Overview of Weather and Network Path Modeling in Support of CDM Work at Virginia Tech

Principal Investigators:
Dr. Hanif D. Sherali*
Dr. Antonio A. Trani**

Project Assistants:
Dr. Hojong Baik**
Maj. Ray W. Staats*

*Department of Industrial and Systems Engineering
**Department of Civil and Environmental Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Project Goals

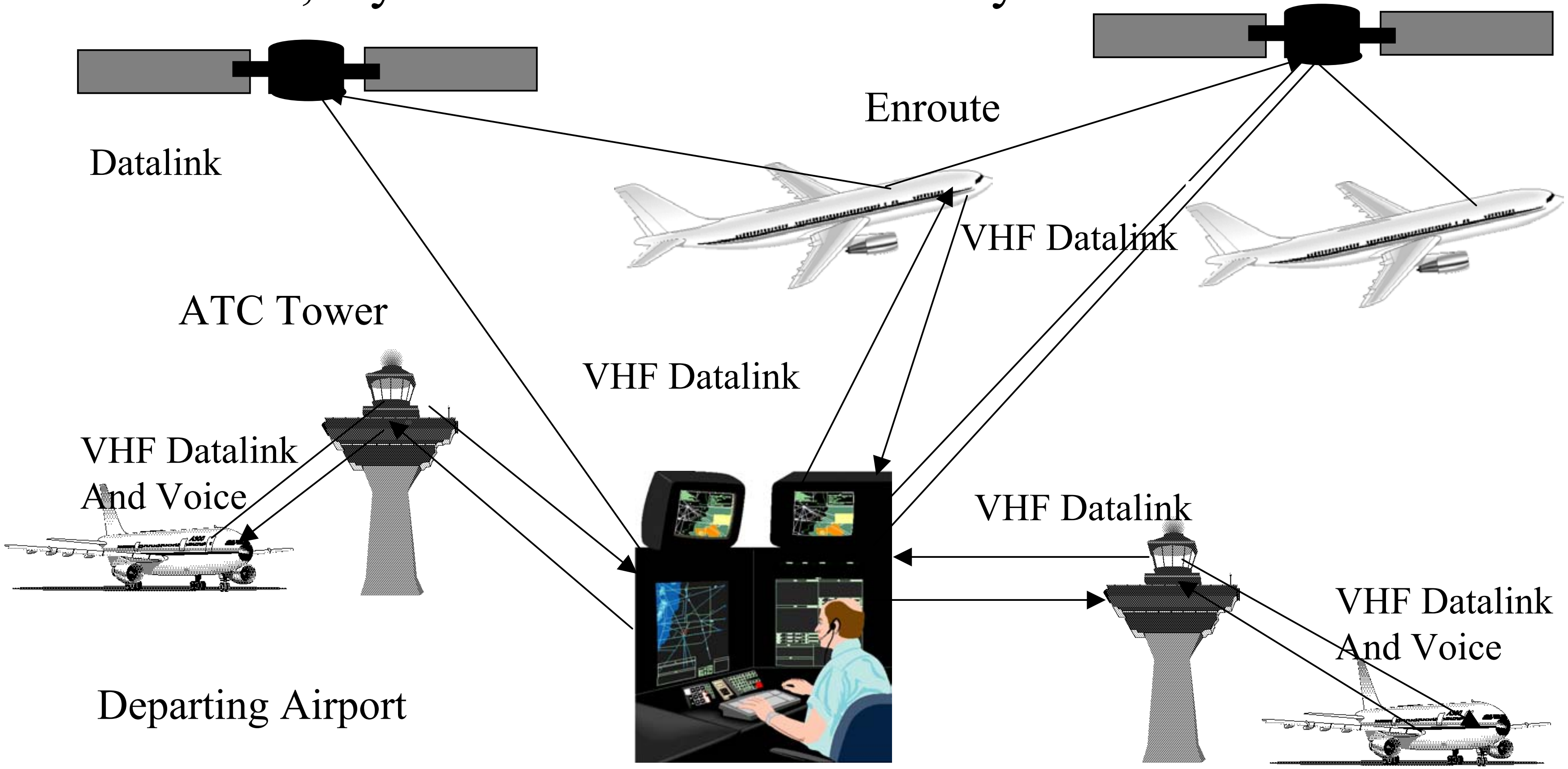
- To develop optimization and simulation-based techniques to manage air traffic in the en-route airspace
- The techniques developed in this project consider realistic air traffic management constraints (weather, safety, sector workloads, airline equity, and aircraft performance among others)

Potential Research Impacts

- Long-term outlook for air transportation services will continue to increase at 1-3% per year
- Delays in the National Airspace System (NAS) continue to grow (due to demand concentration at airport hubs)
- Last year, the cost of delays in NAS was estimated at 3 billion dollars
- The application of advanced methods in air traffic management can produce small/moderate increases in supply

Future NAS ATC/ATM System

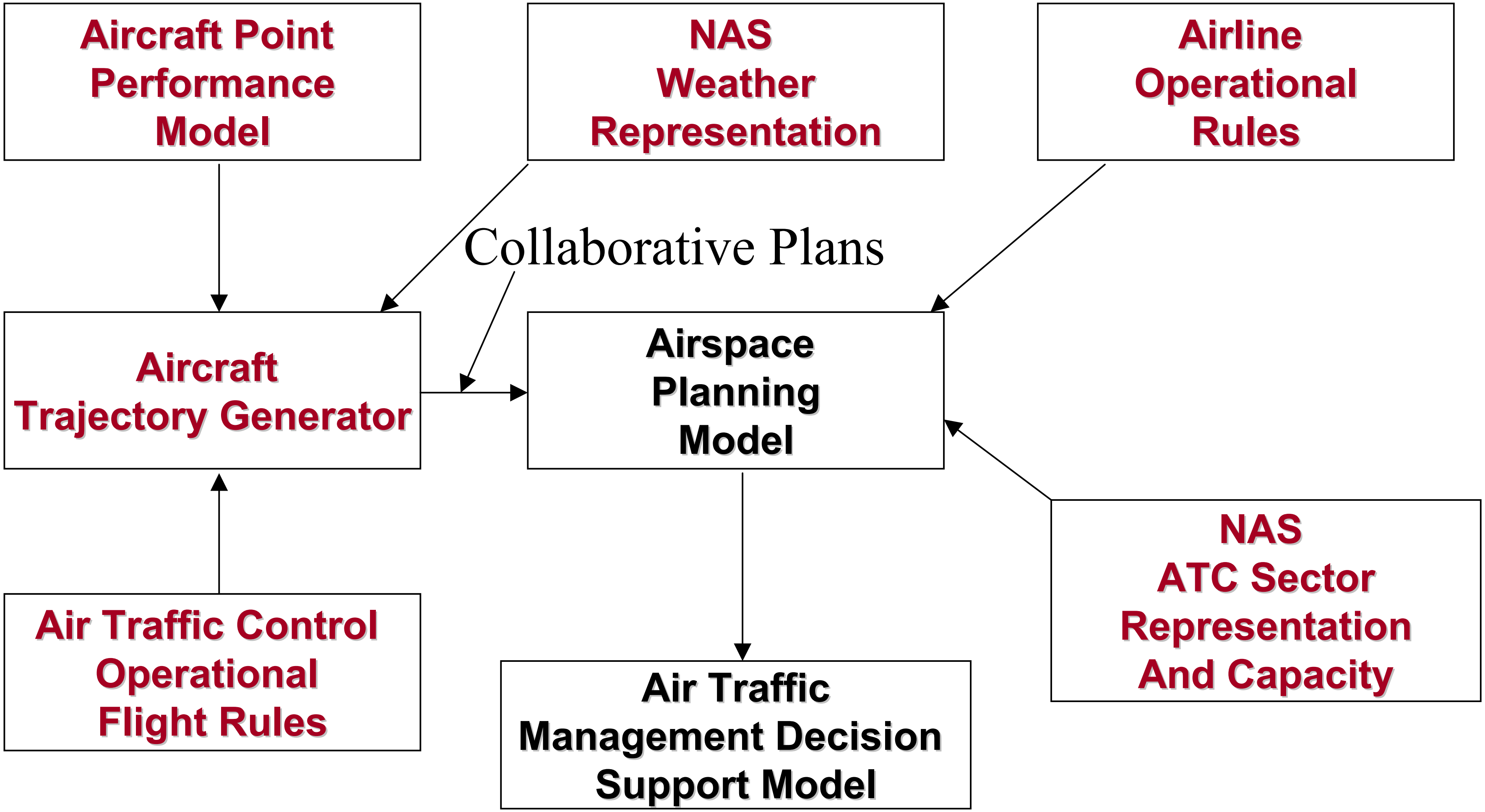
Centralized, Hybrid Air Traffic Control System



ATC TRACON/ARTCC

Arriving Airport

Approach to the Enroute Air Traffic Management Problem



Aircraft Point Performance Model

NAS Weather Representation

Airline Operational Rules

Collaborative Plans

Aircraft Trajectory Generator

Airspace Planning Model

NAS ATC Sector Representation And Capacity

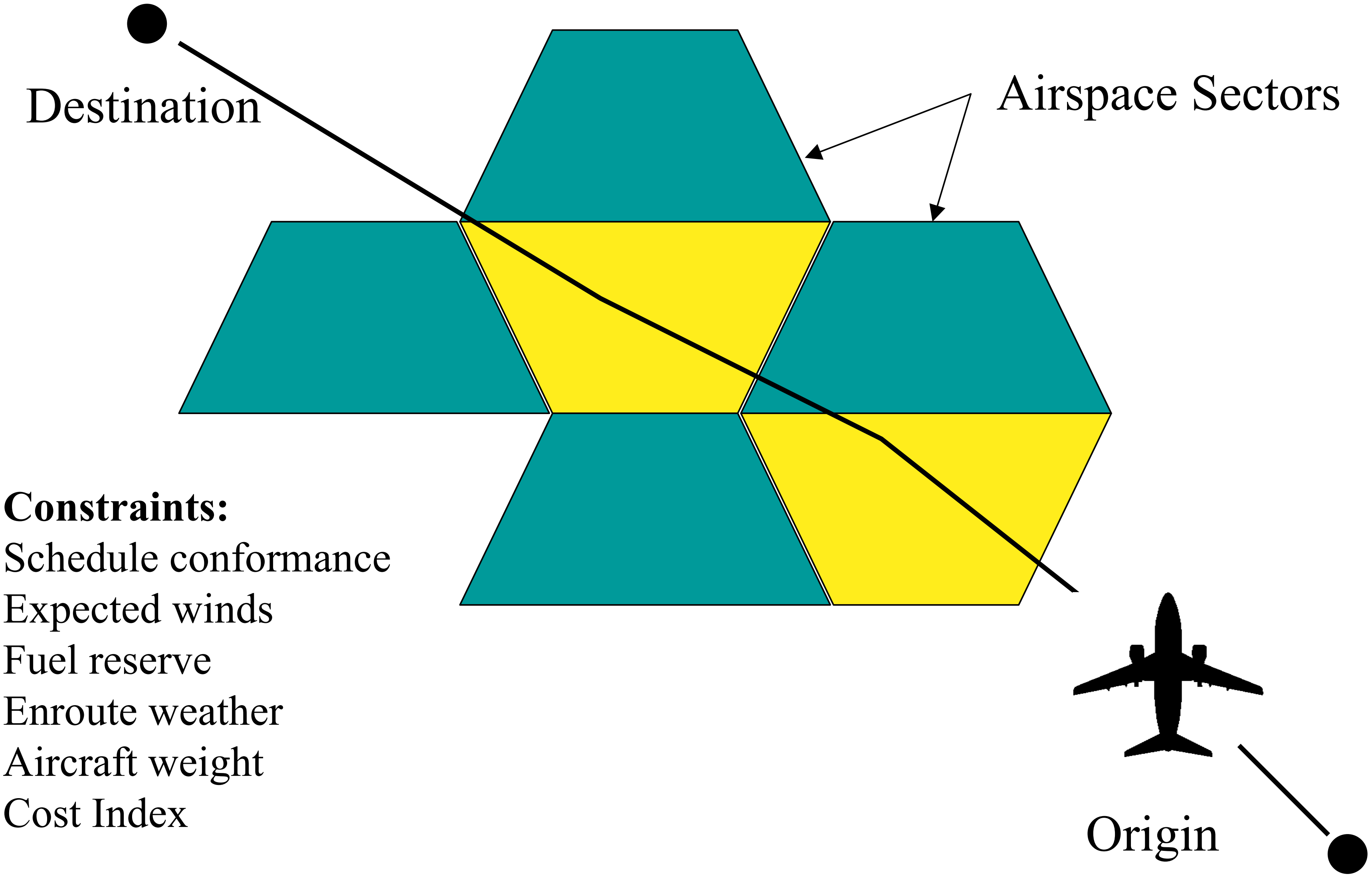
Air Traffic Control Operational Flight Rules

Air Traffic Management Decision Support Model

Enroute Selection Modeling

- Route selection in the context of a highly constrained airspace is a large, complex systems problem.
- The simultaneous selection of a set of routes that achieves system-wide objectives can have a combinatorially large set of alternatives.

