

# BADA: An advanced aircraft performance model for present and future ATM systems

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## SUMMARY

This paper gives an overview of Base of Aircraft Data (BADA), an Aircraft Performance Model developed and maintained by EUROCONTROL. BADA is based on a kinetic approach to aircraft performance modelling, which models aircraft forces. The intended use of BADA is trajectory simulation and prediction in Air Traffic Management (ATM) Research and Development and strategic planning in ground ATM operations. BADA is used for various ATM-related studies which require information on aircraft performances. The paper provides details on the existing BADA family 3 model and the latest achievements in the development of the new BADA family 4 model. Several examples of the applications of using BADA are provided, together with information on how to obtain access to BADA. Copyright © 2010 EUROCONTROL. All rights reserved.

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## 1. INTRODUCTION

Aircraft is one of the key actors in the Air Traffic Management (ATM) system. Consequently, ATM Research and Development (R&D) activities or Air Traffic Control (ATC) systems that require information on aircraft performances rely on a substitute of the real aircraft. This is the role that Aircraft Performance Model (APM) takes on board.

Principal objectives of an APM are to provide realistic, accurate and complete aircraft performance models:

- Capable of supporting accurate computation of the geometric, kinematic and kinetic aspects of the aircraft behaviour,
- Applicable to a wide set of aircraft types, over the entire operation flight envelope, and in all phases of flight,
- With reasonable complexity, maintainability and computing requirements.

There are several existing approaches to aircraft performance modelling nowadays. Kinetic approach models aircraft forces, while kinematic approach directly models the aircraft flight path characteristics without attempting to model the underlying physics. Typical examples of APM that are used today are introduced and described in [1].

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This paper describes Base of Aircraft Data (BADA), an APM, developed and maintained by EUROCONTROL. The paper is structured into eight sections, the introduction being the first one. The second section provides an overview of BADA, its structure and its components with their roles and responsibilities. The third section explains the aircraft model instance generation taking into account the aircraft reference performance data needed and the coefficient identification process. The fourth and fifth sections give an insight into the state-of-the-art and main features of the two existing model families, BADA 3 and 4. Sections six and seven provide examples of BADA application and describe the way to access it. Closing remarks with future plans are provided in the final section.

## 2. BADA OVERVIEW

As depicted in Figure 1, BADA is made of two models: APM and Airline Procedure Model (ARPM). Each aircraft model (specific aircraft type) is described with a set of coefficients that are used by the APM and ARPM. These are referred to as Aircraft Characteristics.

### 2.1. BADA APM

The APM adopted by BADA is based on a mass-varying, kinetic approach. This approach models an aircraft as a point and requires the modelling of underlying forces that cause aircraft motion. As depicted in Figure 1, the BADA APM is structured into four models, namely Actions, Motion, Operations and Limitations.

The **action** model allows the computation of the forces acting on the aircraft which cause its motion. There are three categories of actions: aerodynamic (namely drag  $D$  and lift  $L$ ), propulsive (thrust  $T$ ) and gravitational (weight  $W$ ). Since BADA accounts for mass variation, the propulsive model provides an associated model to compute fuel consumption  $F$ . The corresponding mathematical models are expressed in the form of polynomial expressions.

Total Energy Model (TEM) relates to the geometrical, kinematic and kinetic aspects of the **aircraft motion**, allowing the aircraft performances and trajectory to be calculated. TEM equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy, that is:

$$(T - D)v = W\dot{h} + m\dot{v} \tag{1}$$

where  $h$  is altitude,  $\dot{h}$  is vertical speed,  $v$  is true airspeed (TAS) and  $m$  is aircraft mass.

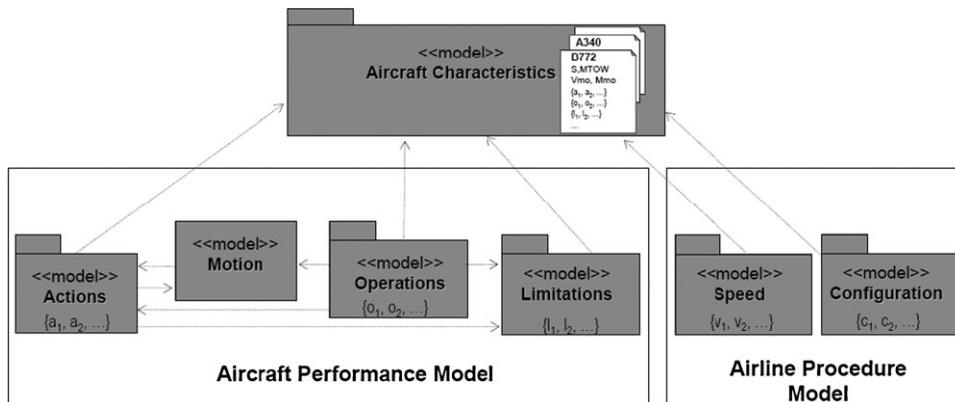


Figure 1. Structure of BADA model.

To facilitate calculations, Equation (1) can be rearranged and vertical speed expressed as:

$$\dot{h} = \left( \frac{T-D}{mg} \right) v \cdot \text{ESF} \quad (2)$$

where  $g$  is the acceleration of gravity and ESF is the energy share factor, defined by:

$$\text{ESF} = \left( 1 + \frac{v}{g} \frac{dv}{dh} \right)^{-1} \quad (3)$$

The variation of mass is accounted for through the fuel consumption model:

$$\dot{m} = -F \quad (4)$$

Equations (2) and (4) together form an Ordinary Differential Equations (ODE) system which can be posed with the respective initial or boundary conditions at each flight segment to compute the aircraft motion in that interval. The computed aircraft trajectory is, then, the result of concatenating the solutions of a sequence of such motion problems.

