GENERAL DYNAMICS
Information Technology

Prototype Implementation and Concept Validation of a 4-D Trajectory Fuel Burn Model Application

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Highlights from the Federal Aviation Administration's Support of the National Airspace System

AIAA Guidance, Navigation, and Control Conference
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The World's Forum for Aerospace Leadership

Overview

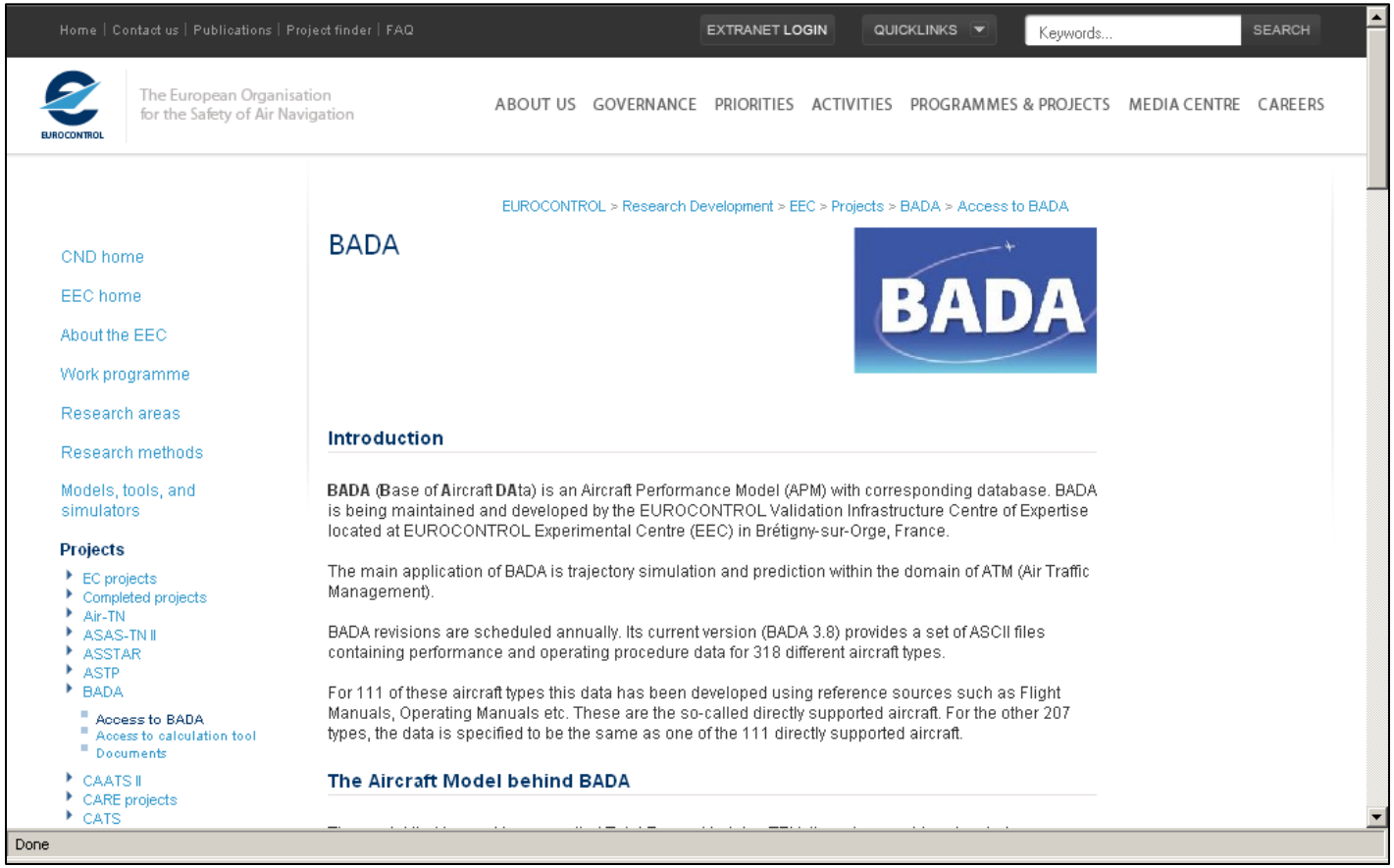
EUROCONTROL Base of Aircraft Data (BADA)

