Real-Time Safety Monitoring and Prediction in the National Airspace

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Motivation

- Projected increases in national air traffic will require advanced tools to maintain the current level of NAS safety, and aid in decision-making
  - Optimal decisions require knowledge of the current state of the NAS, and its future state
- Pilots, flight controllers, and other NAS operators need situational awareness to make informed decisions to avoid unsafe events
- Currently, NAS operators must
  - Consolidate operations-related information from disparate sources
  - Apply domain knowledge to interpret the current NAS state and forecast future NAS state

Research Goals

- Provide *real-time* safety assessment
  - *Nowcast* and *forecast* of safety and risk
  - Holistic framework that combines multiple threats to safety and considers their potential interactions
  - Integrate disparate data sources
- Predict evolution of safety
  - Incorporate multiple sources of uncertainty into the predictions
  - Move from *reactive* decision-making to *proactive* decision-making
  - Avoid unsafe states instead of mitigating them

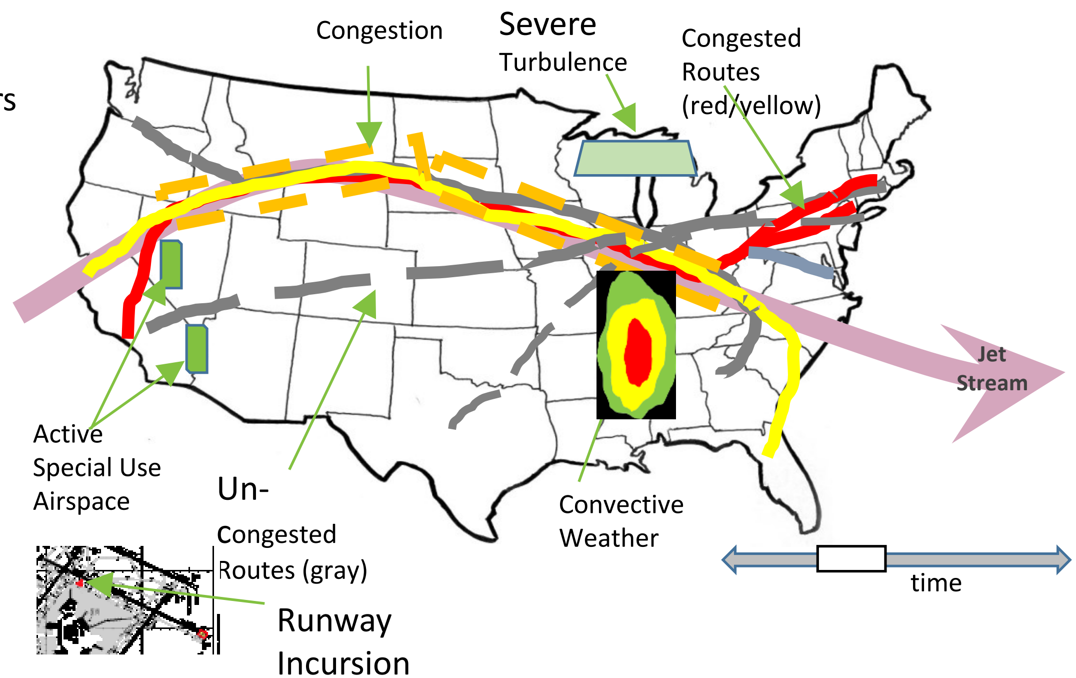
Relevance

Stakeholders

- ATC System Command Center Traffic Managers
- ATC Flight Controllers
- Airline Dispatchers
- Pilots

Example Use Cases

- Preemptively avoid risks
- Anticipate earlier dissipation of safety threats
- Visualize “squeeze” points.
- Ensure adequate staffing
- Optimize route per user preferences
- Ensure availability of airport assets