Although the ODE system above governs any possible aircraft motion, different ways of operating the aircraft result in different trajectories. For instance, flying constant Mach number [2] leads to the following specific form of Equation (3):

$$\text{ESF} = \left( 1 + \frac{\kappa R \beta_T}{2g} M^2 \right)^{-1} \quad (5)$$

where  $\kappa$  is the air adiabatic index,  $R$  is the specific gas constant,  $\beta_T$  is the temperature gradient of the particular atmosphere layer considered and  $M$  is the Mach number. Analogously, flying constant calibrated airspeed (CAS) leads to a different form of Equation (3) and so on for other flight regimes other than constant CAS/Mach. The **operations model** is responsible for capturing those aspects, which are neither directly related to actions nor motion laws, but which are necessary to incorporate into the problem of computing aircraft motion, the knowledge about the way in which the aircraft is operated.

The hypotheses, equations and results obtained by the other models are valid only within certain limits or borders outside of which they no longer reflect the real aircraft behaviour. The **limitations model** restricts the aircraft behaviour in order to keep it between certain limits to ensure the safe operation of the aircraft, or limit the equipment degradation.

## 2.2. BADA airline procedure model (ARPM)

The definition of the standard airline procedures in BADA is driven by a requirement to provide information on nominal aircraft operations to different simulation and modelling tools for various ATM applications. It is widely recognized that the way an aircraft is operated varies significantly in function of specific airspace procedures and operating policies of locally dominant airlines. That is the reason why the resulting speed schedules of the BADA standard airline procedure model may differ from a particular geographical location or an aerospace's specific aircraft operation. Details about the BADA ARPM may be found in reference documents [2, 3].

## 3. SPECIFIC AIRCRAFT MODEL INSTANCE GENERATION

Each aircraft model in BADA is described with a set of coefficients that are used by the Action, Limitations, Operations and Airline procedure models. The process of specific aircraft model instance generation aims at

identifying coefficients of mathematical models with the objective to achieve the best fit between calculated and reference aircraft performance parameters. As a result, the set of aircraft coefficients is identified to describe a specific aircraft type. Although each aircraft model instance is generated for a specific aircraft type and version, it is identified only by a 4-character designation code assigned by the International Civil Aviation Organisation (ICAO) [4], e.g. the A319 instance in BADA 3.7 is based on the Airbus A319-131 aircraft equipped with two V2522-A5 engines.

### 3.1. Reference data requirements

To enable the identification of all the coefficients that describe the aircraft model instance, a number of aircraft performance data items is required. This data can be divided into two categories: technical specification data and performance data. Technical specification data consists of general aircraft characteristics (model, engine, limitations and dimensions), operating characteristics (nominal operating speeds) and aerodynamic configurations. Performance data consist of aircraft flight profile data which provide information on required time, distance and fuel to climb/descend to/from flight level (FL) at specific conditions of aircraft weight, operating speed, atmospheric conditions, engine settings, etc.

Precision and granularity of data values, together with data coverage of the aircraft flight envelope, have the highest impact on the BADA model quality. The performance data are considered to be of low quality when: the data covers only a limited part of the aircraft flight envelope; data are available only for a small number of flight levels; time to climb or descend is rounded to the nearest minute. High quality aircraft performance reference data provide data points for a complete range of aircraft operating conditions in terms of weight, speeds, different atmospheric conditions and associated operating regimes with a high level of data granularity (number of data points) and data precision.

### 3.2. Action model coefficients identification

BADA APM requires modelling of thrust and drag, while fuel flow is modelled as a function of thrust. As the original aircraft data for thrust, drag and thrust-specific fuel consumption are not easily available, a choice was made to use aircraft profile data for BADA action model identification.

The ODE system formed by Equations (2) and (4) together with Equation (6) below provides the way to compute flight profiles based on BADA, once the model coefficients for thrust, drag and fuel consumption are known.

$$\dot{r} = v \cdot \cos \gamma \quad (6)$$

where  $\dot{r}$  is the horizontal speed and  $\gamma$  is the flight path angle.

Figure 2 depicts the model instance identification process.

The objective of the model identification process is to obtain the BADA APM coefficients from a set of known flight data points. Since the ODE system is the law that governs trajectory generation according to BADA model, it can be used for coefficient identification purposes: left side values of expressions (2), (4) and (6) are the observed values, while right side values are estimated values by means of the BADA model.

The better the expressions above estimate the observed derivatives  $\dot{h}$  and  $\dot{r}$ , the more accurately the trajectory resulting from integration of such derivatives will fit the observed ones.

The adopted optimization solution is least-squares (LS) solution that minimizes the sum of square errors (SSE) of vertical speed  $\dot{h}$  as defined in expression:

$$SSE_{\dot{h}} = \sum_{i=1}^n \left[ \dot{h}_i - (T_i - D_i) \frac{v_i}{m_i g} \text{ESF}_i \right]^2 \quad (7)$$

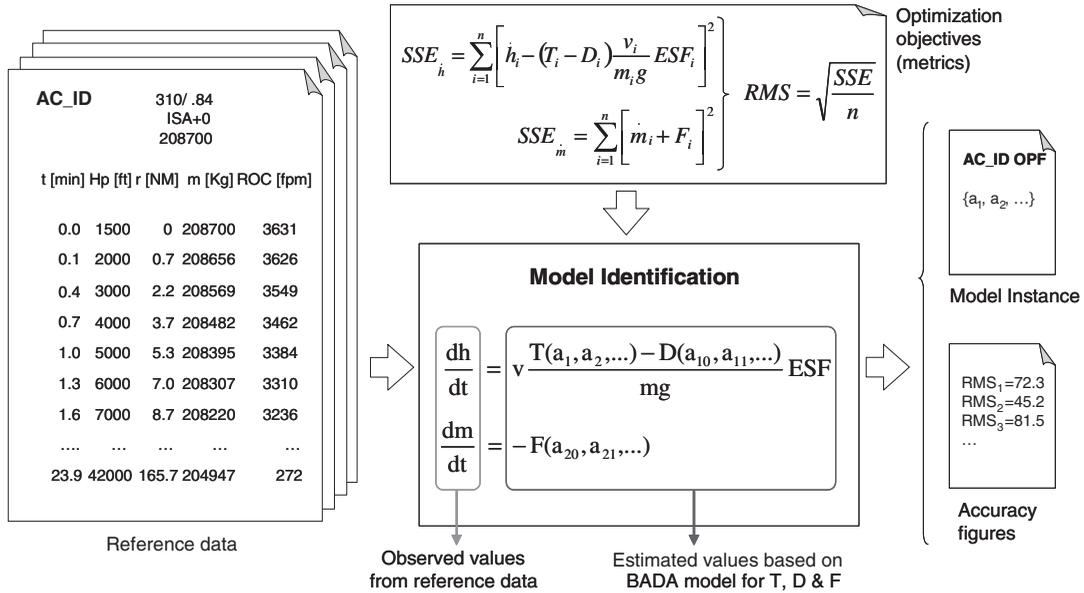


Figure 2. BADA model instance identification process.

where the referred errors are the differences between the observed (reference) values of  $\dot{h}$  and the estimated ones.  $n$  is the total number of data samples through all the trajectories considered for the given aircraft type.

