Constraint-Based Techniques for Managing Movement in Crowded Airspaces

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Outline of Talk

- Management of Crowded Airspaces
- Dynamic Airspace Deconfliction Project
  - Building Conflict-Free Movement Schedules
  - Integrating with distributed, real-time airspace deconfliction processes
- Future directions

Airspace Deconfliction: Civilian Aviation

- Increasing volume of aircraft and congestion around airports
- Complexity of determining corridors and sequencing for takeoff, landing and holding

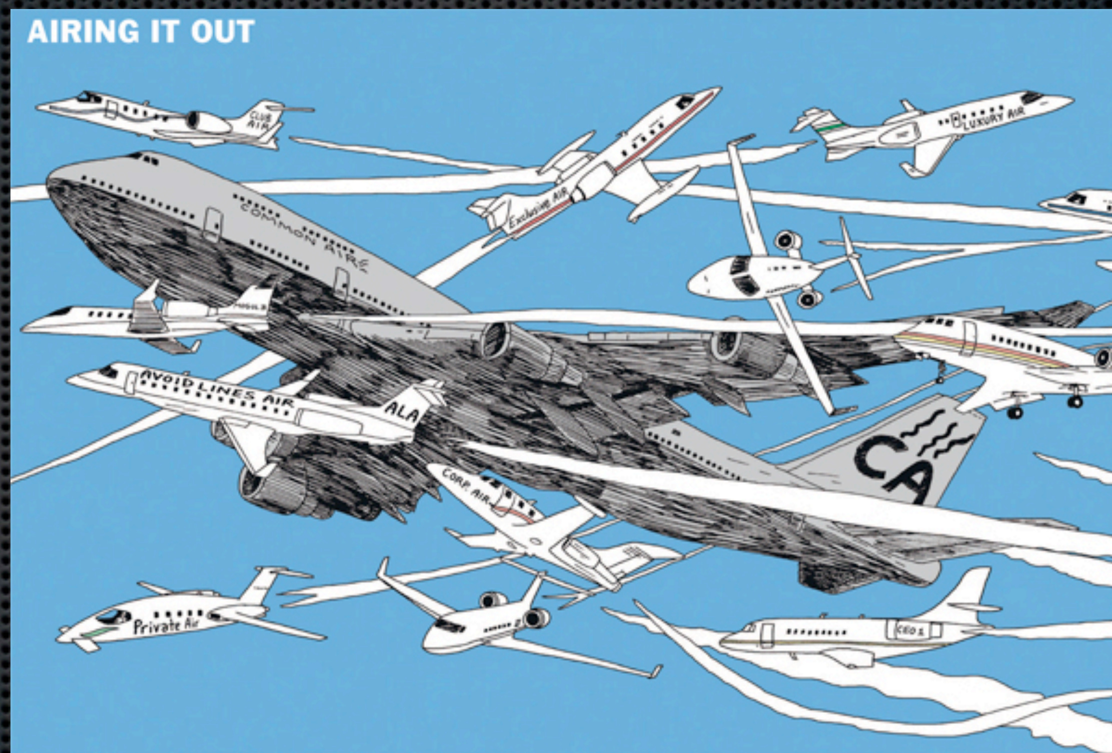
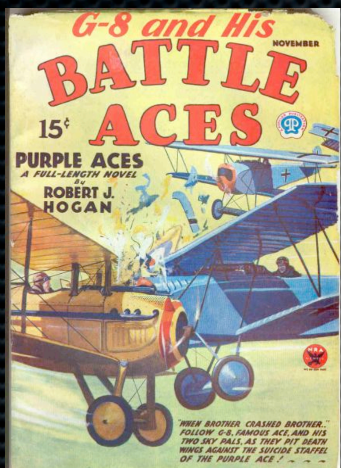


Illustration by Peter Arkle for the New York Times – 26 August 2007

Airspace Deconfliction: Military Aviation



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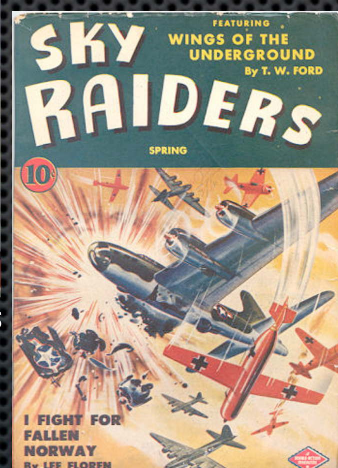

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- Concurrent missions
- Localized and heavily populated environment
- Dynamically generated mission routes
- Increasingly autonomous aircraft
- Pop-up threats, friendly forces
- Strict partitioning of airspace is inefficient

Emerging Concepts: Dynamic Airspace Configuration

- Automated separation assurance (via ground-based or distributed airborne systems)
- User-preferred trajectories
- Dynamic traffic management (adaptive speed control, route modification)
- Adaptable airspace to meet user demand, react to changing weather, maintain safety, etc.
- "DAC allocates airspace as a resource to meet user demand …" [1]

1. P. Kopardekar, K. Bilimoria ad B. Sridhar, "Initial Concepts for Dynamic Airspace Configuration", *Proc. 7th AIAA Aviation Technology, Integration and Operations Conference*, Belfast, Sept. 2007

Dynamic Airspace Deconfliction

Joint Boeing-CMU research collaboration

Goal: Technology components to support planning and execution of conflict-free air operations

Technical Approach:

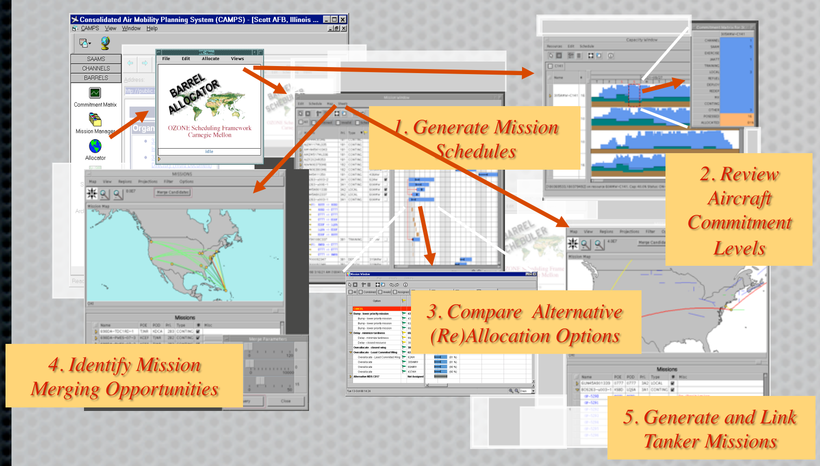
- Leverage previous work in constraint-based scheduling and task allocation
- Investigate and incorporate techniques for representing and reasoning about spatial constraints
- Couple mechanisms for centralized global mission planning with real-time distributed deconfliction processes