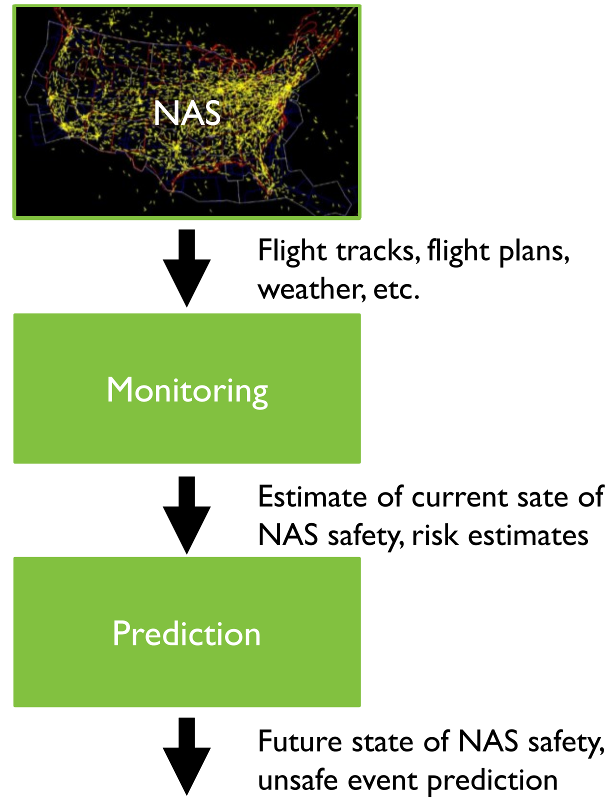


Applicability

- Clearance Based Operations or Trajectory Based Operations (TBO)
- Airport-specific, region-wide, or system-wide, always using system-wide knowledge
- Increasing air traffic

Approach

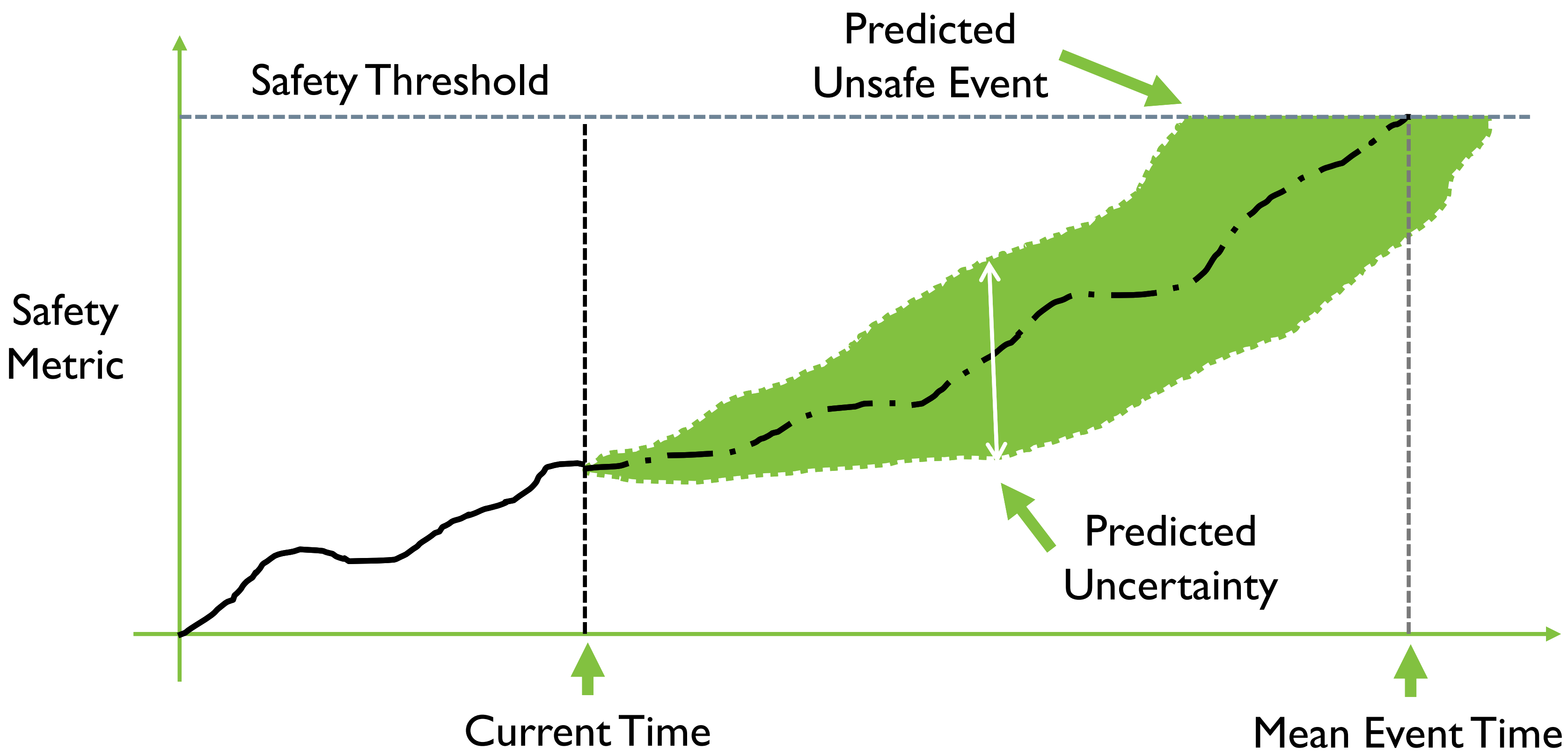
- Safety Analysis & Modeling
  - What are the hazards to safe flight?
  - What unsafe events can occur?
  - Which hazards/events occur most frequently?
- Real-Time Safety Monitoring
  - How do we define "safety" and "risk" in the NAS?
  - How do we measure/quantify it?
  - How do we estimate the current state?
- Safety/Risk Prediction
  - Which unsafe events are likely to occur in the future, if no corrective action is taken?
  - What does the pilot need to be aware of?
  - What does a controller need to be aware of?