To measure goodness of a specific model, the root mean square (RMS) metric defined as  $RMS = \sqrt{\frac{1}{n} SSE}$  is used. This metric provides a measure of how well a specific model fits the reference data used to derive the model in terms of vertical speed.

A similar approach is taken for optimization of the fuel flow coefficients. In that case, the SSE is computed as

$$SSE_{\dot{m}} = \sum_{i=1}^n [\dot{m}_i + F_i]^2 \quad (8)$$

To ensure that obtained coefficients robustly represent aircraft behaviour over normal operation conditions, various flight profiles that cover operations of aircraft for different speeds, aircraft masses and atmosphere conditions are used. The available aircraft performance reference data do not always cater for this requirement of aircraft flight envelope coverage. In this case an aircraft model can be identified, but its fidelity can only be assessed and guaranteed for the range of reference data conditions.

Validation of the resulting coefficients for a specific aircraft type is also done by visual analysis of the plots containing reference against computed trajectories. Examples are provided in Figures 3 and 4, where solid lines represent reference data while dashed lines represent computed values based on BADA model.

#### 4. BADA APM MODEL FAMILIES

There are two existing families of the BADA APM. Both of them, family 3 and family 4, are based on the same modelling approach and have the same structure and components (as described in Section 3).

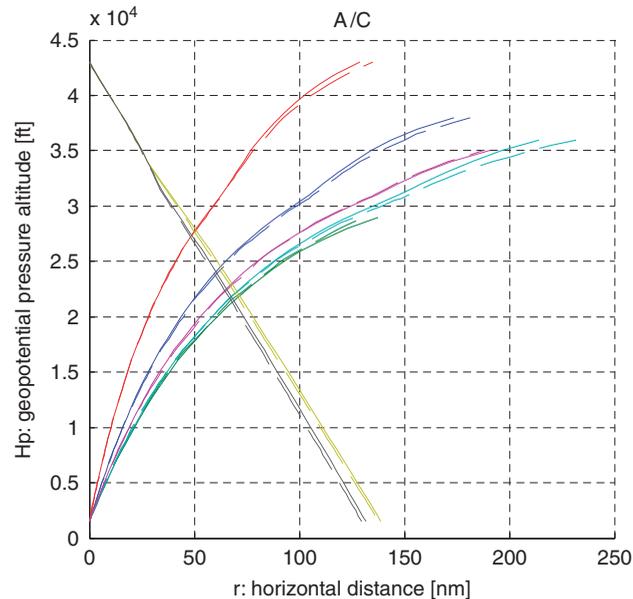


Figure 3. Geopotential pressure altitude as a function of horizontal distance.

The BADA family 3 was developed in the early 90s with the objective to provide for realistic modelling of aircraft performances over a nominal flight envelope. The design decisions were made taking into consideration availability and quality of the existing aircraft performance reference data and computing resources.

Since the time BADA 3 was first developed, applications relying on the APM have broadened significantly with requirements to provide more advanced features to support ATM modelling and simulation needs. The new requirements relate to the accuracy of the modelled aircraft performances, the coverage of the complete aircraft operation envelope, the flight phases that can be represented and the type of operations that an APM can support. The advanced model optimization tools and today's available high quality reference data have been used to study the ability of the BADA 3 model to capture aircraft performances over the whole flight envelope and to identify levels of accuracy that are achievable. This study has confirmed that the BADA 3 model with its underlying mathematical models cannot provide accurate modelling over the entire flight envelope. This finding has been a driver for the development of BADA 4, with the objective to accurately model aircraft performances over the entire aircraft flight envelope covering all phases of flight and aircraft at different configurations.

While elaboration of mathematical models for BADA 3 was limited by the low availability of high quality reference data, and a requirement to keep the model algorithms simple due to limited computing capabilities, the development of BADA 4 took advantage of today's availability and high quality of aircraft performance reference data and significantly improved computing capabilities. The BADA 4 mathematical models were elaborated based on the analysis of the underlying physical laws governing aircraft behaviour and the identification of the physical variables upon which aircraft performance is to be represented.

The use of proper physical dependencies and the selection of appropriate mathematical models to relate them provide higher accuracy in modelling. The physical relationships in BADA 4 are obtained in terms of dimensionless variables. The dimensionless relationship facilitates analysis and comparisons, prevents mistakes and, provided an adequate selection of dimensionless terms, allows discovering physical similarity relationships.

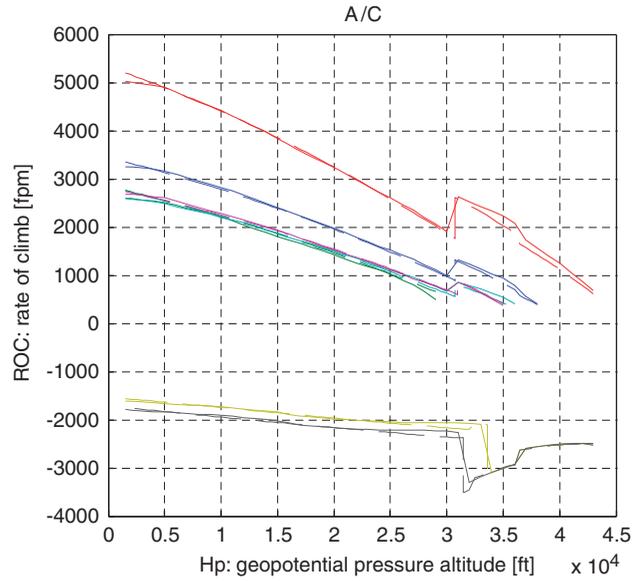


Figure 4. Rate of climb/descent (ROCD) as a function of geopotential pressure altitude.