Starting Point: Dynamic Task Allocation and Scheduling

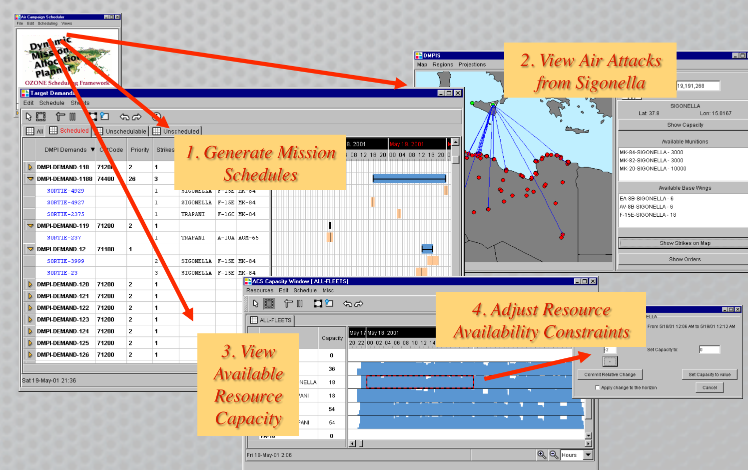
Core Technology: *Incremental, Constraint-based Search*

Applications:

- ***AMC Allocator*** - day-to-day mgnt. of airlift & tanker missions



- ***ACS (Air Campaign Scheduler)*** streaming ATO generation



- ***DARPA Coordinators*** - distributed management of high-quality joint plans

Constraint-Based Search Models

Components:

Properties:

- Modeling Generality/Expressiveness
- Incrementality
- Compositional

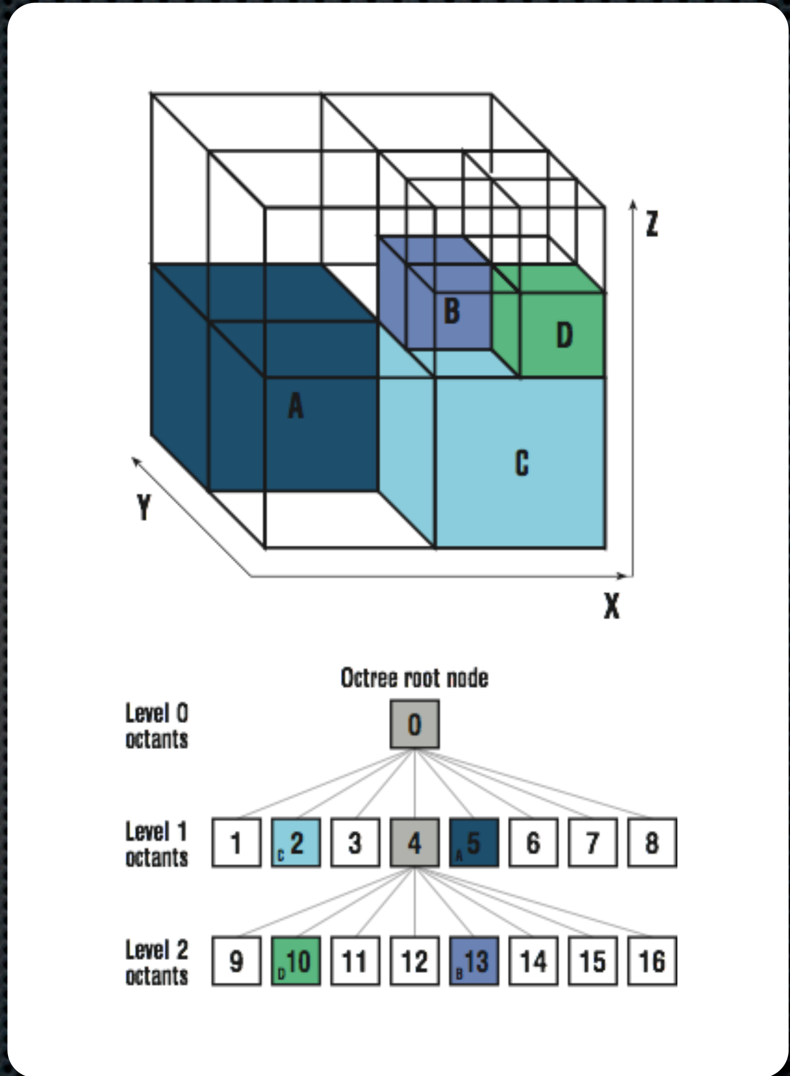
Building Conflict-Free Movement Schedules

Approach:

- View space as a ***capacitated*** resource and treat airspace deconfliction as an extended resource allocation problem
- Exploit ***Octree*** representation of air space volumes over time
- Generalize the notion of contention-based search heuristics
  - Construct and use a profile of spatial contention to make vehicle-routing and sequencing decisions

The Octree

- Hierarchical, three-dimensional data structure (an extension of the 2D **quadtree**)
- Recursively subdivides a spatial volume into smaller subvolumes (called **octants**)
- Localizes common objects indexed by [x,y,z] coordinates



The Linear Octree

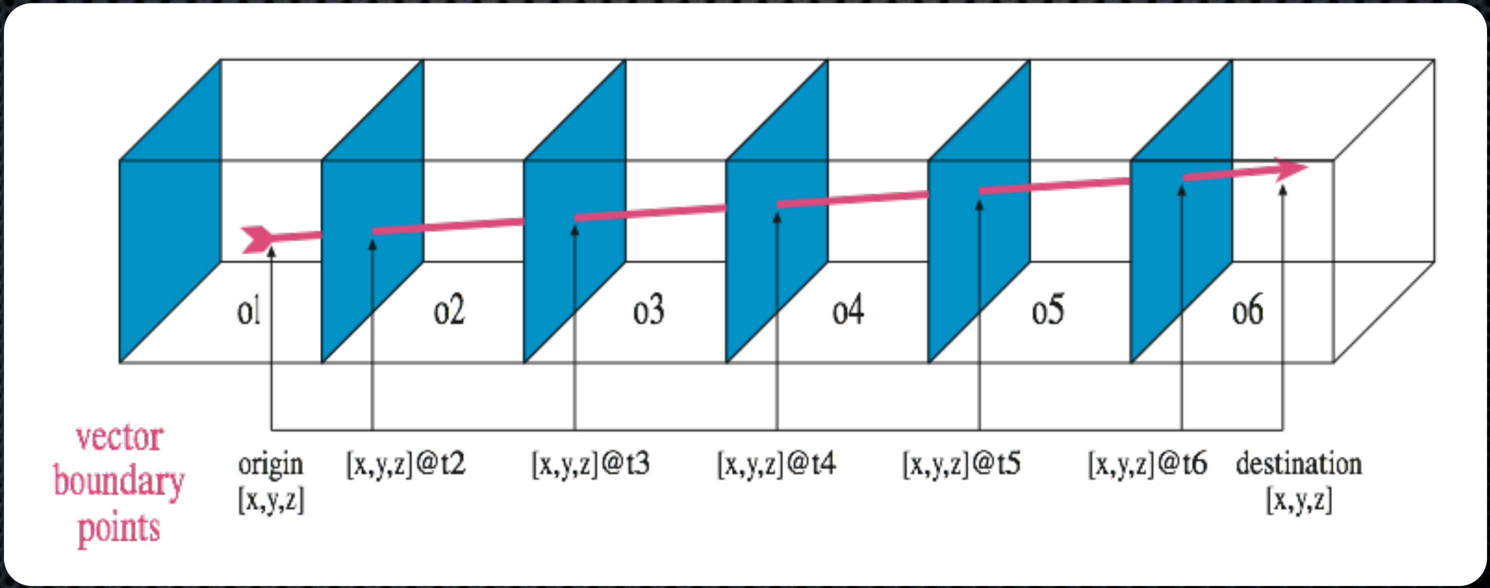
- Represents the octree as a balanced binary tree
- Locational codes computed from the [x,y,z] coordinates of each octant's origin serve as keys in the binary tree
- The result is a leaner and more efficient data structure

