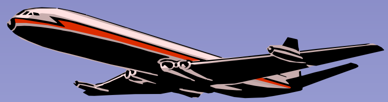

"An Airspace Planning and Collaborative Decision Making Model with Conflict, Workload, and Equity Considerations"

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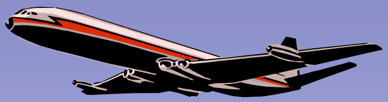
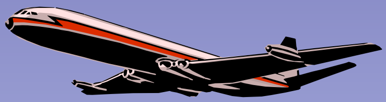
June 10, 2002



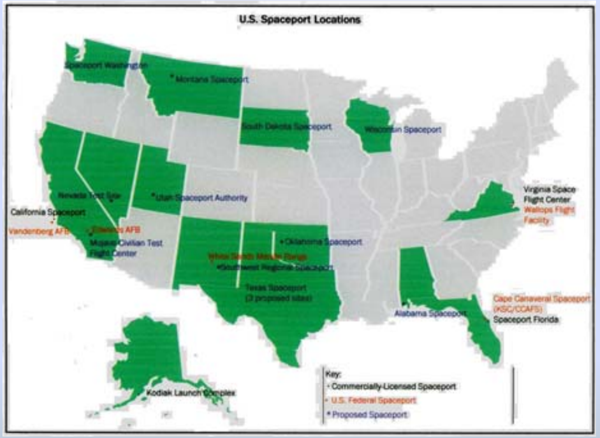
Overview

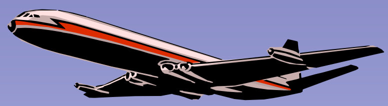
- Motivation & Background
- APCDM
  - Sector Occupancy (AOM)
  - Workload Constraints
  - Conflict Analysis (PAEM)
  - Conflict Resolution Constraints
  - Equity Considerations
  - Proposed Model
- Research Directions



Motivation & Background

- Congested Airspace
  - Number of aircraft flights increasing 1.5 to 3 percent annually
- Delays
  - Weather Systems
    - Cascading delays through NAS system
    - Impact to hubbed operations
    - Reallocation of resources
  - Space Launch
    - 100+ operations annually
    - Special Use Airspaces
    - Proposals for inland spaceports

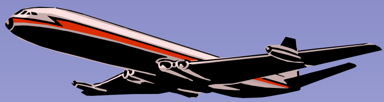




Motivation & Background

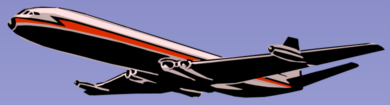
- Airline Competition
  - Fair allocation of constrained resources
  - New entrants and small/medium community service
  - Disparity in distribution of costs
  - Consumer expectations