Prototype Fuel Burn Calculator Implementation

Comparison of fuel consumption rate with known data

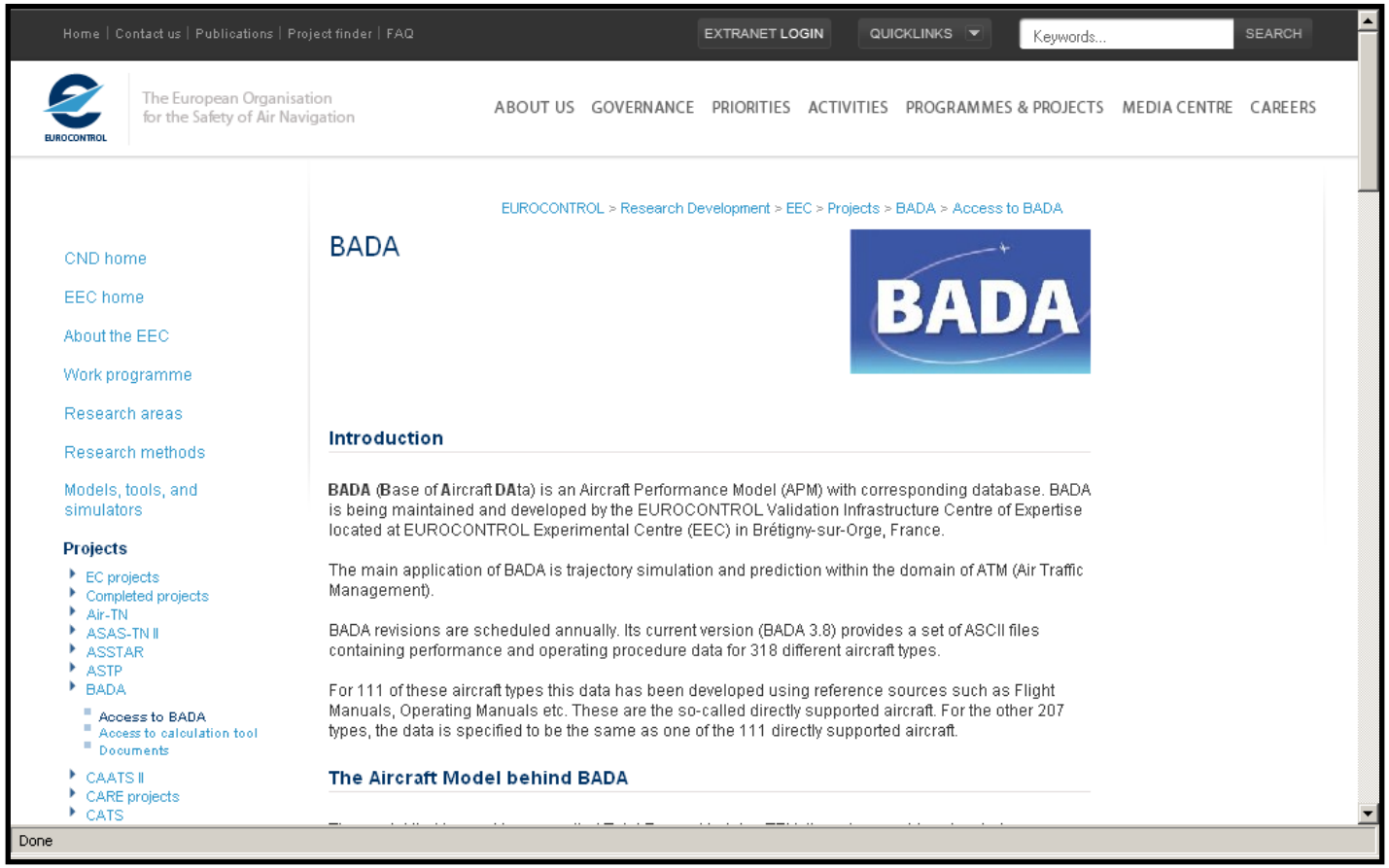
Lessons learned

EUROCONTROL Base of Aircraft Data (BADA)



http://www.eurocontrol.int/eec/public/standard_page/proj_BADA.html

EUROCONTROL Base of Aircraft Data (BADA)



http://www.eurocontrol.int/eec/public/standard_page/proj_BADA.html

EUROCONTROL Base of Aircraft Data (BADA)

"BADA (Base of Aircraft DAta) is an Aircraft Performance Model (APM) with corresponding database. BADA is being maintained and developed by the EUROCONTROL Validation Infrastructure Centre of Expertise located at EUROCONTROL Experimental Centre (EEC) in Brétigny-sur-Orge, France.

The main application of BADA is trajectory simulation and prediction within the domain of ATM (Air Traffic Management).

BADA revisions are scheduled annually. Its current version (BADA 3.8) provides a set of ASCII files containing performance and operating procedure data for 318 different aircraft types."

BADA ASCII Files:

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC CRJ1__.APF CCCCCCCCCCCCCCCCCCCC
```

BADA ASCII Files:

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC CRJ1__.APF CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC/
CC
CC                    AIRLIN
CC
CC      File_name: CRJ1__
CC
CC      Creation_date: Ap
CC
CC      Modification_date
CC
CD
CC
CC   LO=  14.75 to --.--
CC
CC=======================
CC  COM CO    Company nam
CC                    mas
CC    version engines  ma
CC===:=======:=======::==
CD  *** **    Default Com
CD    2B19    CF34     LO
CD    2B19    CF34     AV
CD    2B19    CF34     HI
CC===:=======:=======::==
CC//////////////////////
```

```
                        BADA PERFORMANCE FILE                Apr 30 2002

AC/Type: CRJ1__
                                Source OPF File:                Apr 30 2002
                                Source APF file:                Apr 30 2002

 Speeds:   CAS(LO/HI)  Mach   Mass Levels [kg]         Temperature:   ISA
 climb   - 250/290     0.74   low      -  17760
 cruise  - 250/290     0.74   nominal -  21000         Max Alt. [ft]:  41000
 descent - 250/290     0.74   high     -  23995
==============================================================================
==
 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 |                           |  151   2460 2540 2320    37.1  |  145   810     8.1
    |                           |                                 |
  5 |                           |  152   2450 2470 2300    36.7  |  146   830     8.0
    |                           |                                 |
 10 |                           |  153   2430 2450 2280    36.4  |  152   890     8.0
    |                           |                                 |
 15 |                           |  160   2520 2520 2340    36.4  |  164   960     6.0
    |                           |                                 |
 20 |                           |  161   2500 2500 2320    36.1  |  196  1250     6.0
...
```

BADA ASCII Files:

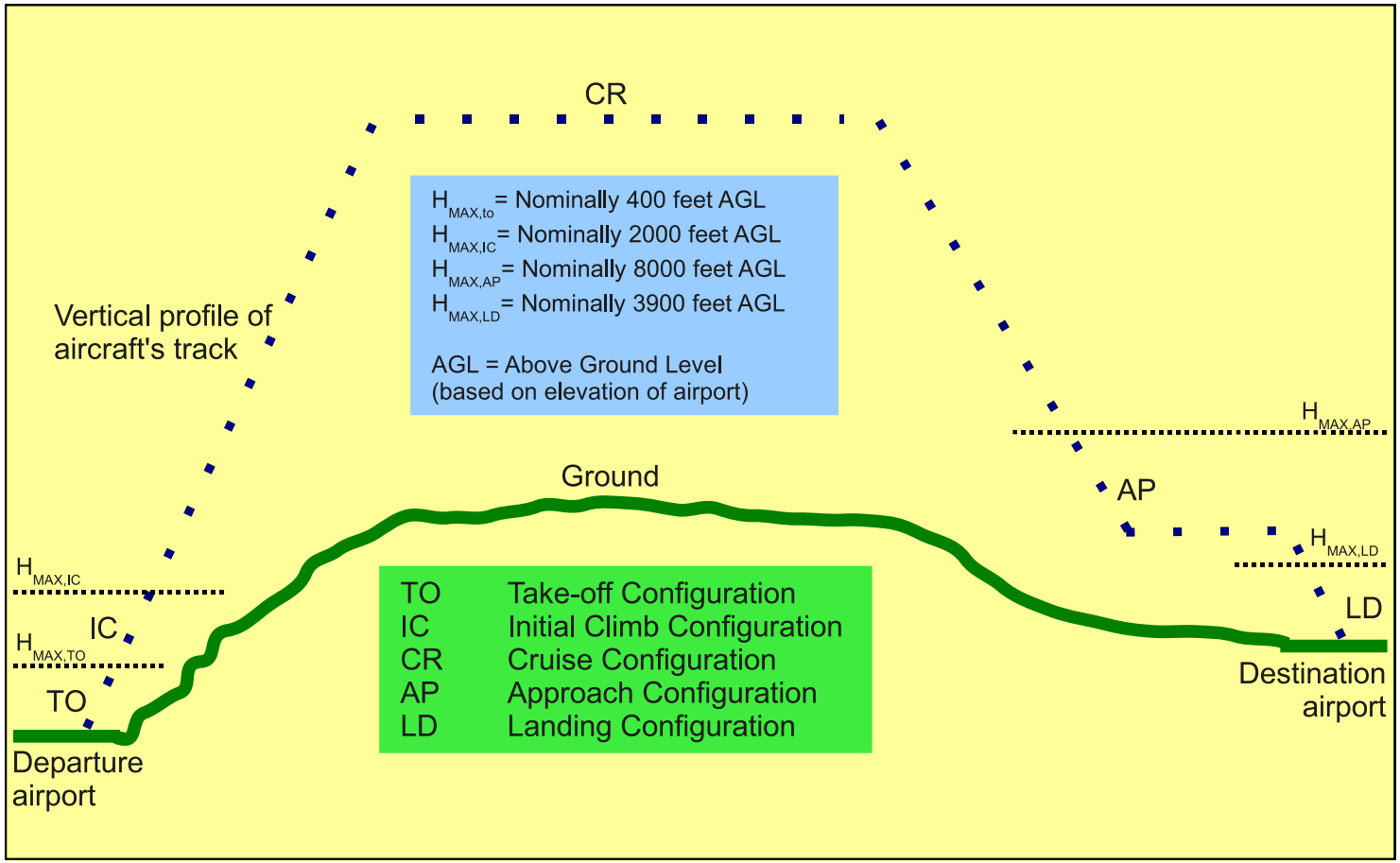
```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC CRJ1__.APF CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC/
CC
CC                    AIRLIN
CC
CC      File_n
CC
CC      Creati
CC
CC      Modifi
CC
CD
CC
CC   LO=  14.7
CC
CC============
CC  COM CO
CC
CC    version
CC===:=======:
CD  *** **
CD    2B19
CD    2B19
CD    2B19
CC===:=======:
CC///////////
```

```
                                BADA PERFORMANCE FILE                Apr 30 2002
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC CRJ1__.OPF     CCCCCCCCCCCCCC/
CC                                                                          /
CC                AIRCRAFT PERFORMANCE OPERATIONAL FILE                     /
CC                                                                          /
CC                                                                          /
CC      File_name: CRJ1__.OPF                                               /
CC                                                                          /
CC      Creation_date: Apr 30 2002                                          /
CC                                                                          /
CC      Modification_date: Apr 30 2002                                      /
CC                                                                          /
CD                                                                          /
CC====== Actype ==========================================================/
CD   CRJ1__          2 engines    Jet                        M             /
CC   Canadair Regional Jet                                   wake          /
CC              (source: Lauda Air Flight Planning Manual)                  /
CC====== Mass (t) ========================================================/
CC    reference      minimum      maximum     max payload  mass grad  /
CD     .21000E+02   .14800E+02   .23995E+02   .52000E+01   .10200E+01 /
CC====== Flight envelope =================================================/
CC     VMO(KCAS)       MMO        Max.Alt       Hmax       temp grad  /
CD     .33500E+03   .85000E+00   .41000E+05   .36500E+05  -.20000E+03 /
CC====== Aerodynamics ====================================================/
CC Wing Area and Buffet coefficients (SIM)                                  /
CCndrst Surf(m2)     Clbo(M=0)       k           CM16                       /
CD 5   .54500E+02   .13800E+01   .86000E+00   .00000E+00                   /
CC   Configuration characteristics                                          /
CC n Phase  Name    Vstall(KCAS)    CD0          CD2        unused        /
CD 1 CR   Clean     .14050E+03   .23178E-01   .35434E-01   .00000E+00 /
CD 2 IC   flap20    .11250E+03   .00000E+00   .00000E+00   .00000E+00 /
CD 3 TO   flap20    .11250E+03   .00000E+00   .00000E+00   .00000E+00 /
CD 4 AP   flap20    .11250E+03   .38000E-01   .43000E-01   .00000E+00 /
CD 5 LD   flap45    .10770E+03   .52000E-01   .40000E-01   .00000E+00 /
...
```

```
2002
2002

  ISA

:  41000

=================

     DESCENT
TAS  ROCD    fuel
kts] [fpm]

      nom    nom
=================

145   810     8.1

146   830     8.0

152   890     8.0

164   960     6.0

196  1250     6.0
```