Definitions

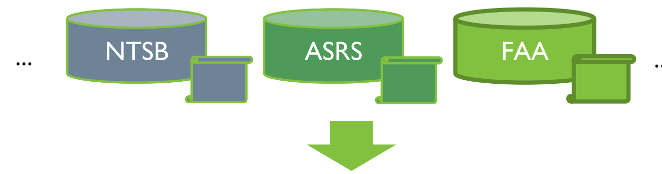
- Unsafe event
  - An event/situation that compromises NAS safety or established safety standards
  - Examples: loss of separation, loss of control, controlled flight into terrain, runway incursion, hard landing, tail strike, collision, etc.
- Hazard
  - A condition that potentially contributes to unsafe events
  - Examples: convective weather, poor visibility, difficult terrain, etc.
- Safety metric
  - A quantitative measure of some aspect of safety of the NAS
  - Examples: distance between two aircraft, distance between aircraft and convective weather region
- Safety threshold
  - Some limit on a safety metric or set of safety metrics
  - Example: Enroute separation of 5 nautical miles
- Safety margin
  - "Distance" between current safety metric(s) and safety threshold(s)

Concepts: 1-D Example



Safety Analysis

- Identify hazards that compromise safety analyzing reports from several national incident and accident databases
  - Generally categorize into airspace, human performance, and environmental categories
  - Down-select hazards based on potential to model, monitor, and predict
- Identify unsafe events that result from hazards



Hazards
- Inoperative Navaid
- Excessive Communication
- Procedure Complexity
- Low Visibility
- Turbulence
- Icing