- Safety and ATC Workload
  - Minimize en-route aircraft conflicts

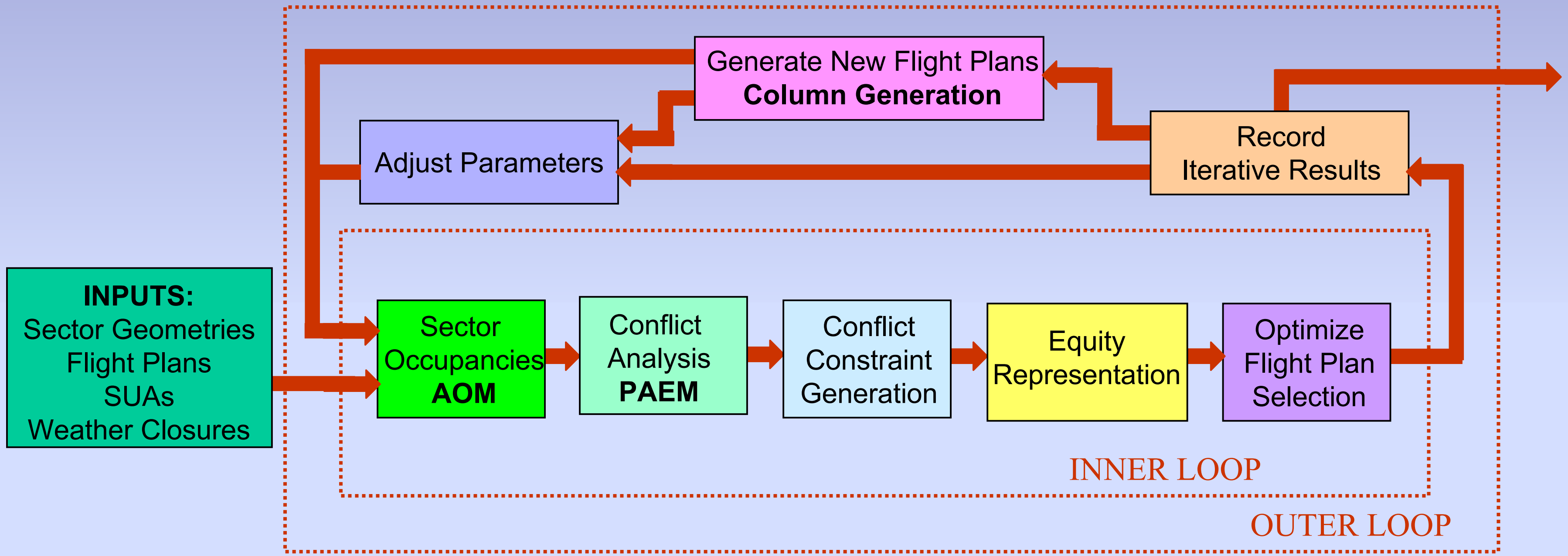


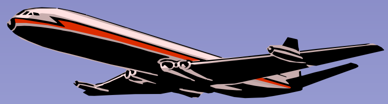
APCDM

- Flight Plan Selection
  - For each flight, select one flight-plan from among alternatives
  - Minimize Flight Costs (Objective Function)
  - Subject to Considerations (Penalty Terms in Objective Function)
    - Sector Workload
    - Safety (Conflict Resolution)
    - Equity



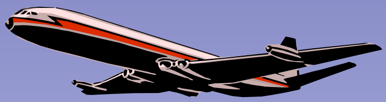
APCDM


Generate New Flight Plans
Column Generation
Adjust Parameters
Record
Iterative Results
INPUTS:
Sector Geometries
Flight Plans
SUAs
Weather Closures
Sector
Occupancies
AOM
Conflict
Analysis
PAEM
Conflict
Constraint
Generation
Equity
Representation
Optimize
Flight Plan
Selection
INNER LOOP
OUTER LOOP



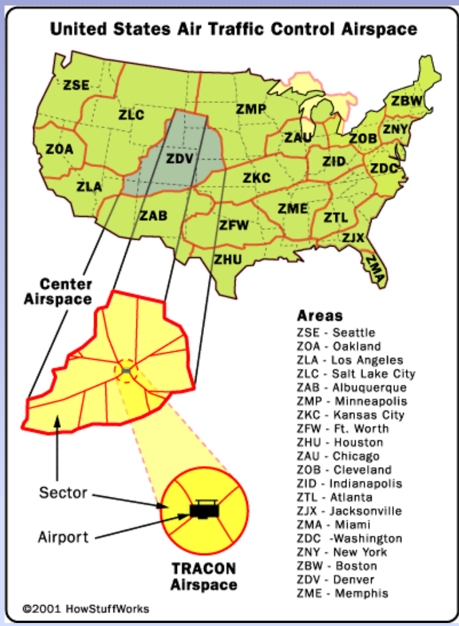
APCDM

- Aircraft Conflict Analysis
  - Stochastic with respect to aircraft trajectory
  - Conflict risk thresholds
- Conflict Resolution Constraints
  - Continuous time formulation
  - Two new classes of valid inequalities
- Equity Considerations
  - Cost Factors
  - Collaboration Efficiency & Equity
- Dynamic Airspace Closures
  - Weather Systems
  - Special Use Airspaces