BADA Phases of Flight



Prototype Implementation (pFBC)

Written as a Java application

Implemented BADA Version 3.6

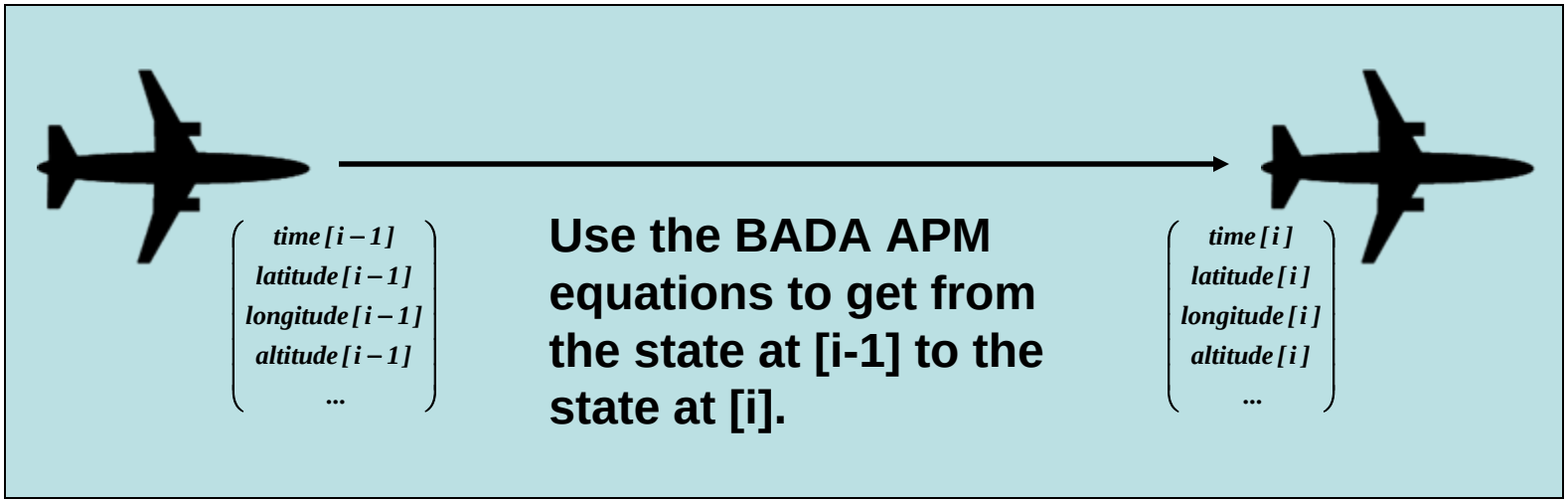
Implemented turboprop and jet engines only

Processes scenarios consisting of 4-D trajectories

- **i.e., it uses BADA as a fuel burn calculator, not as a flight synthesizer**

Using BADA for flight synthesis

The BADA Aircraft Performance Model is primarily intended for "trajectory simulation and prediction"; i.e., to synthesize the state of an aircraft.



Using BADA as a fuel burn calculator

The pFBC uses the given 4-D state of an aircraft and the BADA Model to calculate the fuel burn consumption rate.

The 4-D aircraft state aircraft state come from input scenarios that are obtained from recorded air traffic data or from simulation programs.

$$m[i] = m[i-1] - \left(\frac{f[i-1] + f[i]}{2}\right) \times \left(\frac{t[i] - t[i-1]}{60}\right)$$

where

m is the mass of the aircraft

f is the fuel consumption rate

t is the time of the 4-D trajectory point

Psuedocode: pFBC

```
pFBC {
  Initialization ;
  Synthesize initial flight ;
  Find future state changes ;
  Calculate fuel burn ;
}
```

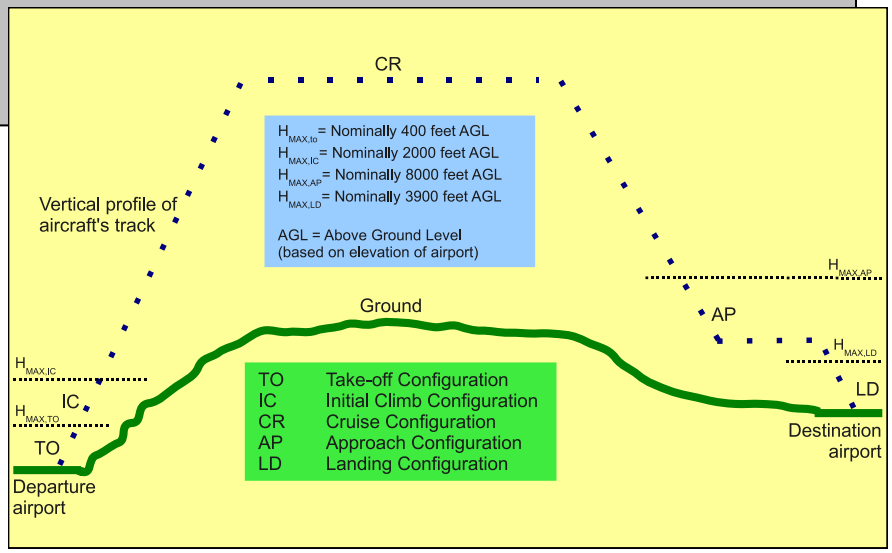
Psuedocode: Initialization

```
Initialization {
  For each aircraft in scenario {
    Retrieve aircraft-specific data ;
    Estimate take-off weight ;
    For each 4-D trajectory point {
      Collect weather data ;
      Calculate true airspeed ;
    }
  }
}
```

