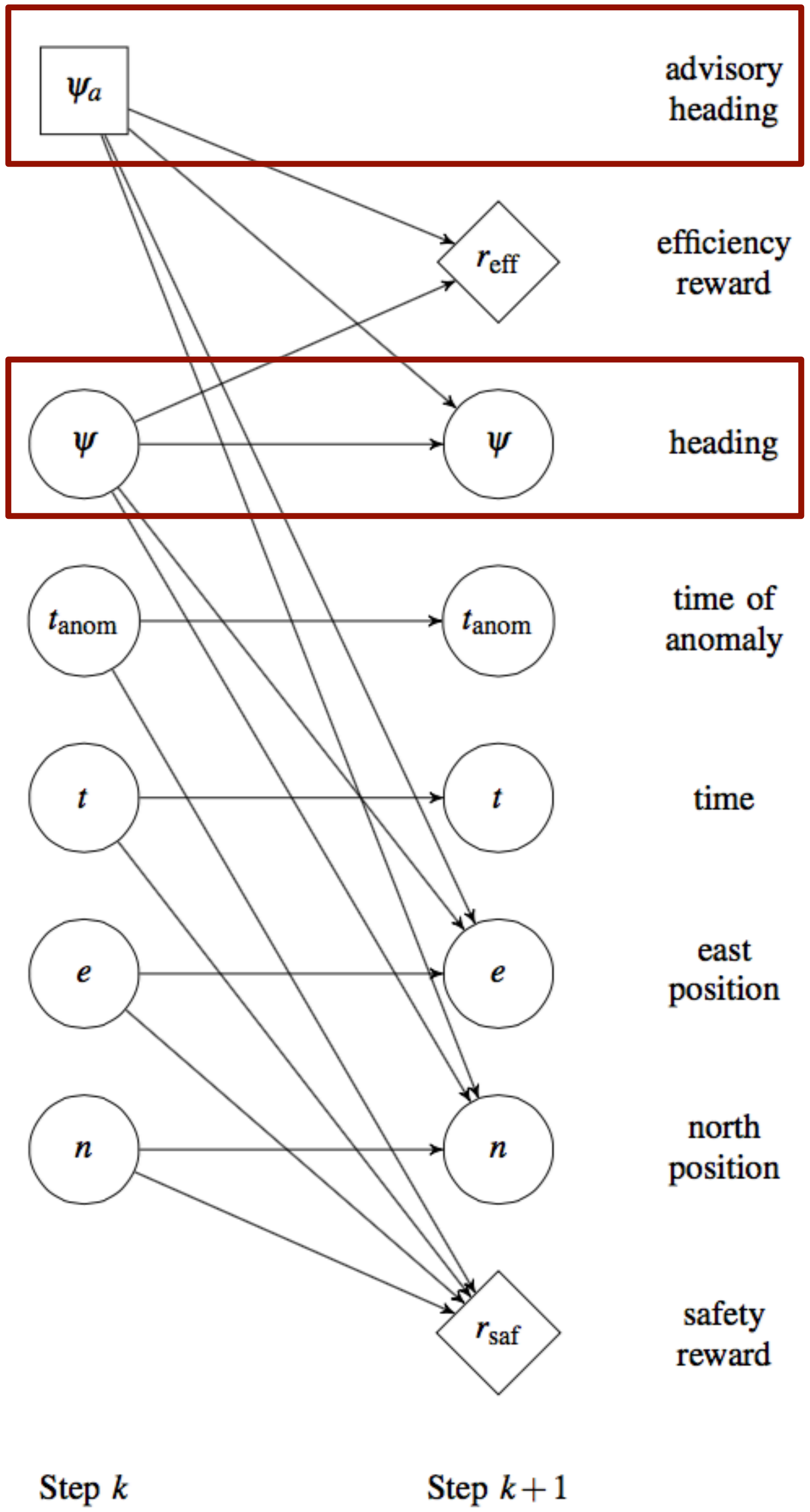
NIL (No Advisory)

- If there is no advisory, the aircraft follows a normal distribution
- This representation accounts for future aircraft trajectory uncertainty