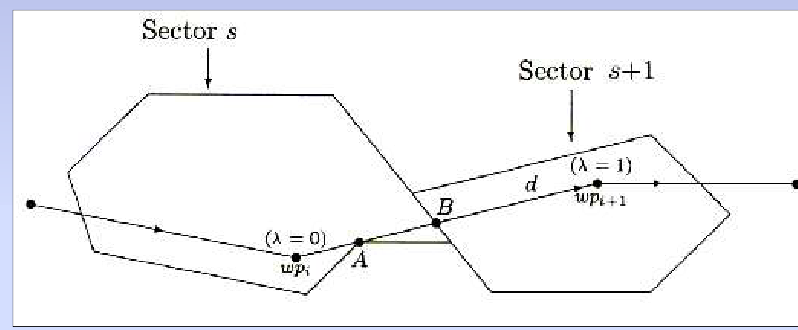


Sector Occupancy

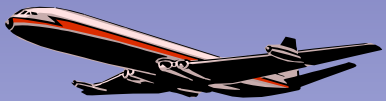
AIRSPACE OCCUPANCY MODEL



- Mathematical NAS representation
- 20 centers each divided into sectors



- Flight plans processed to determine sector occupancy time intervals
- Occupancy data used:
  - To determine maximum sector workloads
  - As pre-processing data for PAEM conflict analysis



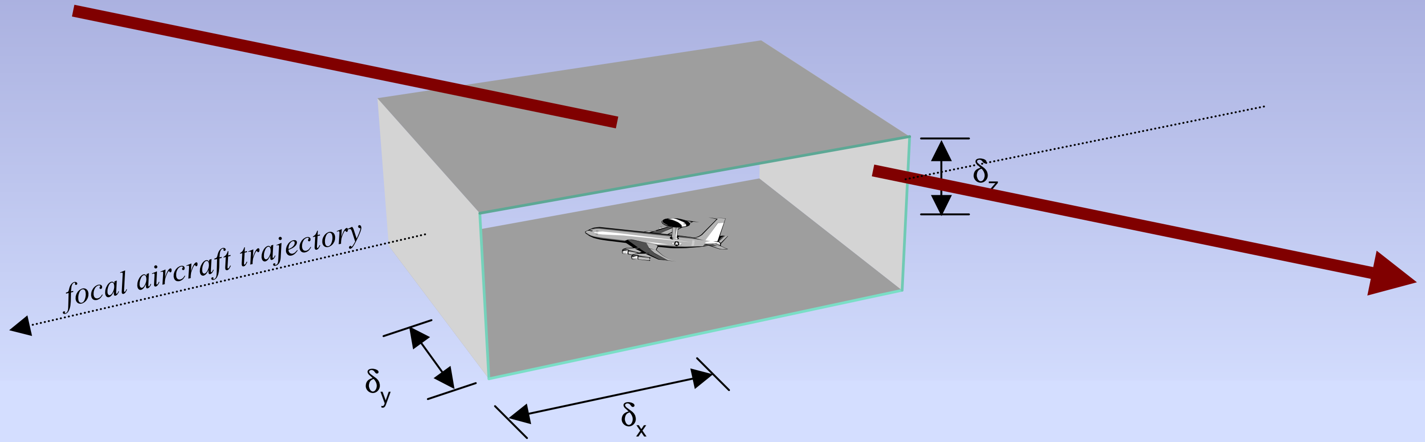
Workload Constraints

- Workload: maximum number of aircraft present in a sector at a given time
  - Maximum number of overlapping flights n_s in sector s
- Penalty Function: $\mu_{sn} = f\left(n_s\right)$
  - Impose a minimum workload (fixed monitoring cost)
  - Impose a maximum workload capacity ($\overline{n}_s$) for each sector
  - Non-linear penalty function