Storage and Manipulation of Vehicle Routes

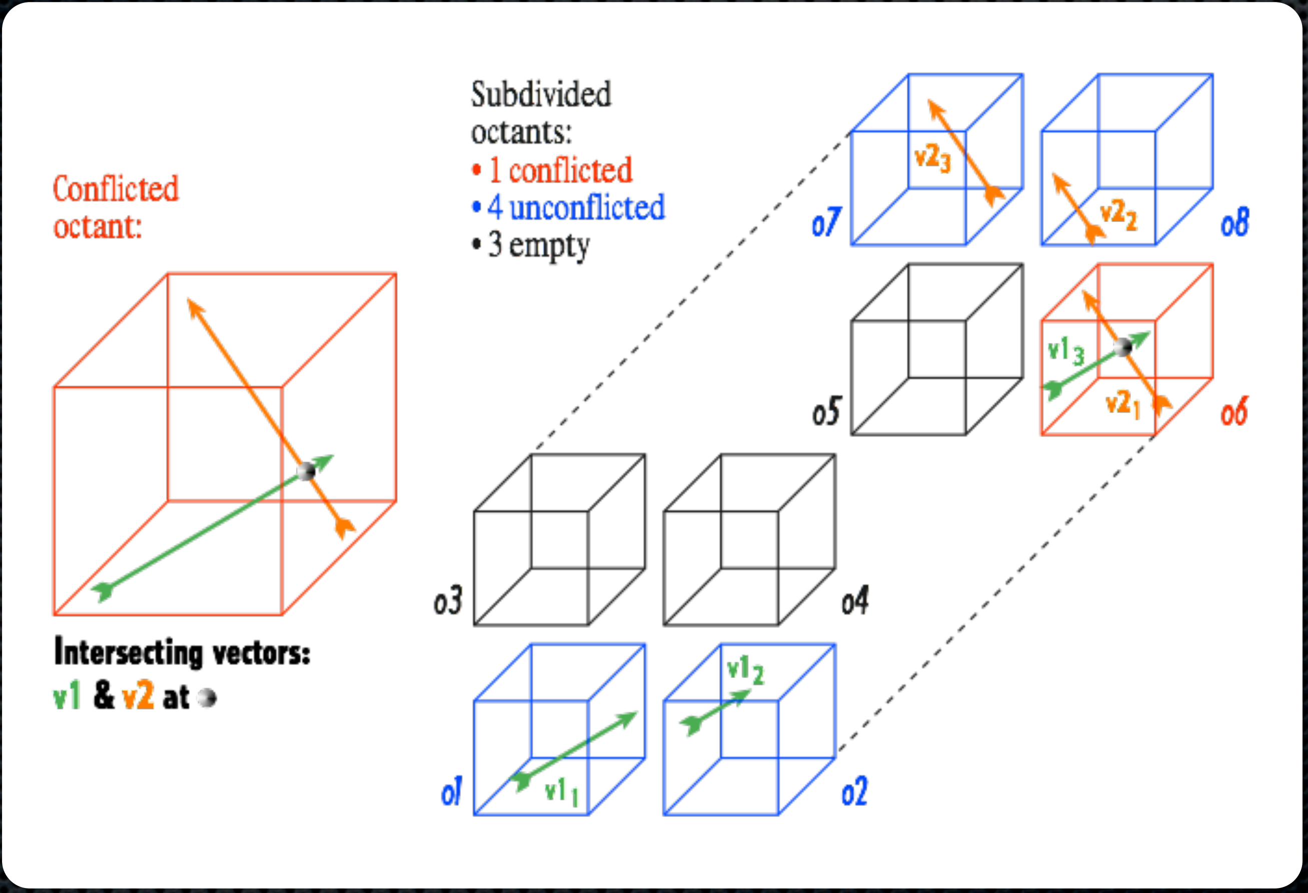
- Allocating vehicle routes to octants (a route is a sequence of 4D vectors)
- Determining conflicts using spherical MAZes (Maneuver Avoidance Zones) and the Closest Point of Approach

Allocating Vehicle Routes to Octants

- Vectors are apportioned across all intersecting octants
- A conflict is signaled by the **spatial and temporal** overlap of two or more vector segments within an octant