Transition Model

Heading Update

- If NIL, there is a normal distribution of possible headings
- If advised heading is current heading, pilot always responds
- If advised heading is new heading, pilot responds 50% of the time (average response delay = 20 sec)



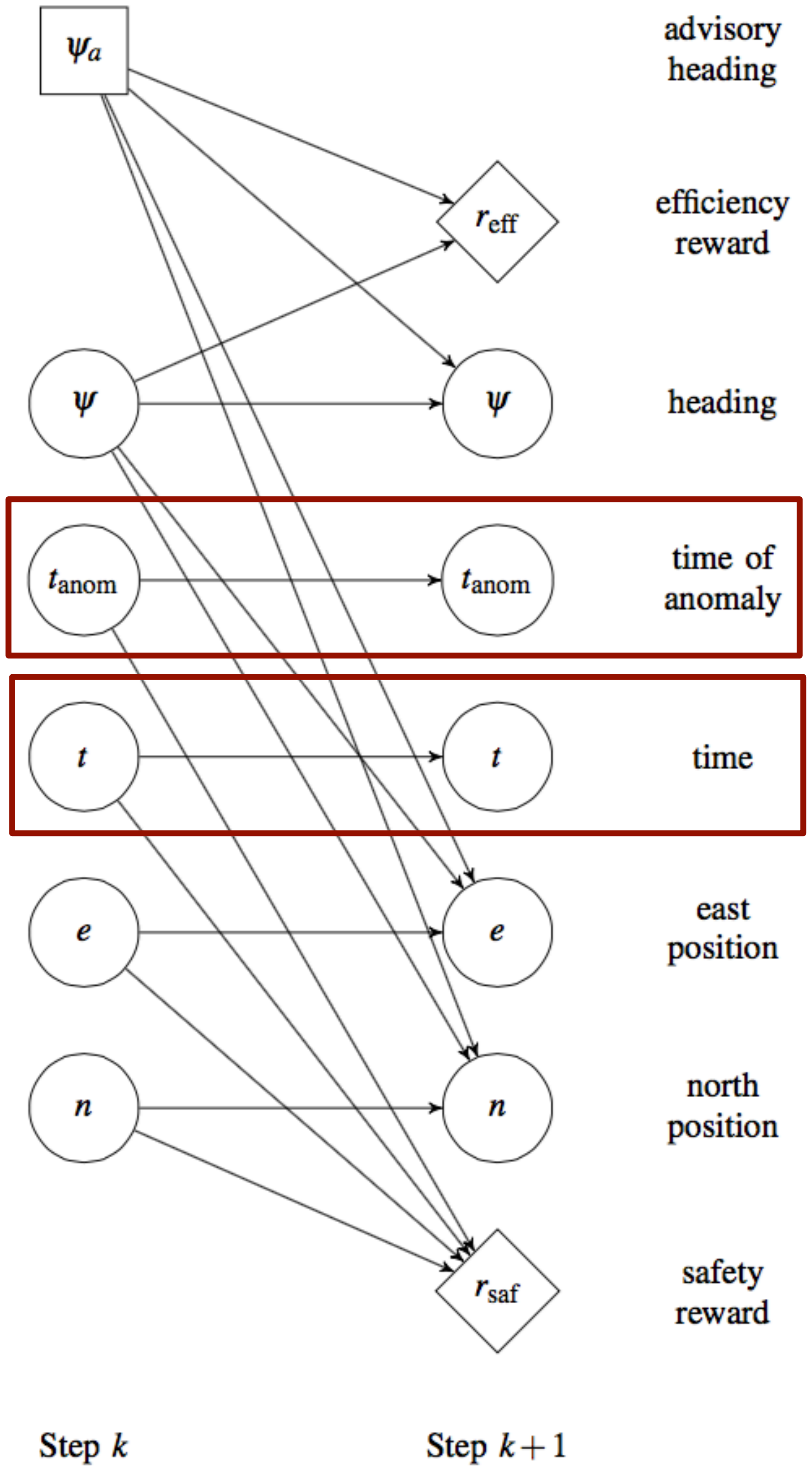
Transition Model

Time of Anomaly Update

- If an anomaly has already occurred, t_{anom} does not change
- If an anomaly has not occurred, 5.2% of the time, an anomaly occurs at the next time step
- The anomaly rate is equivalent to 50% over the duration of the first stage