Conflict Analysis

PROBABILISTIC AIRCRAFT ENCOUNTER MODEL

- Proximity Shell Around Each Focal Aircraft

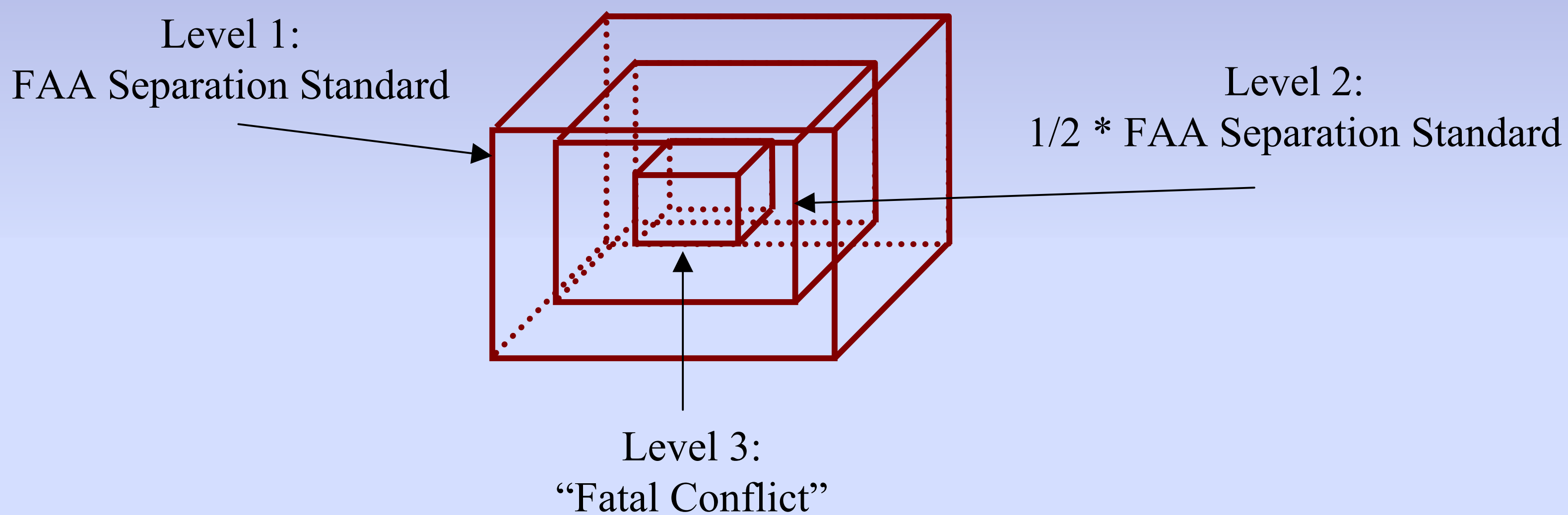


- Moves with aircraft as it traverses its flight trajectory
- Conflict occurs when another aircraft pierces the proximity shell