Single Route Optimization



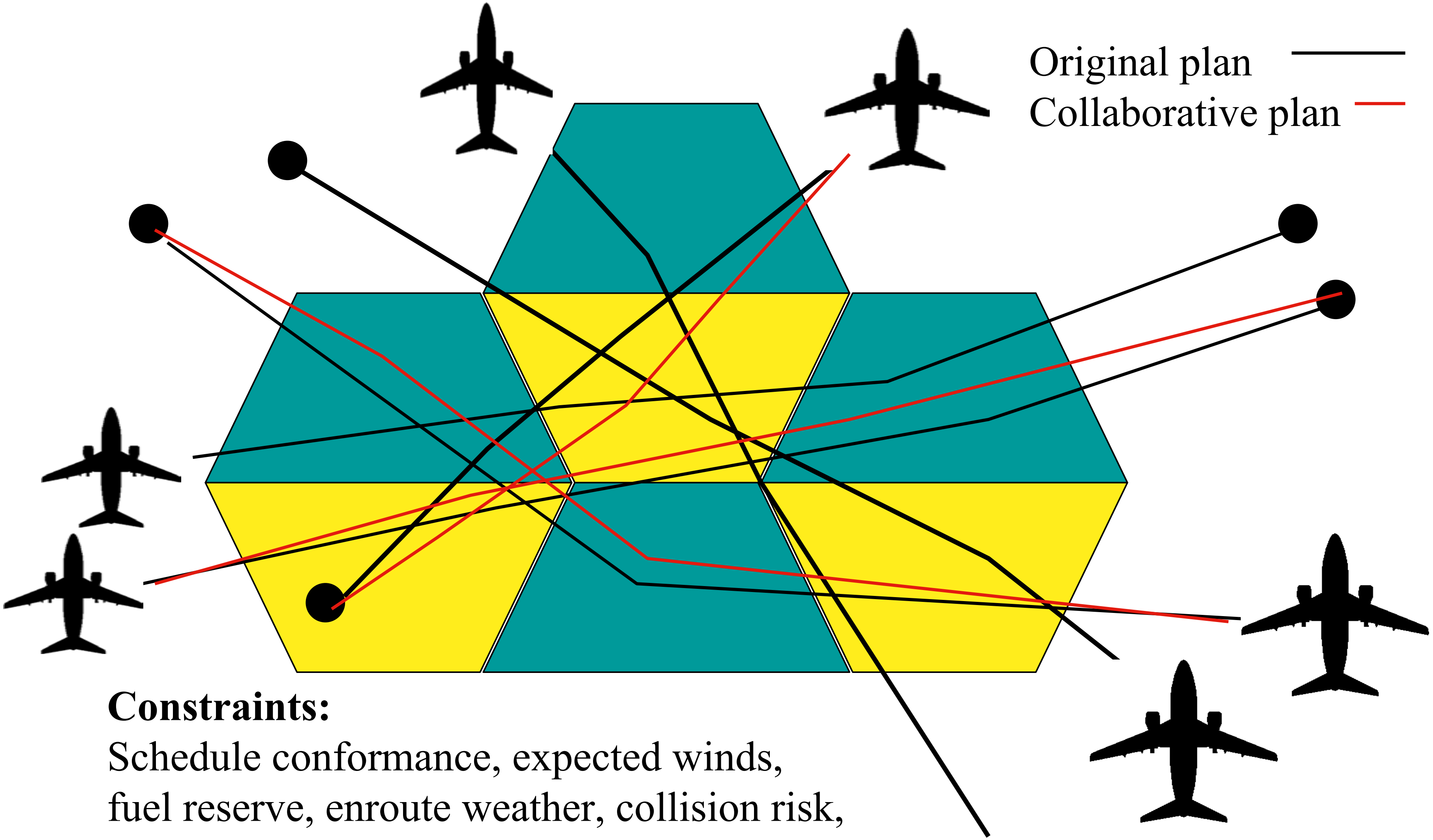
Destination

Airspace Sectors

Origin

Constraints:
Schedule conformance
Expected winds
Fuel reserve
Enroute weather
Aircraft weight
Cost Index

Collaborative Routing

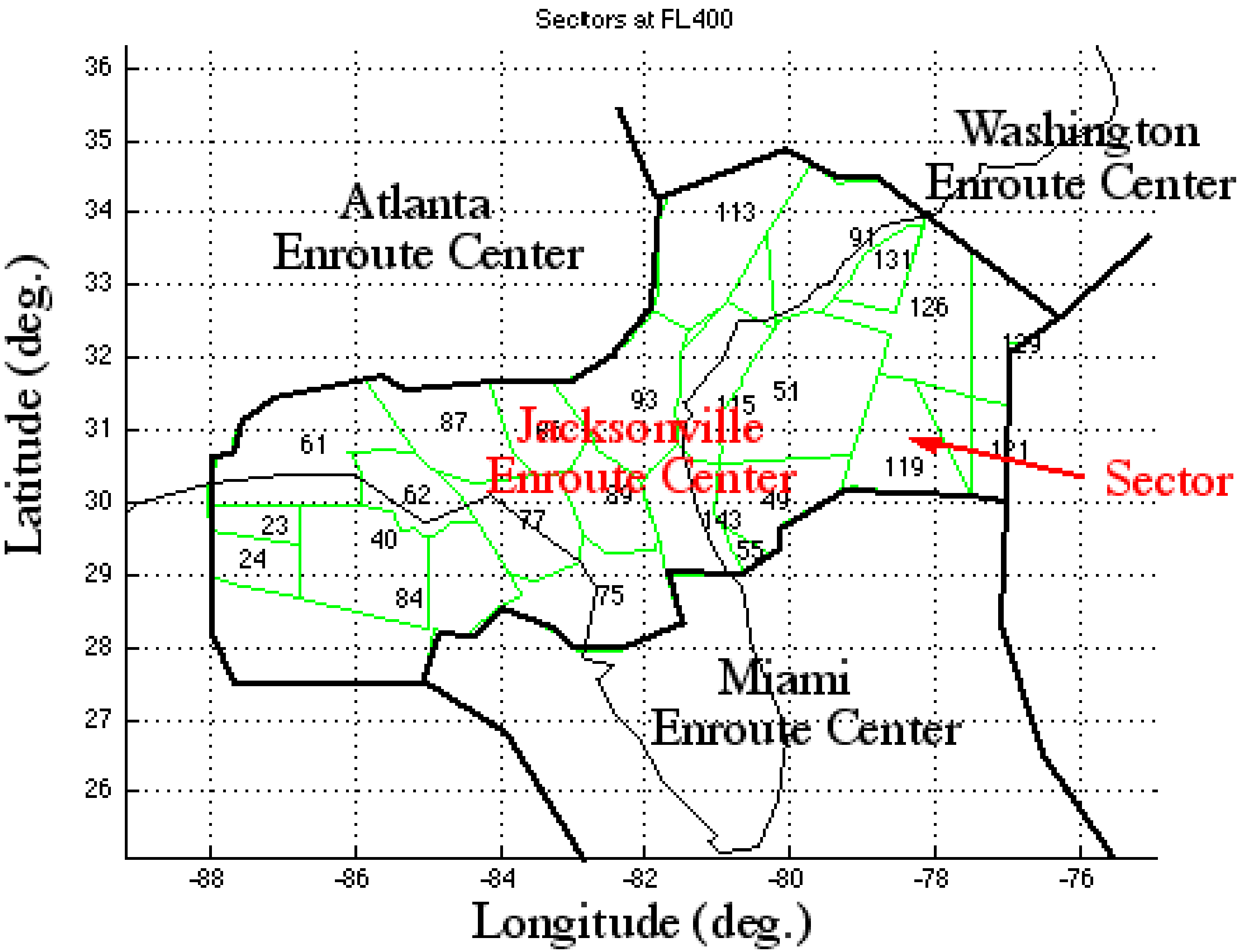


Constraints:
Schedule conformance, expected winds,
fuel reserve, enroute weather, collision risk,
aircraft weight, sector workload, cost index

Route Selection Models (Development issues)

- Consideration of rationing schemes and CDM principles
- Software implementation and integration into TFM tools
- Incorporate collaborative airline-FAA route development strategies
- Consideration of realistic airspace sector capacity limitations
- Consideration of collision risk and safety issues

Airspace Sector Partitions

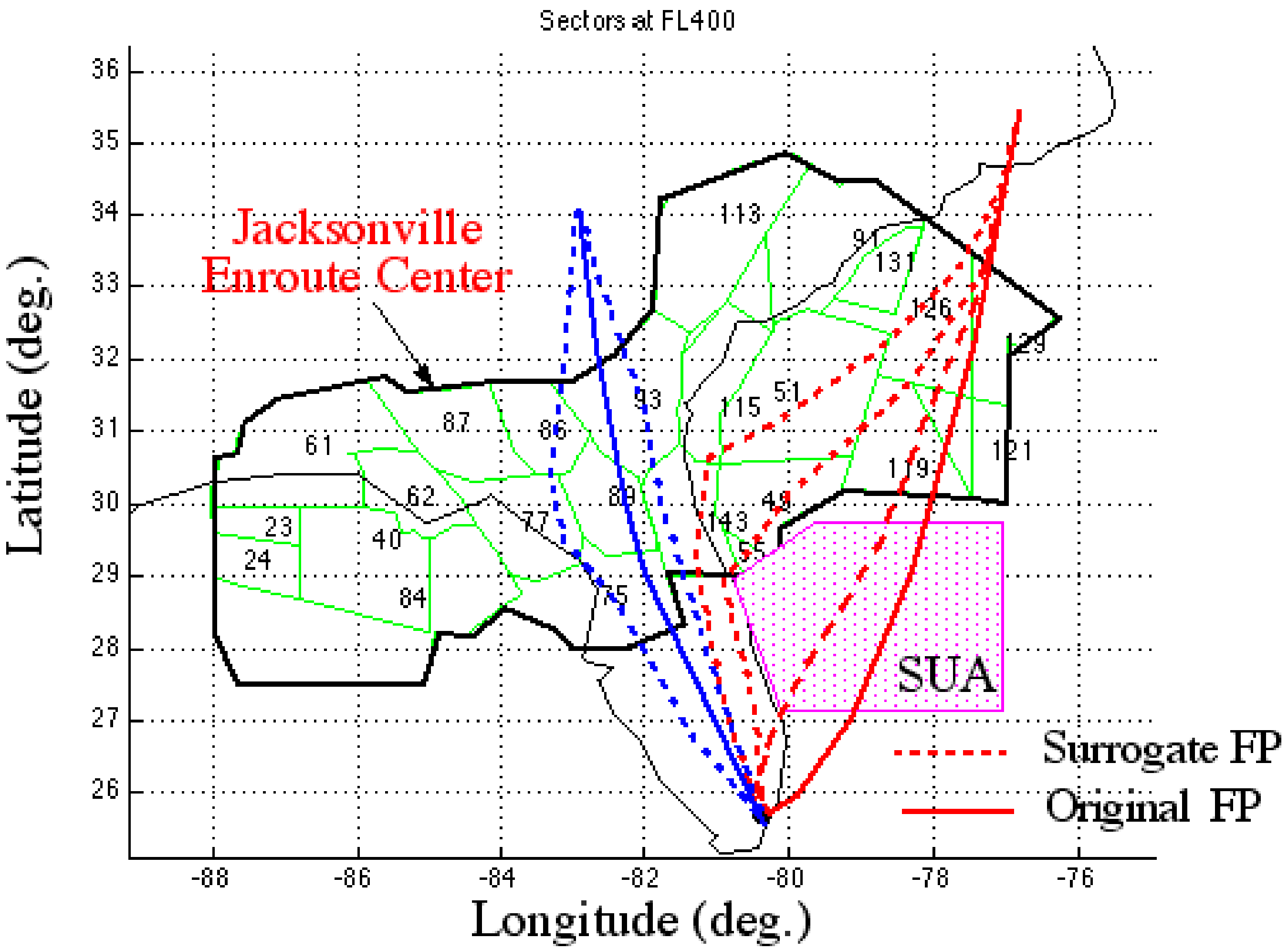


An Airspace Planning Model (APM)