**BADA 3: Max climb thrust for JET aircraft:**

$$(T_{\max \text{ climb}})_{\text{ISA}} = C_{\text{Te}1} \times \left( 1 - \frac{h}{C_{\text{Te}2}} + C_{\text{Te}3} \times h^2 \right)$$

$$T_{\max \text{ climb}} = (T_{\max \text{ climb}})_{\text{ISA}} \times (1 - C_{\text{Te}5} \cdot (\Delta T_{\text{ISA}})_{\text{eff}})$$

$$(\Delta T_{\text{ISA}})_{\text{eff}} = \Delta T_{\text{ISA}} - C_{\text{Te},4}$$

**BADA 4: Max climb thrust for JET aircraft:**

$$\frac{T}{\delta} = W_{\text{MTOW}} (c_1 M + c_2 M^2 + c_3 M^3 + c_4 \delta_T + c_5 \delta_T M + c_6 \delta_T M^2)$$

$$\delta_{T, \text{flat}} = d_1 + d_2 \delta + d_3 \delta^2 + d_4 M + d_5 \delta M^2 + d_6 M^2 + d_7 M^2 \delta$$

$$\delta_{T, \text{temp}} = e_1 + e_2 \theta_i + e_3 \theta_i^2 + e_4 M + e_5 M \theta_i + e_6 M \theta_i^2 + e_7 M^2 + e_8 M^2 \theta_i + e_9 M^2 \theta_i^2$$

Figure 5. Maximum climb thrust models for BADA 3 and BADA 4.

To illustrate differences in underlying mathematical models of BADA 3 and BADA 4, an example of a Maximum Climb Thrust model for both families is given in Figure 5.

The identification of specific aircraft model instances for BADA 4 requires the availability of high quality data with coverage of the entire flight envelope. Only then can BADA 4 provide advanced capabilities and great levels of accuracy of underlying models.

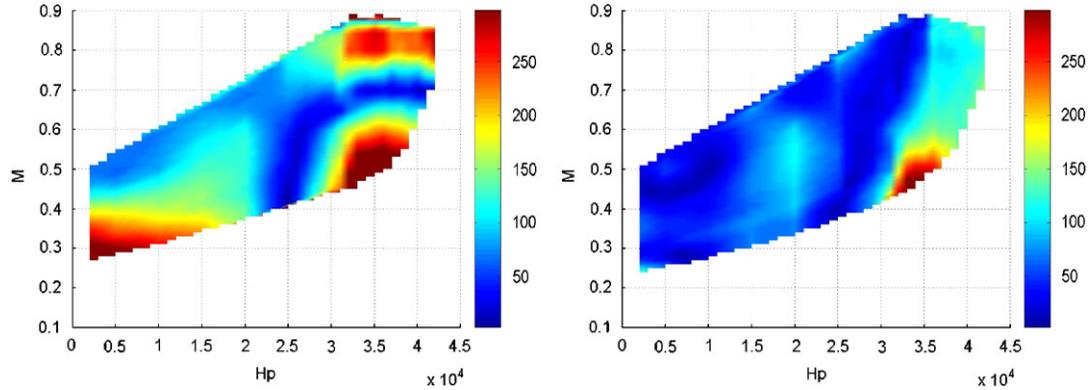


Figure 6. Absolute vertical speed errors (fpm) in function of Mach and pressure altitude, at ISA+15 for a long haul aircraft model in BADA 3 and 4.

As an example of the possible improvements offered by BADA 4, Figure 6 presents the error in vertical speed for a long haul aircraft provided by a BADA 3 model (left side of the figure) and a BADA 4 model (right side of the figure) over the complete range of operational speeds.

## 5. BADA APM STRUCTURE AND FEATURES

As mentioned in Section 3, both BADA 3 and 4 define models for actions, limitations and operations for en-route and Terminal Manoeuvring Area (TMA) operations. The individual model structure and principal differences between BADA 3 and 4 are addressed in the text hereafter.

### 5.1. Actions

5.1.1. *Drag.* Drag in BADA family 3 is calculated through the drag coefficient  $C_D$ , expressed as a function of lift coefficient  $C_L$ , high lift devices position  $\delta_{HL}$  and landing gear position  $\delta_{LG}$ :

$$C_D = f(C_L, \delta_{HL}, \delta_{LG}) \quad (9)$$

$$D = \frac{1}{2} \cdot C_D \cdot \rho \cdot V_{TAS}^2 \cdot S \quad (10)$$

where  $\rho$  is the local air density and  $S$  is the aerodynamic reference area.

BADA 3 defines the following flight phases: take-off, initial climb, climb, cruise, descent, approach and landing. For each phase a typical aerodynamic configuration in terms of high lift device and landing gear positions is assigned.

Figures 7 and 8 depict drag polars generated using the BADA 3 model for an aircraft at different configurations: Clean configuration is assigned for use in climb, cruise and descent phases, C1 in initial climb, C1F for take-off, C2 in approach and Full for landing.

It is worth noticing that the drag model for clean configuration in BADA 3 does not account for the compressibility effect at high altitudes and speeds. Because of this fact there is only one clean drag polar in BADA 3, applicable for all speeds.

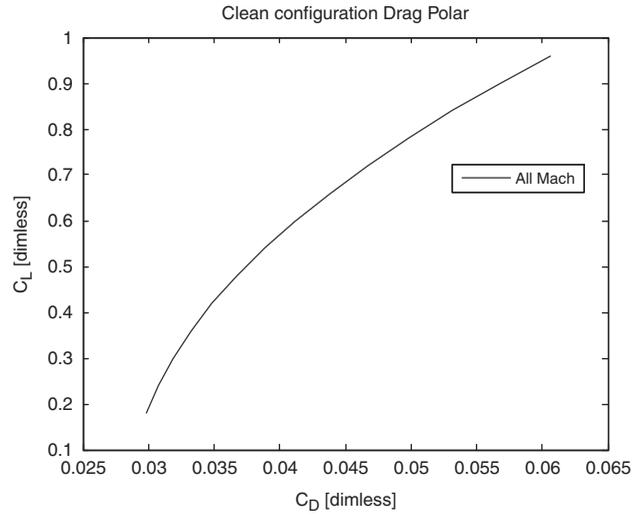


Figure 7. Clean drag polar.