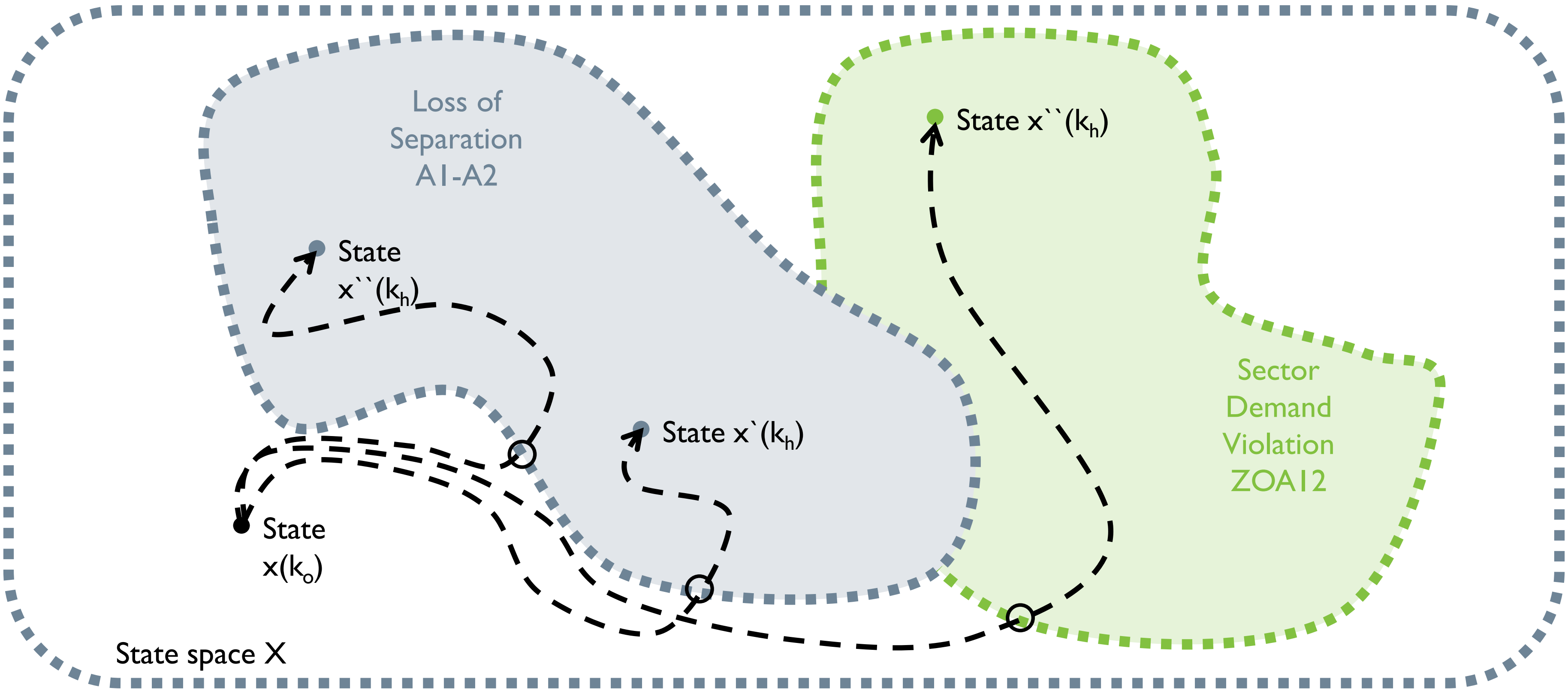
Events
- Loss of separation
- Evasive maneuvers
- Go around/rejected takeoff
- Unstable approach
- Convective weather encounter

Example Safety Issues & Incidents

- ASRS Reports
  - Topics
    - Altitude deviation
    - Bird or animal strike
    - Controlled Flight into Terrain
    - Communication
    - Fuel Management
    - Near Miss
    - Runway Incursion
    - Wake Turbulence
    - Weather
  - Wake turbulence, weather, and congestion are some common causes of unsafe events
- NTSB Accident and Incident Reports (2010 – 2015)
  - Turbulence, congestion, loss of situational awareness are some common causes of unsafe events

- ASRS 1201963: Unusually heavy CRJ-200 encounters **wake turbulence** shortly after takeoff at ATL. *"The new separation minimums between takeoffs in Atlanta needs to be altered. The company needs to present these issues to local ATC to prevent a major accident in the future."*
- ASRS 1195051: Deviating for weather puts flight in **conflict with SUA**
- NTSB 4/27/12 incident: **Loss of Separation** due to simultaneous independent runway operations on runways that do not physically intersect but whose flight paths intersect (LAS, **go-around** on 25L, departure on 19L; two controllers)
- NTSB 12/1/11 incident: **Runway incursion** caused by Tower Local Control clearing aircraft to cross runway immediately after clearing another aircraft to depart