- Examines a finite rolling planning horizon
- Considers a set of flight plans covering this horizon that are relevant to interactions with a particular SUA or weather system event
- Minimizes the total fuel and delay cost while prescribing a set of flight plans to be adopted
- Reflects flight plan cost index, delay costs, sector capacity, collision risk, and airline equity
- Models uncertainties in flight trajectories

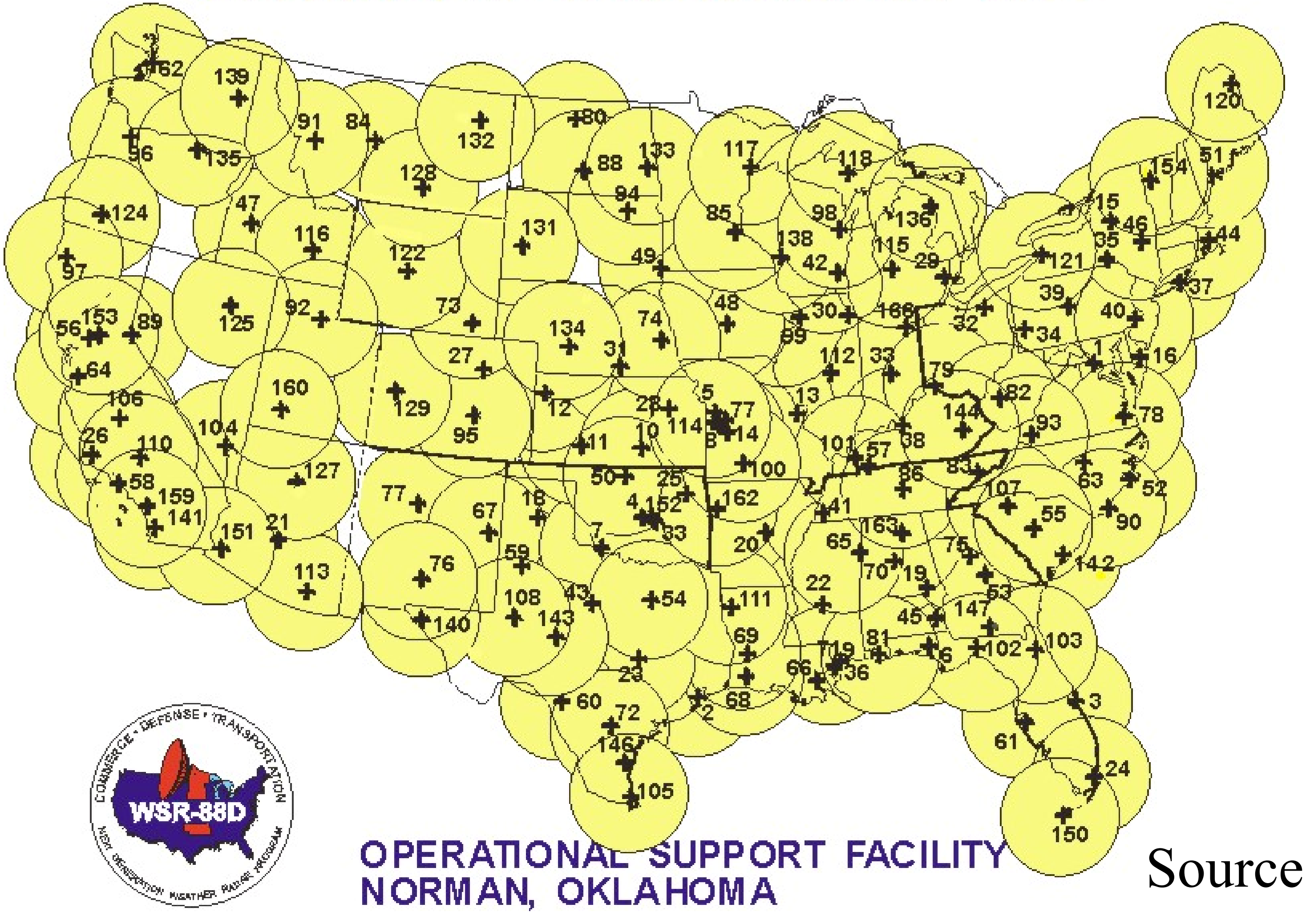
NOTE: Model will be described in a separate presentation by VT

Graphical Interpretation of APM



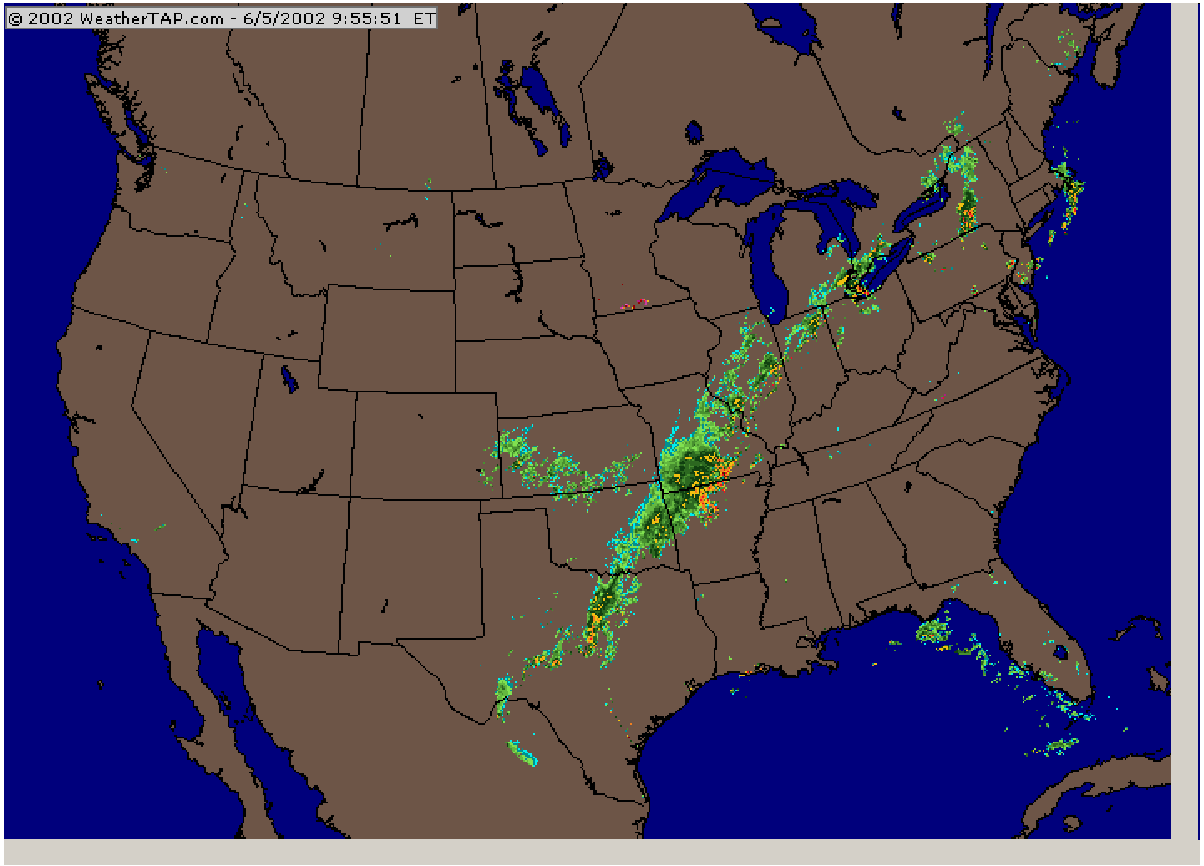
Weather Data Sources

COMPLETED WSR-88D INSTALLATIONS WITHIN THE CONTIGUOUS U.S.

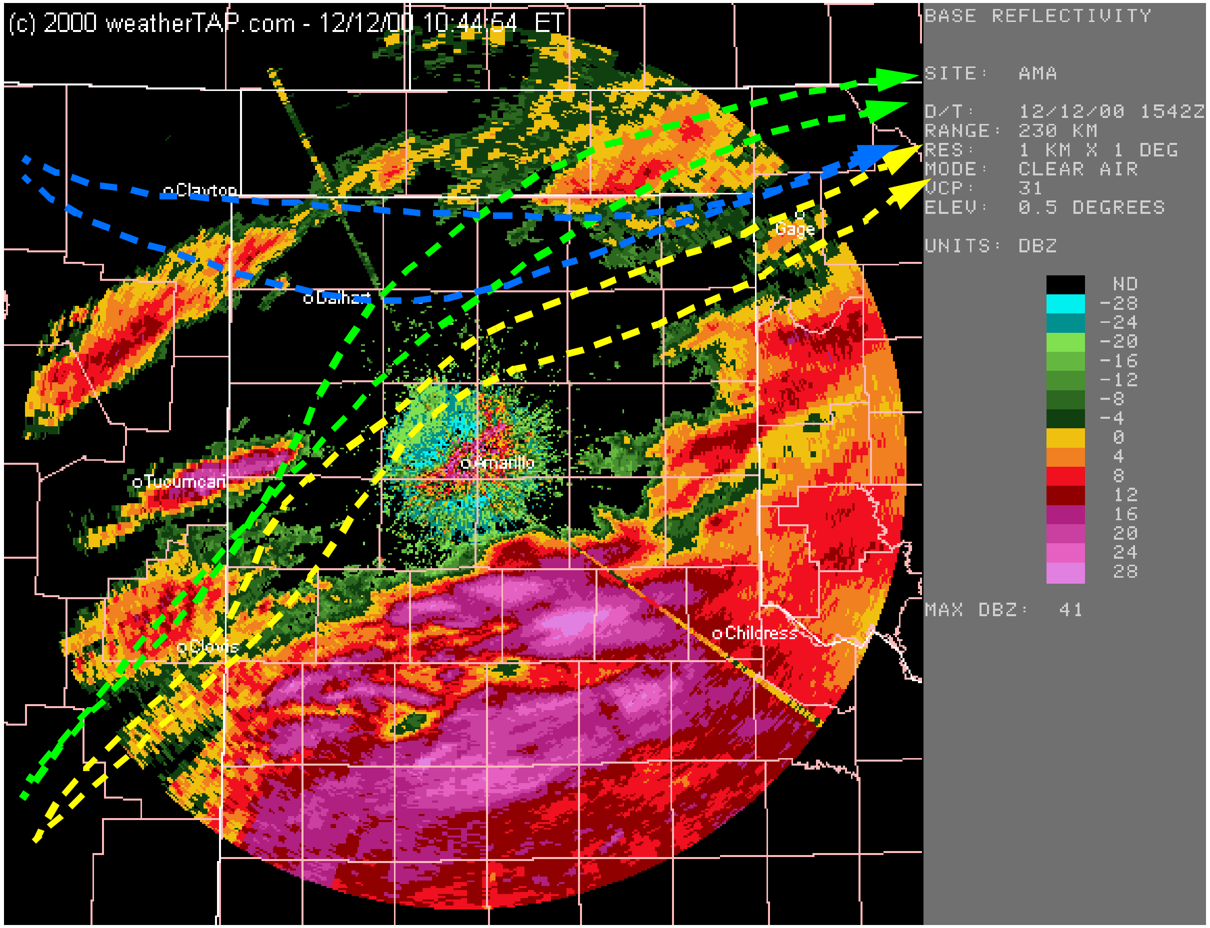


Source: NWS

Weather Data (National Mosaic)