Conflict Analysis

PROBABILISTIC AIRCRAFT ENCOUNTER MODEL

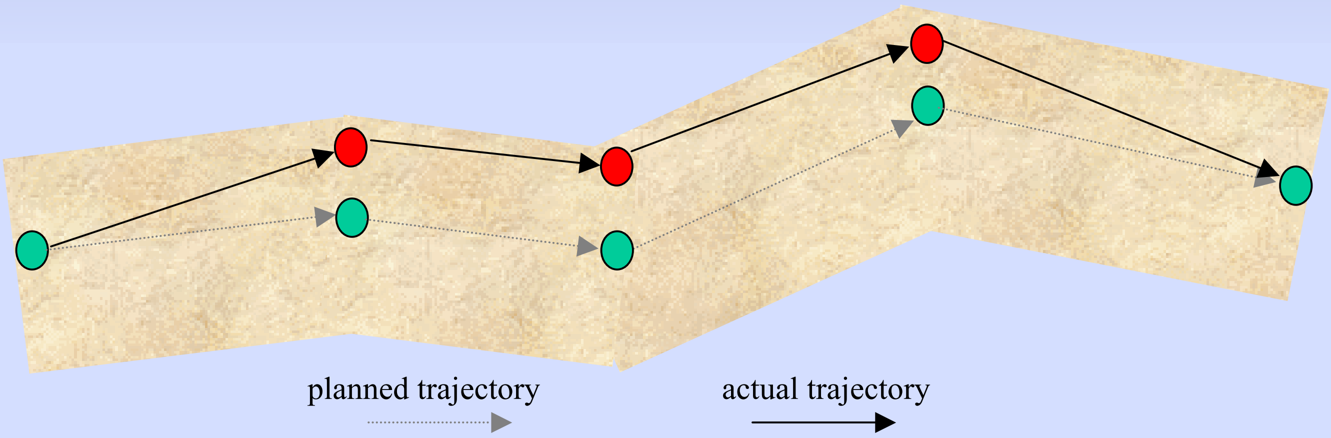
- Conflict Severity



Conflict Analysis

PROBABILISTIC AIRCRAFT ENCOUNTER MODEL

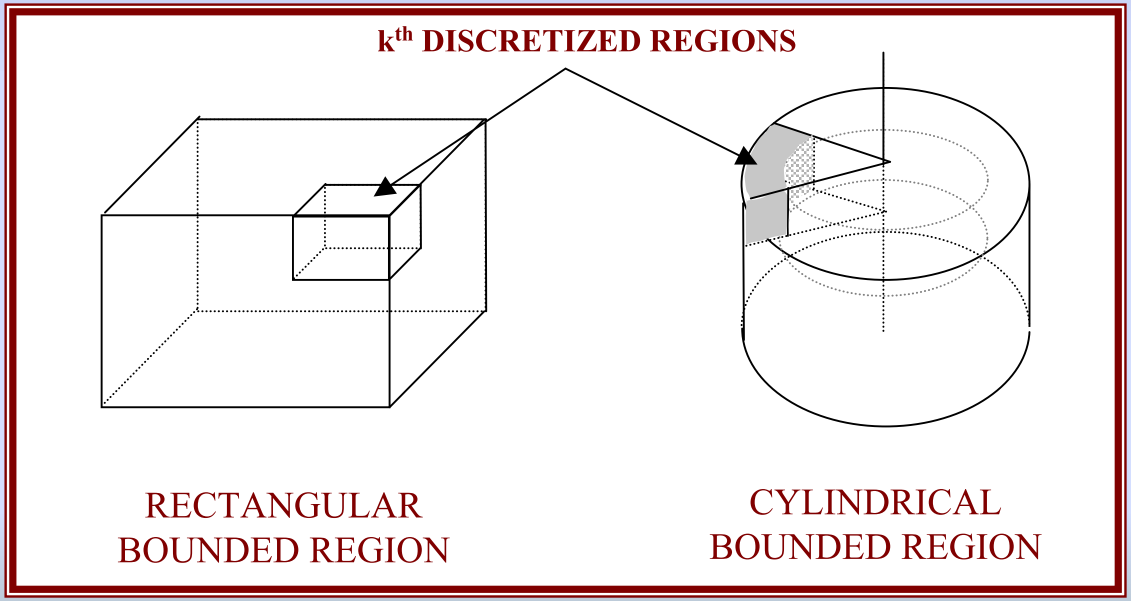
- Aircraft Position & Trajectory Not Known With Certainty
  - Weather Effects
  - Navigation System Inaccuracy
  - Pilot Error