Problem Formulation



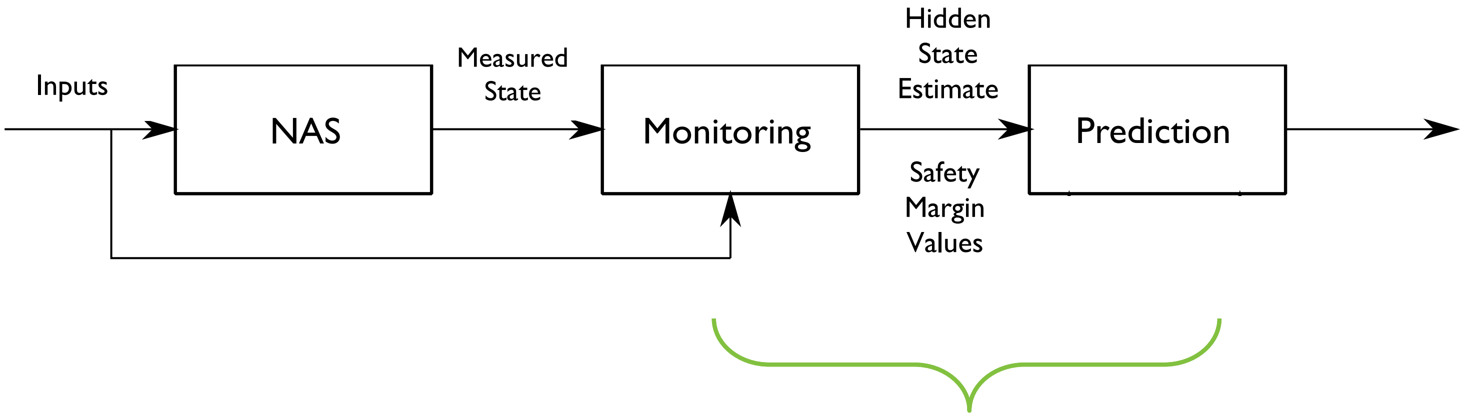
Safety Modeling

- What categories of events can occur?
  - Loss of separation, wake vortex encounter, convective weather encounter, sector demand violation, etc.
- What conditions define the occurrence of the event?
  - Defined as some function of the NAS state
  - Example: Loss of separation between A1 and A2 occurs when the horizontal separation is less than 5 nautical miles and the vertical separation is less than 1000 ft
  - Example: Sector demand is too high when the number of aircraft in a sector meets or exceeds the capacity limit
- How do we compute the safety margin w/r/t an event?
  - Margin is 0% when event is present
  - Margin computed as "distance" to event threshold, over threshold, in [0,100]%
- How do we compute aggregate safety margins?
  - Average safety margins over all potential events

System Modeling

- NAS consists of aircraft, pilots, controllers, weather regions, etc.
  - Model-based approach - require dynamic models
  - Predictions improve with more accurate models
  - Tradeoff between model fidelity and computational performance
- Uncertainty is inherent to the system and must also be captured
  - Uncertainty in the sensor information (sensor noise, message delay, etc.)
  - Uncertainty in the system models
  - Uncertainty in the system inputs (e.g., aircraft intent information)

Computational Architecture



Predicted State

Predicted Safety Margins

Predicted Times of Occurrence of Unsafe Events

Probability of Future Occurrence of Unsafe Events (in next *x* minutes)

Computation can be distributed to different regions of the NAS and consolidated for system-level safety assessment