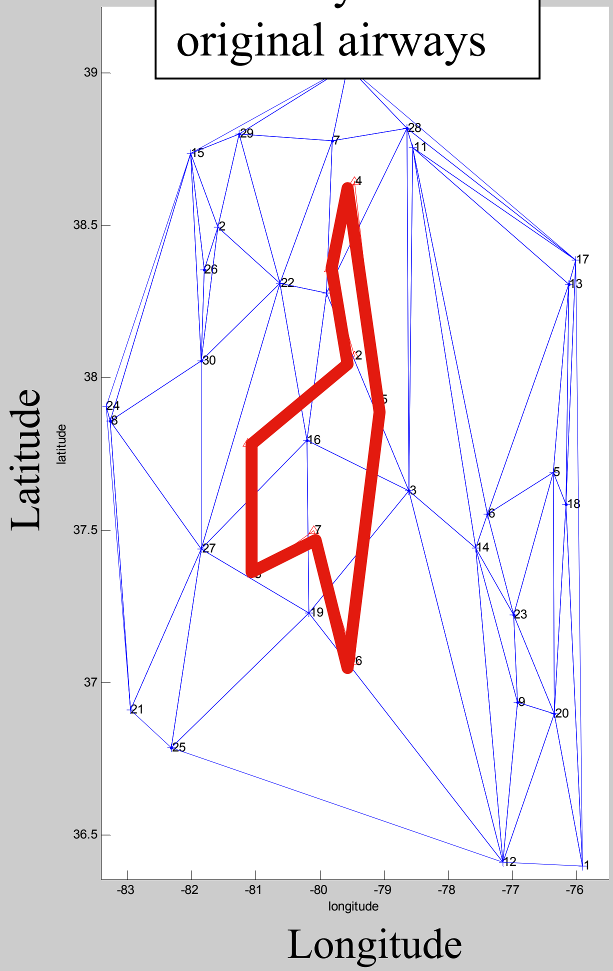


Weather Data (Example)

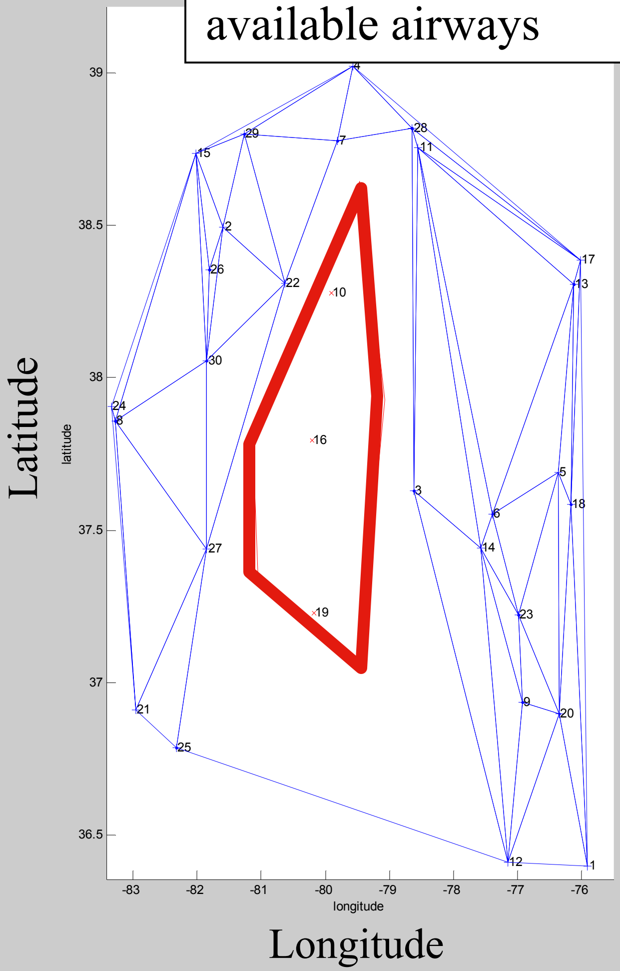


Flight Path Modeling with Severe Weather

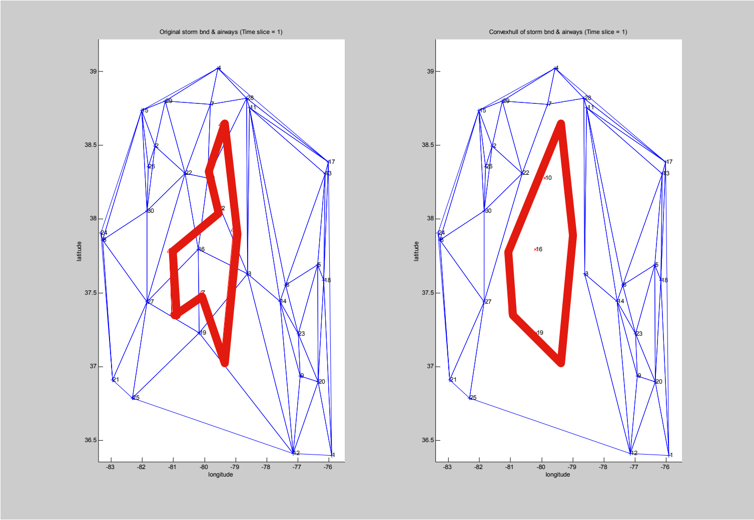
Original storm boundary and original airways



Convex hull of storm boundary and available airways



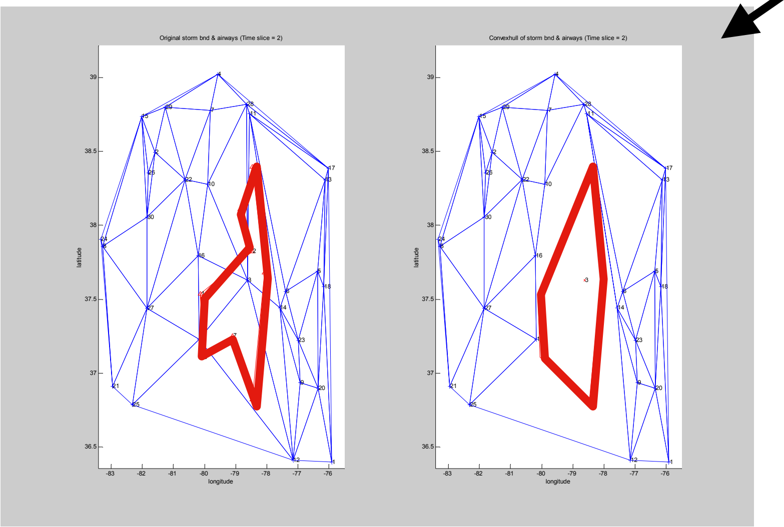
Flight Path Modeling with Severe Weather

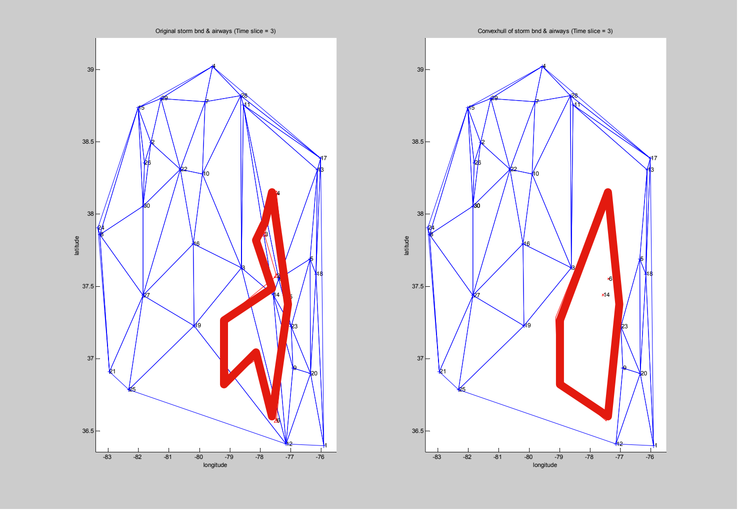


t = 1

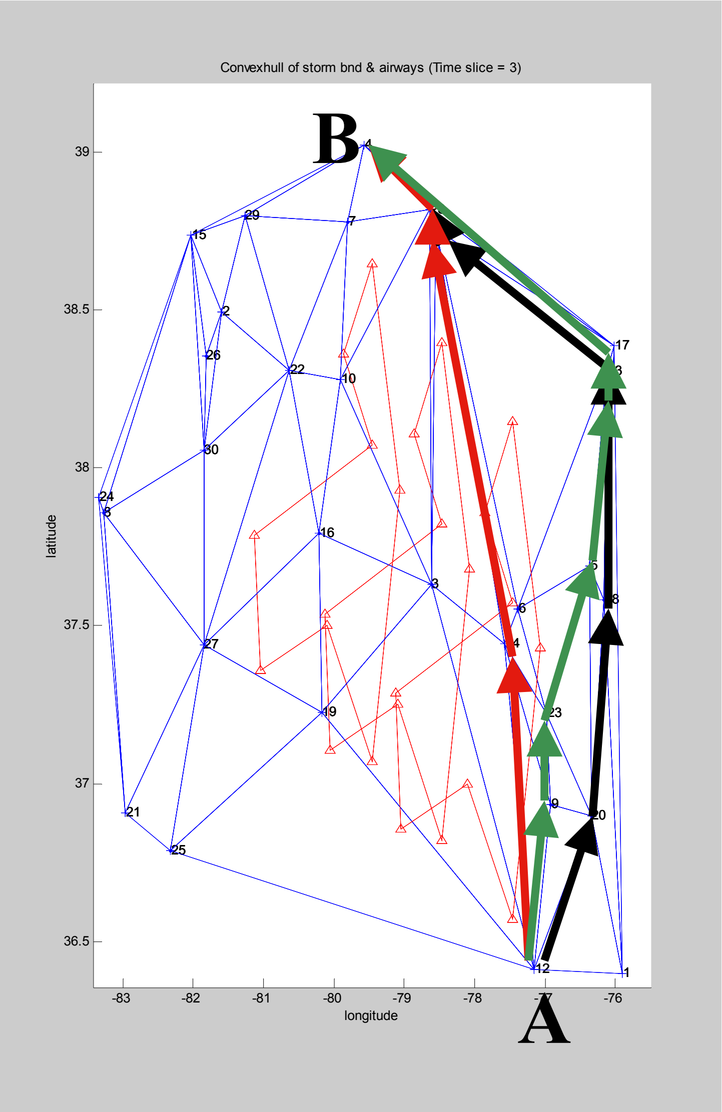
t = 2

t = 3





Routes From A to B (Airbus300, FL300)



→ Static Path

Distance: 151 nm

Travel Time: 19.7 min

Fuel: 1942 kg

→ Time-Dep. Path (1)

Distance: 282 nm

Travel Time: 37.8 min

Fuel: 3619 kg

→ Time-Dep. Path (2)

Distance: 296 nm

Travel Time: 38.7 min

Fuel: 3808 kg

Computational Issues

- Adopt time-dependent shortest path (TDSP) algorithm with double-ended queue (DeQue) data structure.
- Adopt Eurocontrol’s BADA 3.3 aircraft performance model.