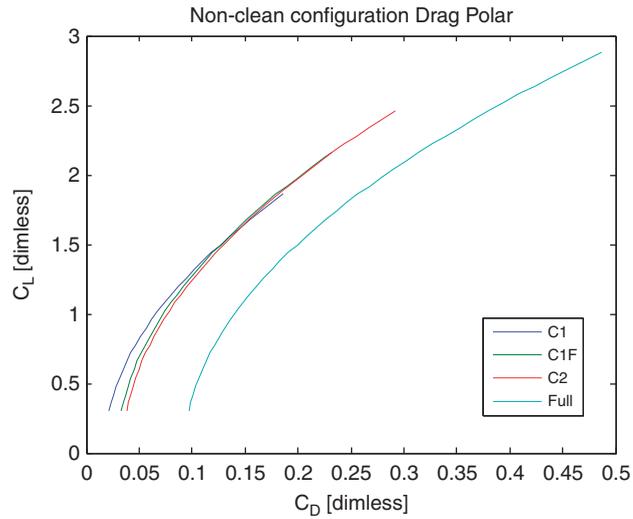


Figure 8. Non-clean drag polar.

Drag in BADA family 4 is calculated through the drag coefficient  $C_D$ , expressed as a function of lift coefficient  $C_L$ , Mach number  $M$ , high lift devices position  $\delta_{HL}$ , landing gear position  $\delta_{LG}$  and speed brakes position  $\delta_{SB}$  as:

$$C_D = f(C_L, M, \delta_{HL}, \delta_{LG}, \delta_{SB}) \quad (11)$$

$$D = \frac{1}{2} \cdot C_D \cdot \kappa \cdot p_0 \cdot \delta \cdot M^2 \cdot S \quad (12)$$

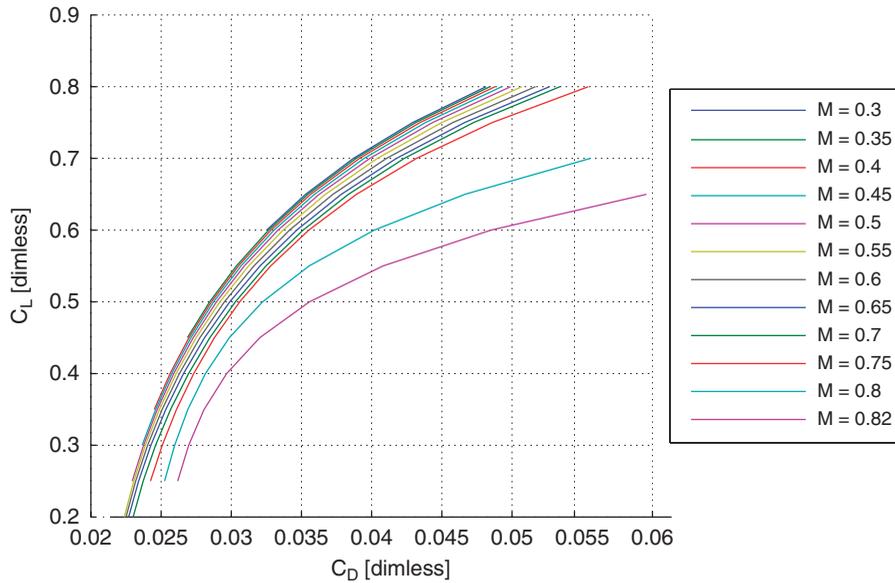


Figure 9. Clean configuration drag polar.

where  $S$  is the reference wing surface area,  $\delta = p/p_0$  is the pressure ratio,  $\kappa$  is the air adiabatic index,  $p$  being the local pressure and  $p_0$  the standard pressure at mean sea level (MSL).

Figure 9 shows the variation of the drag coefficient  $C_D$  with the lift coefficient  $C_L$  for different Mach numbers  $M$  in clean aerodynamic configuration, in agreement with expression (11). The approximately parabolic curves are displaced down and to the right for increasing Mach numbers reflecting the losses caused by the compressibility of the airflow. The figure also reflects that the maximum efficiency (ratio between  $C_L$  and  $C_D$ ) decreases when Mach number increases.

Aerodynamic drag accounts for the drag increase due to deployment of high-lift devices and landing gear. Figure 10 shows the variation of  $C_D$  with  $C_L$  for different high lift devices positions (from 0 to 25 degrees), with the landing gear retracted. Although expression (11) shows a dependency on Mach number, the range of Mach numbers at which the high lift devices can be deployed is too low for it to have any influence in the resulting  $C_D$ . It can be observed that the drag coefficient increases dramatically as the high lift devices are extracted.

**5.1.2. Thrust.** The **thrust** model in BADA family 3 is provided for the calculation of maximum climb (MCMB), maximum cruise and idle descent thrust levels for three different engine types (jet, turboprop and piston).

Jet engine thrust is considered to be independent of speed (considering application of the model in the normal operating speed range) and decreases as altitude increases:

$$T_{\text{MCMB,ISA}} = f(h) \quad (13)$$

Turboprop power is considered as dependent of speed and decreasing as altitude increases. Thrust is obtained by dividing power by speed:

$$T_{\text{MCMB,ISA}} = f(h, v) \quad (14)$$

Piston engine has a similar model as turboprop [2], but thrust is decreasing with altitude and speed.