From database tables

Based on flight distance

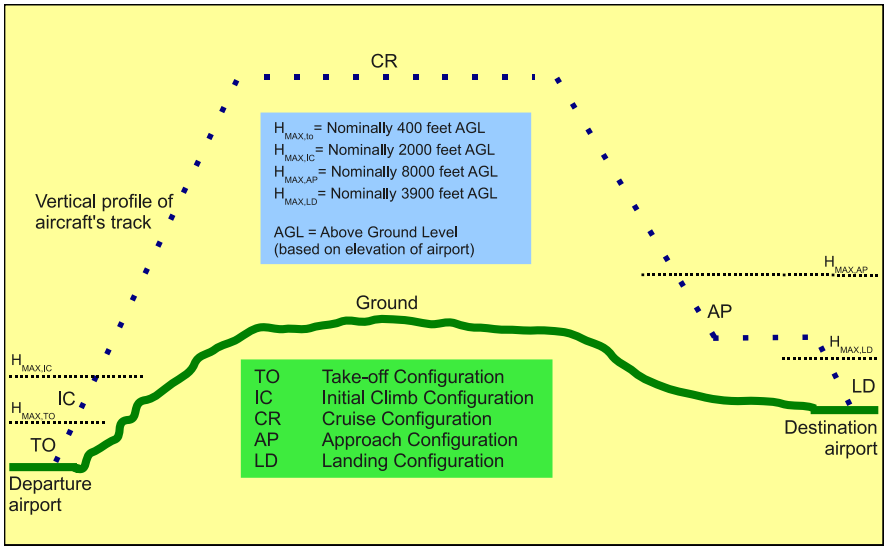
Since we're given "ground speed" not airspeed



Psuedocode: Synthesize Initial Flight

```
Synthesize Initial Flight {
  For each aircraft in scenario {
    Estimate initial weight at 1st trajectory point ;
    Determine initial phase of flight ;
  }
}
```

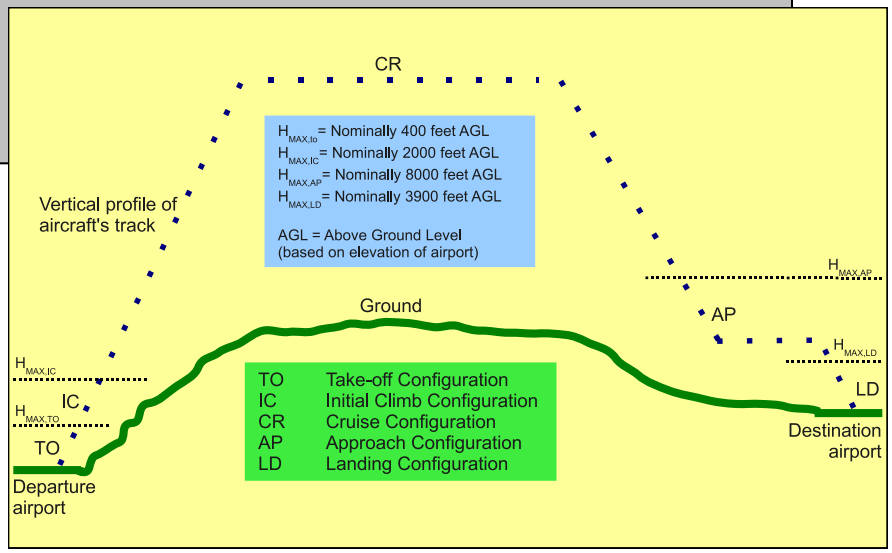
Because our 4-D trajectories do not necessarily start at the departure airport



Psuedocode: Find Future State Changes

```
Find Future State Changes{
  For each aircraft in scenario {
    For each 4-D trajectory point {
      If state changes {
        Interpolate 4-D trajectory point ;
      }
    }
  }
}
```

Because we wanted each segment to be within a single configuration phase



Psuedocode: Calculate Fuel Burn

```
Calculate Fuel Burn {
  For each aircraft in scenario {
    Set initial fuel consumption rate to 0.0 ;
    For rest of 4-D trajectory points {
      Calculate Fuel Consumption Rate ;
      Calculate fuel burned over track segment ;
    }
  }
}
```

```
Calculate Fuel Consumption Rate {
  Calculate lift coefficient ;
  Calculate drag coefficient ;
  Calculate thrust of overcome drag ;
  Calculate thrust to accelerate/decelerate ;
  Calculate thrust to climb/descend ;
  Calculate total thrust ;
  Calculate fuel consumption rate ;
}
```

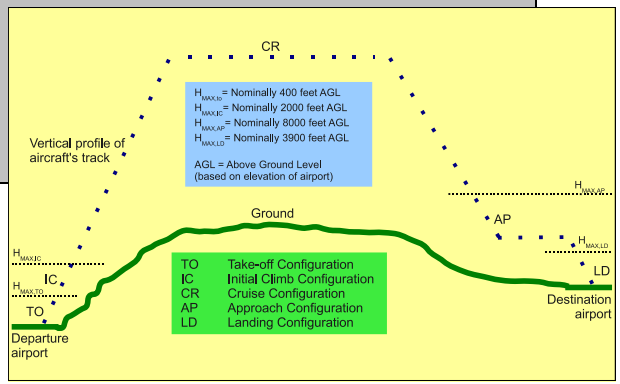
$$m[i] = m[i-1] - \left(\frac{f[i-1] + f[i]}{2}\right) \times \left(\frac{t[i] - t[i-1]}{60}\right)$$

where

m is the mass of the aircraft

f is the fuel consumption rate

t is the time of the 4-D trajectory point



Verification

We verified that we had properly implemented the BADA APM equations through normal software unit testing, but this didn't tell us if the pFBC provided meaningful results.

