Protecting Aircraft in Real-time from a Launch or Re-entry Failure

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Background on FAA Space Vehicle Airspace Integration

The Challenge

- Space vehicles
  - Traverse airspace very rapidly and vertically
  - Have significant possibility of hazarding other aircraft due to a failure which produces falling debris

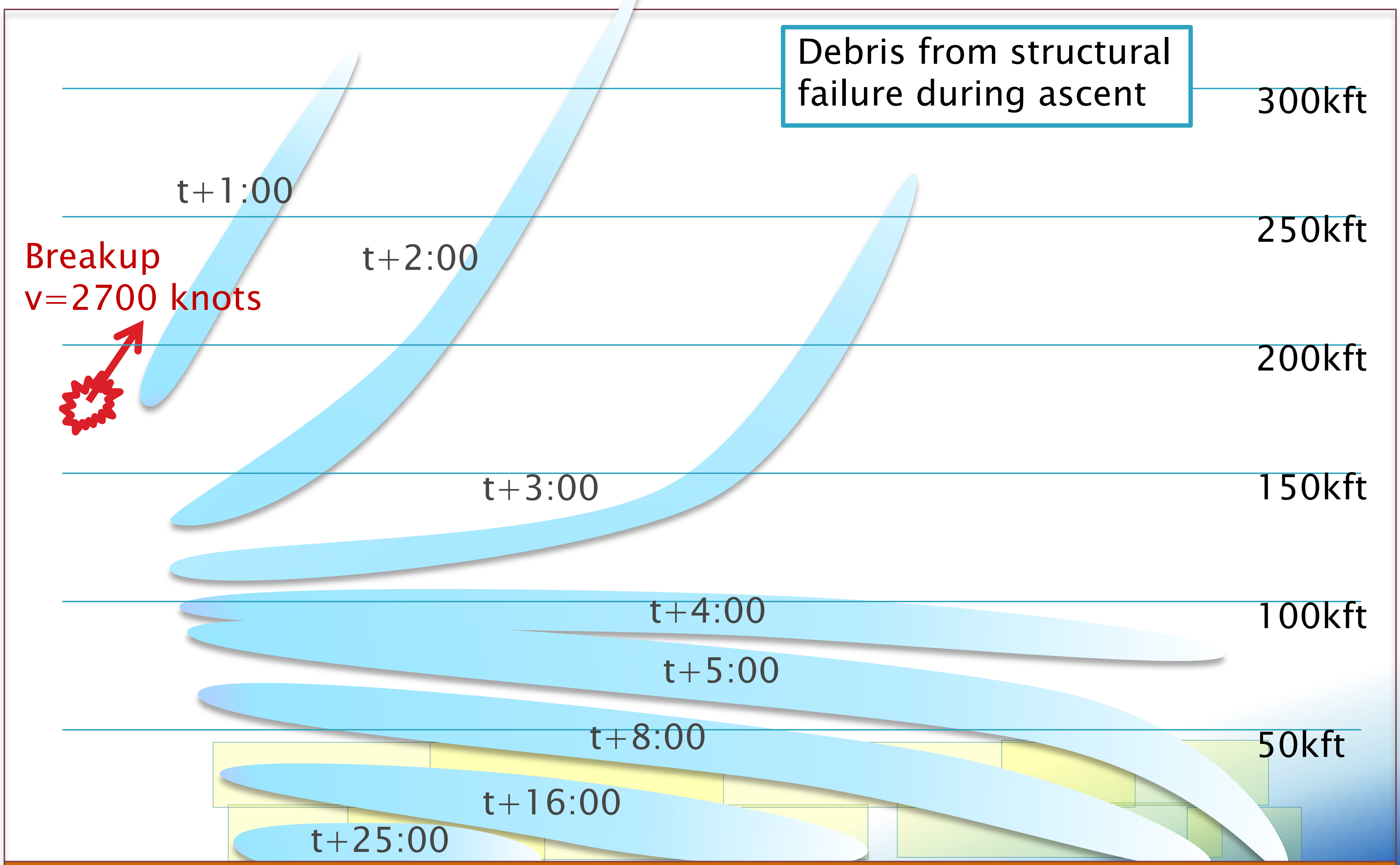
- Current Practice: Airspace Closures
  - Temporary Flight Restrictions (TFRs)
  - Altitude Reservations (ATLRVs)

