Federal Aviation Administration

# Optimal Aircraft Rerouting During Commercial Space Launches


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# Motivation


## Problem:

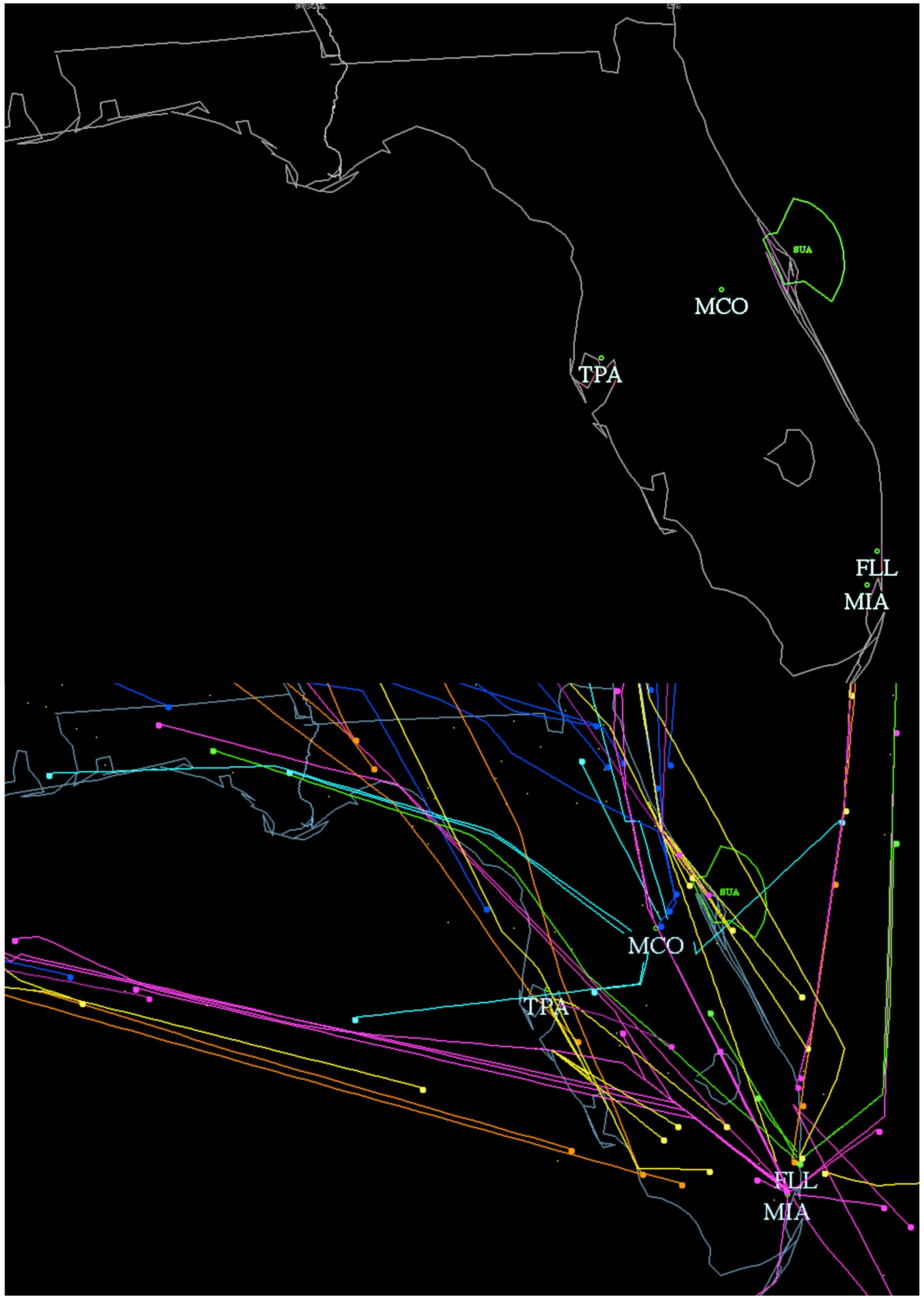
- Launch vehicle anomaly can lead to 10,000+ pieces of debris
- Projected increase in commercial space launches

**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

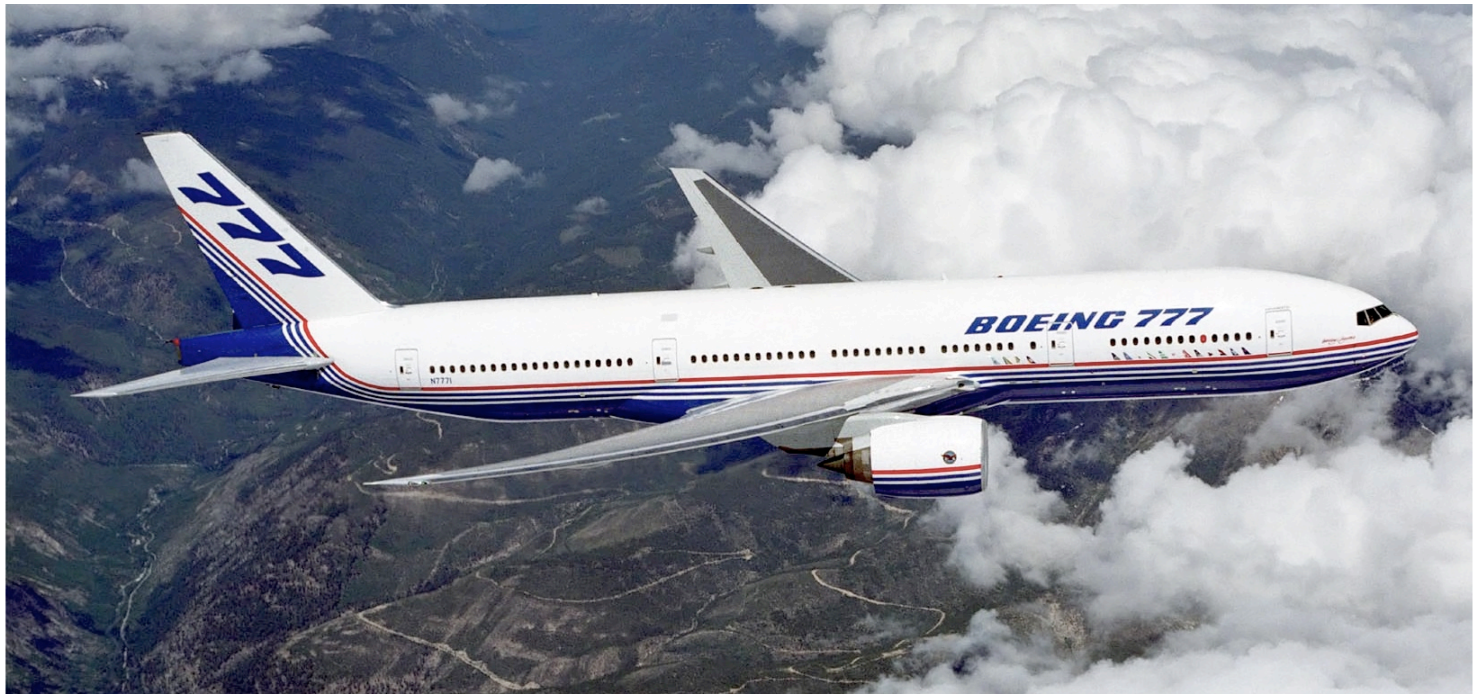
# Scenario

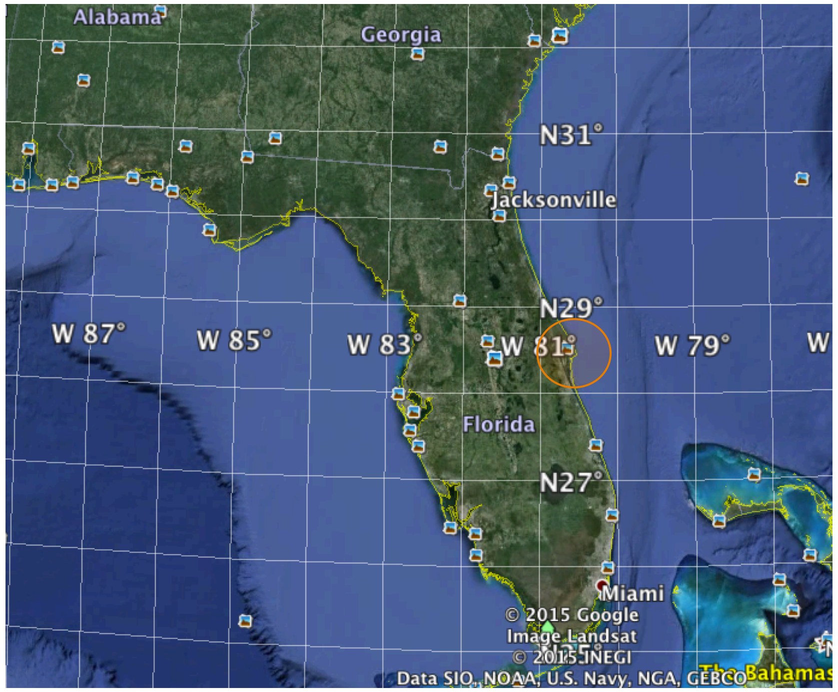
## Launch Environment

- 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)