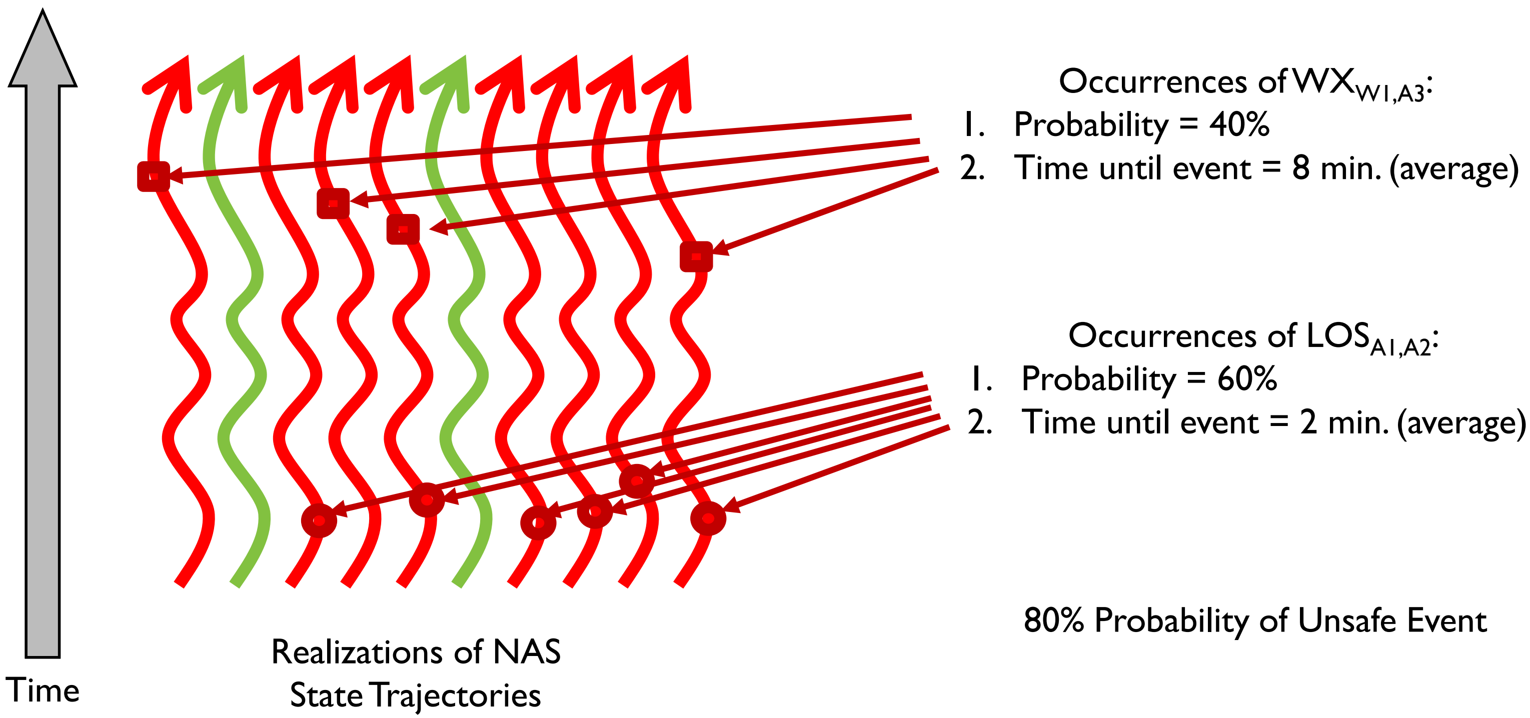
Real-Time Monitoring

- What is the current system state and its associated uncertainty?
  - Input: known system inputs and measured state
  - Output: state estimate (probability distribution)
- Estimation algorithms typically have two steps
  - Prediction step: Using system models, compute the probability distribution for the state one step ahead, starting from state estimate from previous step
  - Correction step: Use Bayes theorem to update prediction based on observations of the system state
  - Examples: Unscented Kalman filter, particle filter
- Given an estimate of the system state, an estimate of the safety, in the form of safety margins, can be computed