Conflict Analysis

PROBABILISTIC AIRCRAFT ENCOUNTER MODEL

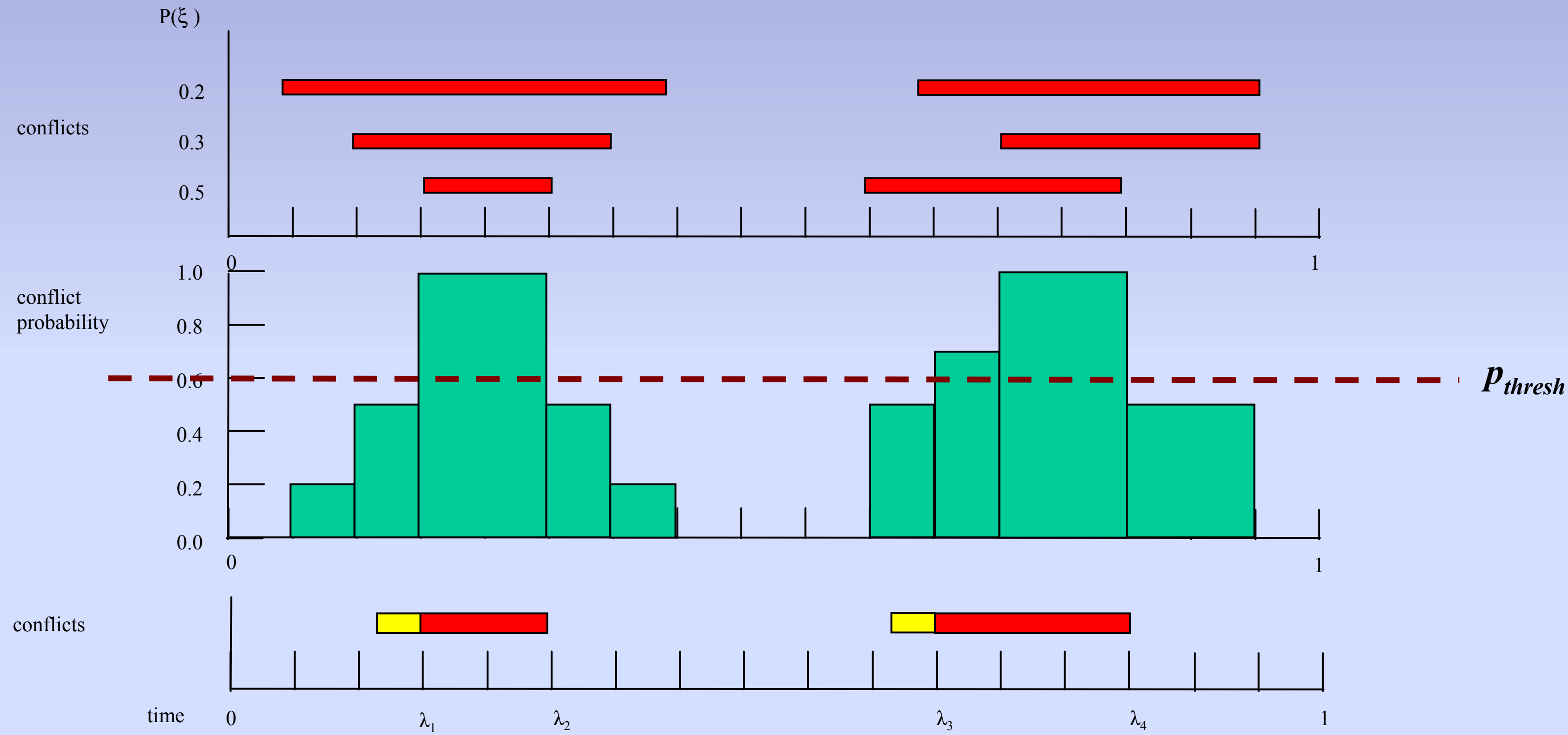
- Bounded Error Regions $\rightarrow$ Probabilistic Trajectory Corridor
  - Rectangular: randomized errors
  - Cylindrical: wind-induced errors
- Discretize error regions for generating possible realizations having given occurrence probabilities



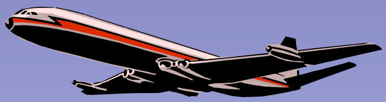
Conflict Analysis

PROBABILISTIC AIRCRAFT ENCOUNTER MODEL

- For each pair of discretized error trajectory realizations (for focal and intruder aircraft) we can compute the Conflict Risk:

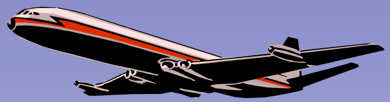


- Add prep-buffers to intervals to accommodate conflict resolution setup times



Conflict Resolution Constraints

- Probabilistic conflicts generated by PAEM are fit into constraint structure of APCDM
- Constraints prohibit selection of particular combinations of flight plans
  - Flight-pairs that have a “fatal” conflict
  - Flight combinations that exceed sector ATC capability to simultaneously monitor
  - Flight combinations that exceed sector ATC conflict resolution capability during any specified time interval
- Polyhedral analysis of conflict constraint structure
  - Derived classes of valid inequalities to tighten representation



Equity Considerations

- Optimal Individual Decisions vs. Optimal Group Decision
  - Each participating airline's decisions represent conflicting objectives
  - Possibly no feasible satisfying solution for these conflicting objectives
  - Inefficient overall use of the NAS

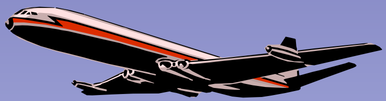
- Collaboration Efficiency
  - Percentage increase in costs for each airline, with respect to its individual optimal strategy, incurred due to resolution between the group's conflicting objectives

- Collaboration Equity
  - Aggregate measure of disparity of costs incurred via group decision

Equity Considerations

COLLABORATION EFFICIENCY

- How do we define “cost” ?
  - *Fuel Costs*--function of aircraft flight time
  - *Delay Costs*--function of the difference between intended and actual arrival times
  - *Flight Network Costs*--function of impacted connecting flights (e.g. cascading delays), slot restrictions



Equity Considerations

COLLABORATION EFFICIENCY

- Airline Collaboration Cost:
  - Difference between individually optimized flight plan and collaborative decision

$$d_\alpha(x) = \sum_{f \in A_\alpha} \sum_{p \in P_f} \left(c_{fp} - c_f^* \right) x_{fp}$$

- Airline Collaboration Efficiency:

$$D_\alpha(x) = \frac{d_\alpha(x)}{\sum_{f \in A_\alpha} c_f^*} = \left(\frac{\sum_{f \in A_\alpha} \sum_{p \in P_f} \left(c_{fp} - c_f^* \right) x_{fp}}{\sum_{f \in A_\alpha} c_f^*} \right)$$

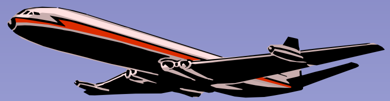
Equity Considerations

COLLABORATION EFFICIENCY

- Total Collaboration Efficiency:

$$\sum_{\alpha=1}^{\bar{\alpha}} \omega_\alpha D_\alpha(x) = \sum_{\alpha=1}^{\bar{\alpha}} \omega_\alpha \left[\frac{\sum_{f \in A_\alpha} \sum_{p \in P_f} \left(c_{fp} - c_f^* \right) x_{fp}}{\sum_{f \in A_\alpha} c_f^*} \right]$$

$$\text{where } \omega_\alpha = \frac{|A_\alpha|}{F} \Rightarrow \sum_{\alpha=1}^{\bar{\alpha}} \omega_\alpha = 1$$



Equity Considerations

COLLABORATION EQUITY

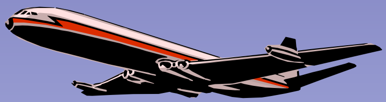
- Relative Collaboration Efficiency: $D_\alpha^r(x) = \left| D_\alpha(x) - \left(\sum_{\alpha=1}^{\bar{\alpha}} \omega_\alpha D_\alpha(x) \right) \right|$
- Collaboration Equity: $\sum_{\alpha=1}^{\bar{\alpha}} \omega_\alpha D_\alpha^r(x)$
- APCDM Formulation:

$$\min \quad \ldots + \mu_r^e x_r^e + \mu_e^D \sum_{\alpha=1}^{\bar{\alpha}} \omega_\alpha D_\alpha(x) ,$$

$$\text{subj to:} \quad \sum_{\alpha=1}^{\bar{\alpha}} w_\alpha D_\alpha^r \le x_r^e$$

$$x_r^e \le \nu_r^e , \quad D_\alpha(x) \le D_{\max} , \quad D_\alpha^r(x) \le D_{\max}^r$$