We would like to have compared pFBC output with real data; but real data is generally proprietary and difficult to obtain.

This paper addresses the verification of a single flight of an aircraft using opportunistic data the aircraft's Flight Data Recorder.

FAA
Bombardier Global 5000
N47

We had access to its Flight Data Recorder data for a 6-hour flight from Atlantic City Int'l Airport to Los Angeles Int'l Airport.

Specifically:
- **Time**
- **Latitude**
- **Longitude**
- **Altitude**
- **Fuel consumption rate**

Verification of the Calculation of Fuel Consumption Rate

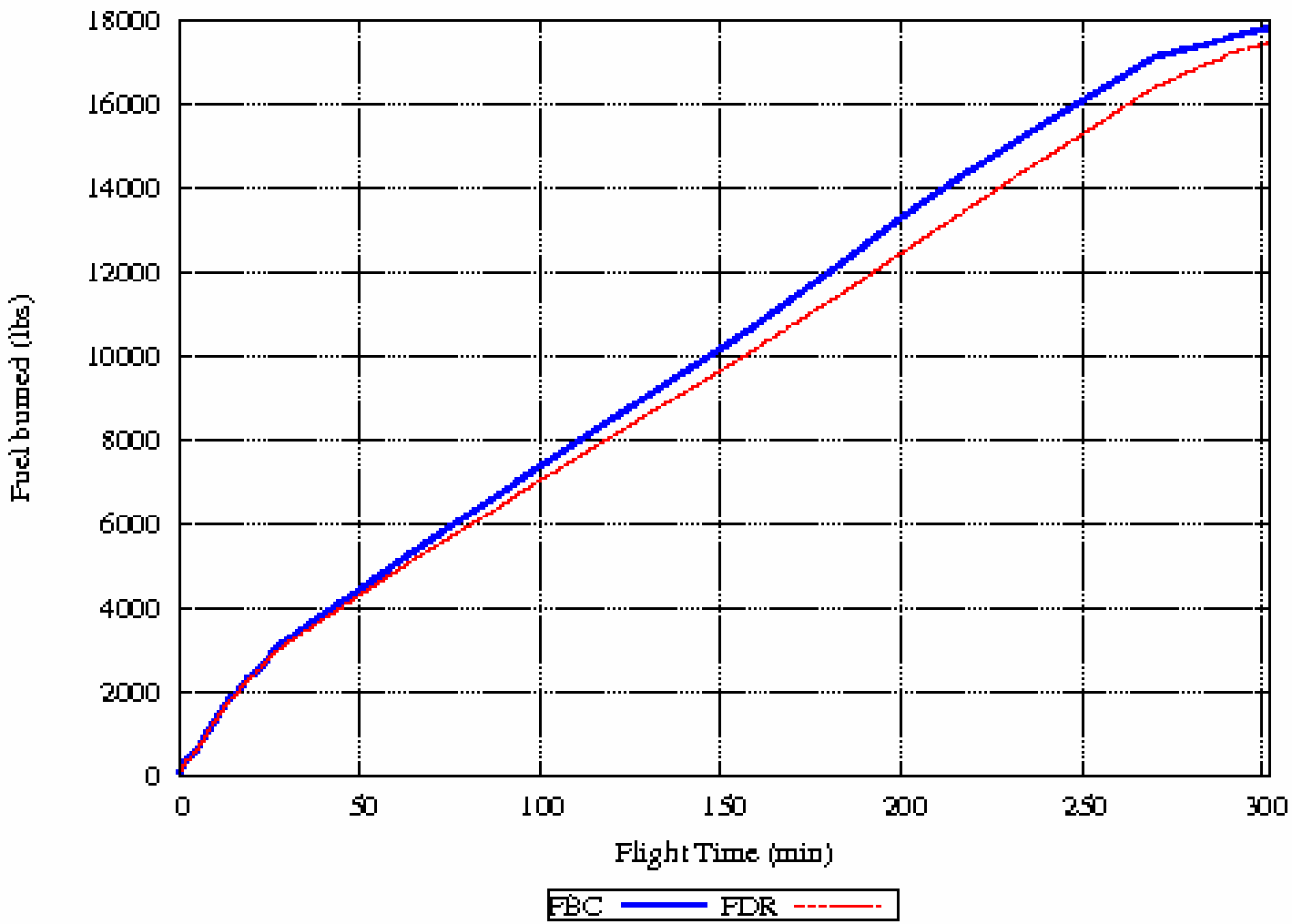
Fuel Burned vs. Flight Time

Fuel Consumption Rate vs. Flight Time During Ascent

Fuel Consumption Rate vs. Flight Time During Cruise

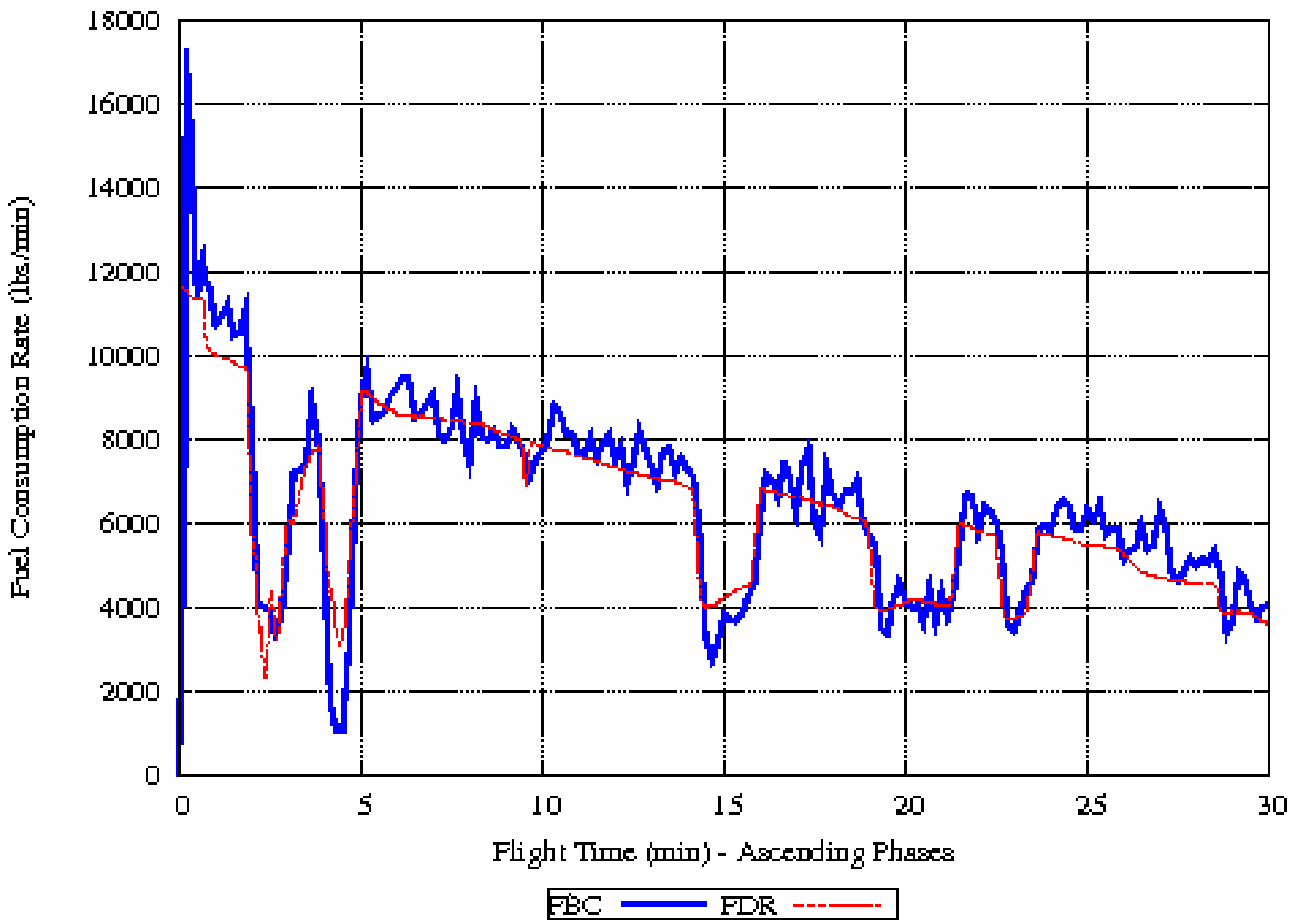
Fuel Consumption Rate vs. Flight Time During Descent