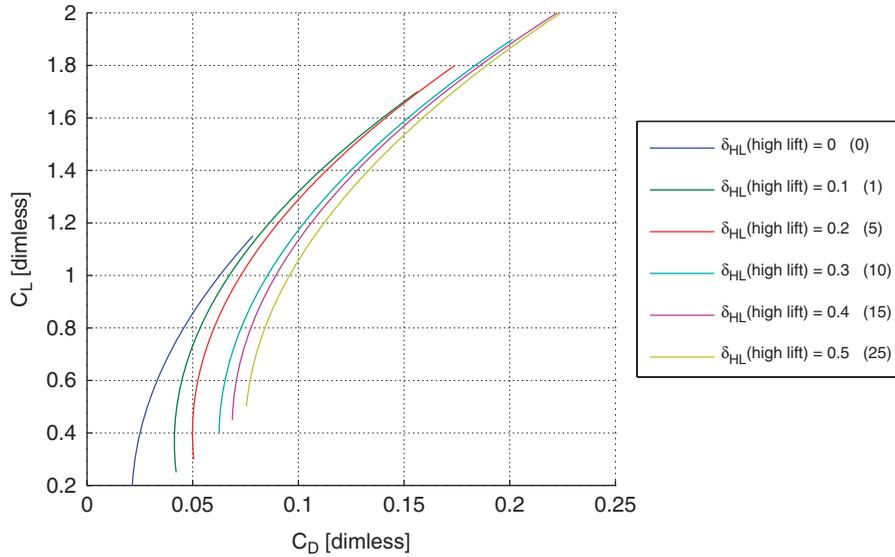


Figure 10. Non clean configuration drag polar.

For all engine types, the maximum climb thrust is corrected for temperature deviations  $\Delta T_{ISA}$  from International Standard Atmosphere (ISA) as:

$$T_{MCMB} = f(T_{MCMB,ISA}, \Delta T_{ISA}) \quad (15)$$

Maximum cruise and descent thrust are then calculated as ratios of maximum climb thrust.

Fuel flow is modelled as a function of thrust and true airspeed:

$$F = f(T, v) \quad (16)$$

Thrust in BADA family 4 is calculated through the new dimensionless thrust coefficient  $C_T$  as:

$$T/\delta = W_{MTOW} C_T \quad (17)$$

where  $W_{MTOW}$  is the maximum takeoff weight and, for idle thrust (IDLE)  $C_T$  has the form:

$$C_T = f(M, \delta) \quad (18)$$

while for maximum takeoff (MTKOF), maximum climb (MCMB) and maximum cruise (MCRZ) engine ratings,<sup>‡</sup>  $C_T$  represents the so-called generalized thrust model, which depends on the Mach number and the throttle parameter  $\delta_T$ :

$$C_T = f(M, \delta_T) \quad (19)$$

<sup>‡</sup>For the sake of simplicity, only the thrust coefficient for jet, turbofan and turboprop engines is presented. In all these cases, the physical dependencies are the same and the concept of engine rating is applicable. This concept is introduced to enhance the accuracy and realism of the propulsion model.

In those cases, separate laws for  $\delta_T$  are provided for the off-ISA atmosphere conditions characterized by  $\Delta T_{ISA}$  below and above the so-called kink point<sup>§</sup>  $T_{BP}$ :

$$\delta_T = f(M, \delta) \quad \text{for } \Delta T_{ISA} < T_{BP} \quad (20)$$

$$\delta_T = f(M, \theta_T) \quad \text{for } \Delta T_{ISA} \geq T_{BP} \quad (21)$$

where  $\theta_T = [1 + M^2(\kappa - 1)/2]\theta$  is the total temperature ratio;  $\theta = T/T_0$  being the temperature ratio,  $T$  the local temperature and  $T_0$  the standard temperature at MSL.

Fuel consumption is calculated through the new dimensionless fuel coefficient  $C_F$  as:

$$F = L_{HV}^{-1} W_{MTOW} a_0 \delta \theta^{1/2} C_F \quad (22)$$

$$C_F = f(M, C_T) \quad (23)$$

where  $a_0$  is the sound speed at MSL and  $L_{HV}$  is the lower heating value.

## 5.2. Operations

The ability to support accurately different ways of operating the aircraft is limited in BADA 3 by the accuracy levels of the underlying action model. As such, the BADA family 3 is best suited to support simulation of flight regimes where any two of three variables of thrust, speed or vertical speed can be controlled, while the third one is calculated.

Figures 11–13 provide an example of a trajectory calculated using the BADA 3 model and a predefined set of trajectory segments described below:

1. Constant CAS (160 kt), MCMB thrust, takeoff configuration until Hp=3000 ft (climb)
2. Acceleration in climb, MCMB thrust, clean configuration until CAS=250 kt
3. Constant CAS (250 kt), MCMB thrust, clean configuration until Hp=10 000 ft (climb)
4. Acceleration in climb, MCMB thrust, clean configuration until CAS=290 kt
5. Constant CAS (290 kt), MCMB thrust, clean configuration until Hp=(transition altitude to M0.74) (climb)
6. Constant Mach (0.74), MCMB thrust, clean configuration until Hp=32 000 ft (climb)
7. Constant ROC (3000 fpm), MCMB thrust, clean configuration until Hp=35 000 ft (decelerated climb: speed decreases)
8. Constant Hp (35 000 ft), MCMB thrust, clean configuration until Mach 0.8 kt (acceleration)
9. Constant Hp (35 000 ft), constant Mach (0.8), clean configuration for 300s (cruise)
10. Constant ROD (1500 fpm), constant Mach (0.8), clean configuration until Hp=29 000 ft (change cruise altitude)
11. Constant Hp (29 000 ft), constant Mach (0.8), clean configuration for 300s (cruise)
12. Constant CAS (300 kt), LIDL thrust, clean configuration until Hp=19 000 ft (descent)
13. Constant Hp (19 000 ft), LIDL thrust, clean configuration until CAS=250 kt (deceleration)
14. Constant path angle (3°), LIDL thrust, approach configuration until Hp=3000 ft (descent).

Based on the improved accuracy of its actions model, the **BADA family 4** provides an operations model with enlarged flexibility in supporting different ways of operating the aircraft. The BADA 4 operations model captures the intrinsic aircraft behavioural characteristics needed to compute manoeuvres such as configuration changes like

<sup>§</sup>Kink point is the design temperature at which the engine throttle starts to be limited by temperature. In almost all modern jet engines, it is ISA+10.