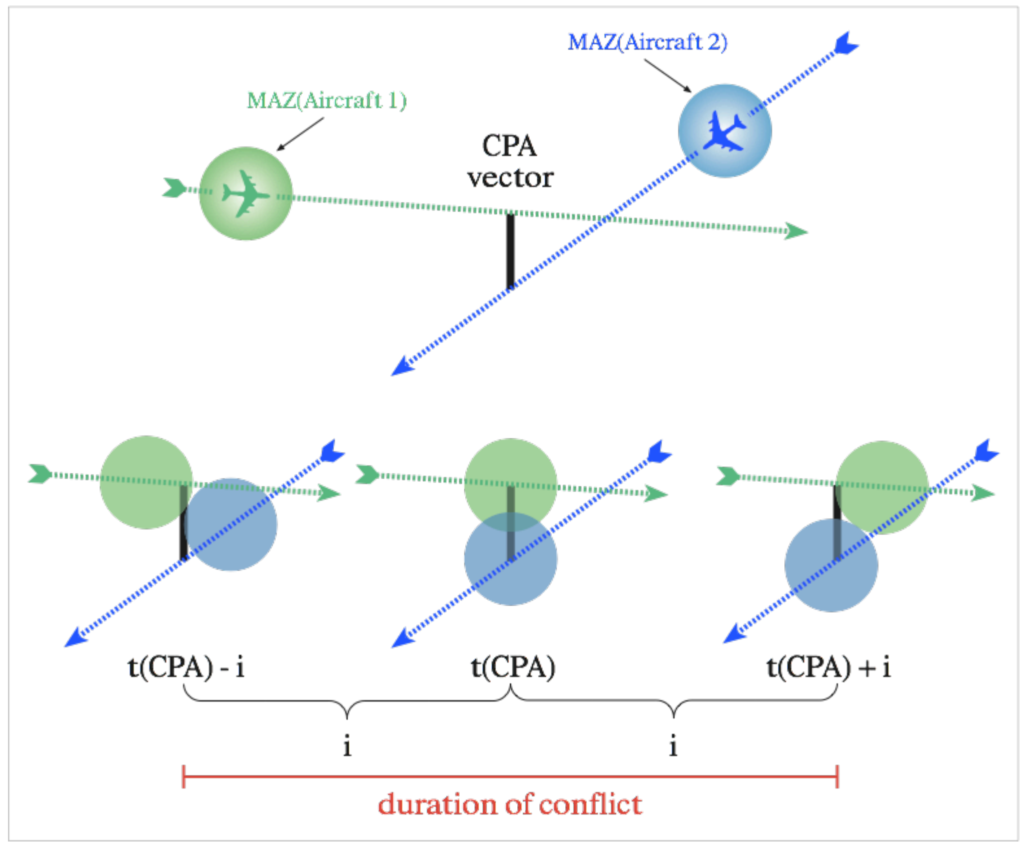


Octant Subdivision in Response to a Conflict



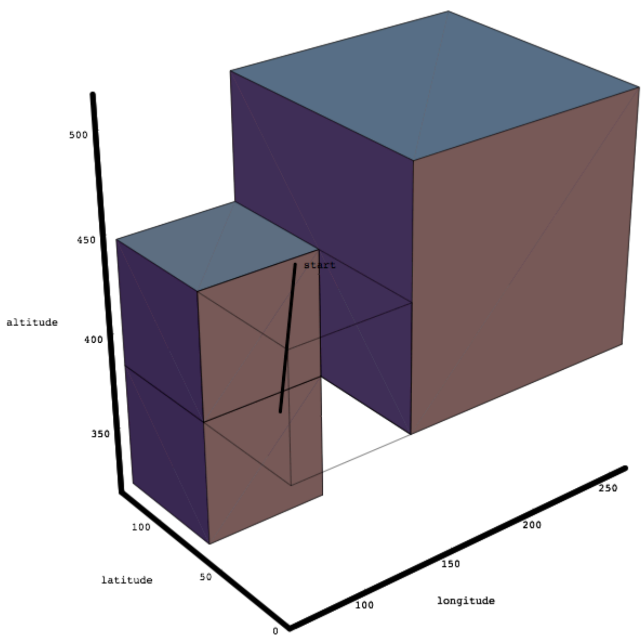
Determining Conflicts

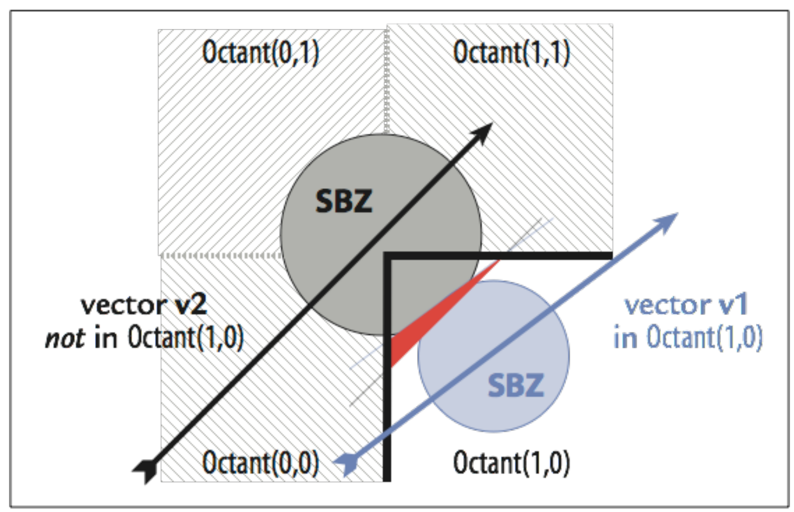
- A conflict between two vehicles is centered around the time of its closest point of approach (CPA)
- The duration of a conflict is measured from the beginning to the end of the spatial overlap



Searching for Conflicts Among Neighboring Octants

- Neighboring octants must be searched for conflicting vectors whenever a vector is too close to an octant boundary