TDSP Algorithm

```
Call Initialize
while(SE list is not empty){
    u = Call deQueue;
    d_u = Label(r, u); // arrival travel at node u starting from r at time t.
    Compute timeSlice_d_u; // compute the time slice corresponding to d_u.
    for(v = all forward star of u){
        d_v = Label(r, v); // travel time from r to v.
        l_uv = Find travelTime(u, v, timeSlice_d_u)  // find the travel time for link (u,v) at timeSlice_d_u
        if(d_v > d_u + l_uv){
            Label (r, v) = d_u + l_uv; // update travel time from r to v
            Predecessor(v) = u; // update predecessor node for node v
            Call enQueue(v);
        }
    } //end for
}// end while
```

```
Procedure Initialize:
    for (j = all nodes){
        predecessor(j) = 0;
        if(j ≠r) Label(r, j) = infinite;
    }
    Label(r, r) = t;
    Predecessor(r) = r;
    enQueue(r);
```

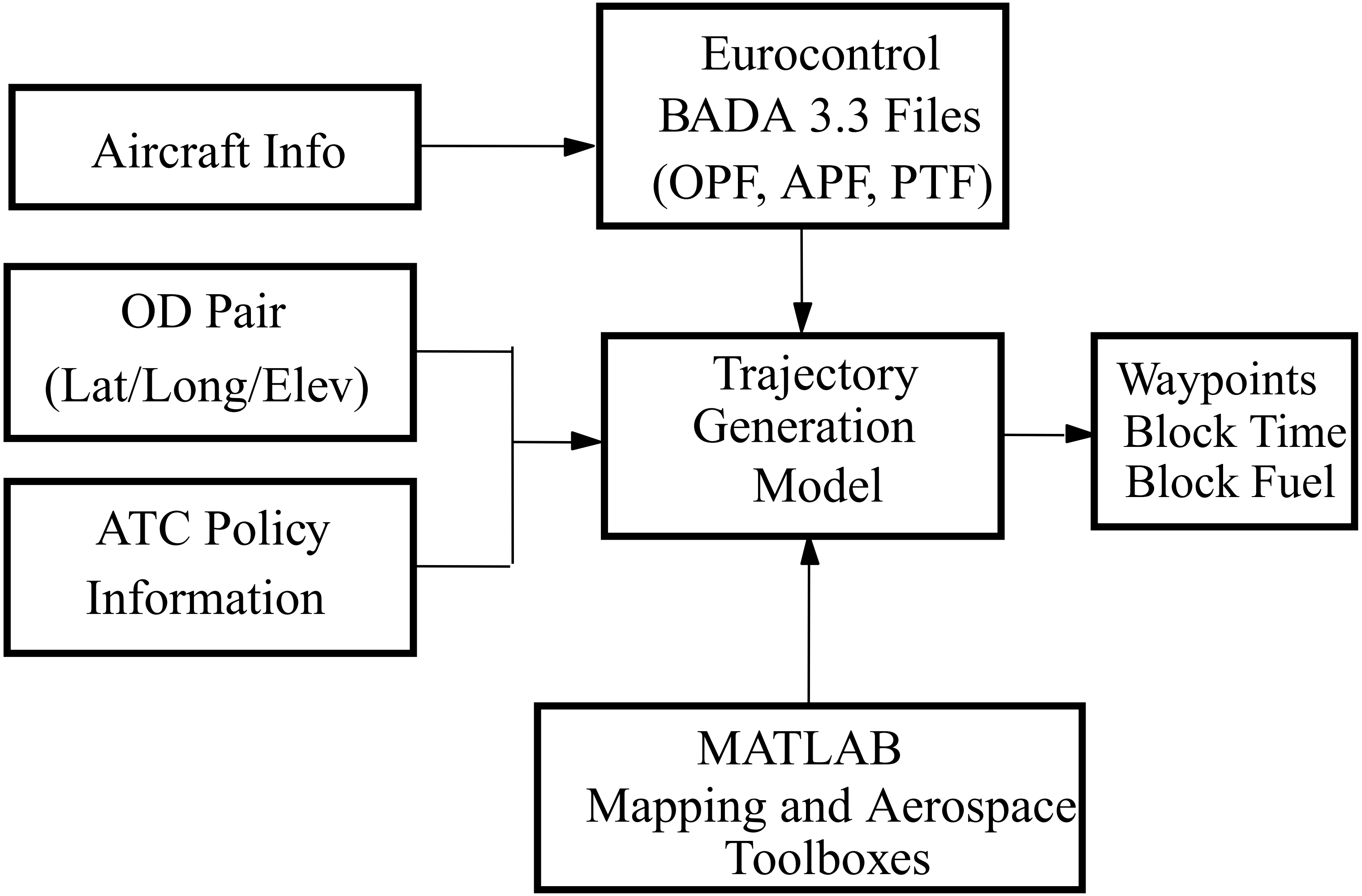
```
Procedure deQueue:
// find the closest node from the
candidate nodes set (i.e., SE list) using
the quick-sort algorithm.
```

```
Procedure enQueue(x):
// insert node x into the candidate
nodes set (i.e., SE list).
```

BADA Model

- The cost of flight detours is a multi-attribute problem:
  - Travel time
  - Fuel cost
- Use Eurocontrol's the Base of Aircraft Data 3.3 (BADA, Dec. 2000)

Using BADA Model



Aircraft Info

Eurocontrol
BADA 3.3 Files
(OPF, APF, PTF)

OD Pair
(Lat/Long/Elev)

ATC Policy
Information

Trajectory
Generation
Model

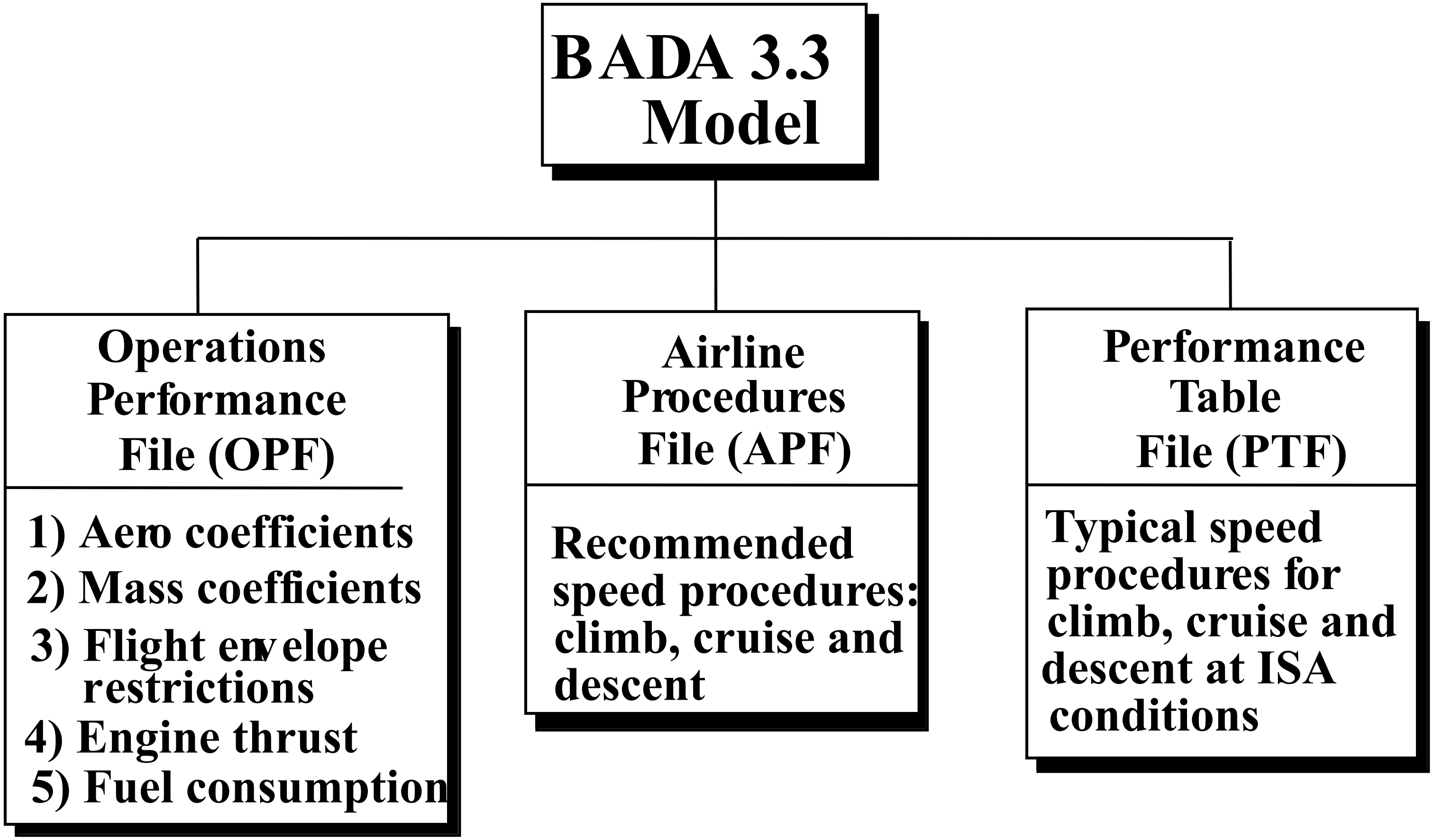
Waypoints
Block Time
Block Fuel

MATLAB
Mapping and Aerospace
Toolboxes

BADA Model (Detail)

- Developed by Eurocontrol Experimental Centre (ECC) to model various Air Traffic Management (ATM) concepts
  - 186 aircraft supported in BADA 3.3
  - 84 aircraft models are supported directly
  - 102 aircraft models are supported indirectly (equivalent models)
- Main outputs of the models are fuel consumption, aerodynamic and speed procedure parameters

BADA Model (Detail)



BADA 3.3 Model

Operations Performance File (OPF)

1) Aero coefficients
2) Mass coefficients
3) Flight envelope restrictions
4) Engine thrust
5) Fuel consumption

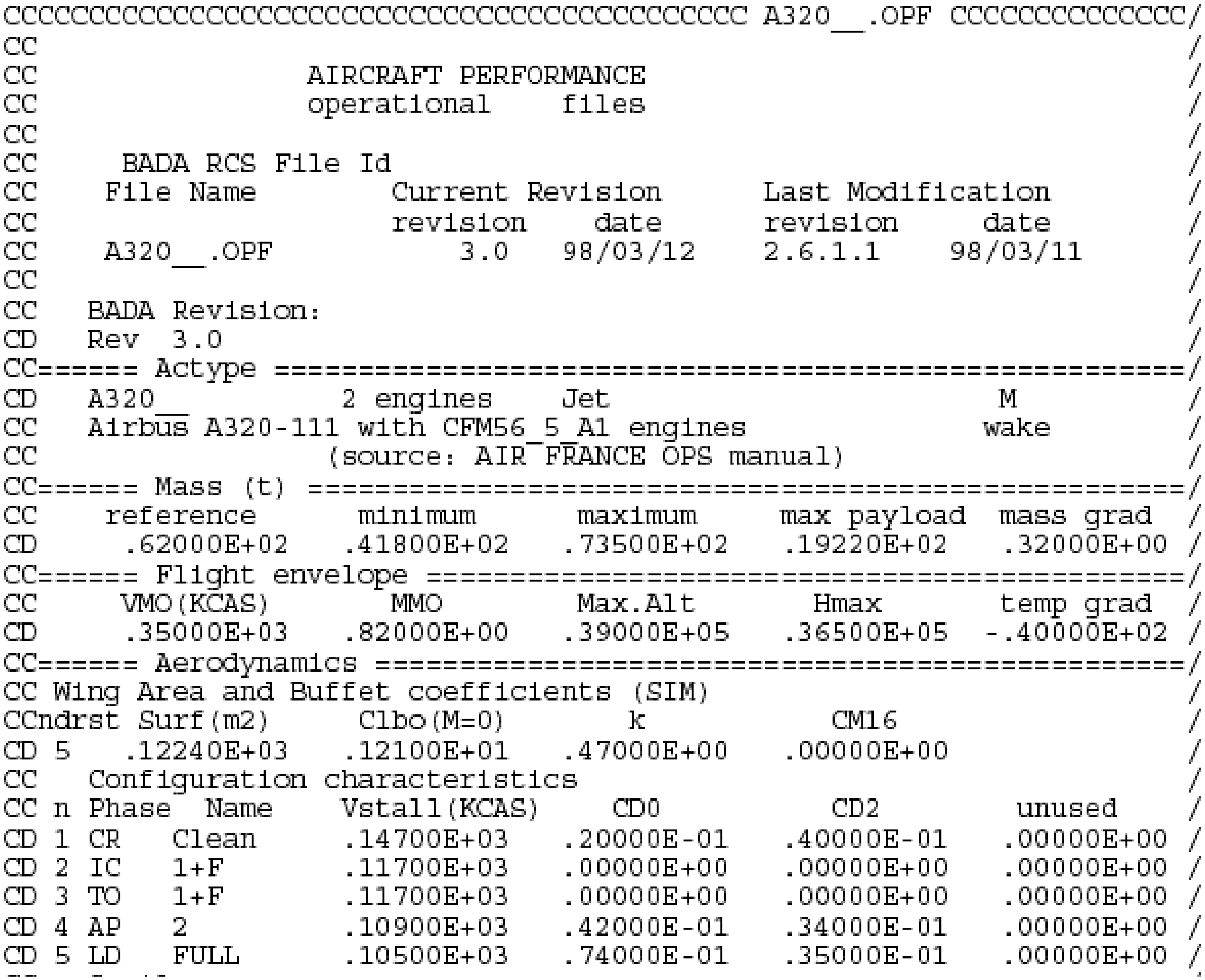
Airline Procedures File (APF)

Recommended speed procedures: climb, cruise and descent

Performance Table File (PTF)

