

Simulation tool for an air traffic control system

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The aim of this project is to develop a system for air traffic simulation that is suitable for carrying out air navigation studies. From a research viewpoint, it can be used to create traffics and simulate their trajectories based on total energy models, as a tool for the construction and validation of flight procedures, and for the detection and study of possible conflicts between traffics in the different phases of a flight and in the vicinity of the aerodromes. From an educational point of view, it serves to create a virtual laboratory for air traffic control, with air traffic controllers and pseudo-pilot positions, in order to enable aerospace engineering students learn how air traffic management is conducted in its last phase - air traffic control.

This simulator uses a flight energy model approved by EUROCONTROL, designed for use in air traffic management studies. It allows the simulation of individual traffics as well as scenarios formed by several traffics flying simultaneously. The pseudo-pilot control window has been specially designed to ease the understanding of the actions of the aircraft to the user and to allow a quick response, by separating the horizontal and vertical flight modes.

Nomenclature

Thr	– thrust that acts parallel to the speed vector of the aircraft	[N]
D	– aerodynamic drag	[N]
m	– aircraft mass	[kg]
h	– geodetic altitude	[m]
g_0	– gravitational acceleration	[m/s ²]
V_{TAS}	– aircraft true airspeed	[m/s]
$\frac{d}{dt}$	– time derivative	[s ⁻¹]

1. Introduction

The air traffic control, known by the acronym ATC, is the last phase of Air Traffic Management, preceded by the phases of Airspace Management (ASM) and Air Traffic Flow and Capacity Management (ATFCM). It takes place from less than an hour before flight to the moment of the flight operation. The fundamental objective of the air traffic controllers is to anticipate the future position of the aircrafts, detect possible conflicts and maintain the minimum separation between them. The objective of this project is to create a tool that will simulate scenarios of different complexity for air traffic control.

This tool must allow the user to create air traffics and interact with them easily and quickly. In turn, simulated traffics must follow a dynamic flight model that is reliable and valid for air traffic management studies. A secondary requirement is to make the system scalable, allowing the simulation of one to many traffics simultaneously. Formerly this approach has been tackled by the use of flight simulators in an interactive environment. The underlying problem is that the complexity of a flight simulator makes it difficult to have a large number of aircrafts in the same airspace. For this reason, an intuitive user interface is needed.

The programming language chosen for the development of this project is Java, due to its portability and cross-platform capabilities across all operating systems including Linux, Windows and Mac OS.

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2. Simulator fundamentals

The flight simulator has been implemented according to the user manual of the "Base of Aircraft Data" (BADA) Revision 3.9 of EUROCONTROL. This database consists of a set of ASCII files with performance and operating coefficients for 338 different types of aircraft. The coefficients include those used to calculate thrust, resistance, fuel consumption and those to specify the nominal speeds of climb, cruise and descent.

The user manual provides a definition for each coefficient and the formulas for obtaining the different speeds. The latest revision of BADA Family 3, named 3.13, was published by the EUROCONTROL Experimental Center in 2015. In the previous version there have only been changes in the remodeling of some aircraft and the incorporation of new models and new aircrafts to the thesaurus document. Therefore, the basis of the operation of the simulator will not be affected if at any time the BADA database version gets updated.

A. Energy model

BADA total energy model equates the work rate produced by the forces acting on the airplane at the rate of increase of the potential and kinetic energies. This model is presented in the form of a single equation, which is the following:

$$(Thr - D) \cdot V_{TAS} = mg_0 \frac{dh}{dt} + mV_{TAS} \frac{dV_{TAS}}{dt}$$

Equation 2.1. BADA energy model.

In this equation we have three variables: thrust, true speed and vertical speed. The input or control variables are two: the throttle and the elevator.

With two variables being controlled, there is a third unknown variable to determine. There are three possible combinations:

- ◆ True speed and throttle controlled. Equation 2.1 is used to calculate the rate of climb or descent (ROCD).
- ◆ Vertical speed and throttle controlled. Equation 2.1 is used to determine the true speed of the aircraft.
- ◆ True and vertical speeds controlled. The necessary thrust to maintain the speeds is calculated by means of Equation 2.1

The main phases of the flight of an aircraft are: climb, cruise and descent. In the climb phase, the true speed, either the CAS or the Mach, remain constant (except in acceleration periods), as well as the thrust, which is fixed, so the combination of variables used will be the first proposed. During the cruise or en-route phase, the true speed is constant, and the vertical speed is zero, therefore thrust can be directly calculated from the third option of combinations. Finally, in the descent phase, the same happens as in the climb phase, the true speed and the thrust (IDLE) remain constant, so the rate of descent can be determined, in the stepped type of descent. In a continuous descent (DCM) the true speed and the slope will be fixed, the latter is defined by the cost index selected for the operation.