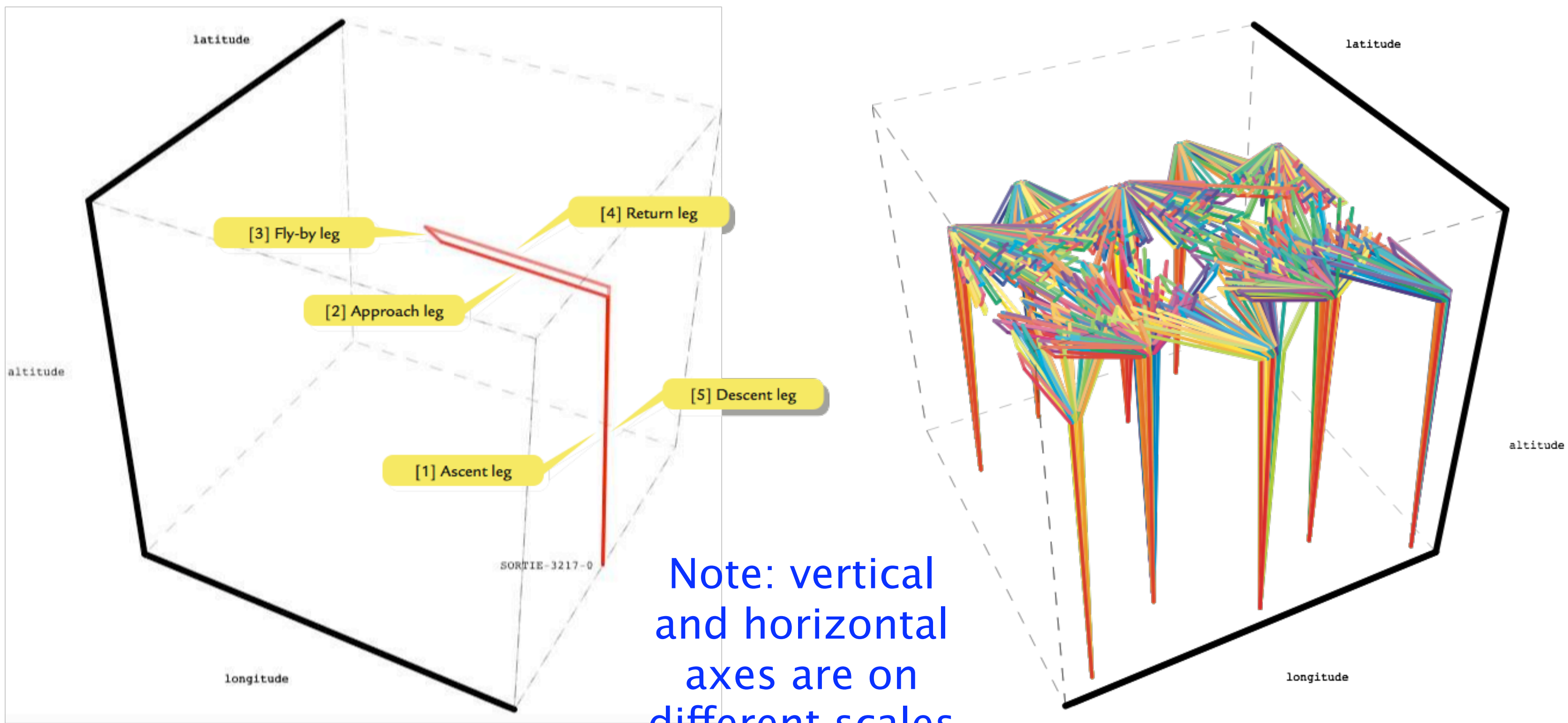




Generating Conflict-Free Schedules

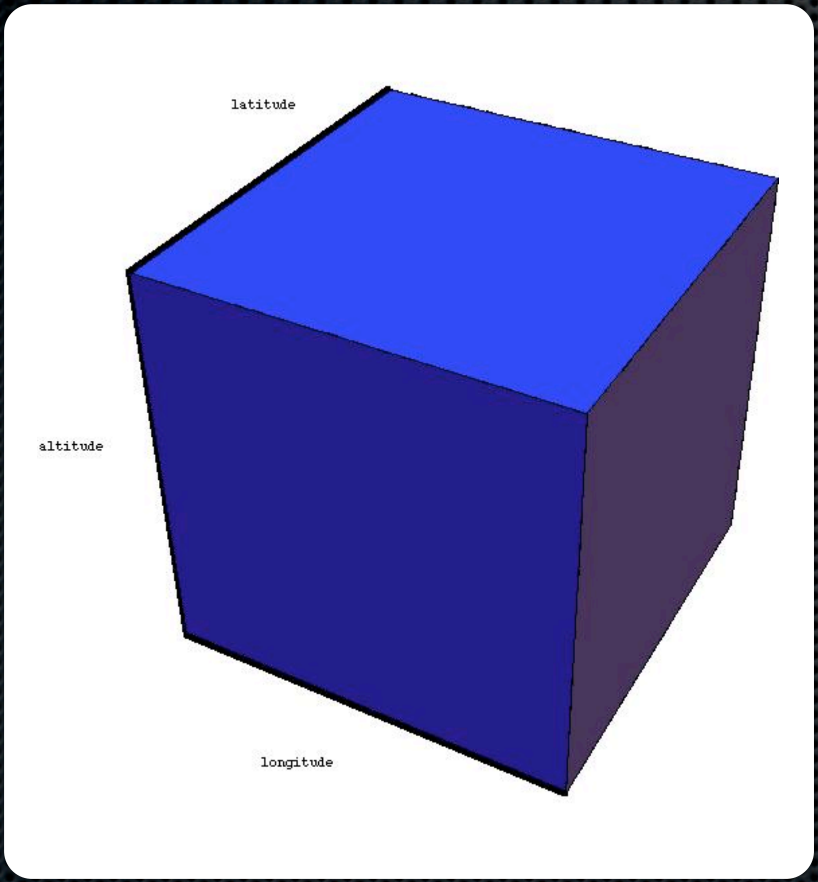
- **Approach:**
  - start with a base scheduling algorithm for computing a resource-feasible schedule for a set of itineraries
  - incorporate a route-planning component
  - extend algorithm to allocate space in the octree
- **Two phase schedule generation procedure:**
  - **priming** phase – build a resource-feasible schedule that ignores spatial capacity constraints
  - **scheduling** phase – use spatial contention profile to build extended solution that enforces spatial constraints

Air Vehicle Mission Routes



Note: vertical and horizontal axes are on different scales

Phase One: Priming the Octree



- The octree is populated by scheduling all expected missions
- Airspace is allocated without consideration of spatial constraints
- Red octants indicate resulting areas of contention

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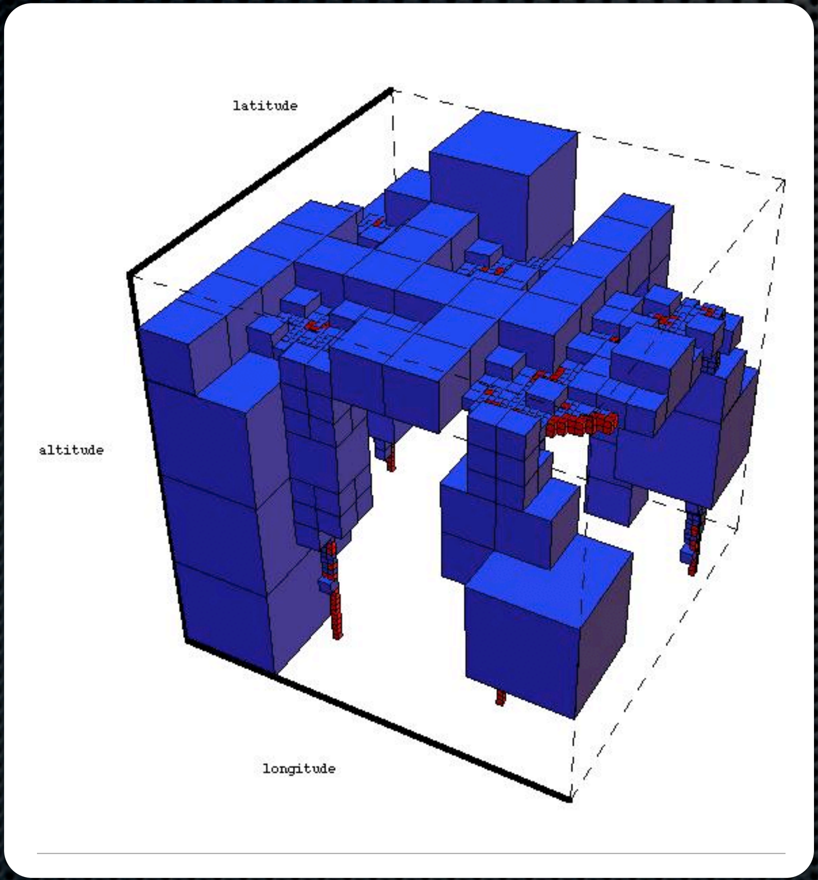