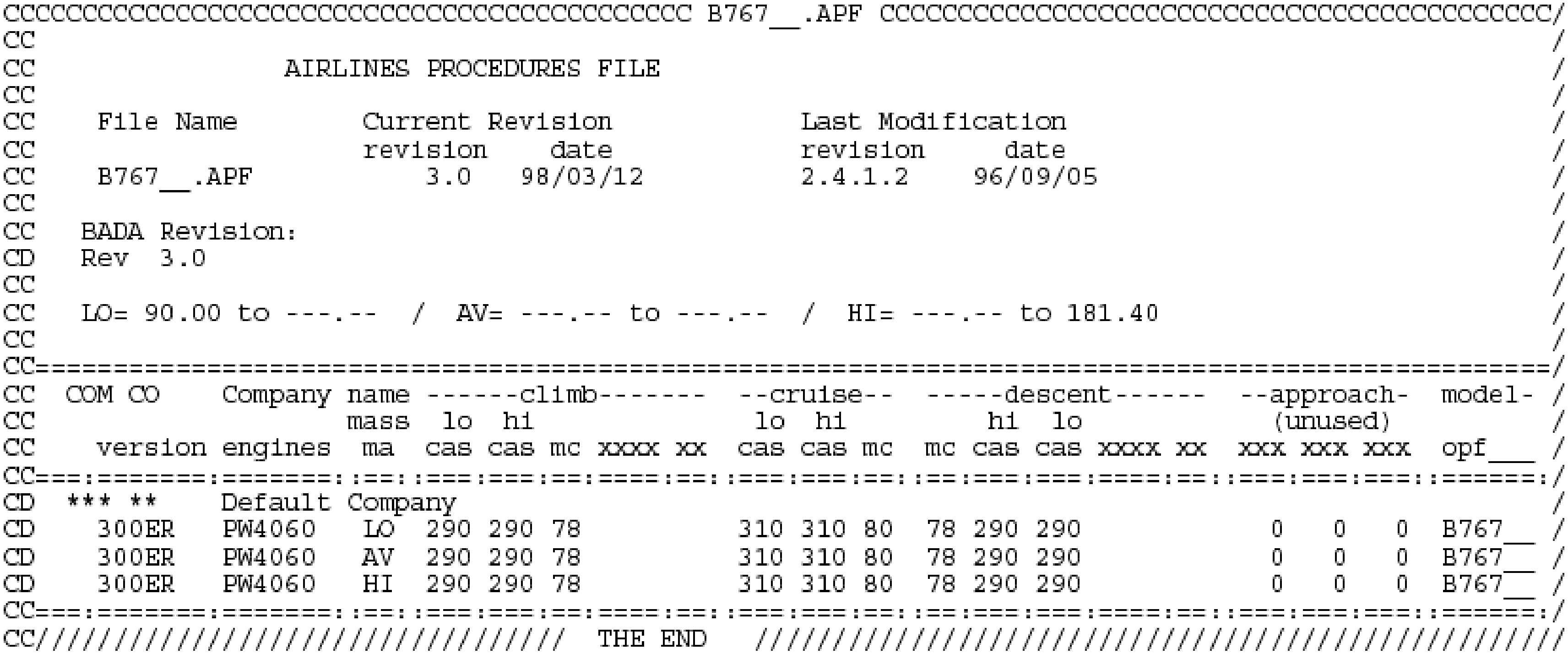
Typical speed procedures for climb, cruise and descent at ISA conditions

Operations Performance File (OPF)



```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC A320__.OPF CCCCCCCCCCCCCC/
CC                                                                    /
CC                AIRCRAFT PERFORMANCE                                /
CC                operational    files                                /
CC                                                                    /
CC     BADA RCS File Id                                               /
CC    File Name        Current Revision      Last Modification        /
CC                     revision    date      revision     date        /
CC    A320__.OPF           3.0   98/03/12    2.6.1.1    98/03/11      /
CC                                                                    /
CC   BADA Revision:                                                   /
CD   Rev  3.0                                                         /
CC====== Actype ======================================================/
CD   A320__          2 engines    Jet                       M         /
CC   Airbus A320-111 with CFM56_5_A1 engines               wake       /
CC                 (source: AIR FRANCE OPS manual)                    /
CC====== Mass (t) ====================================================/
CC    reference      minimum      maximum     max payload  mass grad  /
CD     .62000E+02   .41800E+02   .73500E+02   .19220E+02   .32000E+00 /
CC====== Flight envelope =============================================/
CC     VMO(KCAS)        MMO         Max.Alt       Hmax       temp grad  /
CD     .35000E+03   .82000E+00   .39000E+05   .36500E+05  -.40000E+02 /
CC====== Aerodynamics ================================================/
CC Wing Area and Buffet coefficients (SIM)                            /
CCndrst Surf(m2)     Clbo(M=0)       k          CM16                  /
CD 5   .12240E+03   .12100E+01   .47000E+00   .00000E+00              /
CC   Configuration characteristics                                    /
CC n Phase  Name    Vstall(KCAS)    CD0          CD2        unused    /
CD 1 CR    Clean     .14700E+03   .20000E-01   .40000E-01   .00000E+00 /
CD 2 IC    1+F       .11700E+03   .00000E+00   .00000E+00   .00000E+00 /
CD 3 TO    1+F       .11700E+03   .00000E+00   .00000E+00   .00000E+00 /
CD 4 AP    2         .10900E+03   .42000E-01   .34000E-01   .00000E+00 /
CD 5 LD    FULL      .10500E+03   .74000E-01   .35000E-01   .00000E+00 /
```

Airline Performance File (APF)



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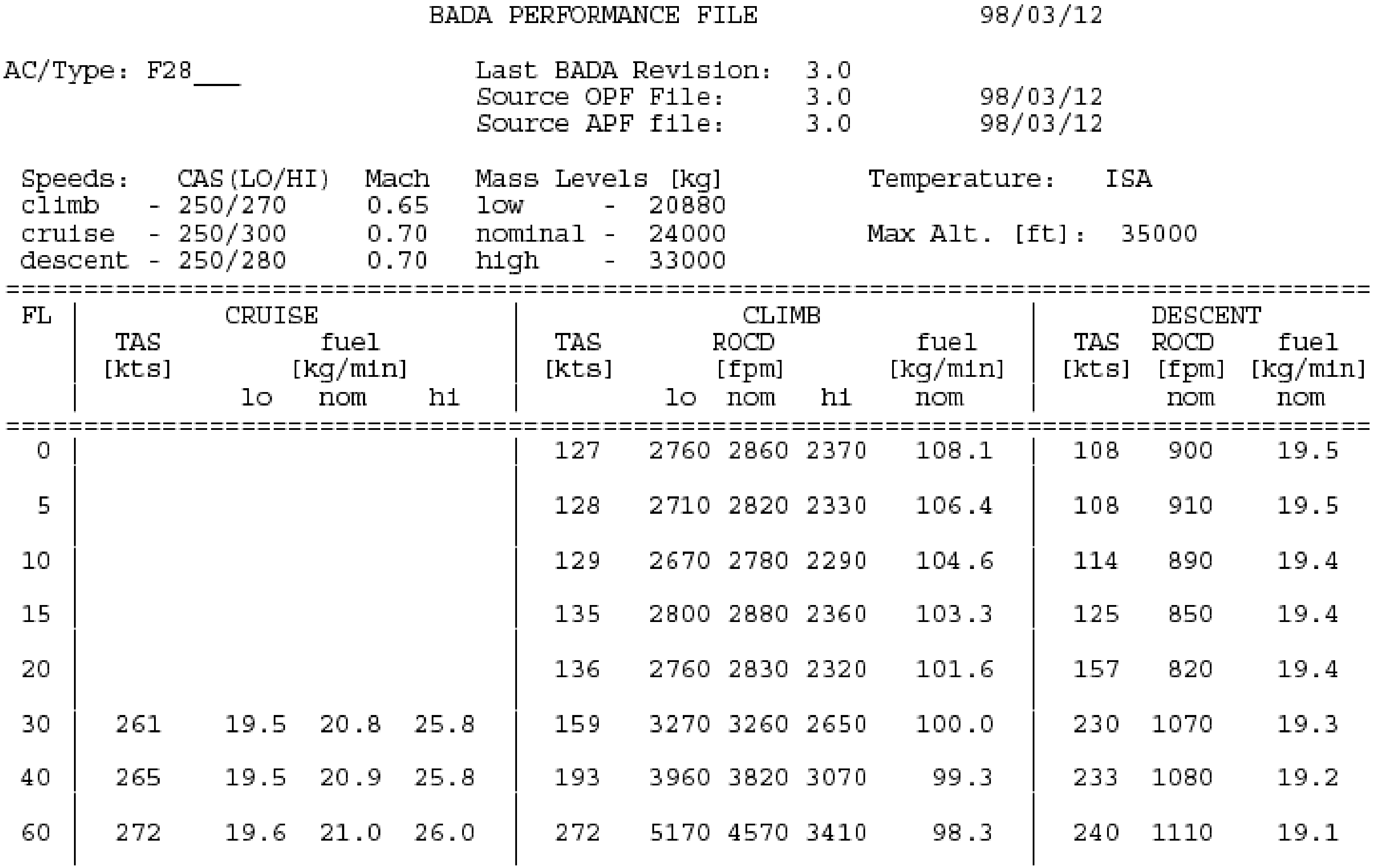
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC B767__.APF CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC/
CC                                                                                                 /
CC                AIRLINES PROCEDURES FILE                                                         /
CC                                                                                                 /
CC    File Name        Current Revision            Last Modification                               /
CC                     revision    date            revision     date                               /
CC    B767__.APF           3.0   98/03/12          2.4.1.2    96/09/05                             /
CC                                                                                                 /
CC   BADA Revision:                                                                                /
CD   Rev  3.0                                                                                      /
CC                                                                                                 /
CC   LO= 90.00 to ---.--  /  AV= ---.-- to ---.--  /  HI= ---.-- to 181.40                         /
CC                                                                                                 /
CC=================================================================================================/
CC  COM CO    Company name ------climb-------  --cruise--  -----descent------  --approach-  model- /
CC                    mass  lo  hi              lo  hi         hi  lo            (unused)          /
CC    version engines  ma  cas cas mc xxxx xx  cas cas mc  mc cas cas xxxx xx  xxx xxx xxx  opf___ /
CC===:=======:=======::==::===:===:==:====:==::===:===:==::==:===:===:====:==::===:===:===::======:/
CD  *** **    Default Company                                                                      /
CD    300ER   PW4060   LO  290 290 78          310 310 80  78 290 290            0   0   0  B767__ /
CD    300ER   PW4060   AV  290 290 78          310 310 80  78 290 290            0   0   0  B767__ /
CD    300ER   PW4060   HI  290 290 78          310 310 80  78 290 290            0   0   0  B767__ /
CC===:=======:=======::==::===:===:==:====:==::===:===:==::==:===:===:====:==::===:===:===::======:/
CC//////////////////////////////////  THE END   ////////////////////////////////////////////////////
```

Performance Table File (PTF)



```
                         BADA PERFORMANCE FILE               98/03/12

AC/Type: F28___                    Last BADA Revision:  3.0
                                   Source OPF File:     3.0         98/03/12
                                   Source APF file:     3.0         98/03/12