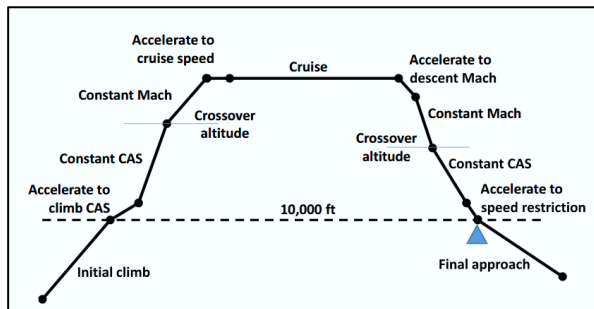


Figure 1. Vertical profile concept

The true speed is set according to BADA Airline Procedure Model, which determines the CAS or Mach speed, based on the speeds defined in the Airline Procedure File, the stall speeds for takeoff and landing, some global coefficients for all the aircraft contained in the "BADA.GPF" file, and the altitude at which the aircraft is located. However, in the cruise phase the true speed is obtained from a cost index introduced for the operation by the user in the flight plan, and thus, the program determines which Mach or CAS number the aircraft should fly at. To vary both the true speed of traffic and the vertical speed or rate of ascent / descent, the maximum accelerations established by BADA for civil aircraft are applied.

The BADA propulsive model to obtain the thrust has been implemented for both aircraft with jet and turboprop engines.

In addition, this energy model requires an atmospheric model, to obtain pressure, temperature, density and speed of sound values based on the altitude at which the traffic is located, for the calculation of its performance (thrust, fuel consumption, aerodynamic coefficients, ...) and CAS / TAS / Mach speed conversions. The model used by the simulator is based on the International Standard Atmosphere (ISA).

B. Flight phases

All traffics are located at the threshold of its departure runway at the start of the program. In all takeoffs performed by the simulator, the balanced field takeoff is applied. BADA provides the FAR Take-Off Length (TOL) or balanced field length, which is the one where the take-off distance is equal to the acceleration-stop distance, regardless of the actual length of the runway on which the aircraft will take off. It only depends on the characteristics of the airplane, its

configuration, weight, and atmospheric circumstances, such as pressure, atmospheric temperature and air density. This distance defines the minimum length of a runway where aircraft can take off with balanced field length condition. It must be taken into account that the length of the runway where the take-off is performed must be greater than the TOL distance, if the simulation is to be adjusted to reality. The additional hypothesis of rotation occurs instantaneously is applied, so $V_R = V_{LiftOff}$. This speed will be equal to the first speed of the BADA Airline Procedure Model.

Then, for each of the following flight phases, the model which each traffic with the vertical navigation system (VNAV) follows is defined. After takeoff, traffic starts the climb phase. The rate of climb or ROC is calculated through the energy model of BADA for all segments of this phase, as mentioned in section A. The aerodromes of the Madrid and Barcelona FIRs also have Standard Instrument Departures. To do this, a configuration file has been created with the information of the restrictions that exist in each point of the SID provided by ENAIRE (air navigation manager in Spain). In addition, the file also contains the minimum slope of climb and the initial altitude to maintain during the SID, if the traffic does not receive another indication by an ATC controller. Traffic must comply with all these restrictions, using the BADA energy model at all times.

Once the cruise flight level has been reached, the Top of climb, the cruise phase begins. In this phase, as mentioned in the previous section, it is necessary to obtain the thrust of the BADA energy model. The hypothesis that the plane is flying at a constant altitude is applied, so the slope and vertical velocity are zero. The speed or Mach number of the aircraft at cruise is calculated on the basis of the cost index selected by the user in the flight plan. This will provide a TAS between the maximum range speed (MRC), which will depend on the instantaneous weight of the aircraft, and the maximum operating speed, or maximum operating Mach, if the transition altitude has been reached. The true cruising speed is constantly recalculated during this phase depending on the weight of the aircraft, which varies due to fuel consumption. This weight variation is so gradual that the cruise flight can be treated with a quasistationary condition at all times. In addition, the lift coefficient remains constant. These hypotheses correspond, according to the flight mechanics, to the second cruise flight program (PVC2), which is based on velocity profiles based on mass. On the other hand, it must be taken into account that the propulsive limitations of the engine cannot be exceeded, that is, the maximum thrust available, and this can only be achieved by limiting the true speed.