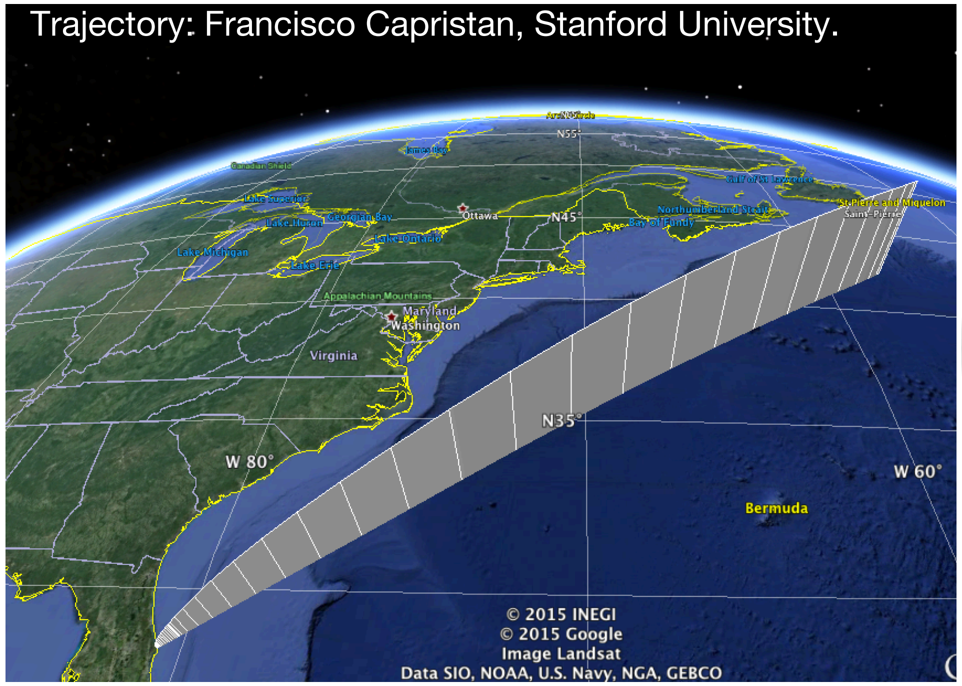



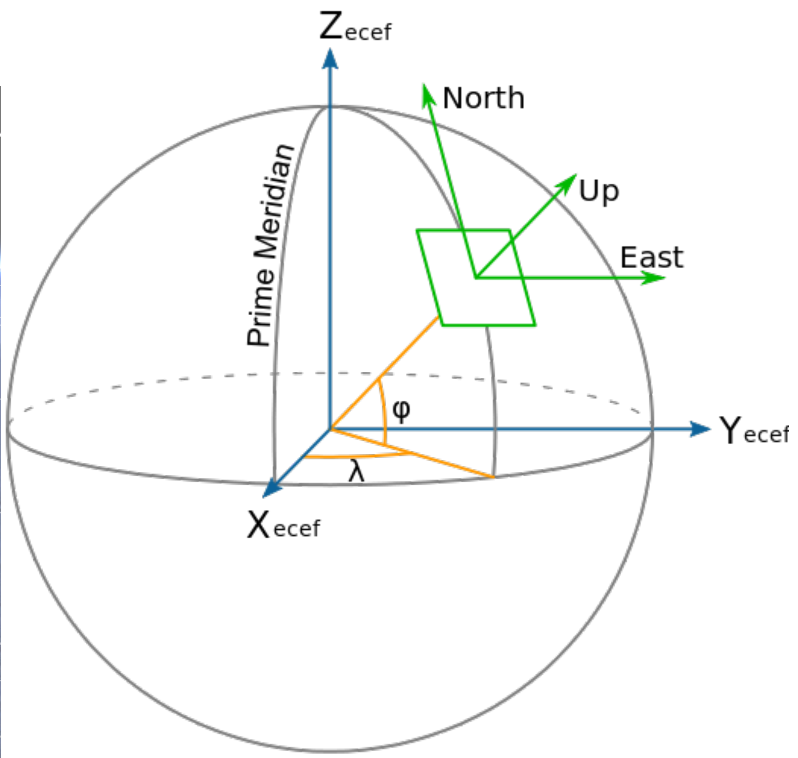
# Launch Vehicle


**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



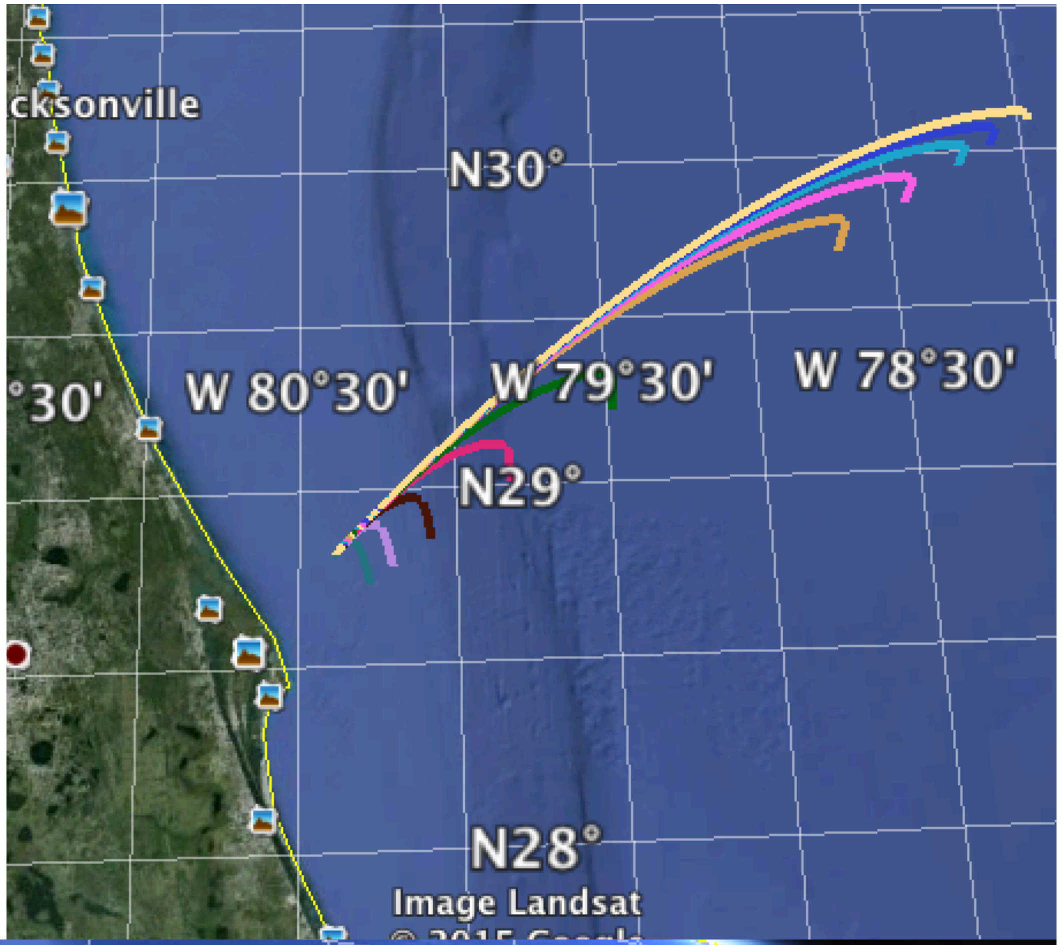
# Debris Model

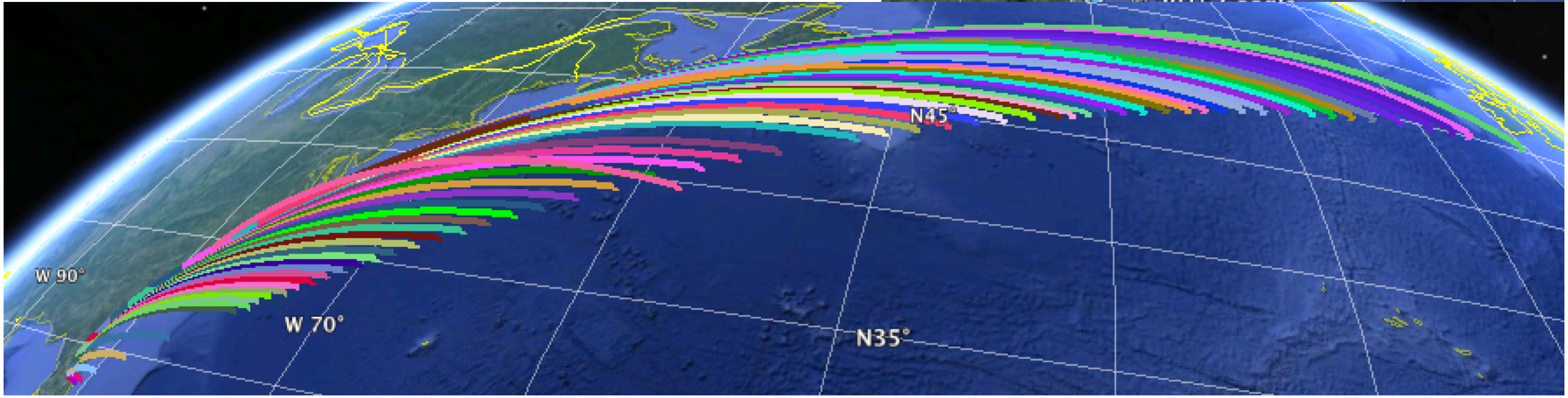