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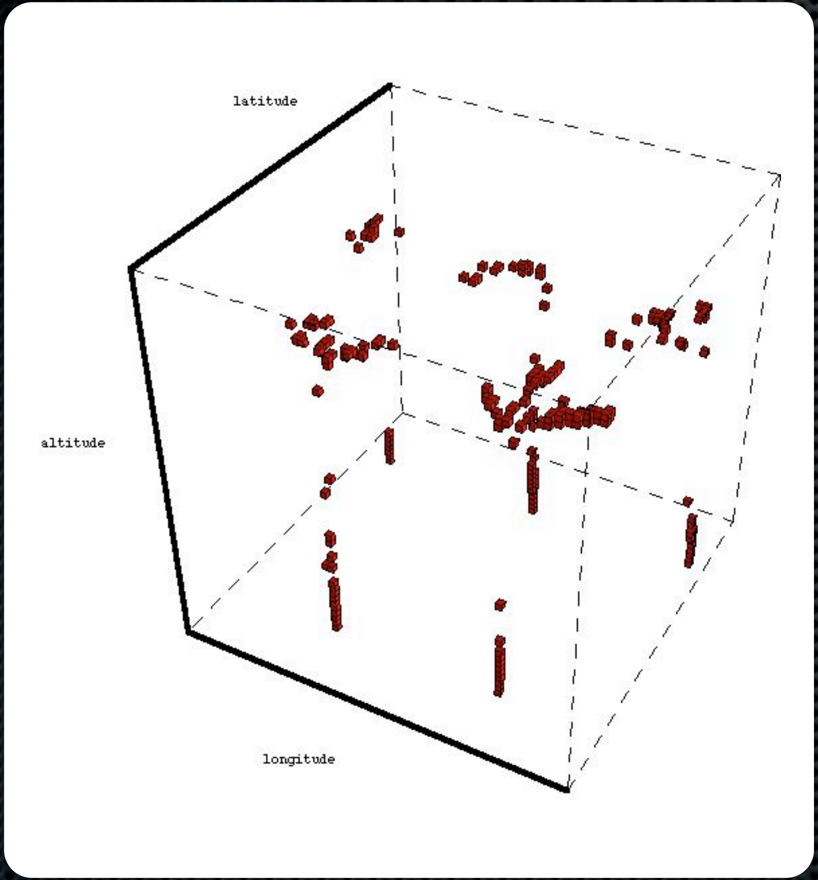

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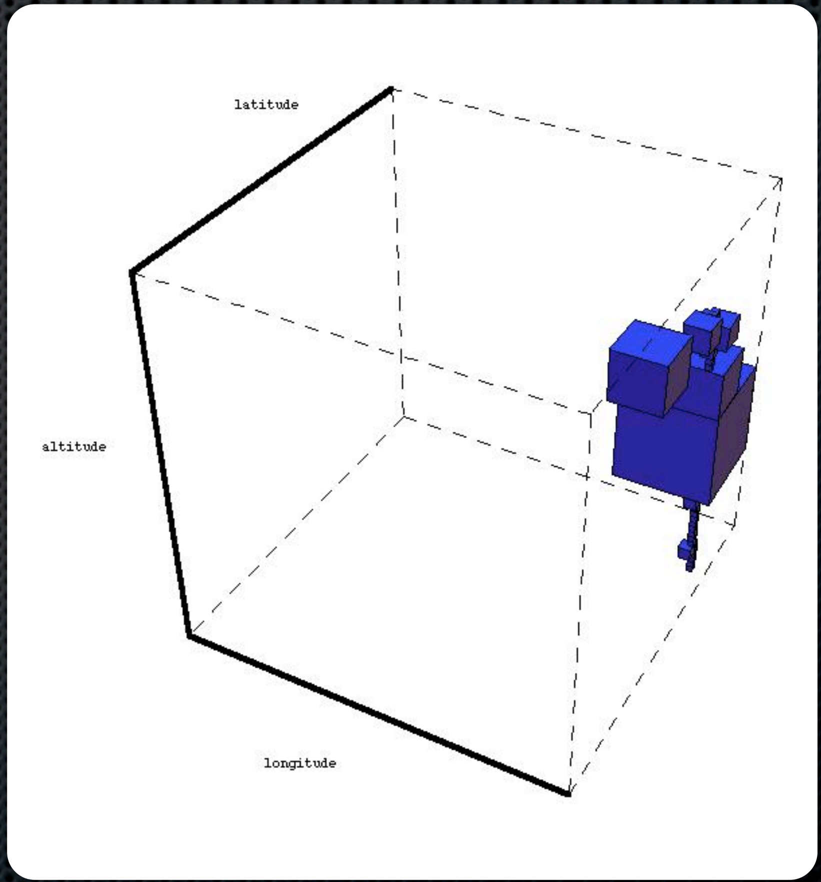
Phase Two: Deconfliction Scheduling

- The primed octree is used to guide the construction of a conflict-free schedule
- Traffic is directed to uncongested areas
- Routes are modified as necessary to avoid conflicts with other vehicles



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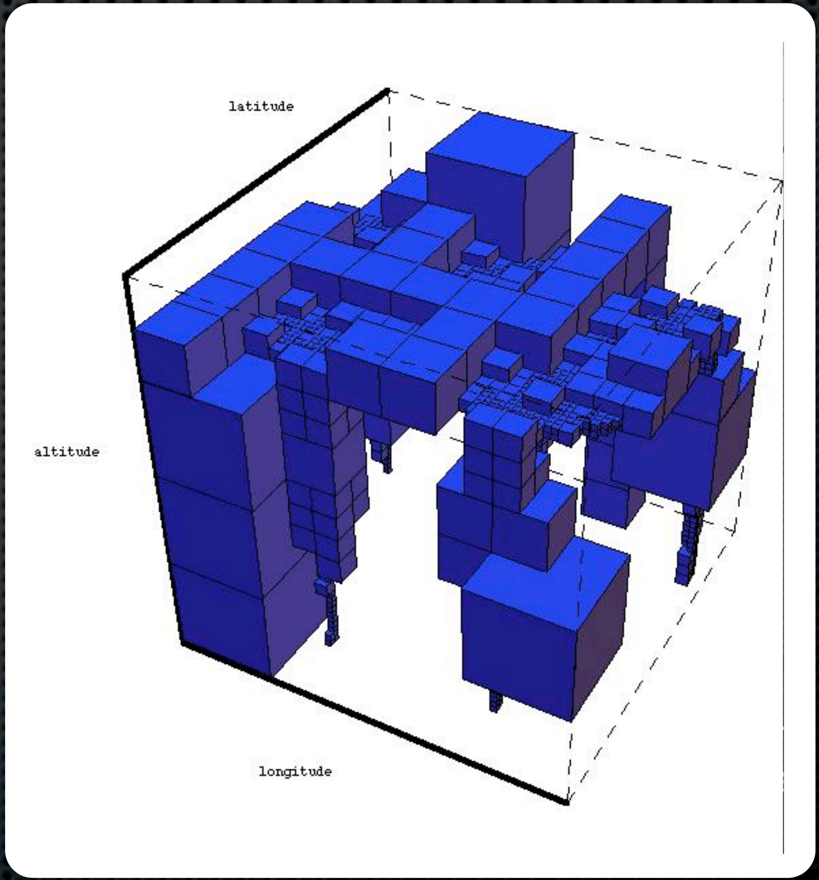
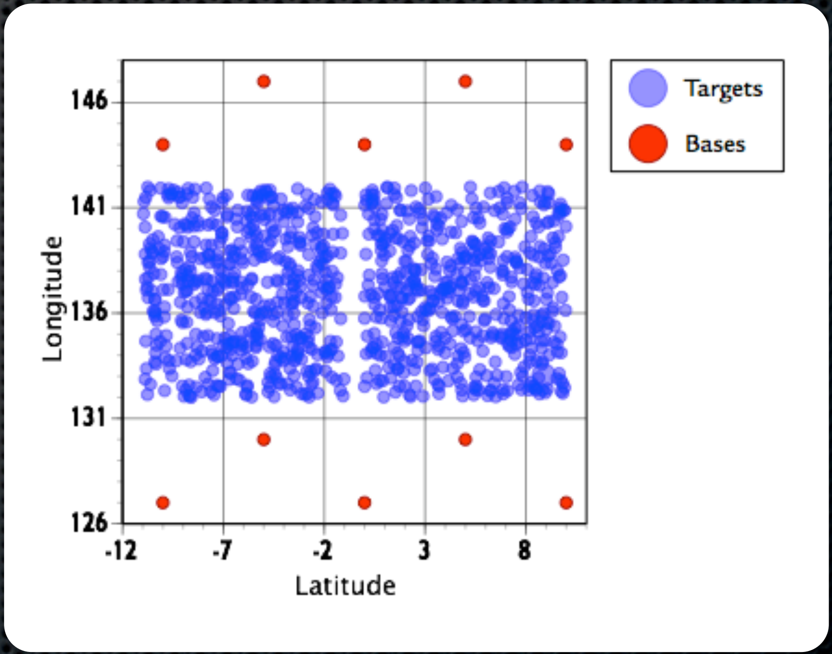