To define the point at which the aircraft will begin to descend, the Top of descent of the route defined in the flight plan has been calculated. To do this, first, a descent slope is defined, which is obtained from the cost index², measured in percentage to generalize across all aircrafts, entered by the user in the flight plan. The limits of the slope are maximum aerodynamic efficiency and maximum operating speed. Three types of descent have been included. The first of them is the continuous descent, with the true speed of BADA and the descent slope obtained from the cost index, the vertical velocity is obtained. To comply with the energy model, since TAS and VS are fixed, it is only necessary to adjust the thrust. The second type of descent is stepping descent, in which the thrust is the IDLE thrust provided by BADA, and the true speed of the aircraft is obtained from the model of the BADA airline. Therefore, it is only necessary to determine the descent rate of the BADA energy model. The third type of descent is experimental, it consists of a combination of the two previous ones, the selected thrust is the IDLE thrust of BADA but the descent slope is a constant slope that adjusts to the altitude restriction of the next waypoint or point of the arrival. In a manner analogous to the climb phase, the Standard Arrival Route for the Madrid and Barcelona FIRs are included with the altitude restrictions obtained from the ENAIRE STAR charts.

In addition, for several Spanish aerodromes the instrumental approach procedures have been included through the IAC charts of the ENAIRE AIP, through a configuration file with the coordinates of the IAF, IF and the FAP (for precision instrumental procedures). From the FAP, it will descend with a constant slope of 3°, γ_{GS} or slope of the glide path. Through this slope and the TAS obtained for the altitude of the aircraft through the Airline Procedure Model, the vertical velocity is obtained for the final segment of the approach. After overflying the FAP, the traffic will continue to descend with a slope of three degrees until reaching the decision altitude / height. At that point, the pilot decides whether he/she will land, depending on his/her visual references of the runway, or whether he/she should continue with the "Go-around" procedure. In the case of this simulator, traffic continues to decrease maintaining the slope of three degrees until reaching 50 ft, where the landing maneuver begins. In the case that for the selected runway of the arrival airport has not included an approach procedure, traffic will perform the following procedure. First of all, the traffic will fly towards the fixed point that is at the intersection of the radius of 10 NM with center at the threshold of the runway and the prolongation of the runway axis. Then, it will fly directly to a fictitious FAP, which is at the intersection of the 5 NM radius arch with center in the threshold, and the extension of the runway axis, at an altitude of 1600 ft. From this point, the maneuver for the final approach section is the same as in the case of having followed an IAC.

Finally, for the landing phase, BADA provides the FAR Landing Length (LDL) which is the distance from a height of 50 ft until the aircraft lands and comes to a complete stop, increased by 67% by the FAA regulatory factor, for a dry runway. The landing distance in the simulator is calculated from the LDL distance, discounting the proportion corresponding to the regulatory factor.

² Fuel Conservation Strategies: cost index explained by Bill Roberson, Senior Safety Pilot, Flight Operations.

In addition to the VNAV mode, the simulator has two other vertical modes. One of them is the "HOLD" mode, which consists of maintaining the altitude in any phase of flight. For this the rate of ascent / descent is gradually decremented until it is null and the CAS speed or Mach at which the traffic flies is maintained. It is necessary to adjust the thrust using the energy model. Finally, the Vertical Speed or V / S mode allows the user to enter a vertical speed, different from that provided by the VNAV mode, which the traffic will maintain until reaching the flight level entered for this mode. Once again it is necessary to obtain the thrust through the energy model. The selected vertical speed will be limited by the maximum available thrust of BADA depending on the flight phase.

The autopilot also incorporates a lateral navigation system (LNAV), in which the route followed by a certain traffic is formed by the fixed points of the Standard Instrument Departure that follows, the route points of the route defined in the flight plan, the fixed points of the Standard Arrival Route, and the intermediate fixed and the final approach point. When one of them is reached, the course that the aircraft must take to reach the next one is calculated. All the way to the next point or fixed, the aircraft recalculates the course. The bearings are orthodromic, although the aircraft will maintain this constant bearing for a period of time, resulting in a quasi-orthodromic route. Nominal roll rates and roll angles are defined by BADA. It has been assumed that all the waypoints in the route will be of the fly-by type, that is, the overflight of these is not obligatory, so the beginning of the turn is anticipated to get the aircraft to go to the next waypoint with the orthodromic course, that is, by going through a maximum circle between them. To calculate the distance of the beginning of the turn, Part III - Section 2, Chapter 1, of Doc. 8168 "Aircraft Operations" Vol. II of ICAO was used.