Look at 11 types of debris

- 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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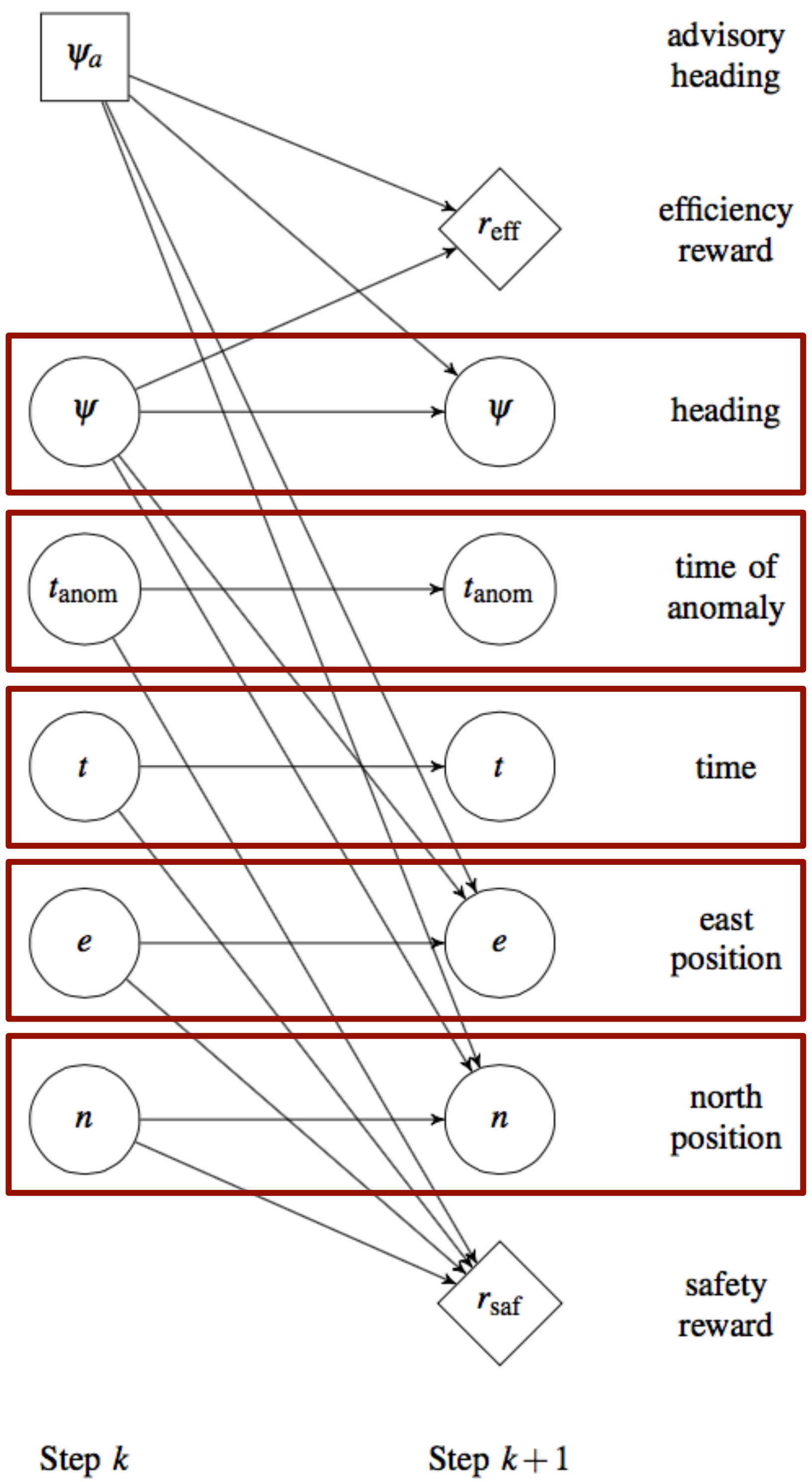
# Markov Decision Process Overview