Evaluation: The Problem Set

- 20 data sets
  - 50 to 1000 randomly generated targets (in increments of 50)
  - Two 700-miles-square target areas
  - 10 identically equipped bases

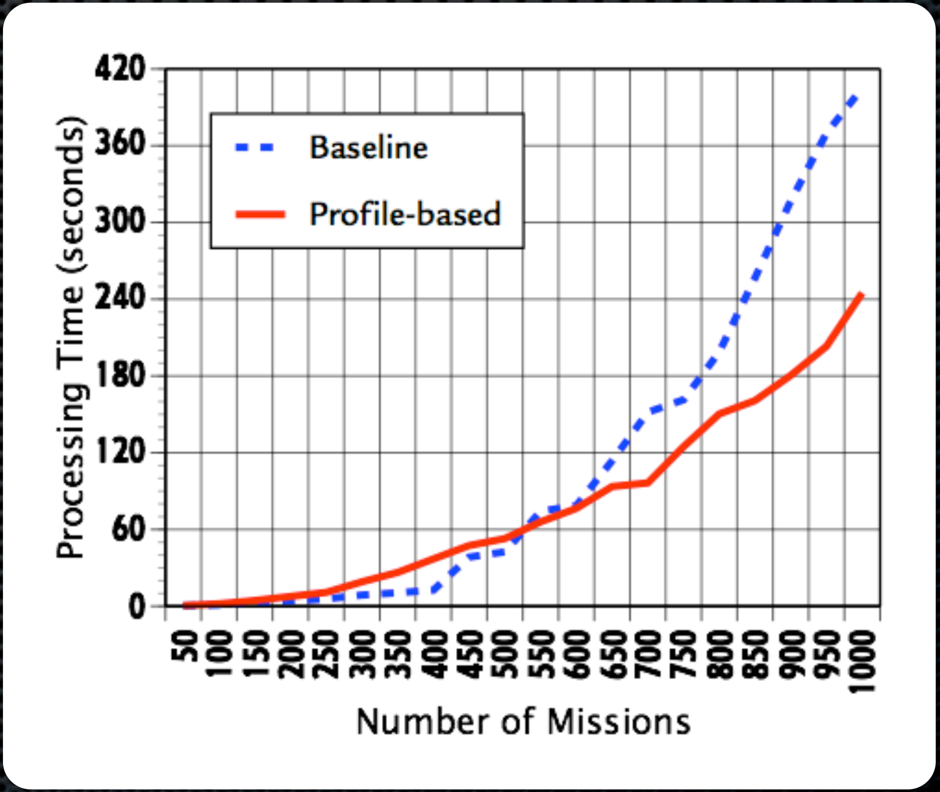


Evaluation: Two Deconfliction Strategies

- **Baseline Approach**
  - No primed octree (**myopic**): if a conflict is detected, an attempt is made – based on the current partial state – to deconflict through route modification
- **Profile-based Approach**
  - Create and utilize the primed octree to guide route modification in response to conflicts

Evaluation: Results

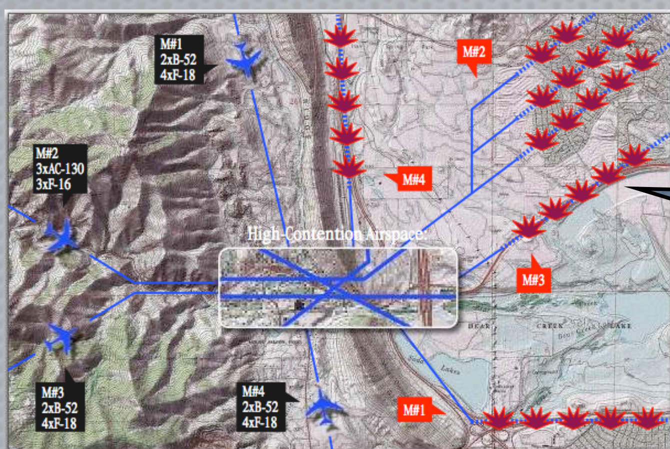
- Additional overhead for building the spatial contention profile is compensated for by an improvement in overall scheduling performance for sufficiently sized runs



Multi-Level Airspace Deconfliction Framework

Airspace Sensitive, Multi-Mission Scheduling

- Mission trajectories, timings
- Potential conflicts



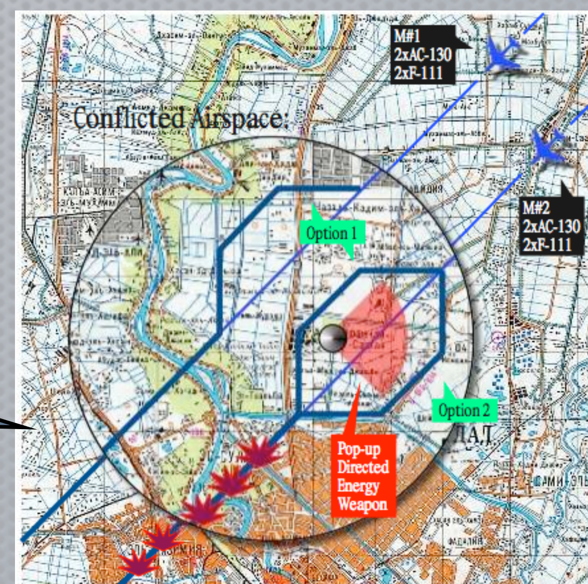
Predictive Guidance (Potential Conflicts)