In addition to the horizontal and vertical modes, a Throttle mode is included, called VCAS, in which the user sets the CAS to which the traffic wants to fly, and from this the true speed is obtained, instead of using the one fixed according to the cost index and weight, in the cruise phase, or that obtained from the Airline Procedure Model, in the climb and descent phases. In this way, the thrust will adjust to the new true speed. The activation of this feature is compatible with all flight modes of the simulator, since only the source of the true speed is modified, so in all cases the model of the energy of BADA will continue to be fulfilled. For fuel consumption, a fuel flow is calculated based on the flight phase, with the model of the BADA user manual.

For each flight phase, regardless of the active modes, a specific aerodynamic configuration is used. For each of them, the OPF file of BADA provides the stall speed provided by the aircraft manufacturer and the polar coefficients, CD0 and CD2 (assumed to be a parabolic polar of constant coefficients). Each of these configurations, in turn, receives a name, which indicates the position of the flaps and slats.

3. Running the simulator

A. About the application

ATSim is a Java based desktop application, which allows to simulate air traffics, enabling in turn the creation and execution of scenarios with several traffics. The trajectory of these traffics complies at all times with the energy model of the BADA project of EUROCONTROL.

The simulator interface includes a situational map for each traffic. Even so, this tool has been designed to be compatible with the EuroScope air traffic control client software (figure 2), which, in addition to displaying all the traffic in a given ATC sector, allows performing control functions depending on the control unit that is selected.

To run the application, it is only necessary to have the Java Runtime Environment (JRE) package previously installed and updated to its latest version in order to avoid compatibility problems with the application. This package is available for Linux, Mac and Windows operating systems.

B. Traffic simulations

When initiating a simulation session, the user has the possibility to create a new traffic or to load a scenario with a set of previously created traffics, as when the user wants to reproduce a specific conflicting situation. This section will focus on the first case and the next on the second.

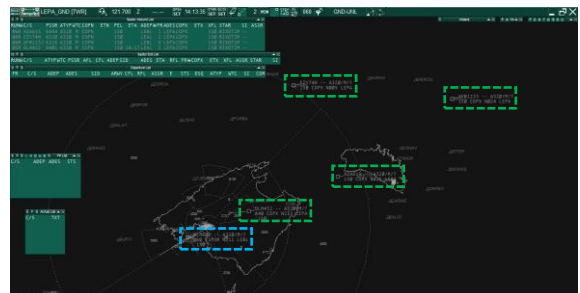


Figure 2. Compatible simulation with EuroScope.

The user will then fill in a connection form, with a callsign, a usercode and a password. Next, the simulation mode will be selected from three different possibilities: the regular mode, in which the traffic will be connected at the threshold of the runway of the selected airport of departure; the "free position" mode, in which the user will choose the starting position of the simulation, in addition to the initial speed at which the traffic flies; and finally, an external simulator mode, in which the system will use data extracted from a flight simulator (X-Plane), instead of the pseudo-pilot contained in the program. Once the simulation mode has been selected, the user must fill in the flight plan form. It has the ICAO format and is similar to the ICARO system of ENAIRE (Figure 3).

Finally, the departure and arrival runways of origin and destination airports which had been chosen in the flight plan are selected. After these simple steps, the traffic will appear connected in the main menu of the program (Figure 4).

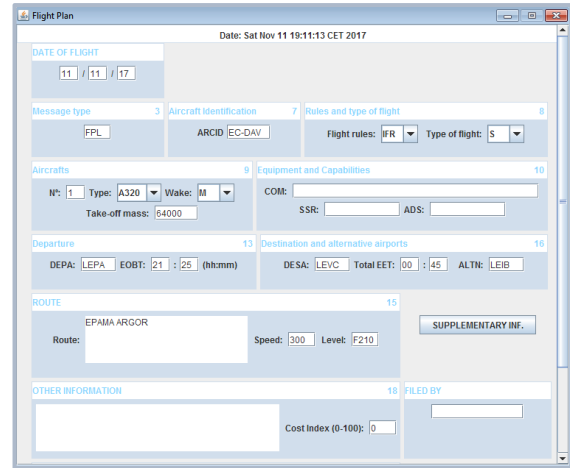


Figure 3. Flight plan form window.