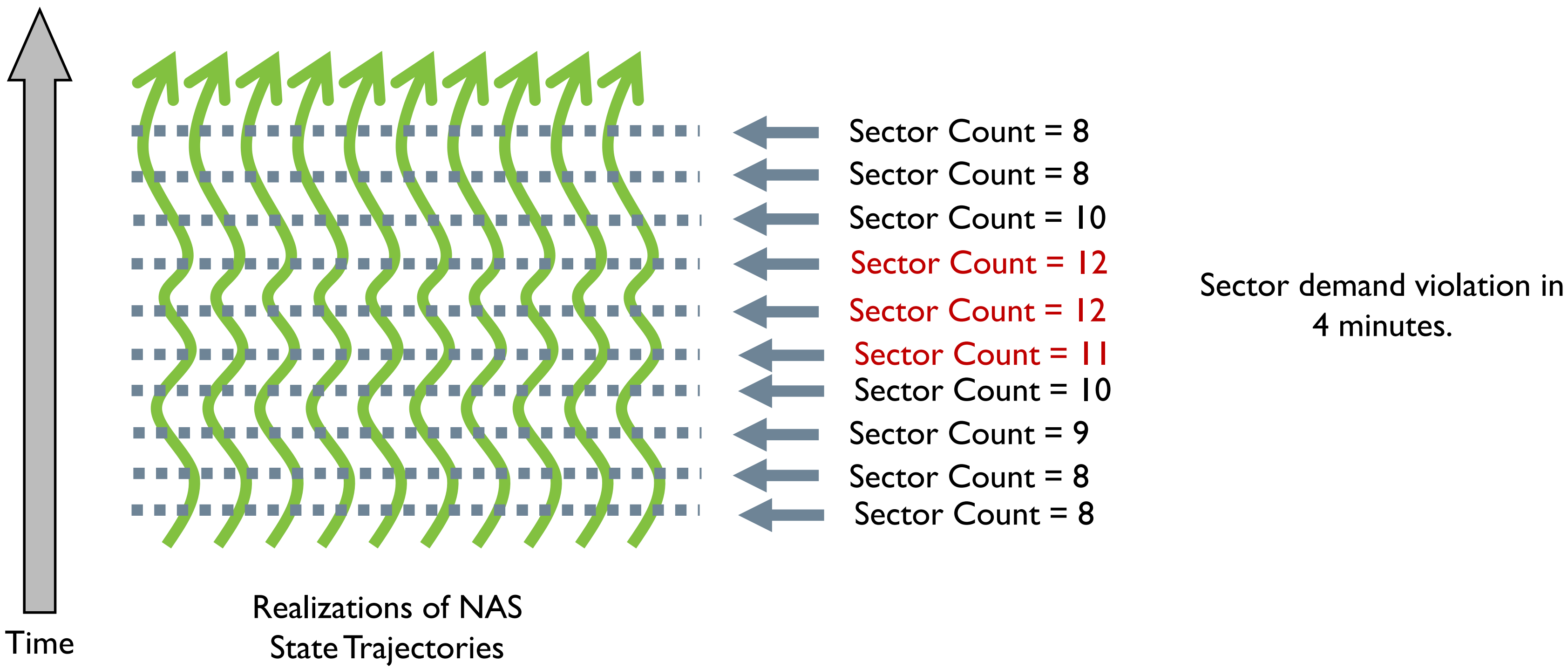
Prediction

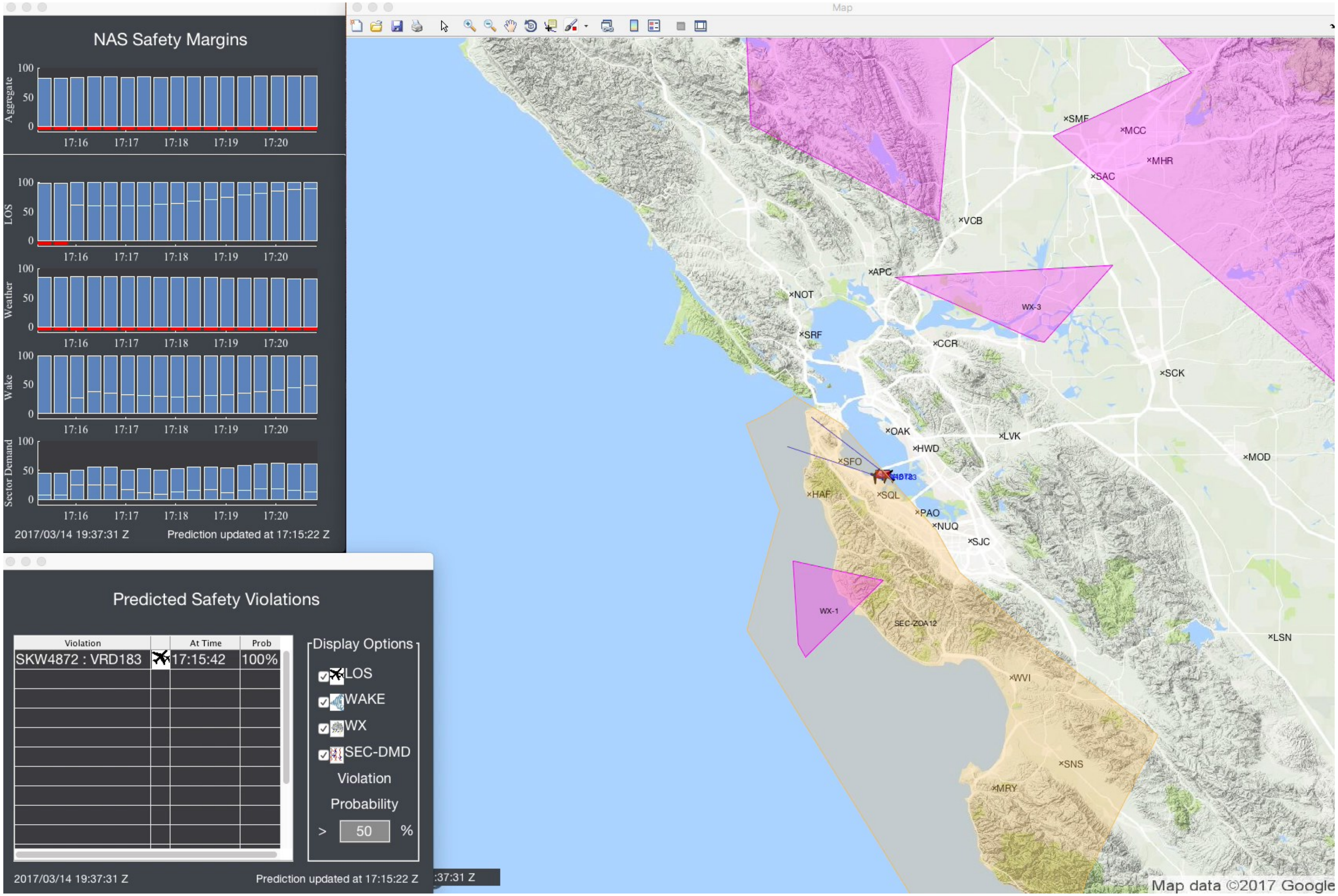
- Requires dynamic models of the system
- Algorithms use models to simulate the system ahead
  - – Require some knowledge of future system inputs
    - Examples: flight plans, weather forecasts
    - This is highly uncertain; and this uncertainty must be included
  - – Simulate forward in time to some specified prediction horizon (for example, 20 minutes)
    - Determine if and when predicted state violates safety thresholds
- Algorithms must handle uncertainty
  - – Uncertainty is present in the current state estimate, in the future system inputs, in the system models, etc.
  - – Example: Monte Carlo sampling – simulate forward many realizations (samples), sampling from all uncertain variables