Time Update

- Time increments by 10 sec



Transition Model

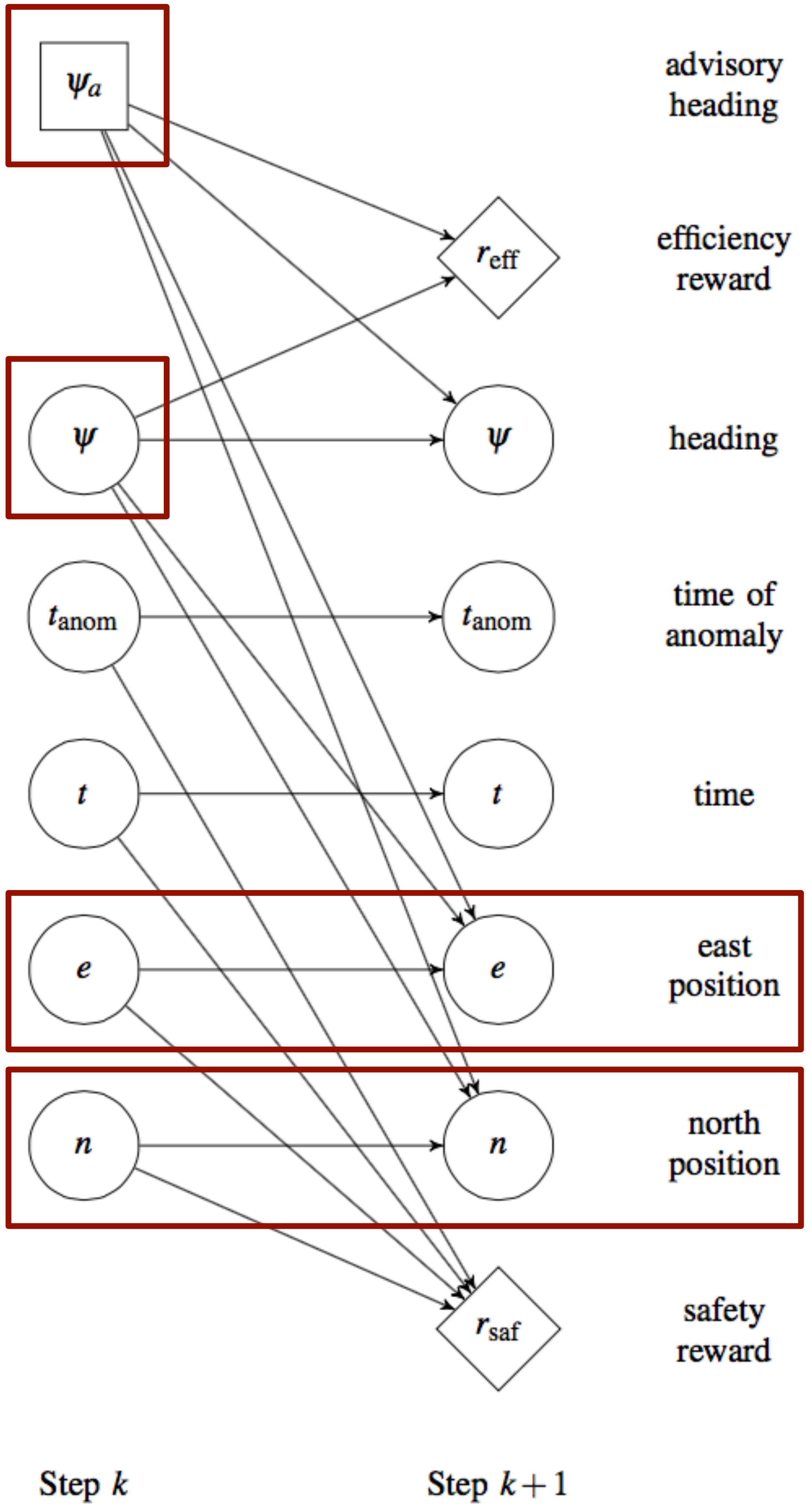
Position Updates

$$\begin{bmatrix} e \\ n \end{bmatrix} \leftarrow \begin{bmatrix} e + v\sin(\psi) \\ n + v\cos(\psi) \end{bmatrix}$$