- Problems
  - Lots of airspace (extent, duration) required for each mission
  - Significant advance notice required (weeks)
  - Capability for responding to unexpected events is slow, limited and fragile

Space Vehicle Operations Concept of Operations

- Improved automation and data exchange
  - Data exchange standards
  - Streamline processes for planning SV operations
- Real-time space vehicle data to ATC
  - Live operator telemetry data provided to FAA
  - ADS-B and space-based tracking
- Real-time accident response
  - Computed in real-time based on accident data
  - Electronically transferred to ATC systems
- Pre-mission airspace closure reduced
  - Reduced 4-D volume
  - Just-in-time activation

Animation of debris fall



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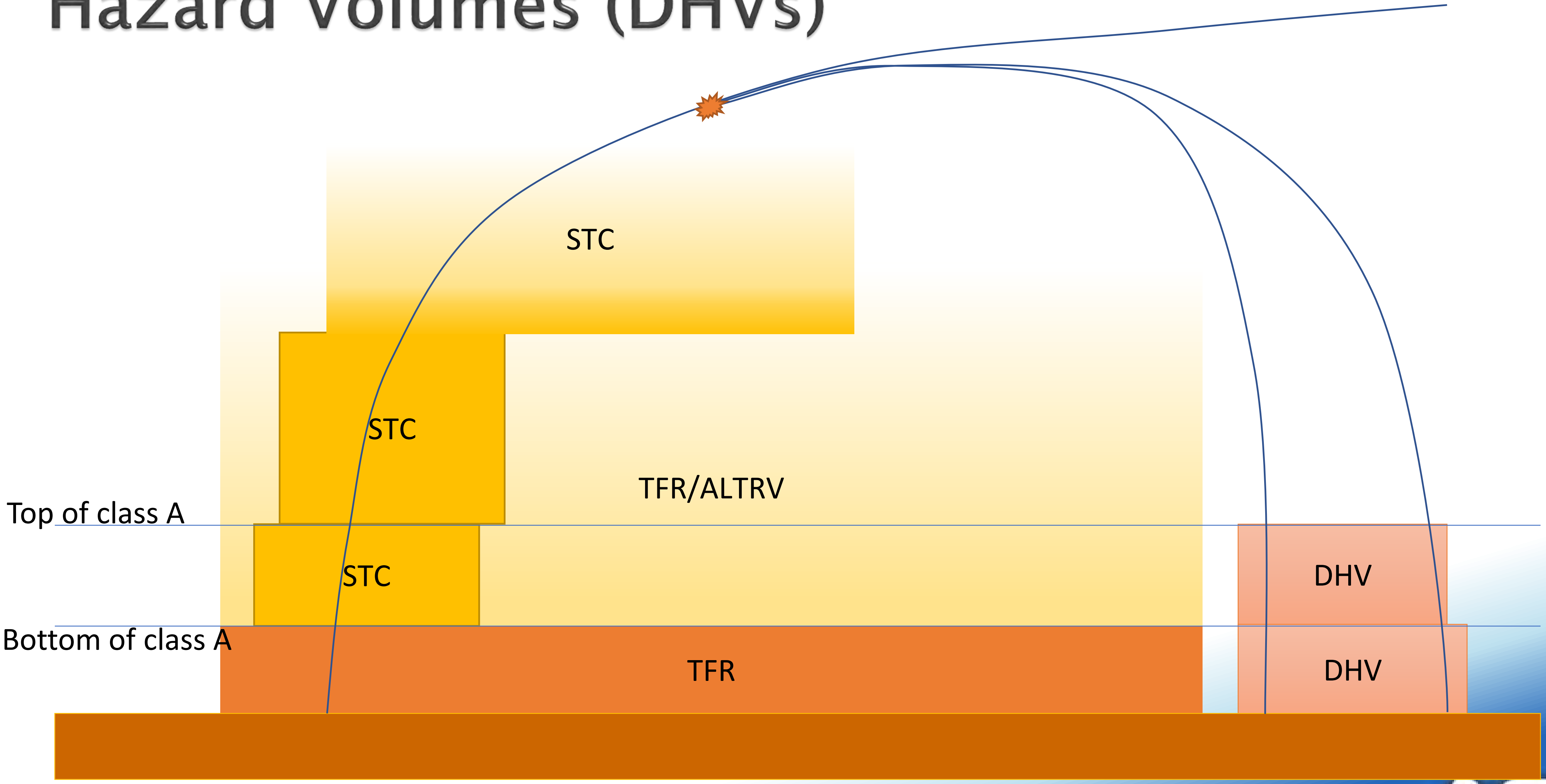
Space Transition Corridors (STCs) and Debris Hazard Volumes (DHVs)