**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

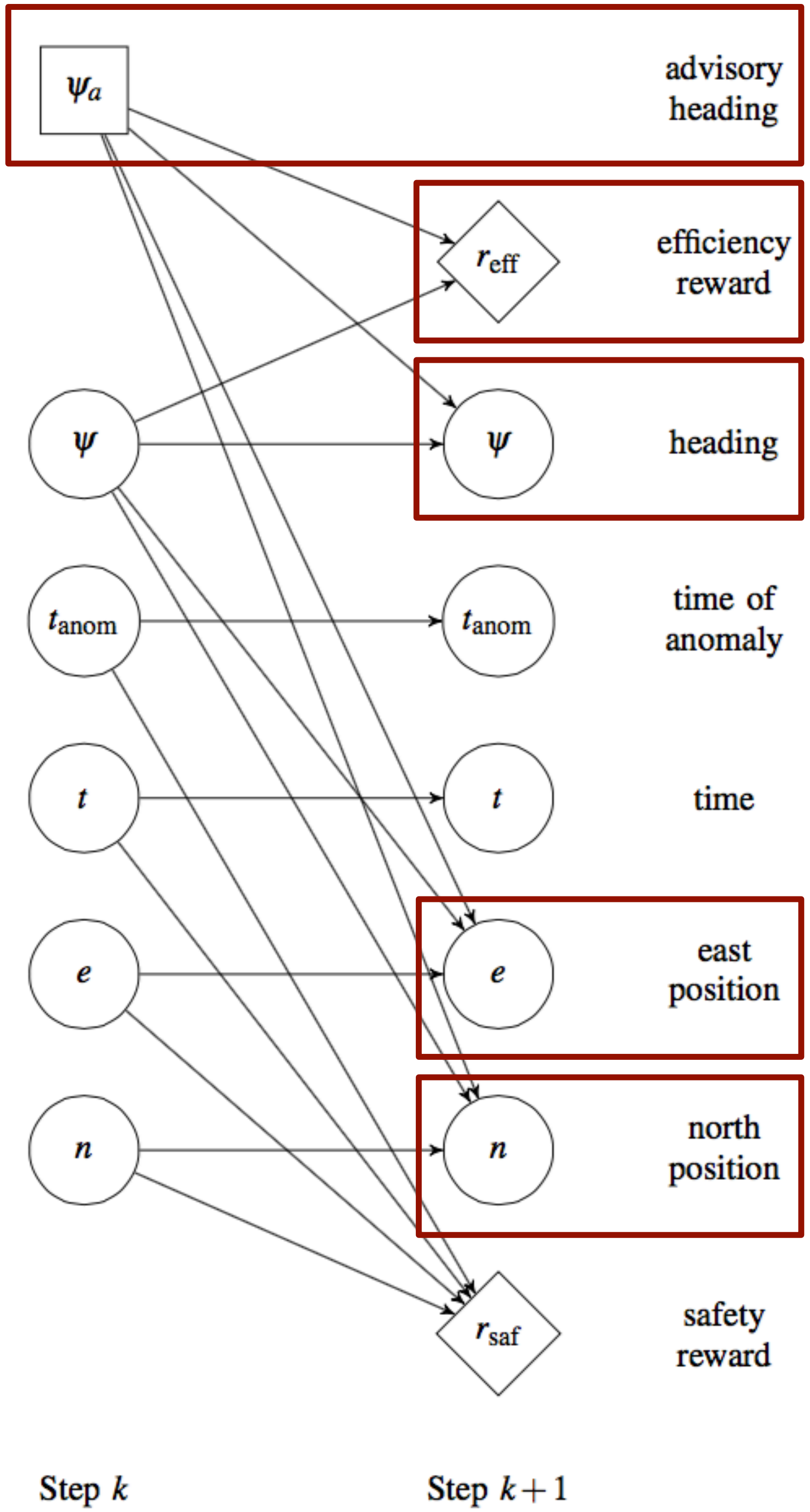


# Markov Decision Process Overview

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

An action a ∈ A corresponds to:

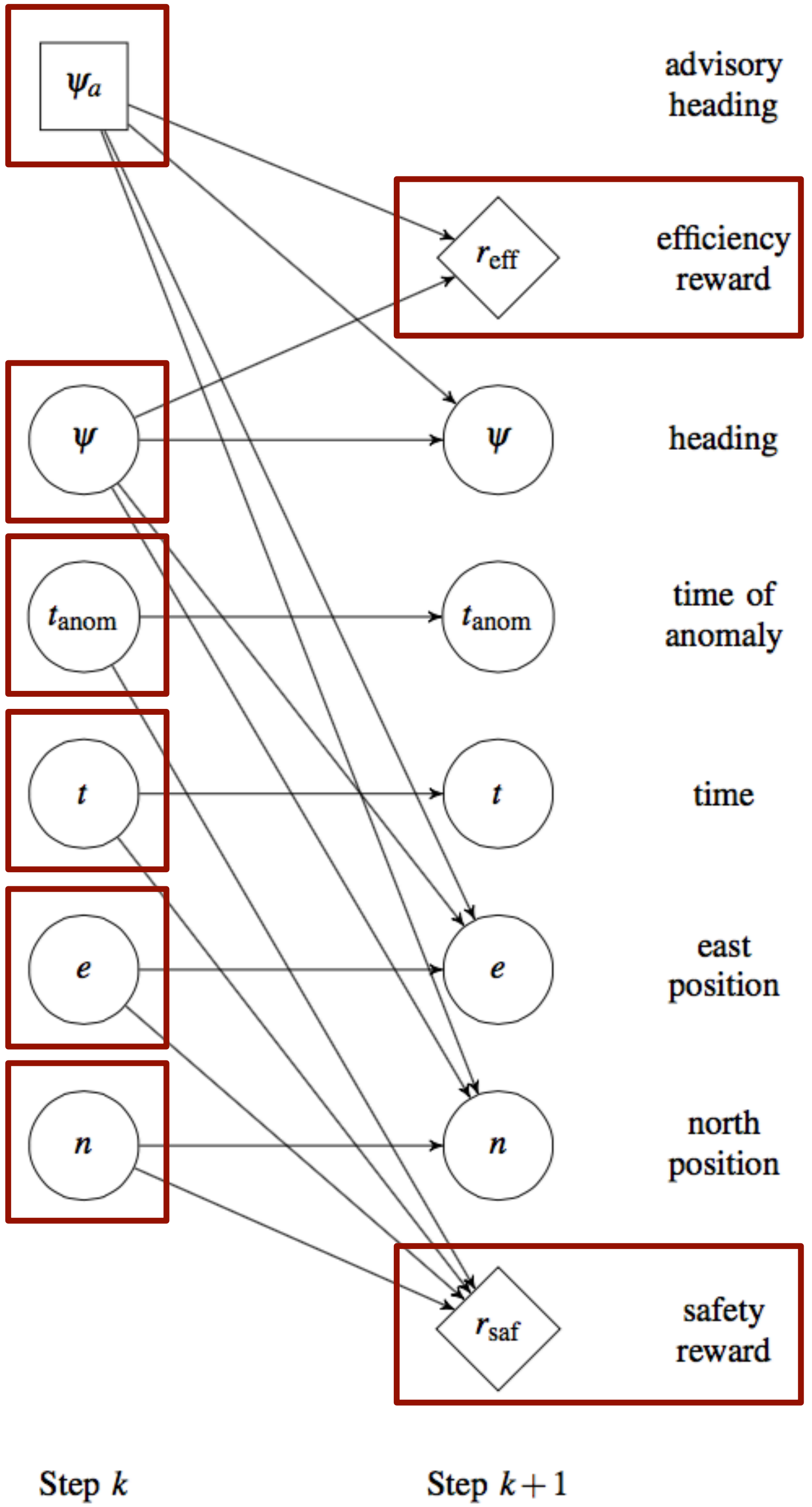
- heading change advisory



# Markov Decision Process Overview

**R** is the **reward model**:

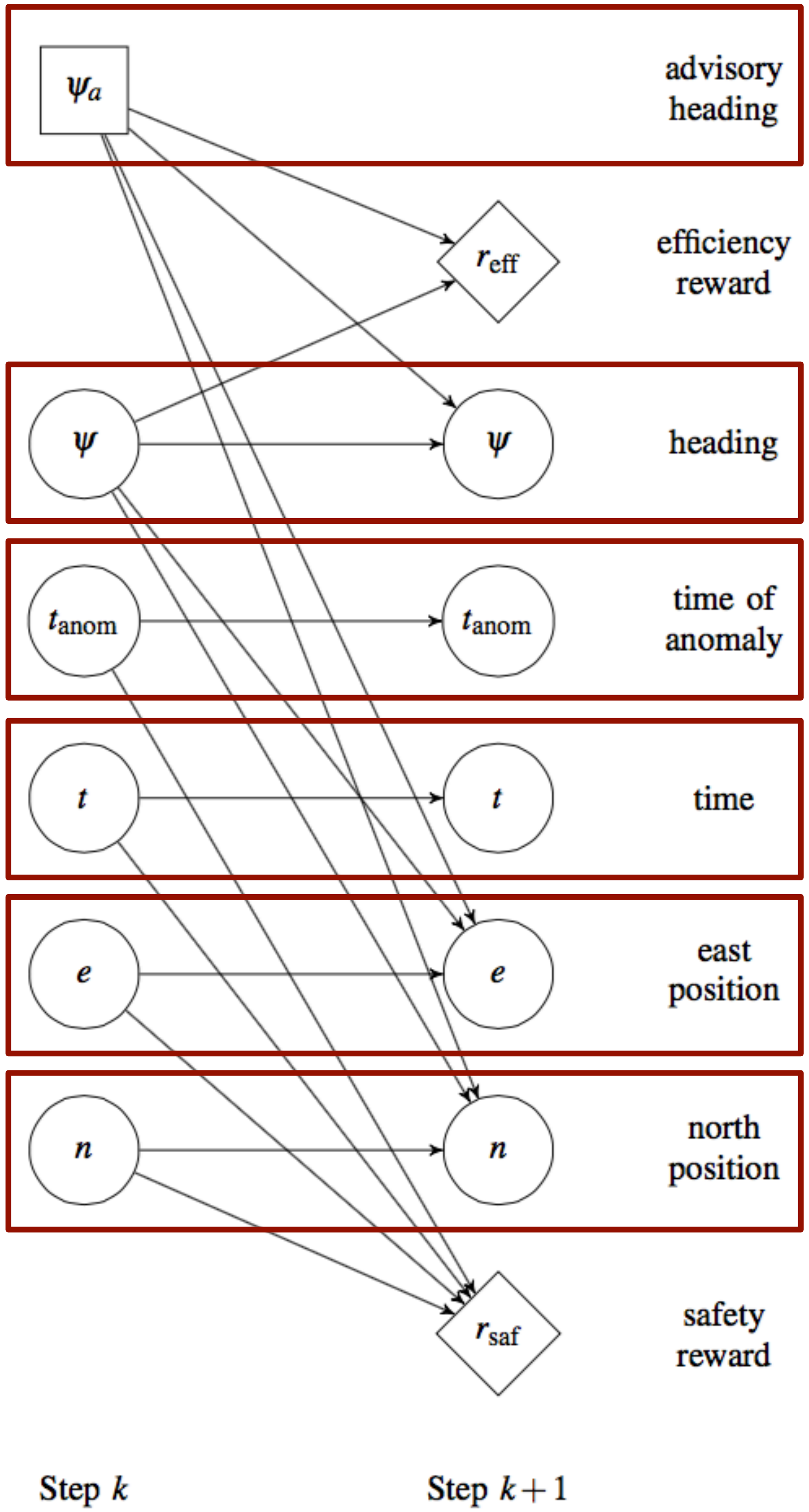
- Current state, s
- Action, a
- Immediate reward: R(s, a)
- Reward penalizes disruption and violations of safety thresholds