- v = 0.84 Mach

Comments

- Values are interpolated if not exactly on a grid node
- MDP terminates at 810 sec



Reward Model

Reward = $\lambda\, r_{eff} + r_{saf}$

Efficiency	
$\psi = \text{NIL}$	0
No Change	-0.01
ψ Change $\leq 30°$	-1
ψ Change $> 30°$	$-\infty$
Safety	
$\leq$ Threshold from Launch Vehicle	-1
$>$ Threshold from Launch Vehicle	0
$\leq$ Threshold from Debris	-1
$>$ Threshold from Debris	0

Solution

Returns:

- Policy: action for every possible state
- Optimal policy maximizes immediate rewards(utility):

$$U^*(s) = \max_{a \in A} \left[R(s,a) + \sum_{s' \in S} T(s' \mid s,a) U^*(s') \right]$$

Method: Backward Induction Value Iteration

- Cycles over all of the possible states and actions

  Backward induction allows a single sweep through all of the states

Computing an optimal policy required ten minutes on 20 Intel Xeon E5-2650 cores running at 2.4 GHz

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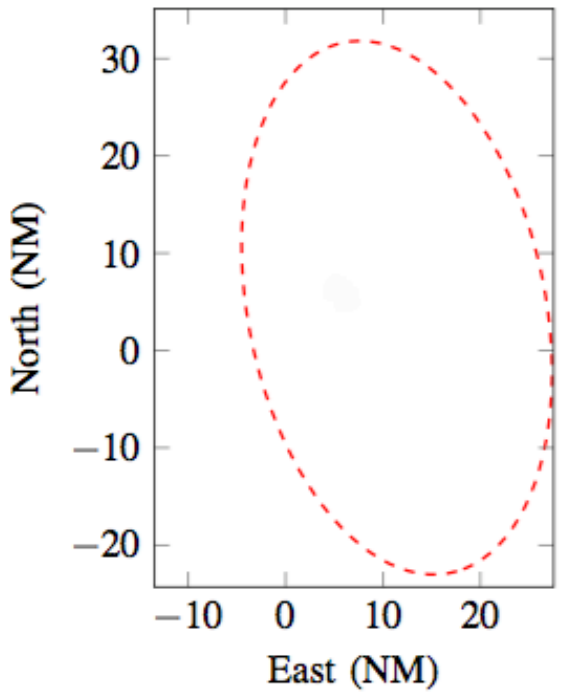
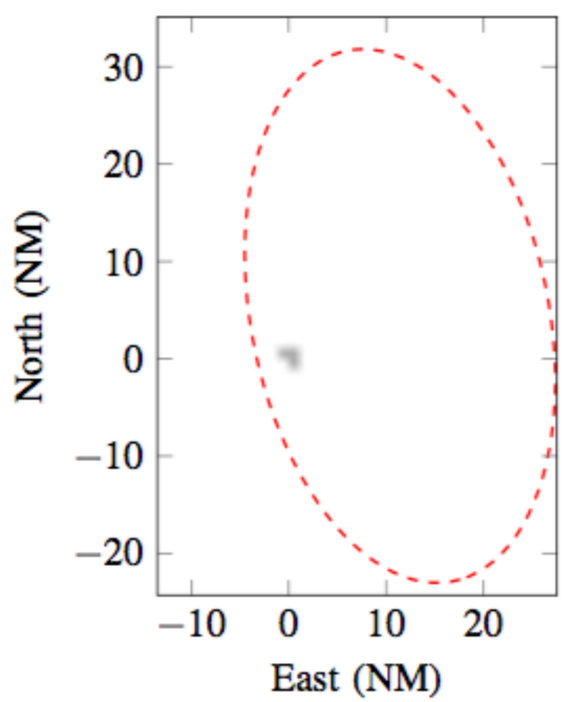
Utility Results

Aircraft headed 225°, Anomaly at 80 s after launch



0 s after launch:

- No anomaly knowledge
- Knowledge on debris trajectories
- Pilot response rate
- Launch vehicle traverses at 50 sec



50 s after launch:

- Region with a negative utility where Launch vehicle traverses

Utility Results

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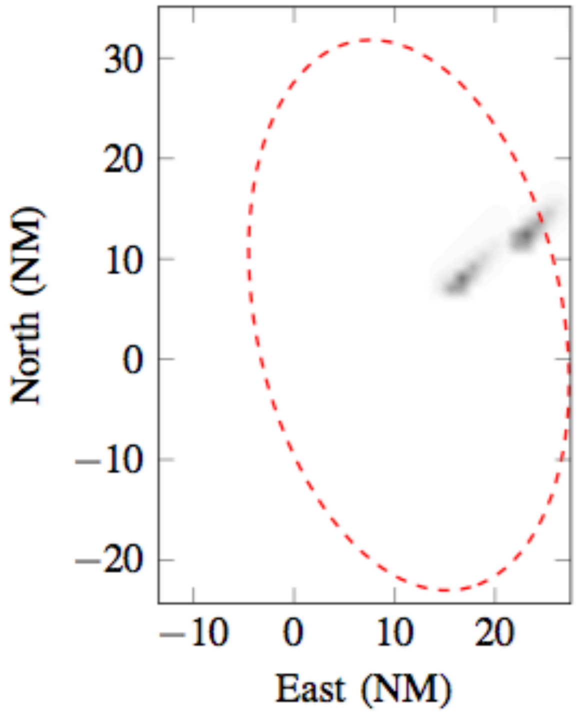
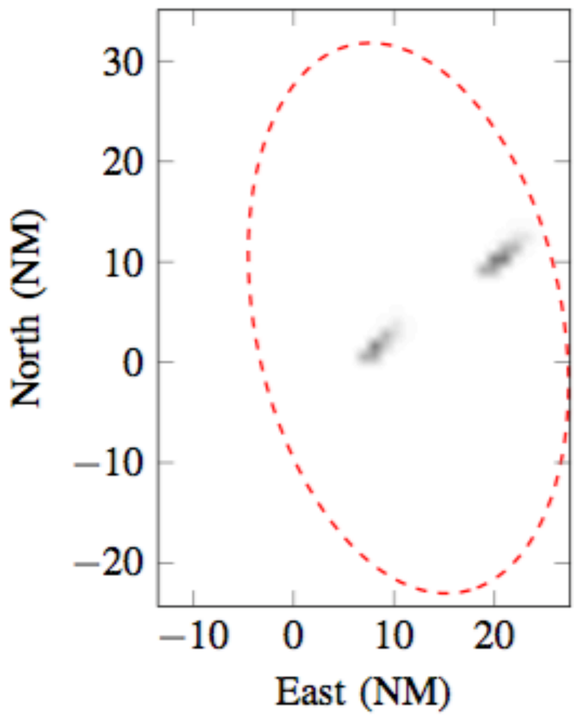


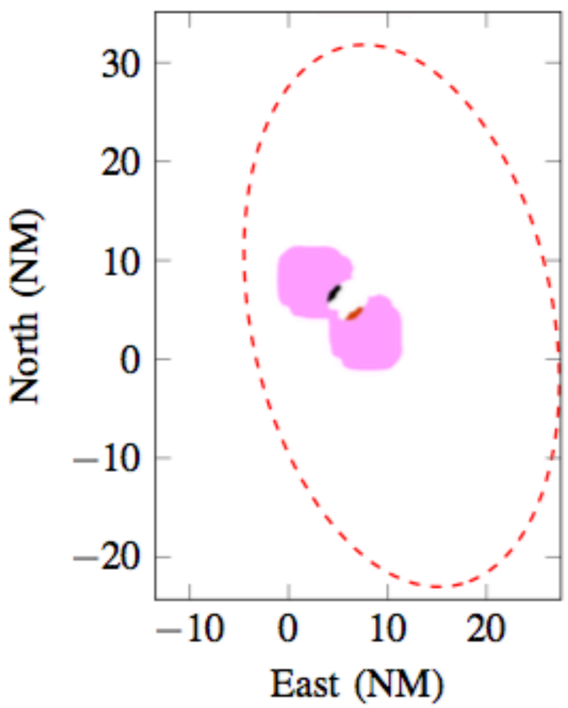


250 s after launch and 400 s after launch:

- Positions of the debris known
- Positions of debris or future debris have large negative utilities
- Negative utilities cover direction of the aircraft leading to those locations

Policy Results

Aircraft headed 225°, Anomaly at 80 s after launch



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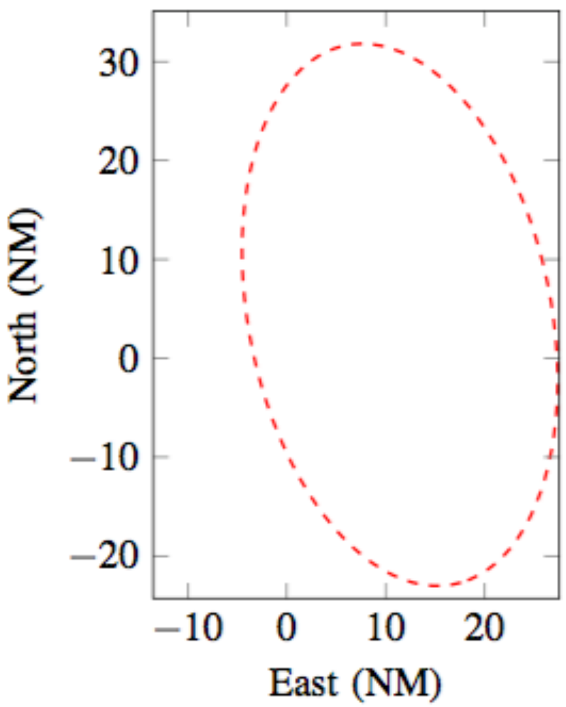


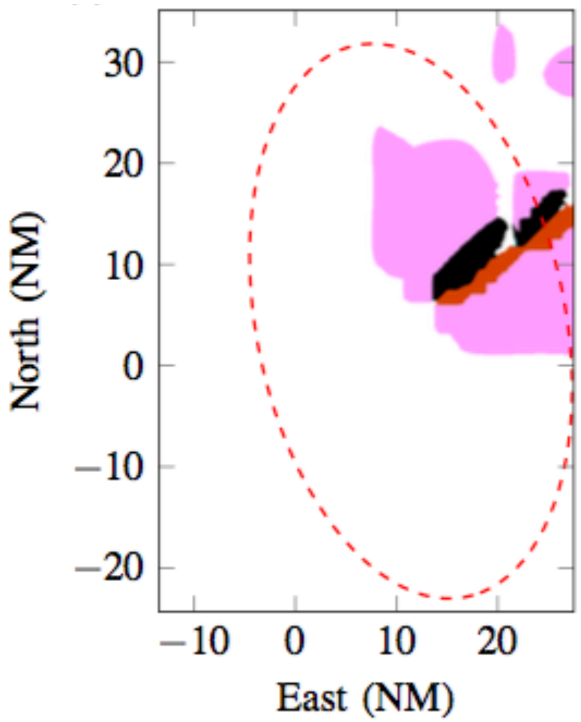
50 s after launch:

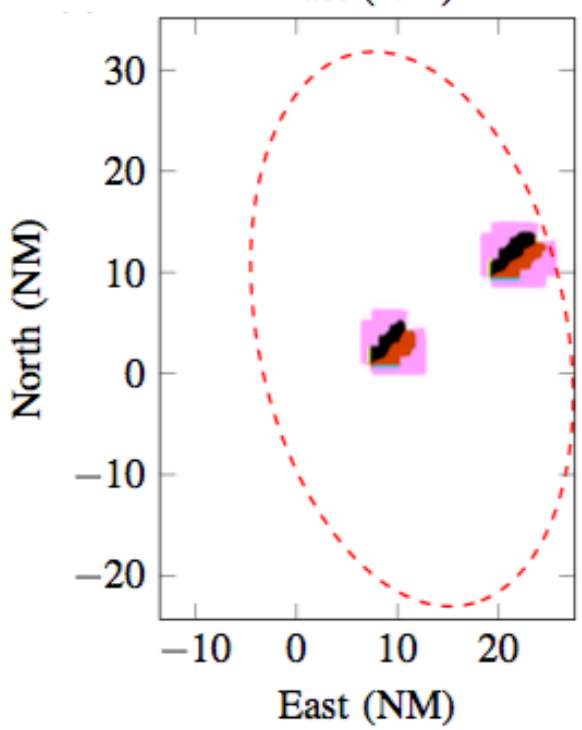
- Too late to direct around Launch vehicle
- Too early to direct around potential debris

no action, maintain, turn right 30°, turn left 30°, turn right 15°, turn left 15°