Failure & Breakup Modeling

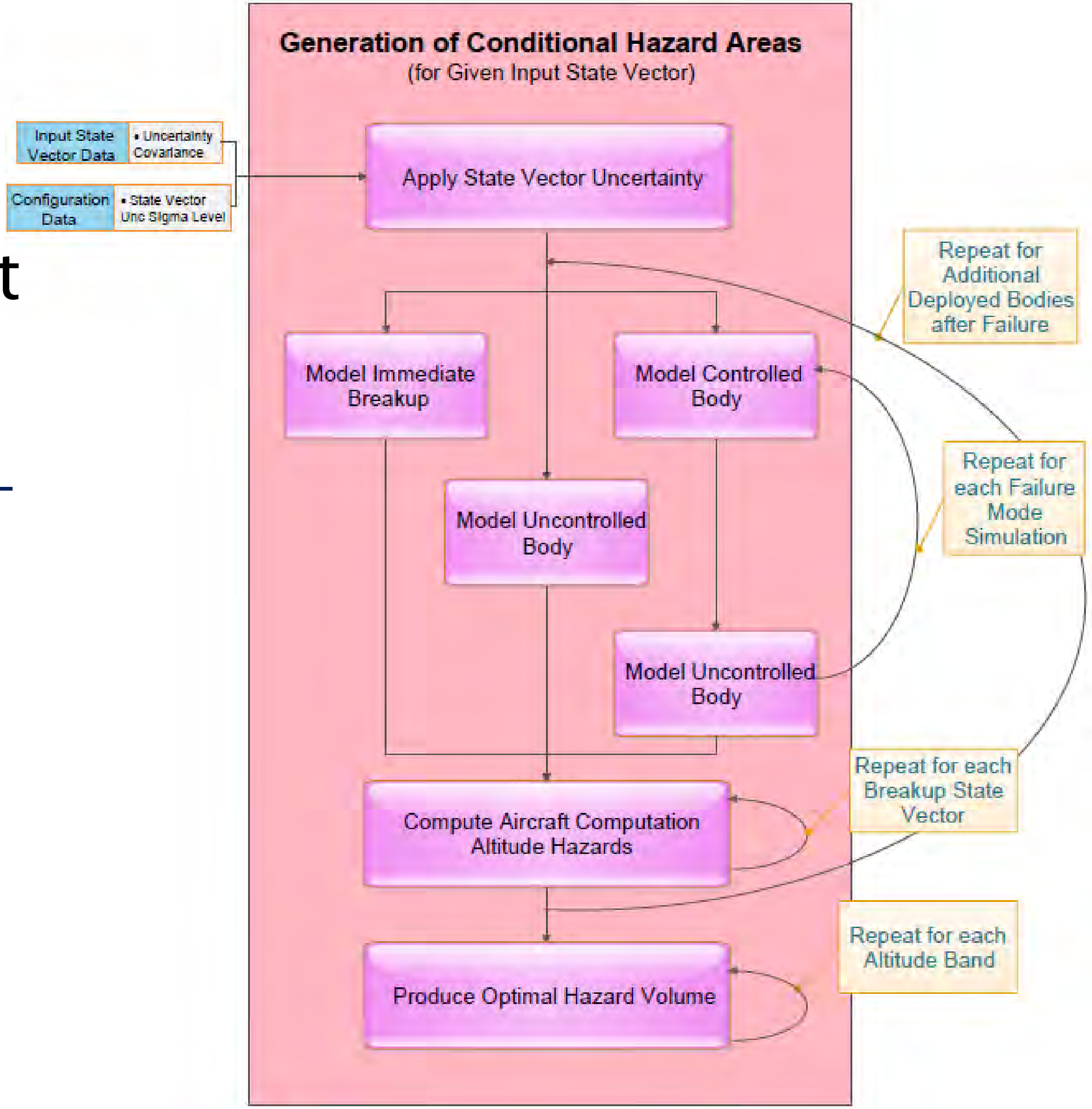
Prototype software: Hazard Risk Assessment & Mitigation (HRAM)