 Speeds:   CAS(LO/HI)  Mach   Mass Levels [kg]        Temperature:   ISA
 climb   - 250/270     0.65   low     -  20880
 cruise  - 250/300     0.70   nominal -  24000        Max Alt. [ft]:  35000
 descent - 250/280     0.70   high    -  33000
==============================================================================
 FL |          CRUISE           |              CLIMB              |       DESCENT
    |  TAS         fuel         |  TAS       ROCD         fuel    |  TAS  ROCD    fuel
    | [kts]      [kg/min]       | [kts]      [fpm]      [kg/min]  | [kts] [fpm] [kg/min]
    |         lo   nom    hi    |         lo  nom   hi    nom     |        nom     nom
==============================================================================
  0 |                           |  127   2760 2860 2370   108.1   |  108   900     19.5
    |                           |                                 |
  5 |                           |  128   2710 2820 2330   106.4   |  108   910     19.5
    |                           |                                 |
 10 |                           |  129   2670 2780 2290   104.6   |  114   890     19.4
    |                           |                                 |
 15 |                           |  135   2800 2880 2360   103.3   |  125   850     19.4
    |                           |                                 |
 20 |                           |  136   2760 2830 2320   101.6   |  157   820     19.4
    |                           |                                 |
 30 |  261    19.5  20.8  25.8  |  159   3270 3260 2650   100.0   |  230  1070     19.3
    |                           |                                 |
 40 |  265    19.5  20.9  25.8  |  193   3960 3820 3070    99.3   |  233  1080     19.2
    |                           |                                 |
 60 |  272    19.6  21.0  26.0  |  272   5170 4570 3410    98.3   |  240  1110     19.1
    |                           |                                 |
```

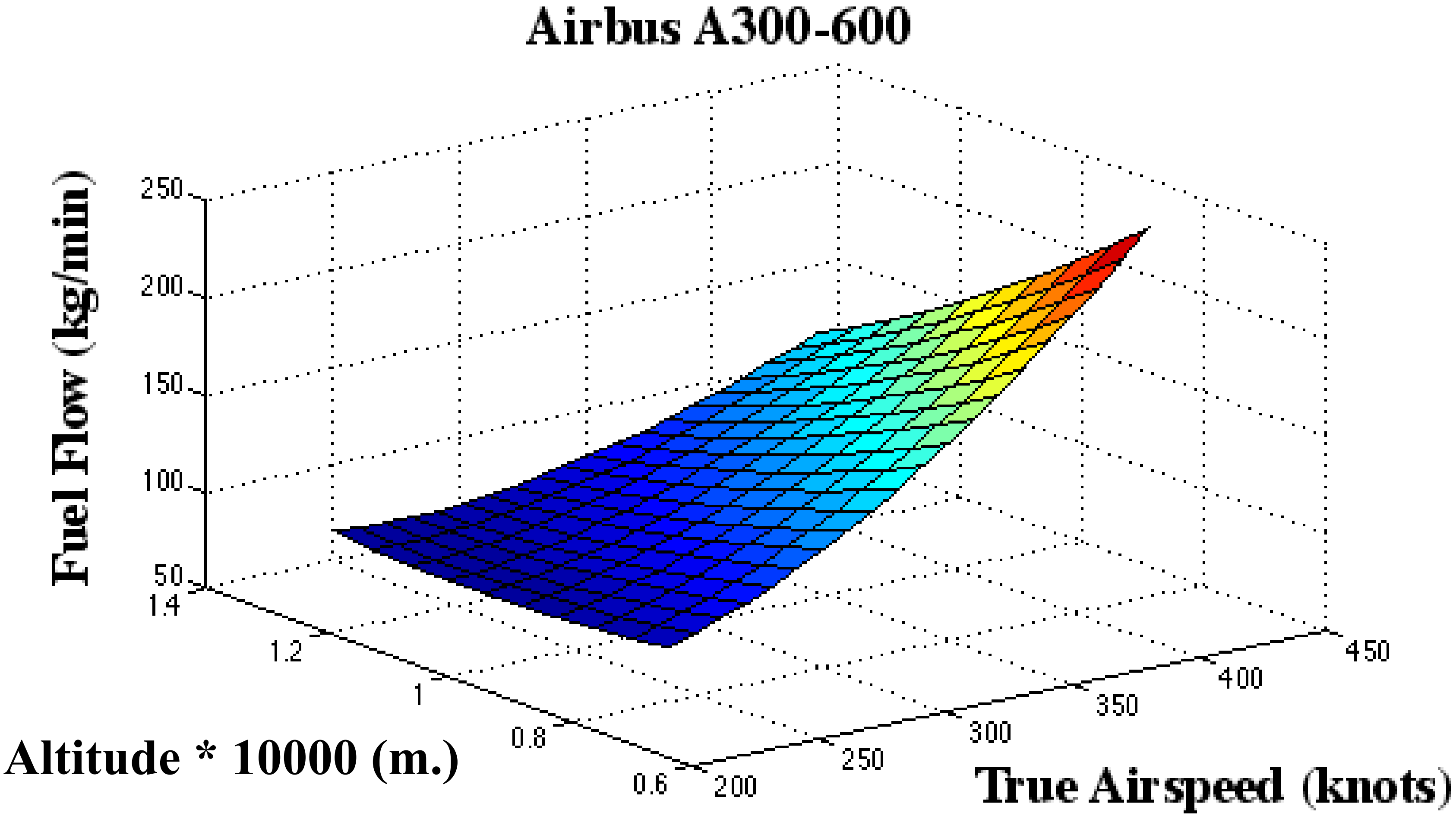
Mathematical Model