Myopic Avoidance Actions

Downstream Impact

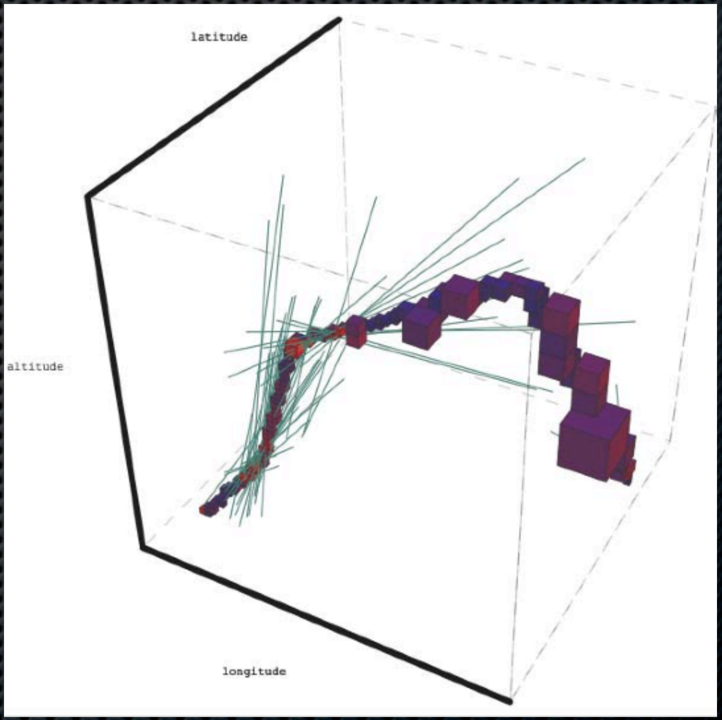
Distributed Real-time Airspace Deconfliction

- Turn left, slow down



Integrating with Real-Time Deconfliction Processes

- Use globally computed information to drive local deconfliction processes
  - Routes
(i.e., sequences of waypoints)
  - Potential Conflicts
(time and location)
  - Airspace Volume (given a 3D/4D region, where is the traffic?)
  - Airspace Corridor (are there sequences of under-populated 3D regions over time?)



An example query: given a route, determine its traversed octants and all conflicting vectors (in green)

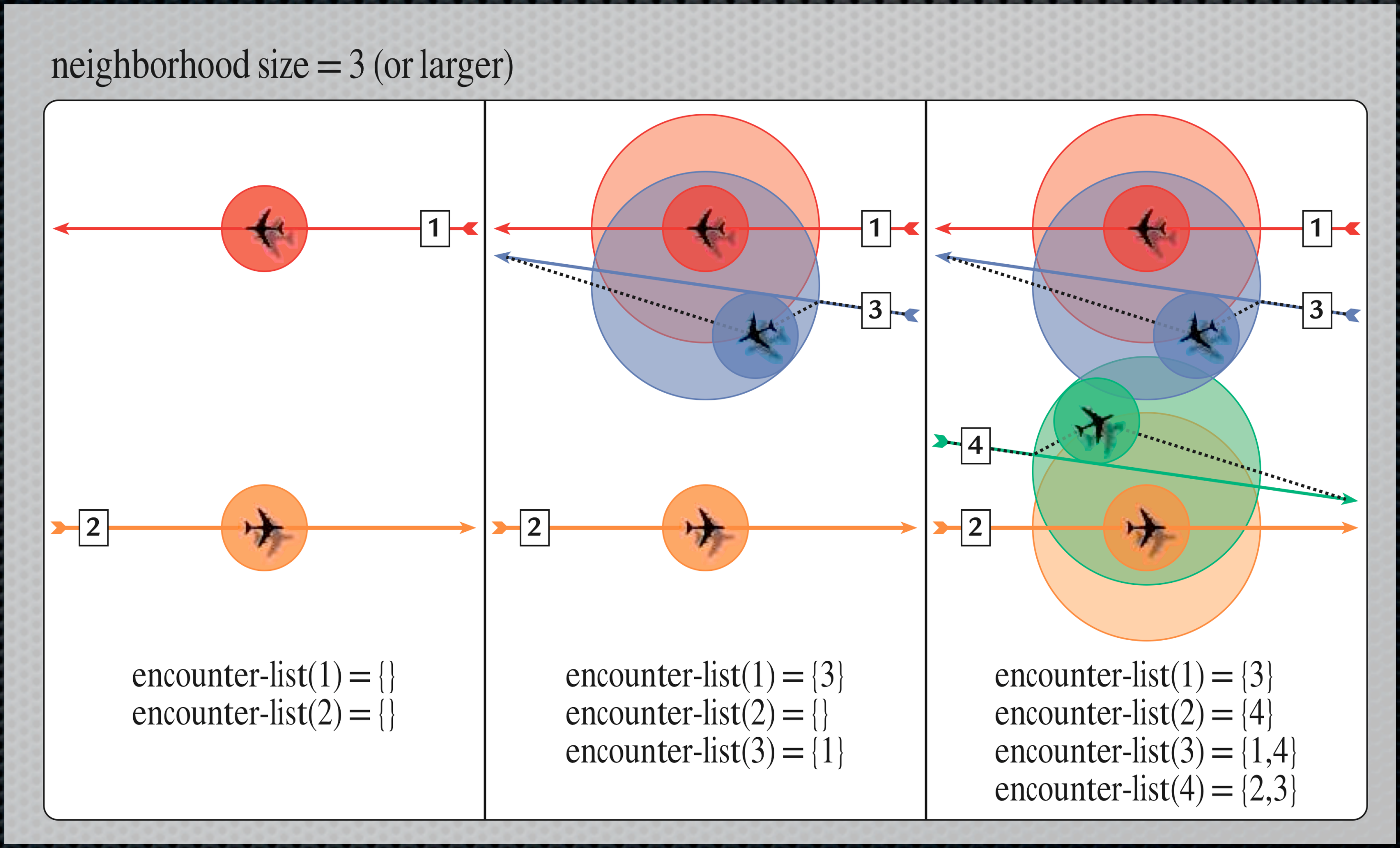
Operating Concept

- Distributed airborne processes assume responsibility for local deconfliction at execution time
- Global guidance is computed to provide an appropriate envelope of operations
- When any local route change is made, a query is made to the global scheduler to determine downstream impact and re-compute guidance

Computing Potential Conflicts

- ***Neighborhood size*** – the number of aircraft allowed to simultaneously violate separation constraints within an octant before a conflict is signaled
- ***Encounter region*** – the sum of the separation constraint and the distance a vehicle is allowed to deviate from its path to avoid a conflict
- ***Encounter list*** – for a given neighborhood size >1, the set of other air vehicles falling within the encounter region of a given aircraft's itinerary. This list constitutes the set of potential conflicts.

Encounter Lists



Status

- Initial, distributed deconfliction process operational (running in simulation)
  - Formulated as a distributed constraint satisfaction problem
  - Protocol for conflict resolution via cooperative partial centralization
  - Encounter lists determine who to interact with
- XML API in place for requesting and communicating global guidance

Future Directions

- Expansion of the spatial constraint model
- Consideration of more real-world constraints (e.g., maneuverability, fuel)
- Strategic analysis of conflict trajectories
- More sophisticated search and optimization procedures

Reference

- D. W. Hildum and S. F. Smith, “Constructing Conflict-Free Schedules in Space and Time”, *Proceedings 17th International Conference on Automated Planning and Scheduling (ICAPS-07)”*, Providence RI, September, 2007.