Failure & Breakup Modeling Requirements

- Compute aircraft hazard volume in real-time
  - Calculation time must be O(seconds)
  - Volume must be small enough to be cleared
  - Results must be accurate enough for re-directing air traffic
- Model vehicle behavior after loss-of-signal
  - Failure flight, could be thrusting (e.g. CRS-7) or lifting (e.g. DreamChaser)
  - Potential breakup during controlled or ballistic flight (e.g. during re-entry)
- Account for vehicle configuration changes
  - Change in failure behavior
  - Multiple simultaneous volumes
- Publish STCs and DHVs
  - Adjust/compute based on real-time mission status updates

Physics-based Modeling

- Controlled malfunctioning flight during possible loss of signal
  - Model varies based on vehicle control system (thrust vector, aero-surfaces, attitude control, etc.)
- Uncontrolled intact flight
- Breakup (can be progressive)
- Propagate debris
  - Limited debris set to produce pseudo-containment to make calculation fast
- Optimize 4-D hazard volumes



Evaluations

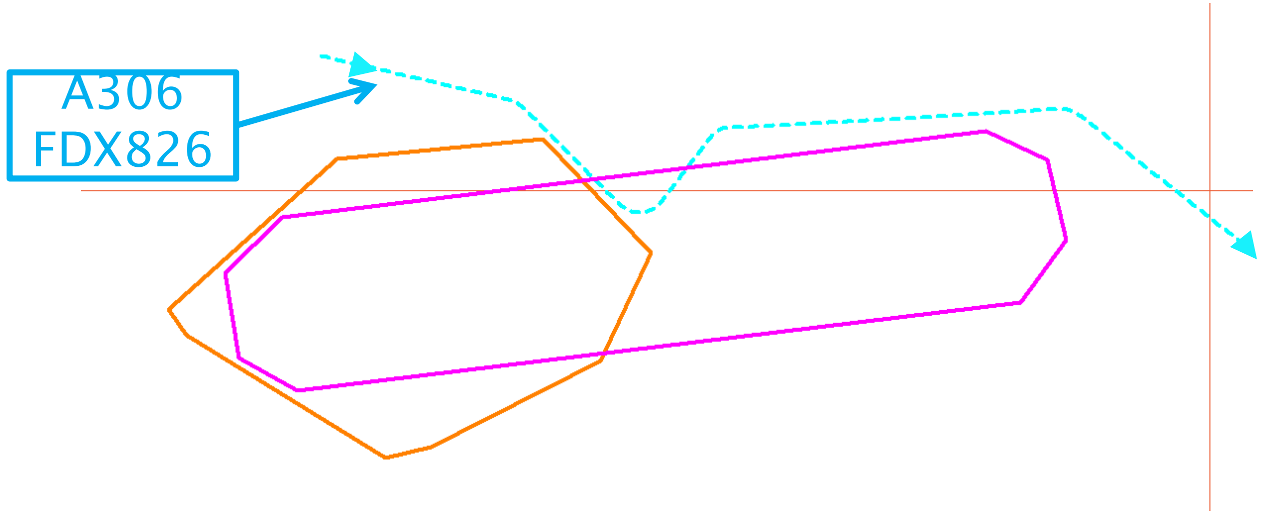
SVO Human-in-the-Loop Test (HITL)
Failure Scenarios Experiments