# 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 |
| $\psi$ | $0, 15, \ldots, 360$ | degrees |
| $t_{\text{anom}}$ | $\text{NIL}, 0, 10, \ldots, 110$ | 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

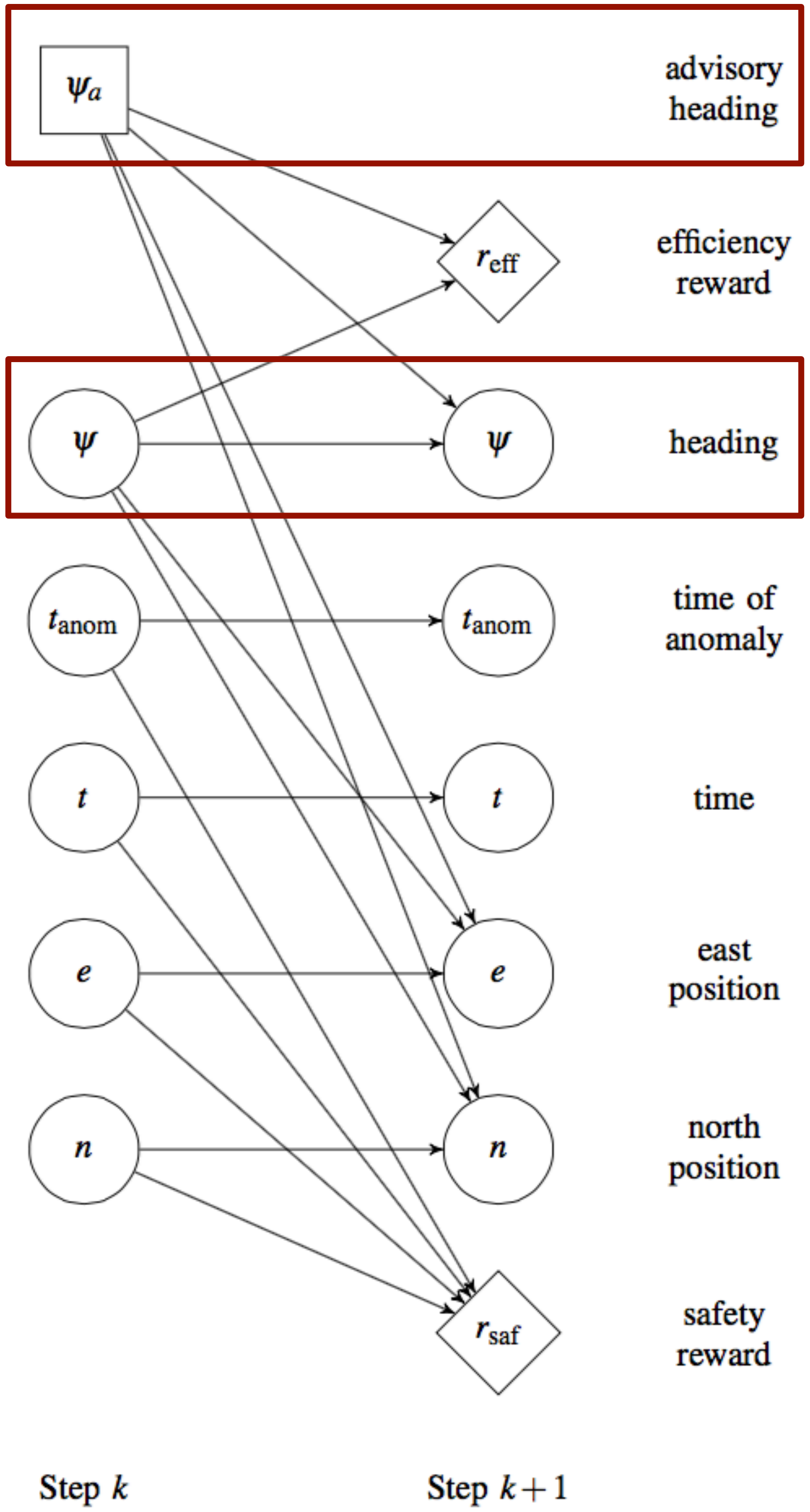
## NIL (No Advisory)

- 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)