Policy Results

Aircraft headed 225°, Anomaly at 80 s after launch



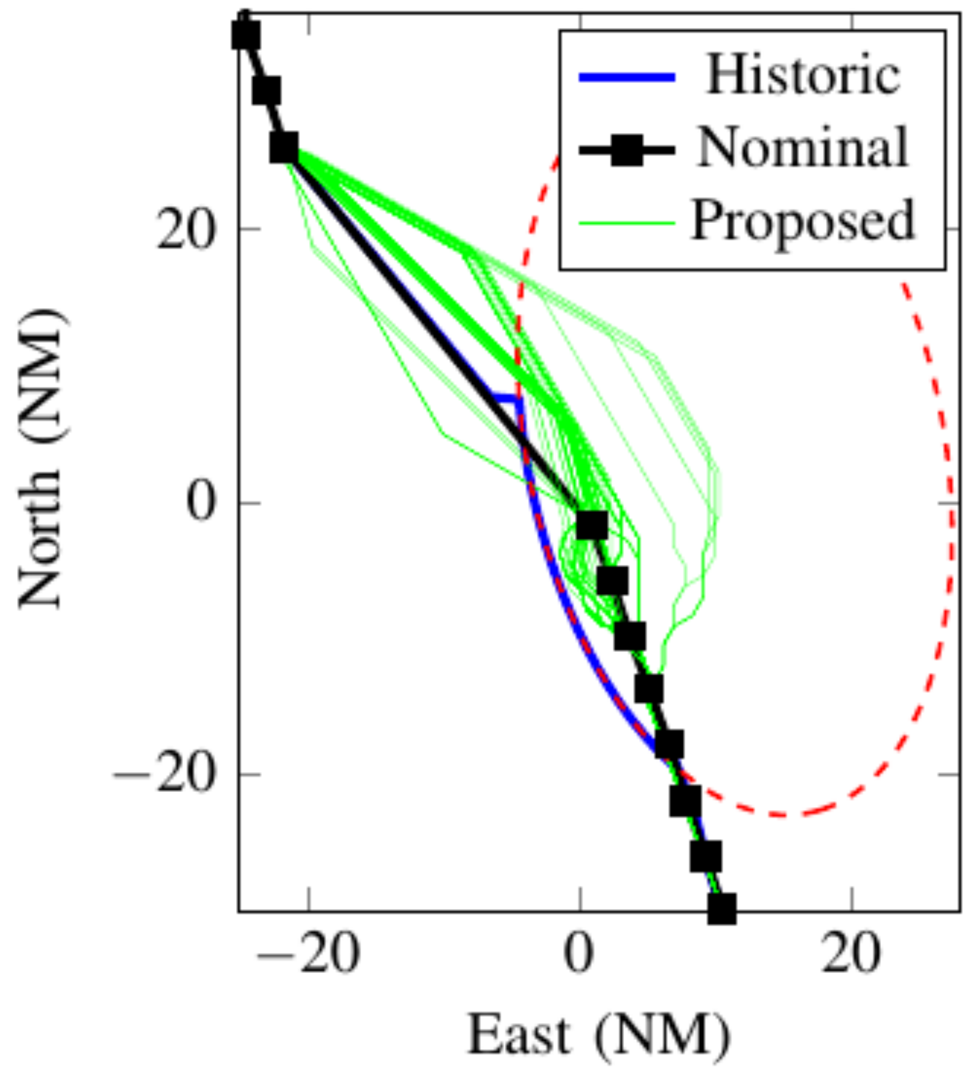


250 s after launch and 400 s after launch:

- Positions of the debris known and direct around where they will be
- Many maintain actions as expected and desired
- 15° and 30° cost the same so more 30° actions