HITL Overview

- Objective to determine if safety of vehicles is maintained while increasing operational flexibility
- ATC involvement
  - Pilots – flying simulated airplanes
  - Controllers – viewing planes, rockets, hazard volume on slightly modified ERAM
  - Traffic managers – viewing on slightly modified TSDs
- HRAM running in real-time
- Two space vehicle scenarios were developed to test SVO concept
  - Suborbital rocket flight (ascent only)
  - Capsule performing a reentry

HITL Results

- To avoid hazard aircraft were routed out of STC, but re-routes modified when DHV issued.



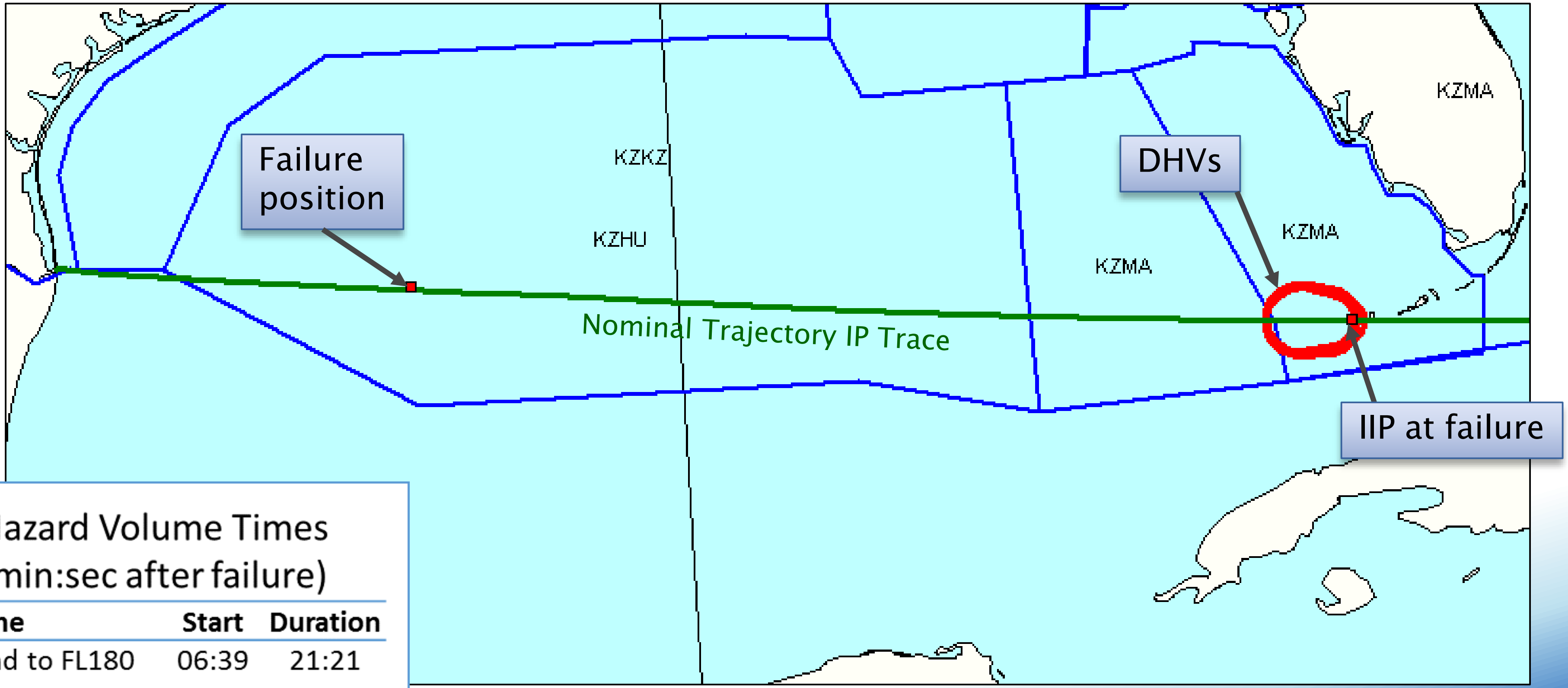
HITL showed
- Real-time response system tools, including HRAM, implemented into ATC tools
- Air traffic controllers and traffic managers could effectively apply STCs and DHVs to re-route planes
- Real-time aircraft re-routing adequate to protect aircraft (via residual risk analysis)