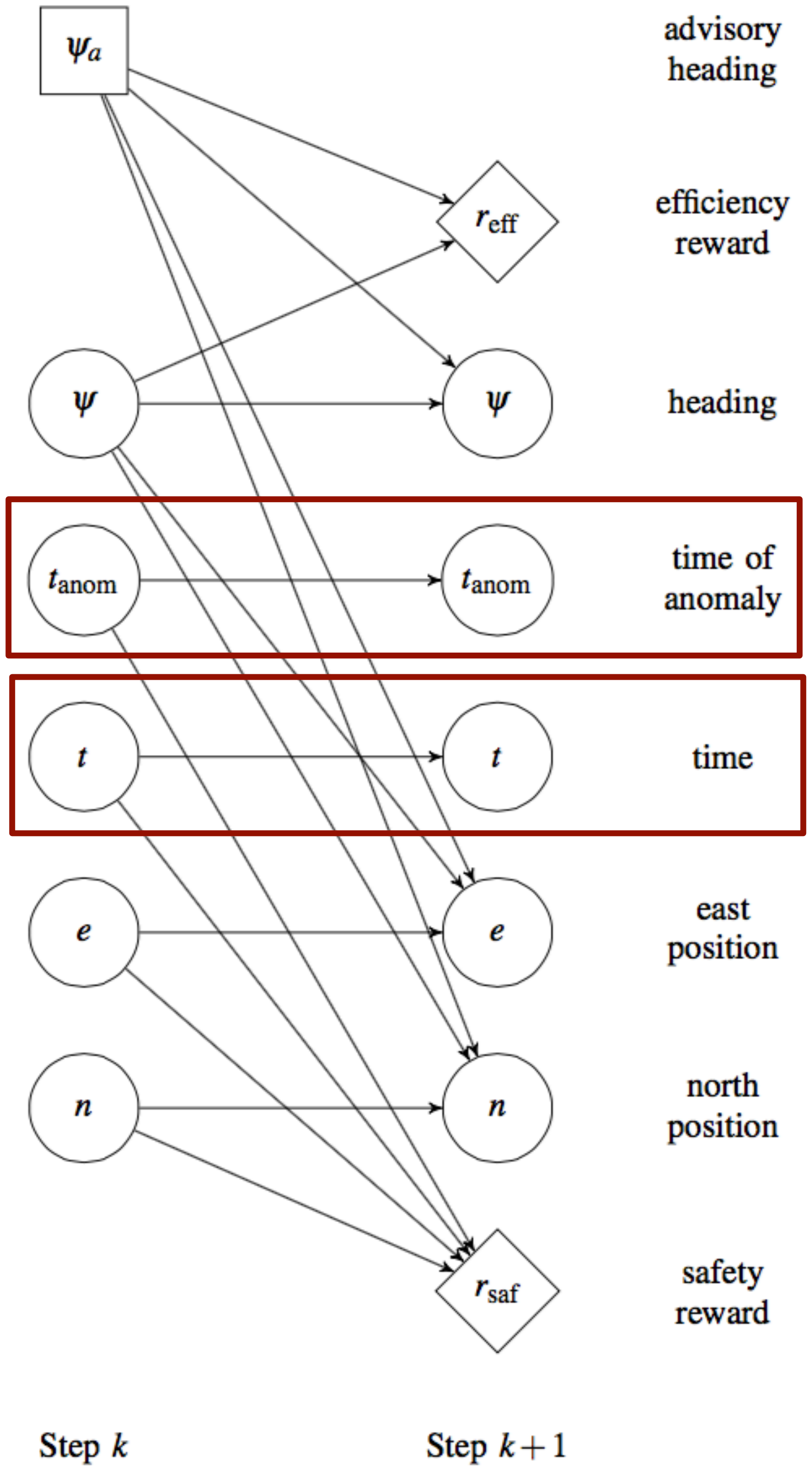
# Transition Model

## 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

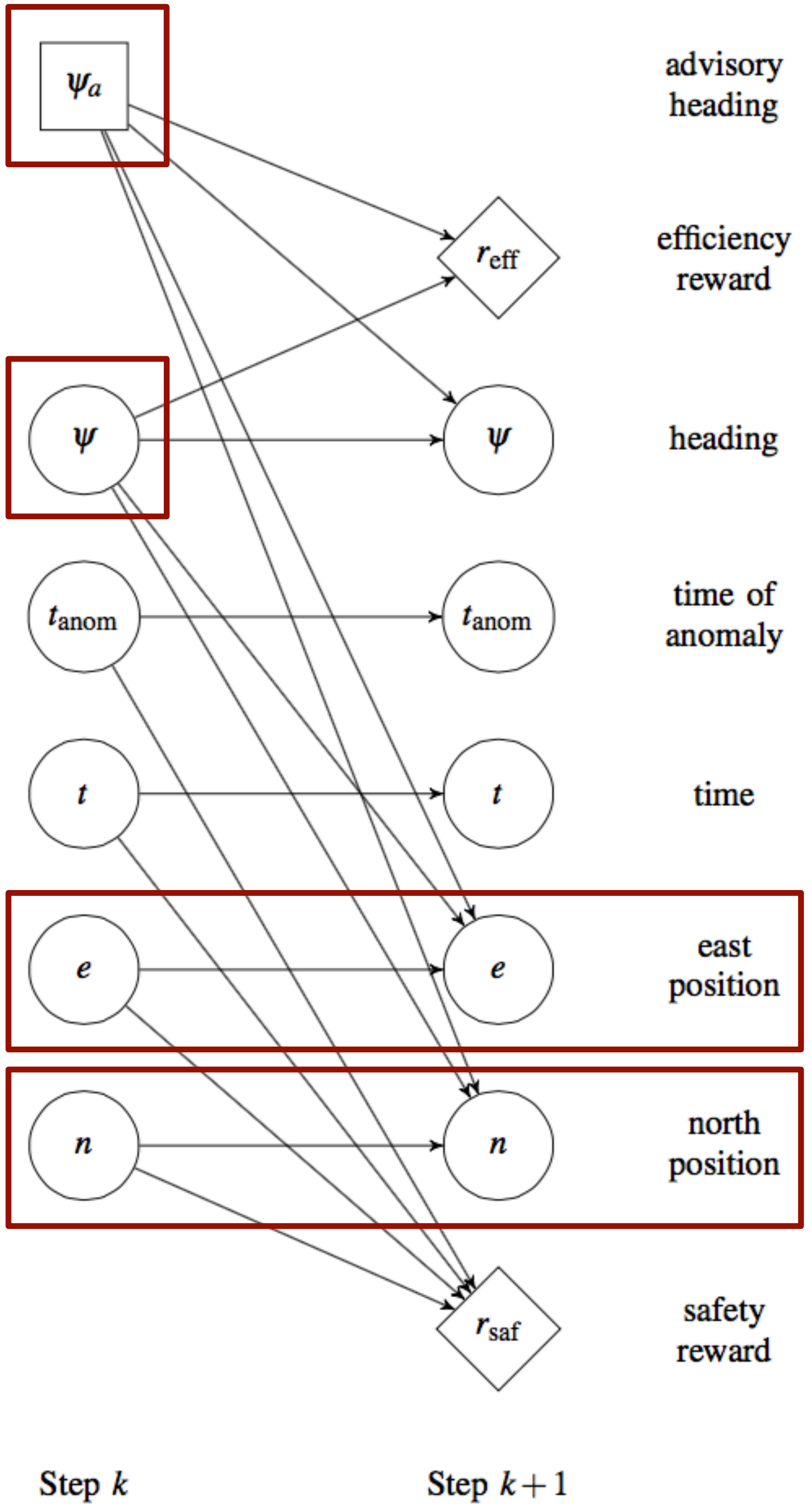
## Position Updates

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

- v = 0.84 Mach

## Comments

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



# Reward Model

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

| | |
|---|---|
| **Efficiency** | |
| $\psi = \text{NIL}$ | 0 |
| No Change | $-0.01$ |
| $\psi$ Change $\leq 30°$ | $-1$ |
| $\psi$ 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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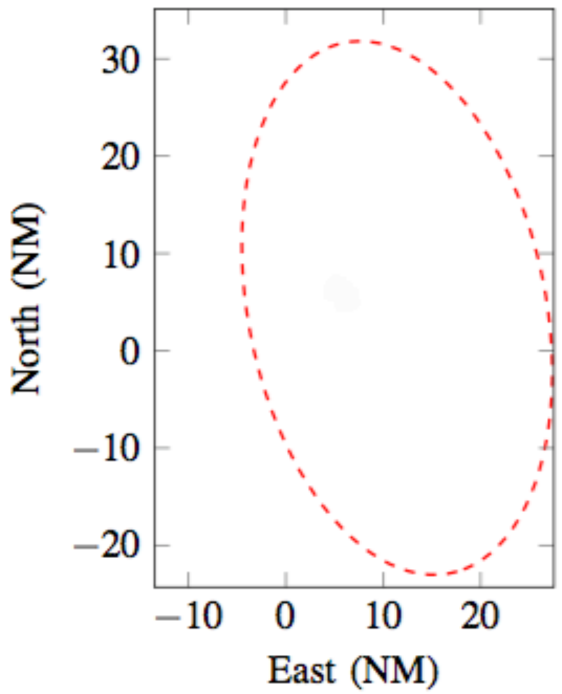
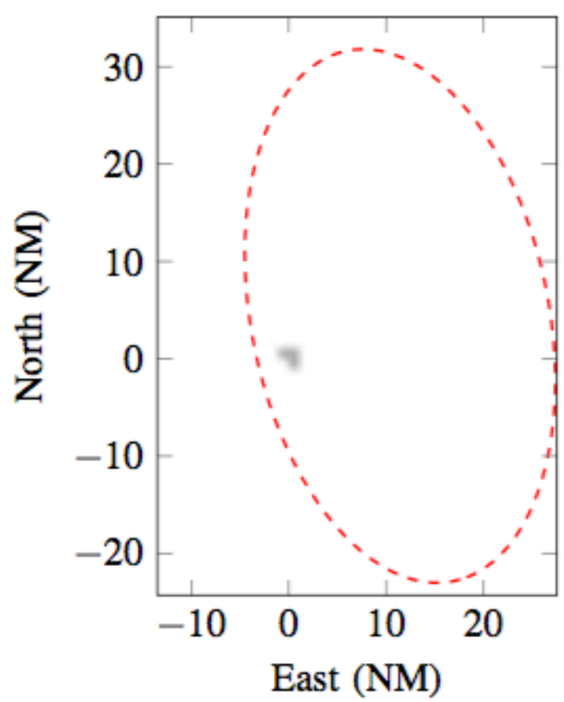
# Utility Results