Scenario Simulation Results

- Real Flights – Cape Canaveral
- Simplified temporary flight restriction representation
- 100 different start times
- Varying times of anomaly
- Results weighted based on likelihood

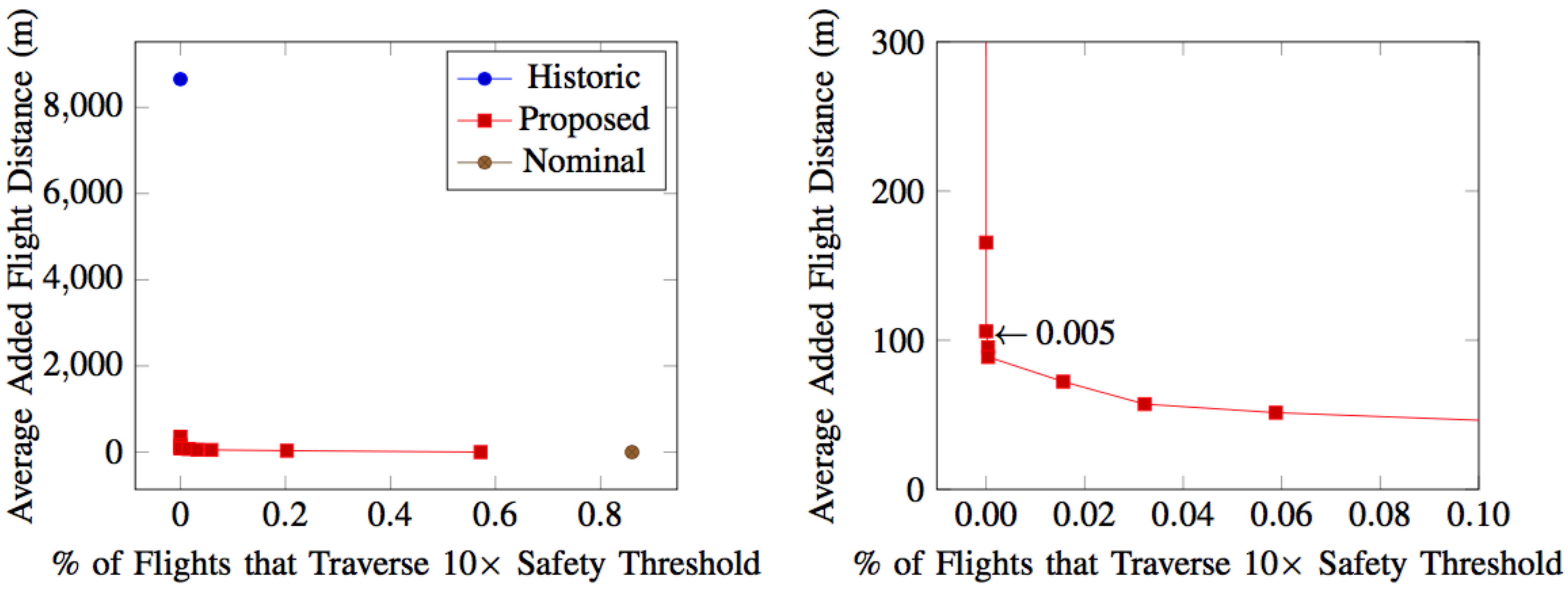


	Nominal	Historic	Proposed
% Rerouted	0.00	100.00	2.90
Average Added Distance (m)	0.00	8654.30	106.00
% Traverse 10× Safety Region	0.86	0.00	0.00

Efficiency Trade-Off Analysis

Reward = $\lambda\ r_{eff} + r_{saf}$

Investigation on the weighting of efficiency vs. safety



Conclusions

- Modeled commercial space launch and interactions with aircraft as MDP
- Dynamic safety regions much smaller than historic static regions
- Compared to historic safety regions, proposed safety regions result in fewer rerouted flights, smaller flight deviations during reroutes, and no degradation of safety
- Number of aircraft rerouted with proposed system is approximately 3% of the historically rerouted flights

Future Work

- Investigate additional metrics with the use of FACET
- Continue efficiency trade-off analysis
- Model additional debris trajectories
- Explore necessity of real time weather information

Thank you, Questions?

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