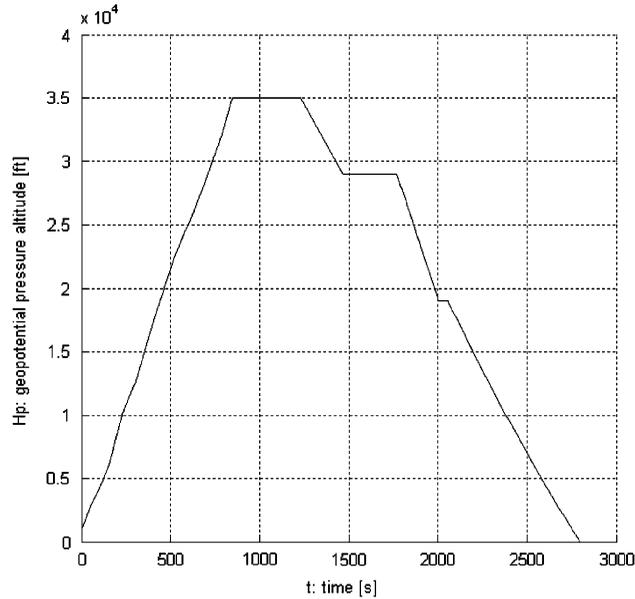


Figure 11. Geopotential pressure altitude as a function of time.

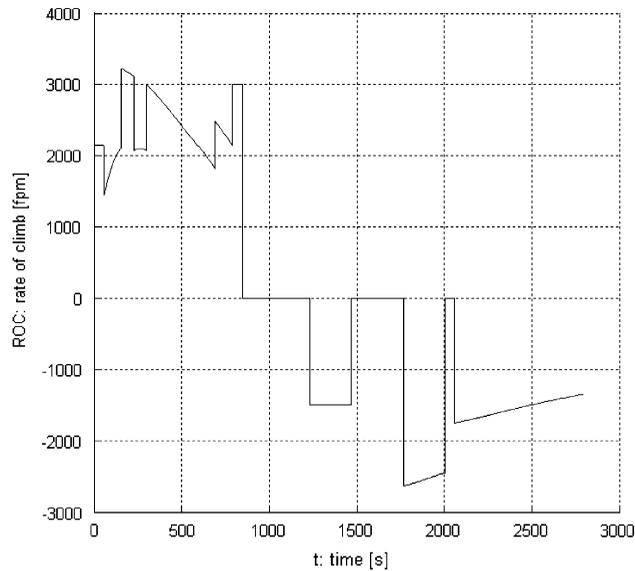


Figure 12. Rate of climb/descent as a function of time.

the deployment/retraction of high-lift devices. BADA 4 also includes an analysis of complex instructions that pursue specific objectives (such as maximum range cruise (MRC), economy cruise (ECON), maximum rate of climb (MROC), economy climb (ECONCMB), among others) to obtain the equations in which they derive.

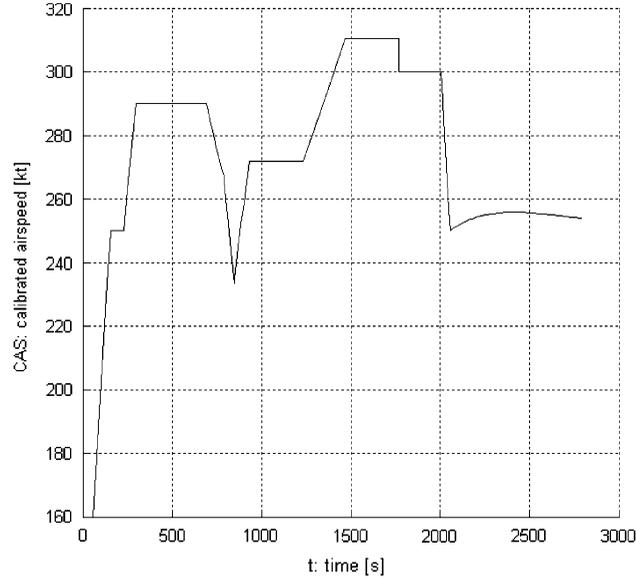


Figure 13. Calibrated airspeed as a function of time.

As an example, the economy cruise operation is defined by the flight costs minimization, and results in two equations that provide the optimum altitude and Mach as a function of the aircraft weight.

$$M_{\text{ECON}} = f(W) \quad (24)$$

$$\delta_{\text{ECON}} = f(W) \quad (25)$$

These two laws determine the aircraft motion in the vertical plane, and result in a flight that minimizes the flight costs; they depend on the cost index, which is the ratio between the airline time and fuel costs for that specific flight.

Another example of the capabilities of the BADA 4 is depicted in Figure 14<sup>¶</sup> which combines several different plots on top of drag coefficient  $C_D$  versus Mach number  $M$ . The background is formed by several thin lines at different weight coefficients  $C_W$  that constitute the basic figures of cruise flight, which result in the only Mach number for which an aircraft of given weight can fly in cruise conditions (load factor unity) at a given pressure altitude.

Five differently coloured thick lines are also printed. They show: maximum endurance cruise (MEC) Mach number in function of  $C_W$ ; maximum range cruise (MRC) Mach number as a function of  $C_W$  for zero wind; economy cruise (ECON) mach number as a function of  $C_W$  for zero wind at three different cost index coefficients  $C_{ci}$ .

### 5.3. Accuracy levels

Most of the aircraft types modelled in BADA family 3 demonstrate a mean RMS error in vertical speed lower than 100 fpm over the normal operations part of the flight envelope.<sup>||</sup> Fuel consumption is modelled with mean error lower than 5% for the same conditions.

<sup>¶</sup>See the graph legend for description of lines.

<sup>||</sup>This corresponds to mean error of vertical speed lower than 5% for operational range of flight envelope under assumption that 2000 fpm is an average vertical speed value.