## 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

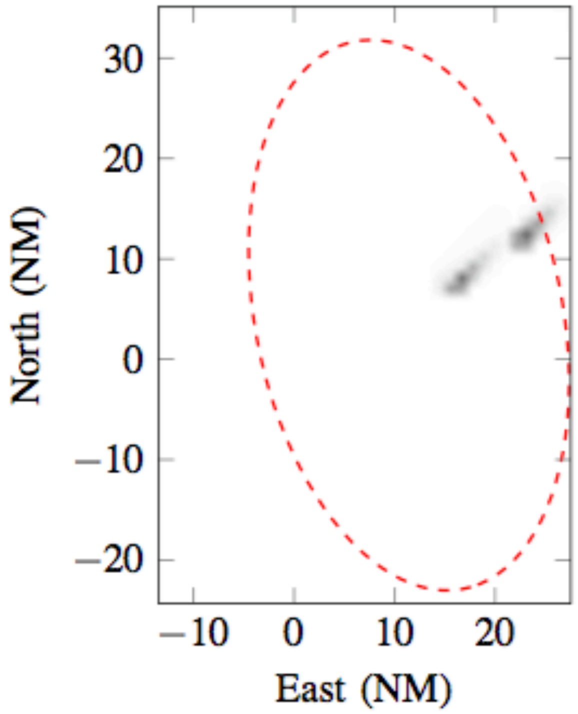


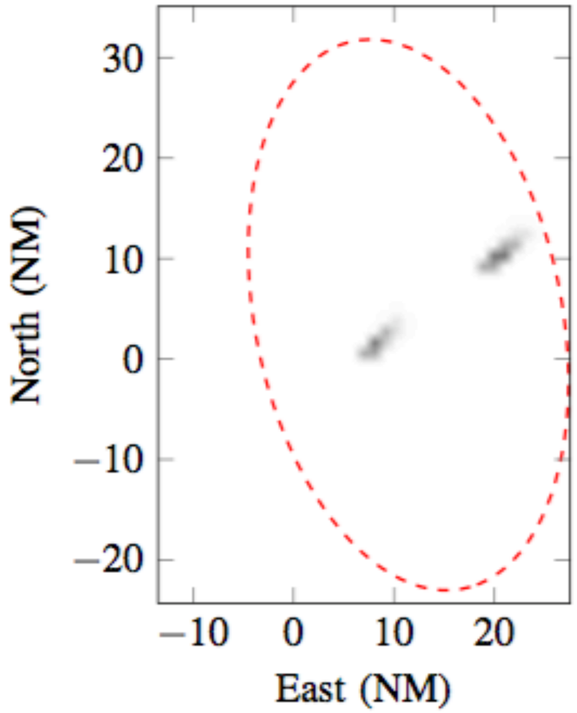

**50 s after launch:**

- Region with a negative utility where Launch vehicle traverses

# Utility Results

Aircraft headed 225°, Anomaly at 80 s after launch



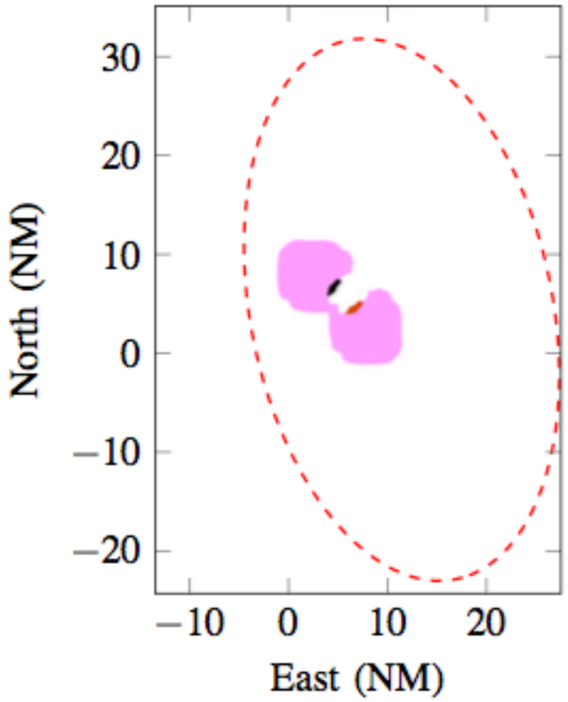




**250 s after launch and 400 s after launch:**

- 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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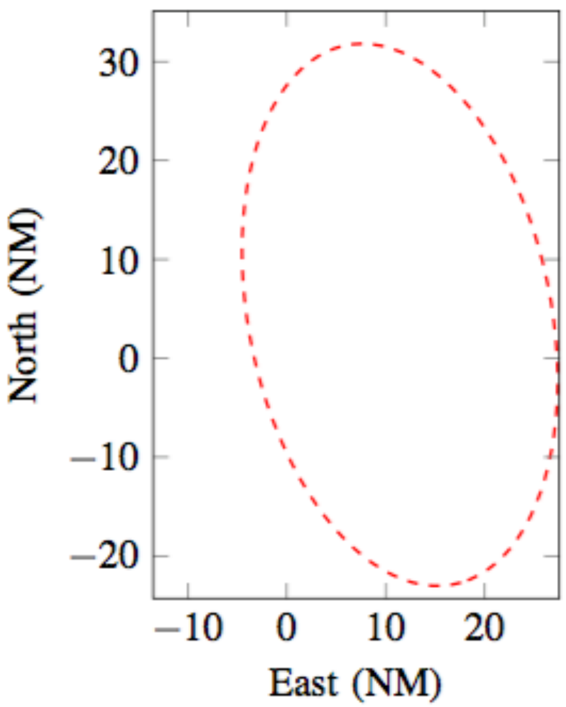