- BADA uses a total energy model to derive aircraft performance

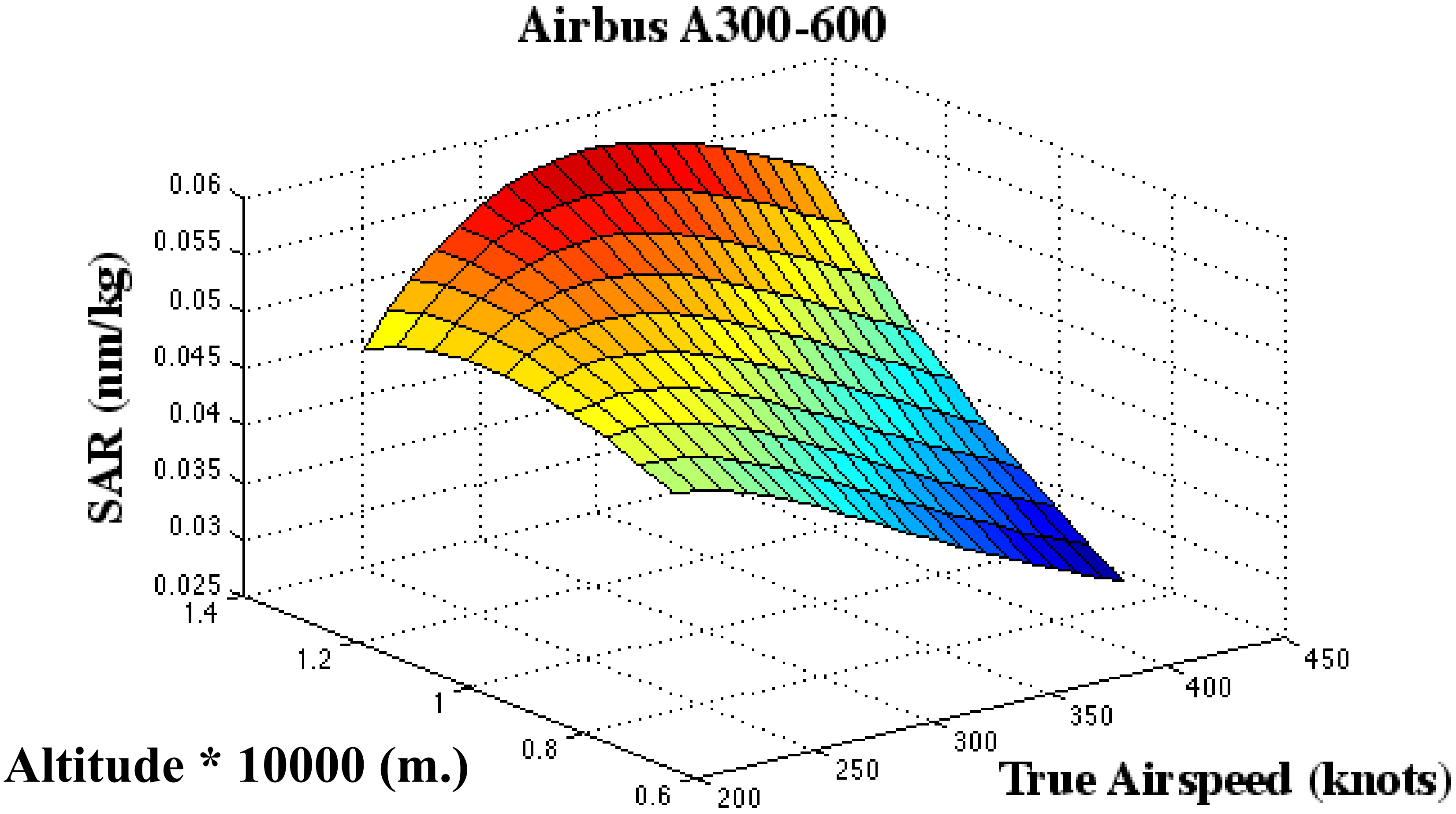
$$(T - D)V = mg\frac{dh}{dt} + mV\frac{dV}{dt}$$

where: dh/dt is the rate of climb (m/s)
dV/dt is the acceleration along the flight path (m/s^2)
h is the aircraft altitude (m)
V is the aircraft speed (m/s)
T and D are aircraft thrust and drag (N)

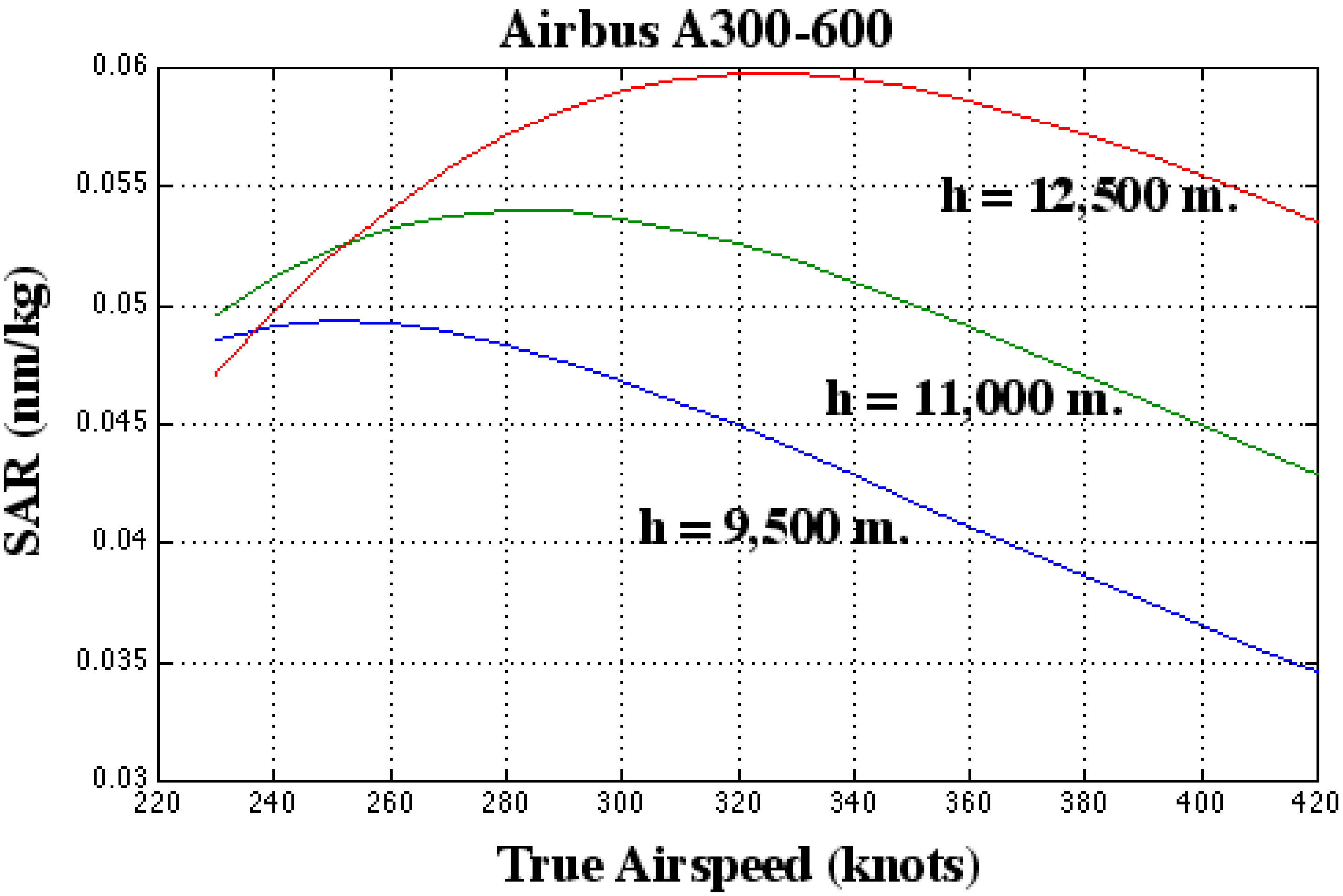
BADA Fuel Consumption Results



BADA Results (Specific Air Range - SAR)



Sample BADA Results (SAR)



Mathematical Description of APM (Objective Function)

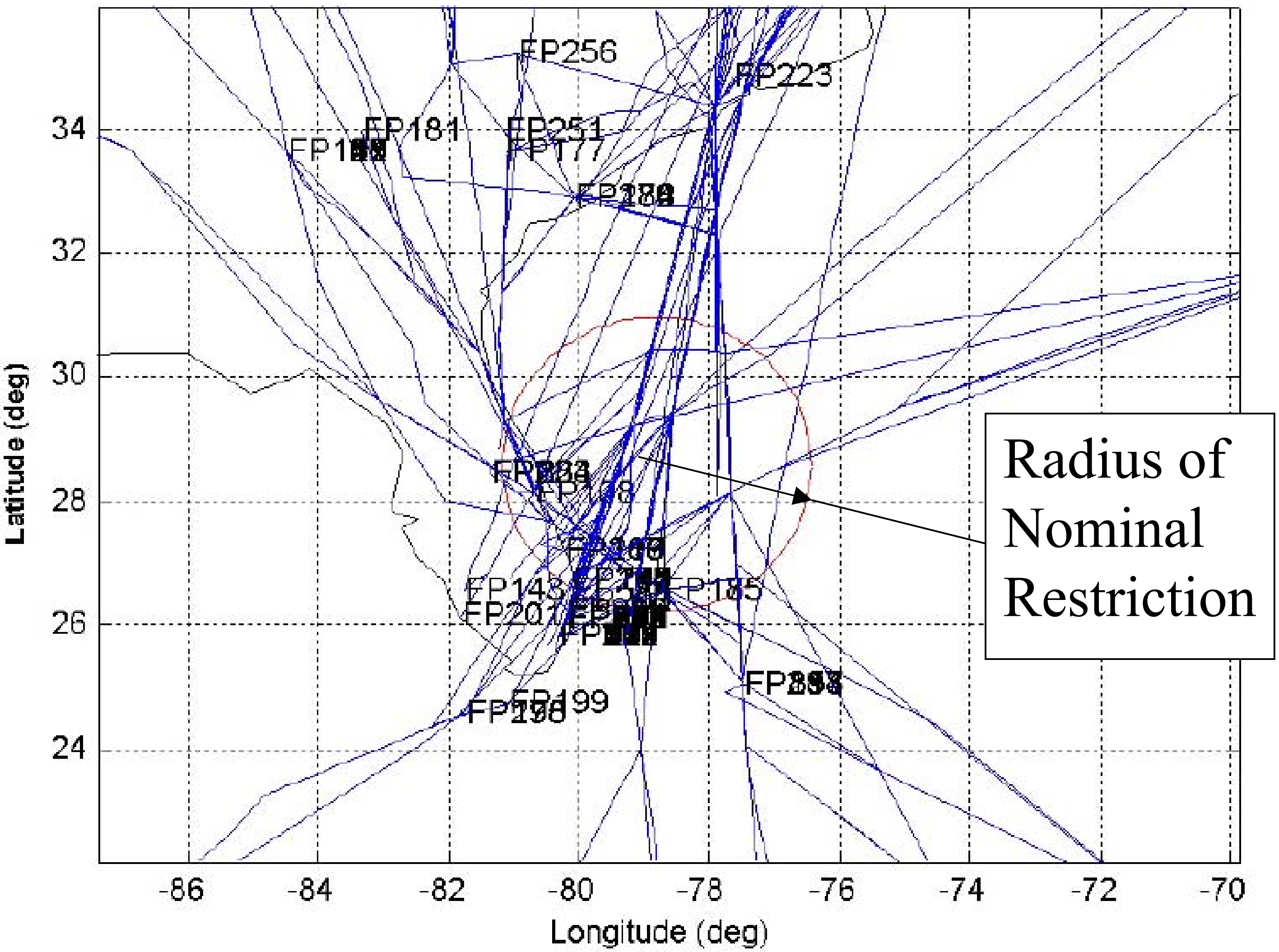
Minimize $$\sum_{i\in M}\sum_{p\in P_i} C_{ip}x_{ip} + \sum_{s\in S}\sum_{n=1}^{\overline{n}_s}\mu_{sn}y_{sn} + \mu_e(x_u^e - x_l^e) + \mu_u x_u^e$$

Cost of adopting
A mix of flight plans

Penalty associated
with sector load

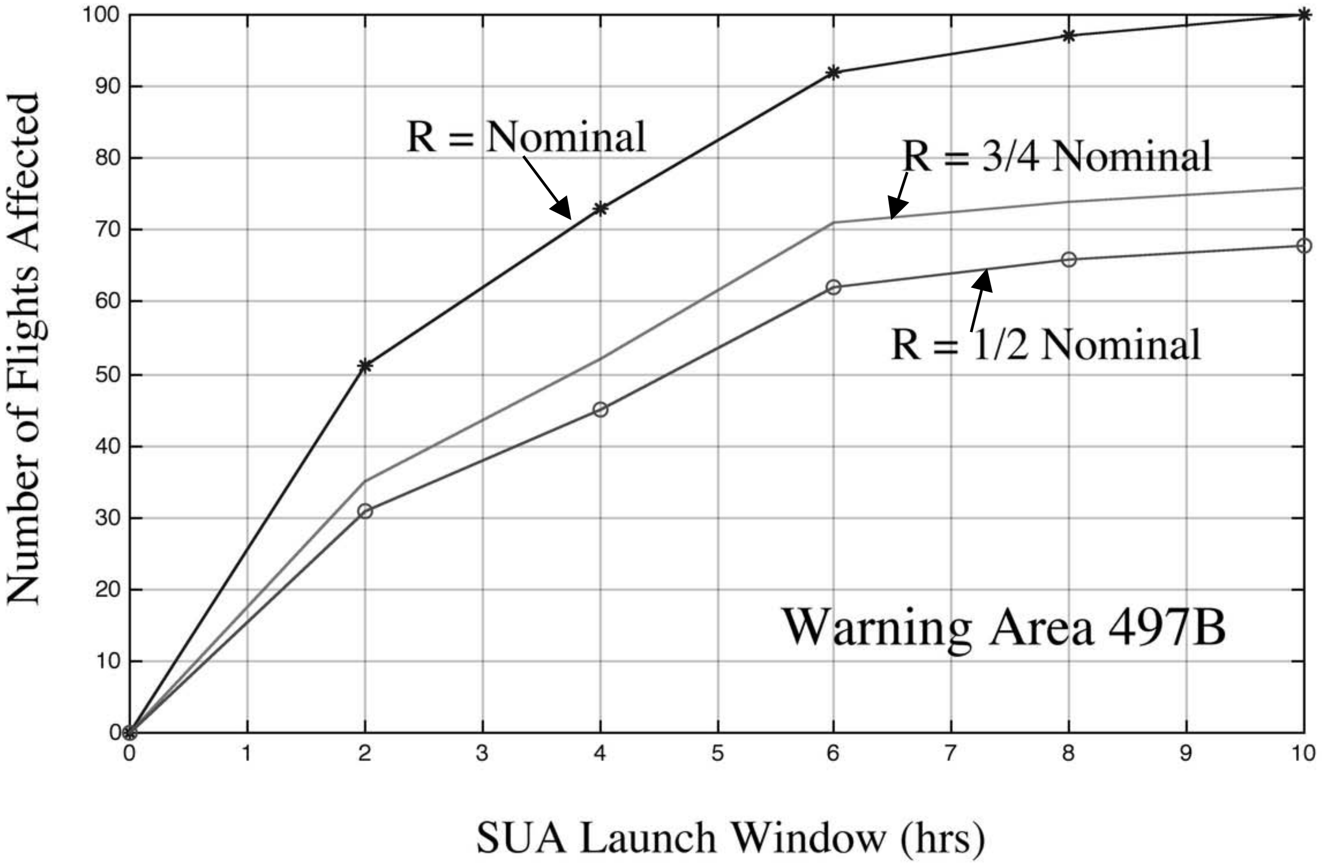
Penalty to maintain
equity among airlines

Sample Scenario

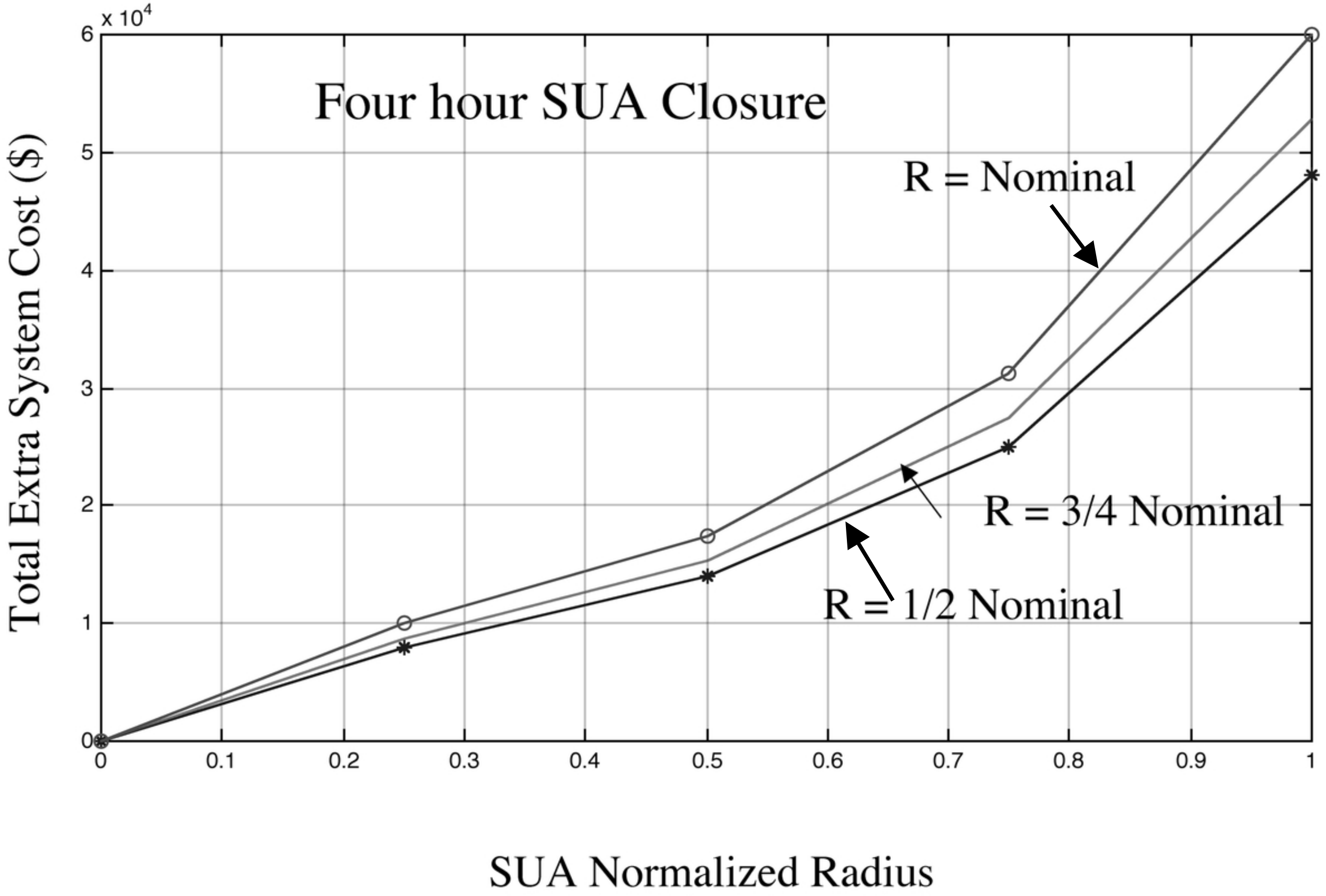


Radius of Nominal Restriction

Computational Experience



Enroute Airspace Detour Costs



Critical Issues in CDM Route Model Development

- Assessment of sector capacities and workload constraints
- Modeling credible aircraft flight track uncertainty
- Definition of "good" finite surrogate flight plan sets
- Flexibility of performance indices to accommodate airline and FAA practices (system level)
- Real-time implementation issues

Research Findings

- ATM problems considering path uncertainty are very complex combinatorial optimization problems (large arrays and real-time solutions)
- RLT techniques provide some time savings to solve the problem
- Solutions obtained with APM are very dependent on the quality of the initial set of flight paths generated in the problem

Recommendations for Future Research

- Improvements to model uncertainty of the flight path is critical
- Improvements in modeling weather patterns is needed
- Better integration between ATM Decision Support Tools and weather information is needed
- The airport ground component is critical to improve the overall capacity of the National Airspace System