Prediction


Occurrences of $WX_{W1,A3}$:
1. Probability = 40%
2. Time until event = 8 min. (average)
Occurrences of $LOS_{A1,A2}$:
1. Probability = 60%
2. Time until event = 2 min. (average)
80% Probability of Unsafe Event
Time
Realizations of NAS State Trajectories

Prediction


Sector Count = 8
Sector Count = 8
Sector Count = 10
Sector Count = 12
Sector Count = 12
Sector Count = 11
Sector Count = 10
Sector Count = 9
Sector Count = 8
Sector Count = 8
Sector demand violation in 4 minutes.
Time
Realizations of NAS State Trajectories


NAS Safety Margins
Aggregate
LOS
Weather
Wake
Sector Demand
100
50
0
17:16
17:17
17:18
17:19
17:20
2017/03/14 19:37:31 Z
Prediction updated at 17:15:22 Z
Predicted Safety Violations
Violation
At Time
Prob
SKW4872 : VRD183
17:15:42
100%
Display Options
LOS
WAKE
WX
SEC-DMD
Violation
Probability
> 50 %
2017/03/14 19:37:31 Z
Prediction updated at 17:15:22 Z
Map
SMF
MCC
MHR
SAC
VCB
APC
NOT
WX-3
SRF
CCR
SCK
OAK
HWD
LVK
MOD
SFO
HAF
SQL
PAO
NUQ
SJC
WX-1
SEC-ZOA12
LSN
WVI
SNS
MRY
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Decision-Making

- Current framework provides an open-loop prediction
  - If operations go as currently planned, will any unsafe situations arise?
- Can be integrated within decision-making algorithms
  - Assume a certain decision will be made, use the framework to predict the result w/r/t safety, and evaluate the quality of the decision
  - Search over the possible decision space to find an optimal solution

Conclusions

- Demonstrated feasibility of real-time safety monitoring and prediction framework for the NAS
  - Computes current and future safety state w/r/t safety margins
  - Computes probabilities of future unsafe events
- Future work
  - Adding more event categories
  - Scaling up: more efficient algorithms, distributed/cloud implementations
  - Further maturation with stakeholder feedback
  - Integration with decision-making

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