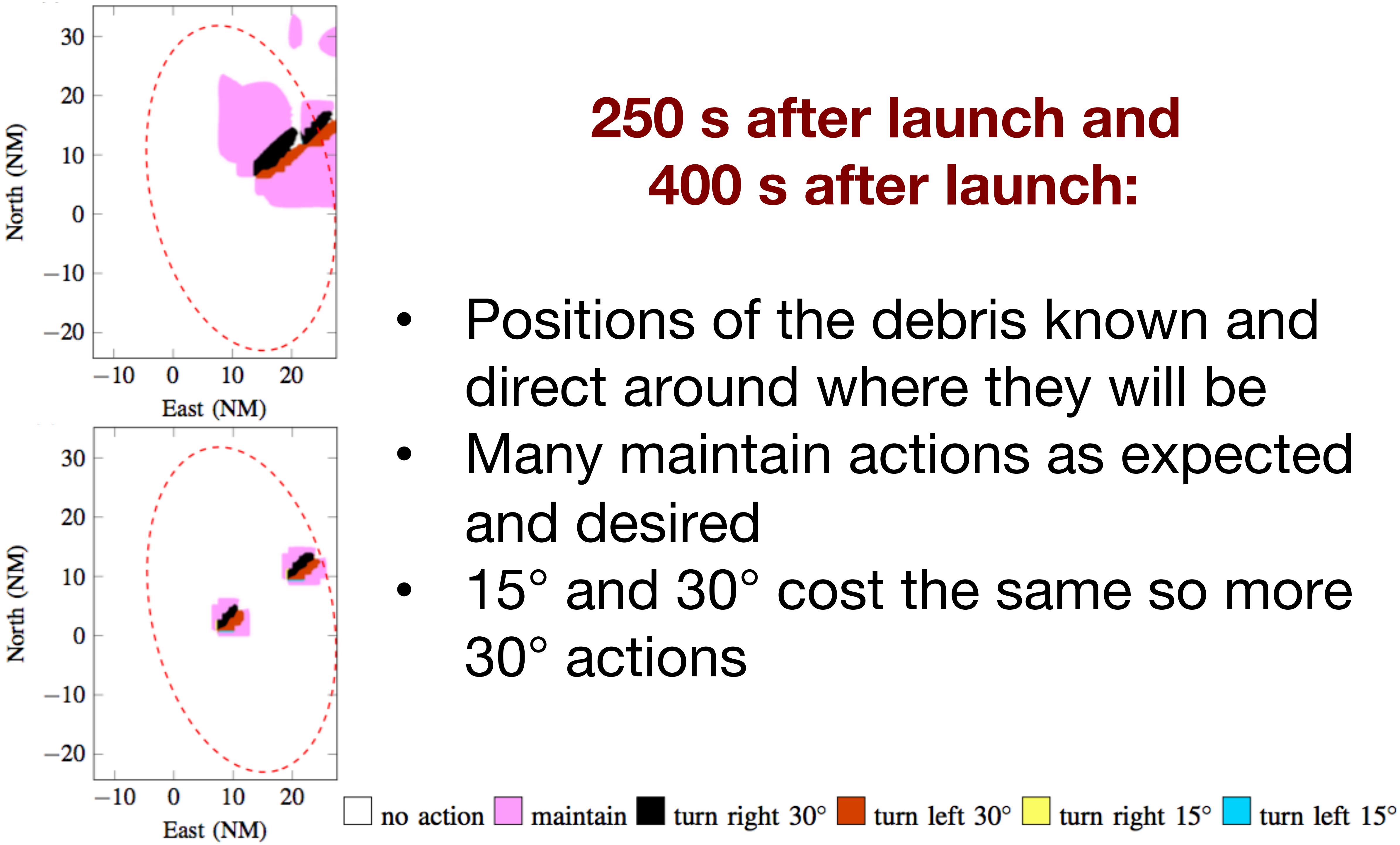

**50 s after launch:**

- 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

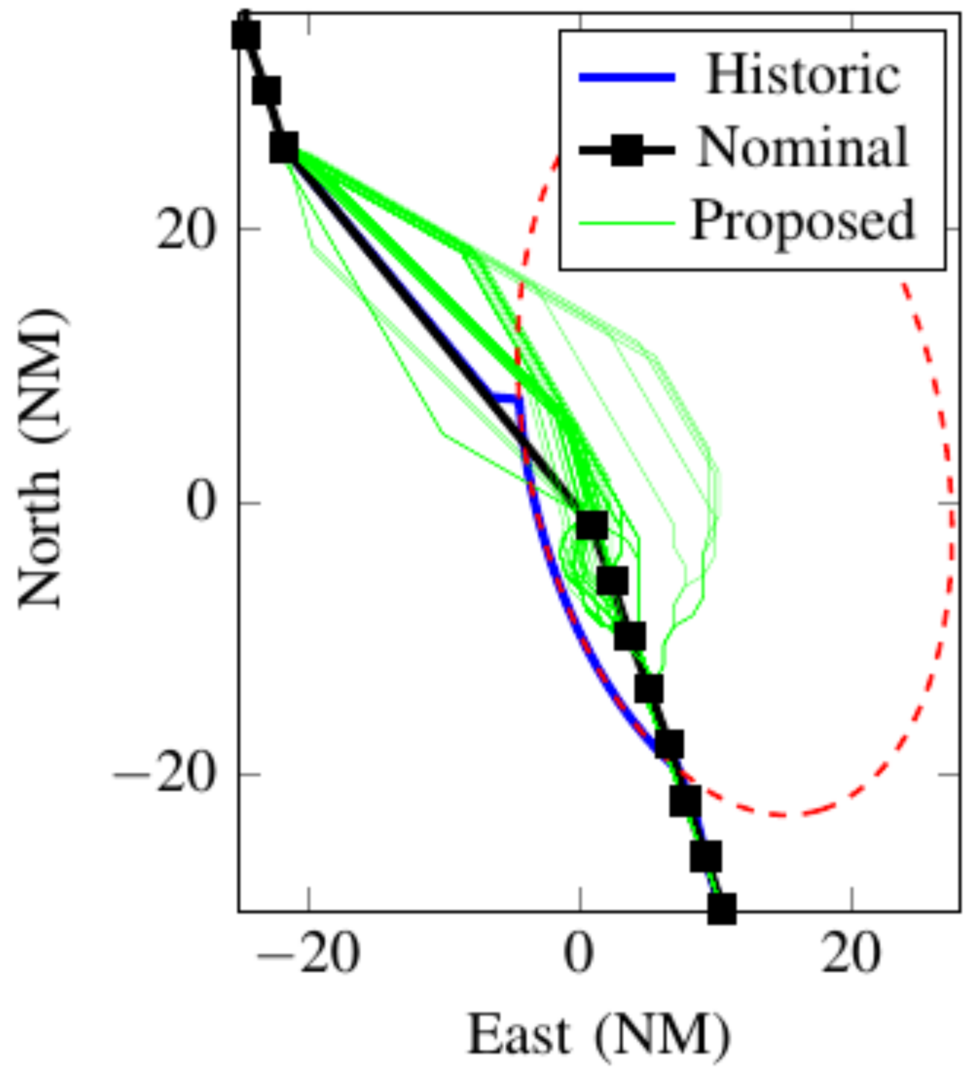



**250 s after launch and 400 s after launch:**

- 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

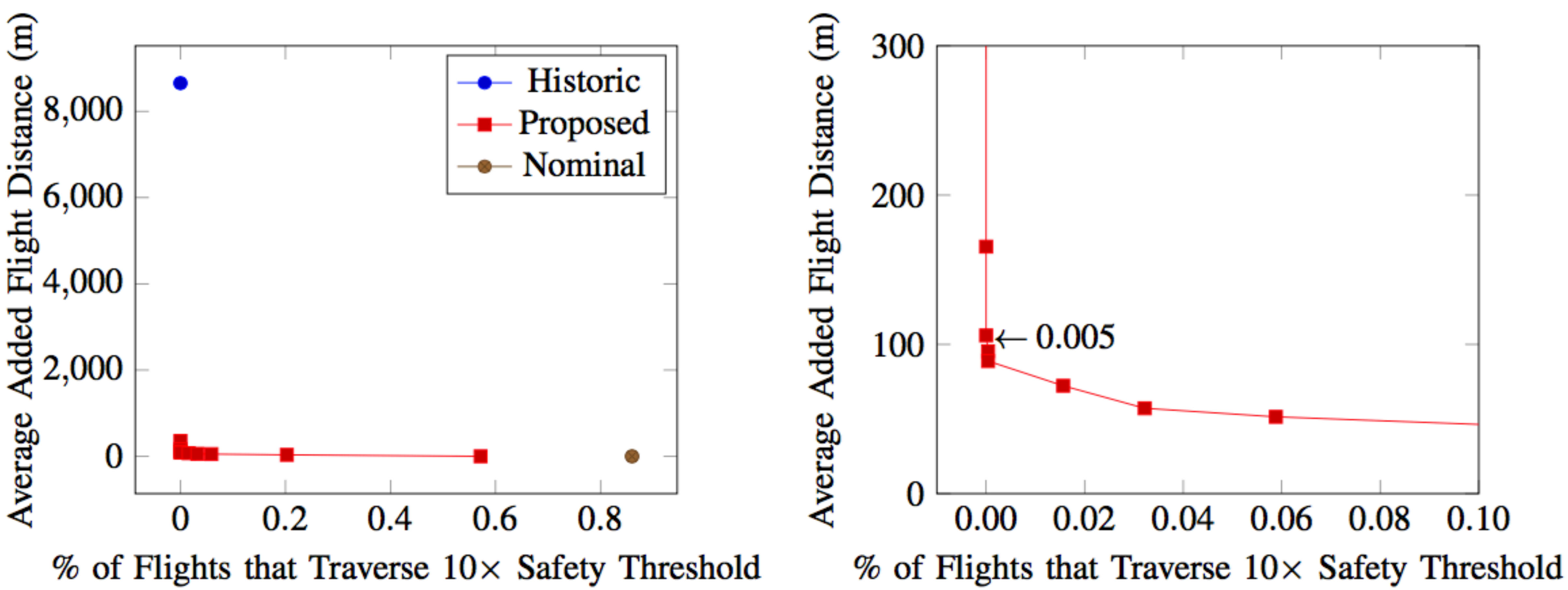



| | Nominal | Historic | Proposed |
|---|---|---|---|
| % Rerouted | 0.00 | 100.00 | 2.90 |
| Average Added Distance (m) | 0.00 | 8654.30 | 106.00 |
| % Traverse 10× Safety Region | 0.86 | 0.00 | 0.00 |

# 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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