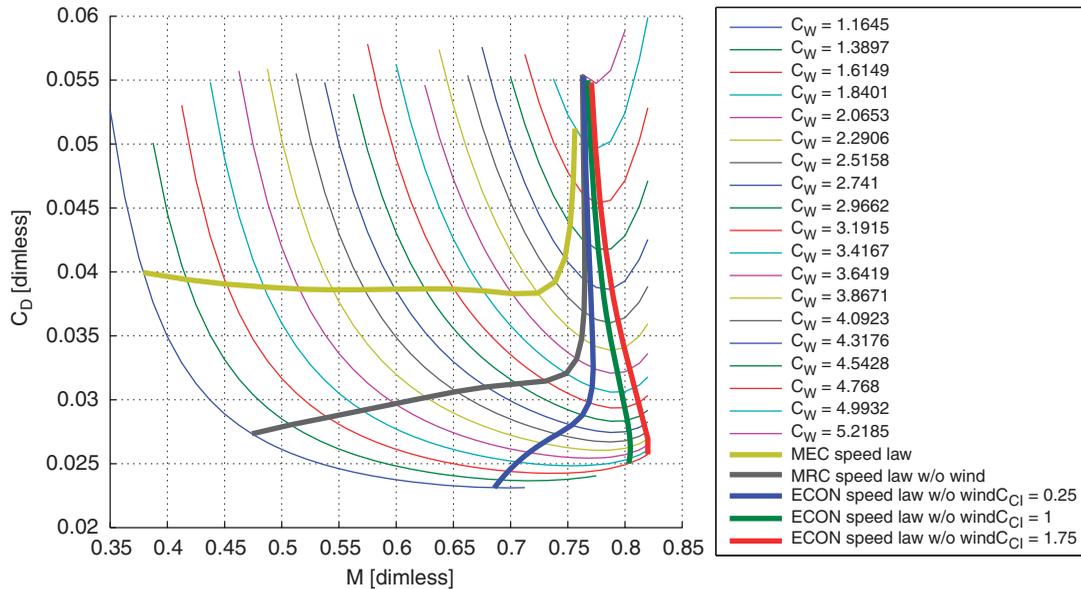


Figure 14. Optimum cruise speed laws over basic figures of cruise flight.

BADA family 4 provides similar accuracy levels, but for the entire aircraft operational flight envelope. For 25 aircraft tested so far, over the complete operations envelope, the mean RMS error in vertical speed is lower than 70 fpm. Mean error of fuel consumption is lower than 5% for the same conditions.

## 6. APPLICATION OF BADA

The information provided in BADA is designed for use in aircraft trajectory simulation and prediction. As such, BADA is a fundamental enabler for:

- trajectory simulation in the air traffic modelling and simulation tools
- trajectory prediction in the ground-based operational ATM systems.

Air traffic modelling and simulation tools are used to support development, validation and assessment of new ATM concepts, ATC procedures, advanced controller decision support tools and equipment before they are introduced into operational service. These tools can be grouped into three broad categories: mathematical models, fast time and real-time simulation platforms. They are used to obtain performance measurements (safety, capacity, efficiency, environmental impact) and human acceptability of the system under investigation.

One representative example of real-time simulation tools is the EUROCONTROL Simulation Capability and Platform for Experimentation (ESCAPE). ESCAPE is a large-scale ATM simulation system which provides a platform for real-time human in the loop simulations and trials. It is unique in a sense that it is based on components from ATM industry. The ESCAPE platform is intensively used for airspace validation simulations performed not only at the EUROCONTROL but also at other European research institutions (i.e. ENAV, AENA). ESCAPE is used for *ab initio* training by the EUROCONTROL Upper Area Centre in Maastricht (MUAC), the EUROCONTROL Institute for Air Navigation Services in Luxembourg (IANS) and the Portuguese Air Force.

An example of modelling tools that uses BADA is AEM (Advanced Emission Model). The AEM is used to estimate aviation emissions and aircraft fuel burn. It can be used to study emissions around airports as well as estimation of global emissions taking into account large geographical coverage and large size of air traffic.

Trajectory prediction tools used within the ground-based Flight Data Processing Systems provide means for modelling and strategic planning of traffic flows; a better planning of aircraft flows can reduce delays, operating costs and minimizing adverse environmental impact. BADA is widely employed by the ATM systems supply industry—companies such as Thales, Indra and Barco are building their new operational systems using BADA for trajectory prediction.

## 7. ACCESS TO BADA

Although detailed data on aircraft performance are confidential and commercially sensitive, BADA transforms it such that aircraft models can be made available to a wide audience. The use of BADA is not limited to EUROCONTROL.

The BADA family 3 model is provided to the ATM community worldwide and is used by R&D organizations, academic institutions, ANSP's and ATM support industry. Its use is free of charge, but regulated through a licence agreement that safeguards the interests of the aircraft manufacturers who are the principal aircraft performance reference data providers for BADA.

All new BADA 3 requestors are invited and guided to fill and submit the on-line registration form at the following address: <http://badaext.eurocontrol.fr/licence37/licence.php>.

The BADA 4 has not yet been deployed to the ATM community. The negotiations with aircraft manufacturers are currently on-going to define the terms and conditions for use of BADA outside of EUROCONTROL.

## 8. CLOSING REMARKS

This paper gives an overview of the BADA model by providing details on the existing BADA family 3 and insight into the latest achievements in the development of the BADA family 4 model. The BADA model is used worldwide and has become a de facto standard for aircraft performance modelling.

The current version of BADA family 3 (3.7) provides 103 aircraft type models developed from original aircraft data and referred to as original models. Another 191 aircraft types may be simulated by using an equivalent to an original BADA model. BADA model family 3 has demonstrated its ability to accurately model aircraft performances for aircraft normal operating conditions.

Research work in aircraft performance modelling demonstrated that enhancements of the BADA aircraft performance model are possible by exploiting today's aircraft performance resources, data and software that were not available in the past, when the BADA was initially developed.

This resulted in the development of the BADA 4 model, whose enhanced models for drag, thrust and fuel ensure significant improvements in modelling of the vertical speed and fuel flow over the entire aircraft flight envelope. The more realistic and accurate modelling of forces and fuel will enable the computation of new flight regimes such as climb at maximum climb capability or minimum fuel, that are untreatable with the current BADA 3 model.

EUROCONTROL shall continue to maintain the BADA 3 in the future with objective to continuously improve in terms of number and quality of aircraft models. BADA 4 developments will go on in parallel. Preliminary implementation activities for the BADA 4 aircraft models are currently undertaken. The results of this work will serve as an input in the preparation for BADA 4 deployment with the deployment strategy to be defined by the end of 2010.

## BADA: AN ADVANCED AIRCRAFT PERFORMANCE MODEL

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