- Formulation linearizes the $\bar{\alpha}$ absolute value terms



Equity Considerations

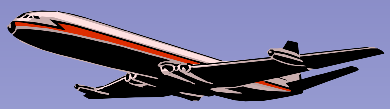
COLLABORATION EQUITY

- Motivating Example
  - Suppose we have the following two feasible solutions involving six participants

$$\textbf{S1:}\quad D_1(x)=5,\quad D_2(x)=5,\quad D_3(x)=8,\quad D_4(x)=8,\quad D_5(x)=9,\quad D_6(x)=10$$

$$\textbf{S2:}\quad D_1(x)=5,\quad D_2(x)=6,\quad D_3(x)=7,\quad D_4(x)=8,\quad D_5(x)=9,\quad D_6(x)=10$$

- For both of these solutions, the minimal, maximal, and hence the range, are identical
  - **S1**: $\alpha=1$ and $\alpha=2$ have preferential solutions
  - **S2**: uniform cost distribution
- Collaboration Equities (using $\omega_\alpha = 1/6,\ \forall\alpha$):
  - **S1**: *1.67*
  - **S2**: *1.50*



Model APCDM

$$\min \; \boxed{\sum_{f=1}^{F}\sum_{p\in P_f} c_{fp}x_{fp}} + \boxed{\sum_{s\in S}\sum_{n_s=1}^{\bar{n}_s}\mu_{sn}y_{sn}} + \boxed{\mu_r^e x_r^e + \mu_e^D \sum_{\alpha=1}^{\bar{\alpha}} \omega_\alpha D_\alpha(x)}$$

subj to: $\sum_{p\in P_f} x_{fp} = 1$

Workload Constraints

Conflict Resolution Constraints

Equity Constraints

$$\sum_{(f,p)\in C_{si}} x_{fp} \le n_s \quad \forall i=1,\dots,M_s, s\in S$$

$$n_s = \sum_{n=1}^{\bar{n}_s} n y_{sn} \quad \forall s\in S$$

$$\sum_{n=1}^{\bar{n}_s} y_{sn} = 1 \quad \forall s\in S$$

$$y_{sn} \ge 0 \quad \forall n=1,\dots,\bar{n}_s, s\in S$$

$$D_\alpha(x) = \left(\frac{\sum_{f\in A_\alpha}\sum_{p\in P_f}\left(c_{fp} - c_f^*\right)x_{fp}}{\sum_{f\in A_\alpha} c_f^*} \right) \quad \forall \alpha = 1,\dots,\bar{\alpha}$$

$$\sum_{\alpha=1}^{\bar{\alpha}} w_\alpha D_\alpha^r \le x_e^r$$

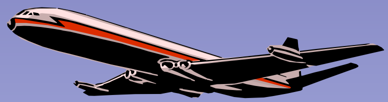
$$D_\alpha(x) \le D_{\max}, \quad D_\alpha^r \le D_{\max}^r, \quad x_r^e \le v_r^e$$

$$\sum_{(i,j)\in A_{sk}} z_{ij} \le r_s, \quad \forall (s,k)$$

$$\sum_{j\in J_{sk}(i)} z_{(ij)} \le r_s x_i, \quad \forall i\in N_{sk} \text{ s.t. } |J_{sk}(i)| \ge r_s + 1, \ \forall (s,k)$$

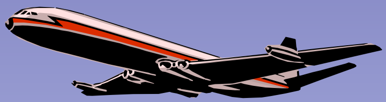
$$z_{ij} \ge x_i + x_j - 1 \quad \forall (i,j)\in A$$

$$z \ge 0, \ x \text{ binary}$$



Research Directions

- Alternate Utility Theory based equity considerations
- Enhancements to workload formulation
- Aircraft trajectory error analysis
- Computational experience using alternative conflict resolution constraint formulations
- Flight cost modeling
- Flight plan generation
- Dynamic Airspace Issues
  - Weather Systems
  - Space Launch SUAs
  - Dynamic Resectorization
- Strategic and tactical scenario tests



QUESTIONS ?