Scenario on Examination Objectives

- Evaluate the debris hazard algorithms and processing using prototype software
- Obtain feedback from an air traffic control perspective for incorporation into revisions of the concept,
- Assess the impact on the air traffic system of space vehicle operations, through measures such as the spatial and temporal extent of airspace affected,
- Validate hazard protection by comparing HRAM approach to existing approaches,
- Inform the development of prototype and operational ATC systems for space vehicle operations, and
- Develop test scenarios for use in future implementation of prototype, demonstration, and operational systems.

Example 1: Falcon 9 Downrange Explosion

- Launch from Brownsville
- Failure not long after 2nd stage ignition

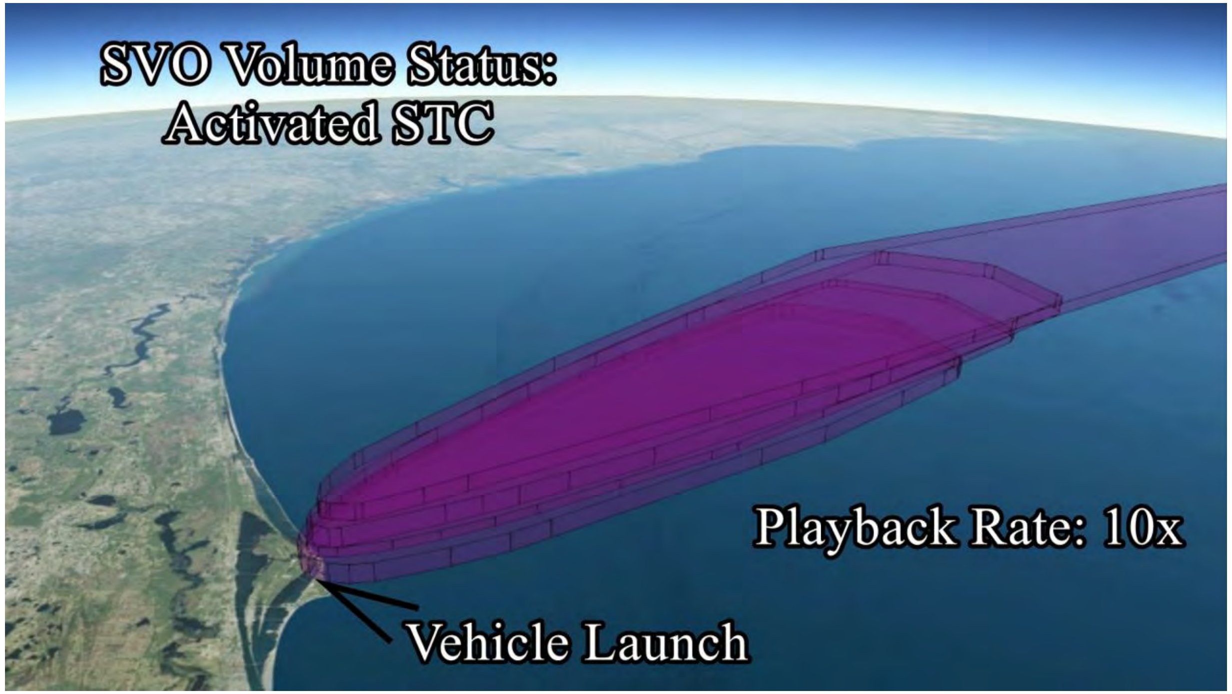


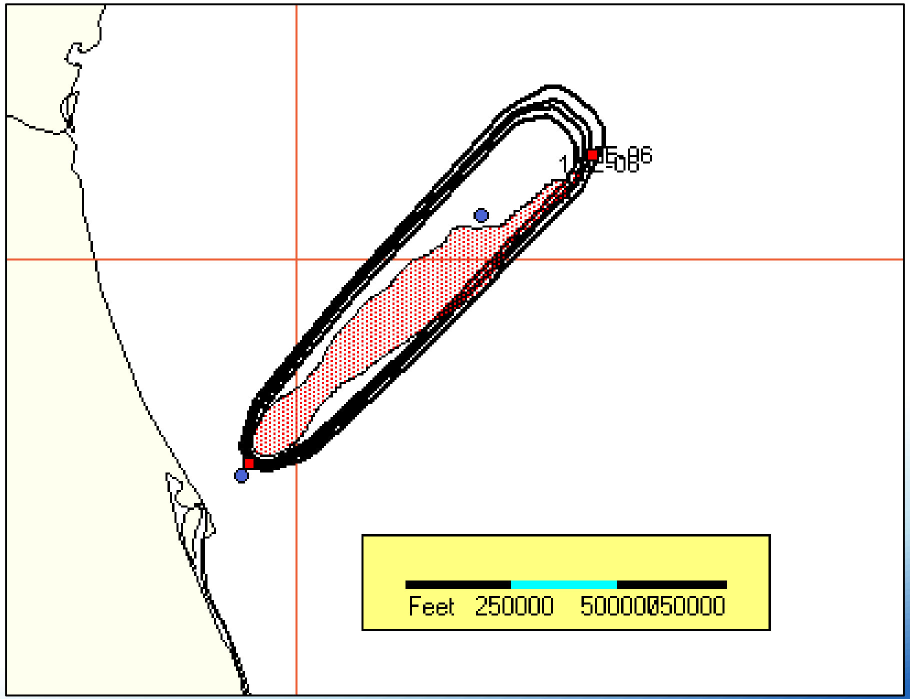
Hazard Volume Times
(min:sec after failure)

Volume	Start	Duration
Ground to FL180	06:39	21:21
FL180 to FL270	06:28	14:38
FL270 to FL450	06:16	12:02
FL450 to FL600	06:12	07:38

Example 2: CRS-7 Mishap

- Very interesting scenario: 2nd stage exploded, then 1st stage continued to thrust for 8 seconds with no guidance





Key Lessons Learned

- Debris fall time provides pragmatically useful response window for many launch and re-entry failure scenarios
  - Air traffic control personnel are positive about the concept
- Real-time response would provide additional safety for low probability events than current practice
- Often the real-time hazard volume is small
  - Small: <10 miles x 30 miles; high risk over small area
  - Largest for breakups in upper atmosphere, longest for re-entry
- Failures with downward velocity lead to challenging timeline
  - Lifting body re-entry failures between 100kft & 200kft
  - Launch vehicles: termination criteria to protect failure that powers back down toward airspace would be very helpful