Fuel Burned vs. Flight Time

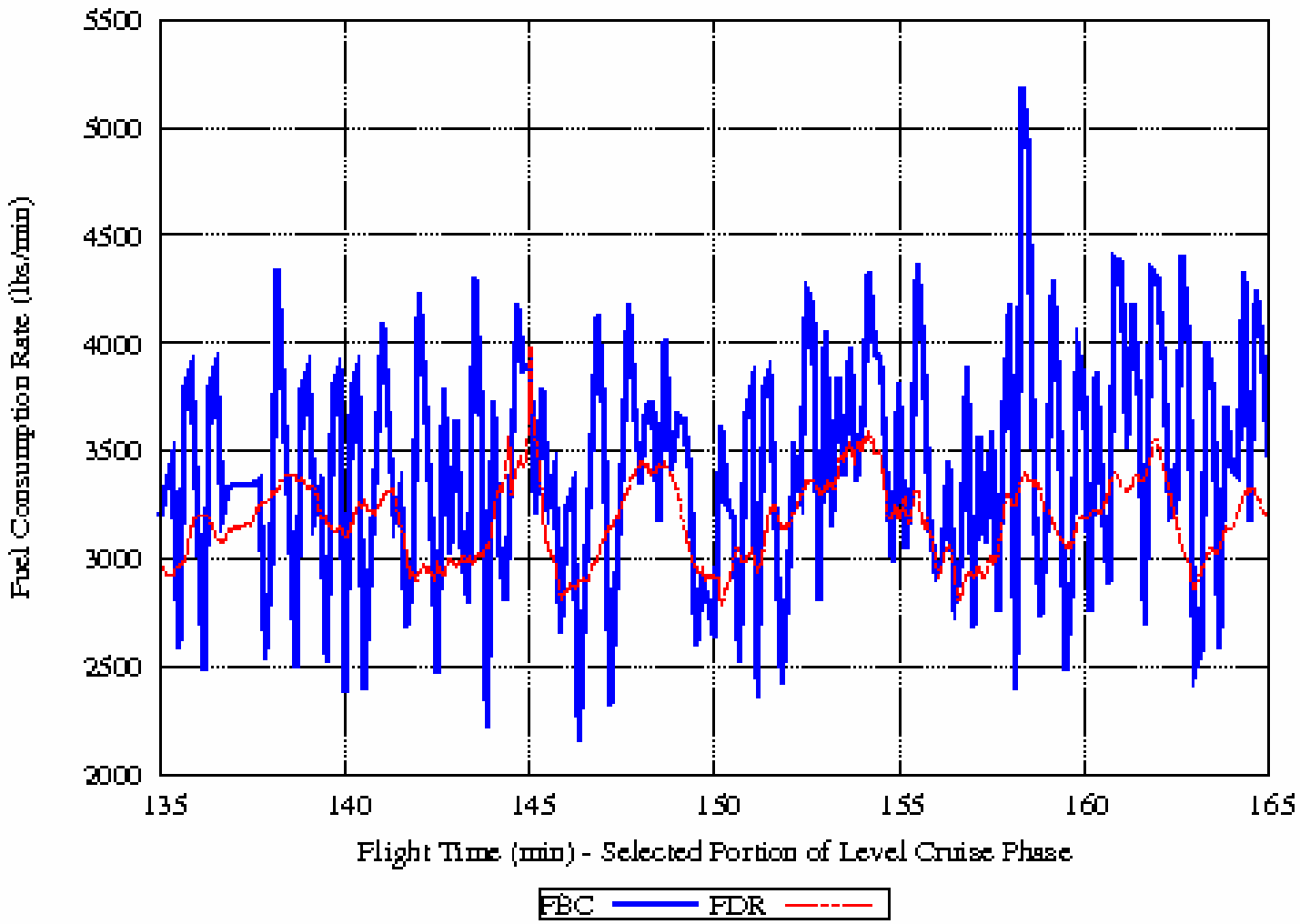


Difference:
- **342 lbs**
- **2.0%`**

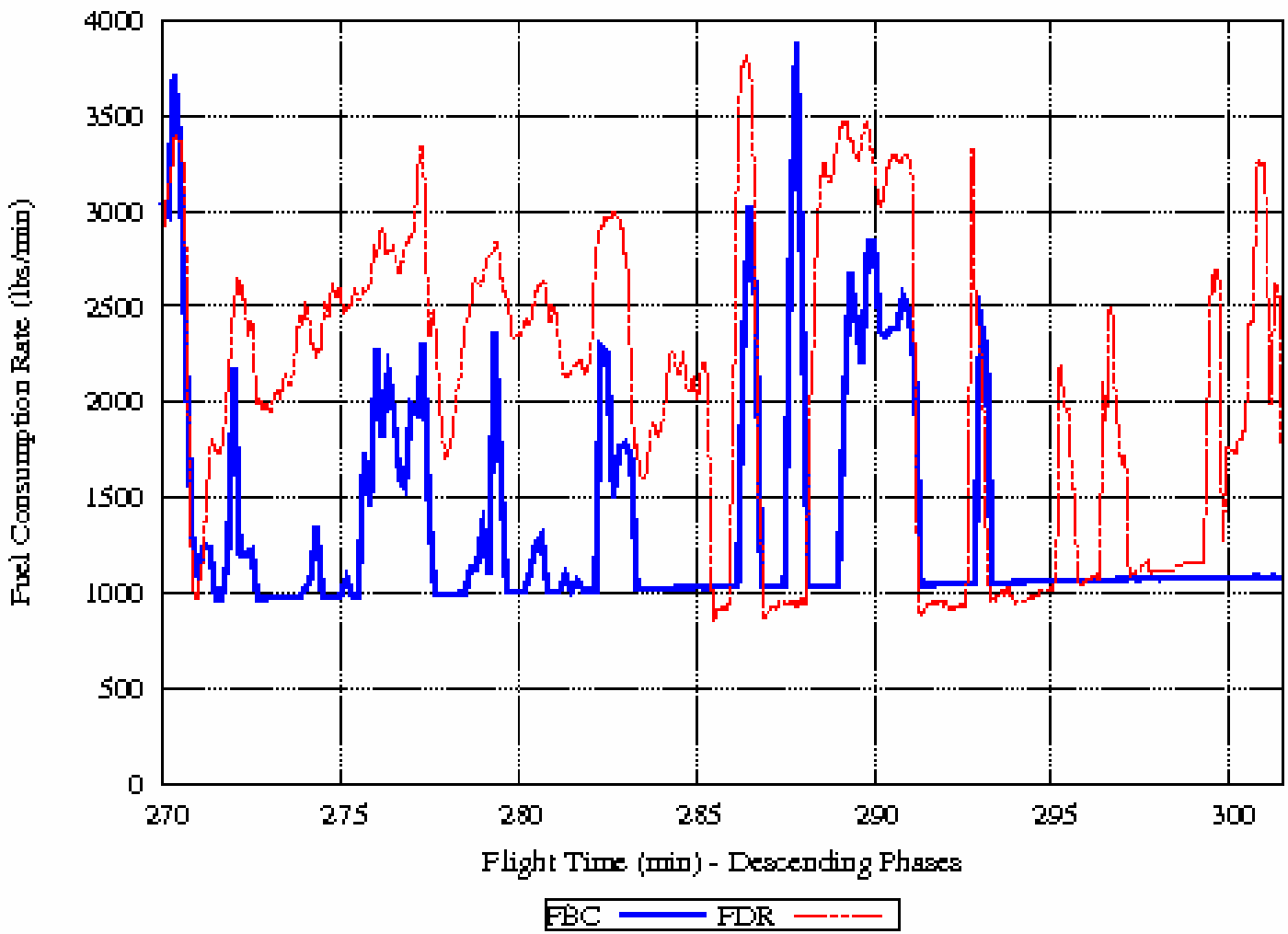
Fuel Consumption Rate vs. Flight Time During Ascent



Fuel Consumption Rate vs. Flight Time During Cruise



Fuel Consumption Rate vs. Flight Time During Descent



Lessons Learned

This comparison verified the technique; and we learned a lot:

For this verification we knew the aircraft's take-off weight; but for our production implementation we need to improve our estimation of take-off weight.

For this verification the weight of our initial 4-D trajectory point was the take-off weight, which we knew. For our production implementation we need to improve our estimation of the initial weight.

We know from this experience and from other studies that 4-D trajectory data is noisy; we need to improve our data smoothing technologies.

This verification identified some problems with our weather retrieval techniques; which we have addressed.

We need more verification and in our production implementation we plan to conduct detailed studies to verify the integrity of the results.

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