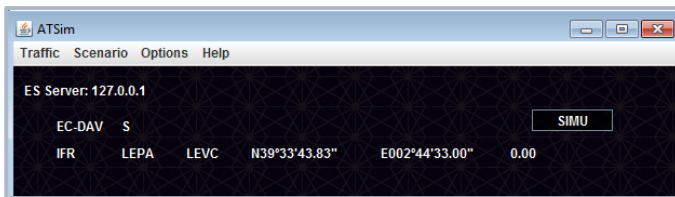


Figure 4. Main menu – traffic viewer.

If the SIMU button is pressed, the pseudopilot window of the corresponding traffic will be opened (figure 5) to the right of the traffic (not available in the X-Plane simulation mode). In the upper part of this, the situational map appears with the traffic located at the threshold of the runway of the departure airport and the route that has been defined by the user in the flight plan.

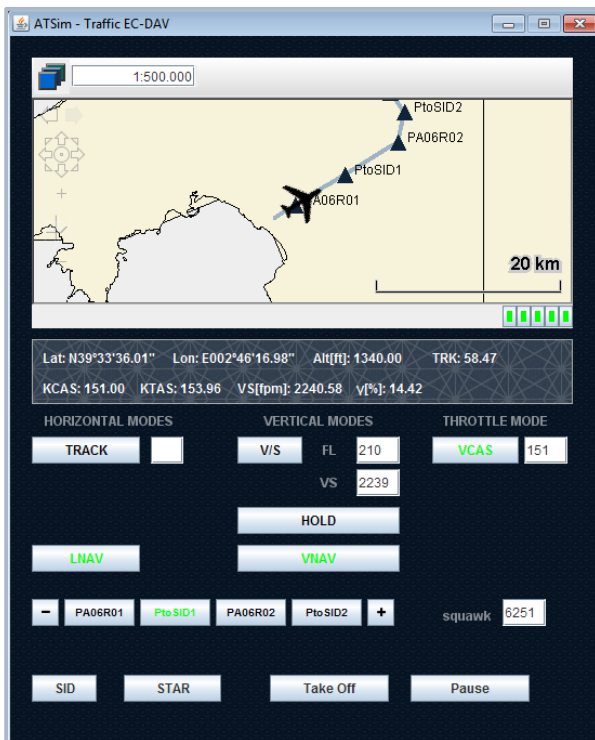


Figure 5. Pseudo-pilot window.

Below, are the controls of the simulator, grouped in three columns. The first one refers to the lateral navigation modes. These are, LNAV, in which the traffic will follow the route of the flight plan, and TRK, which allows to select the bearing of the traffic manually. The second column allows you to control the vertical profile of traffic. The VNAV mode will follow the calibrated speed profile and vertical speed of BADA, depending on the selected aircraft and takeoff mass. The HOLD mode allows you to maintain a certain altitude. And, the Vertical Speed mode, V / S, allows to enter a different vertical speed until reaching a selected flight level. The altitude limitation is always controlled by the user which, by default corresponds to limitations of the SID, or in its absence, to the cruise flight level. The third column contains the Throttle VCAS mode, in which the simulator controls the thrust of the traffic according to the calibrated speed selected by the user. This mode is compatible in turn with any lateral and vertical modes that are activated.

At the bottom of the window, in addition to the takeoff and pause / resume buttons, are the selection buttons for the Standard Instrument Departures and the Standard Arrival Routes, which allow modifying the SID and STAR assigned by the simulator by default depending on the first and last waypoint of the flight plan route. In the case of the STAR, it also allows selecting the descent mode, among those explained in section 2. Simulator fundamentals.

From the moment of connection of each traffic, its position (geodetic coordinates), course, speeds (CAS, TAS and VS), pending, configuration and time since the beginning of the connection are stored, in a file automatically saved in a subfolder of the program, which makes possible the post-processing of the trajectory.

C. Scenarios

Simulation through scenario loading is a quick and simple way to simulate air traffic situations. It is only necessary to create the scenario file, save it in the "Scenarios" folder of the program and select it after starting the program. Each file, with extension ".sf", must contain connection information, flight plan, and position, speed and initial instant. In addition, it is possible to execute several scenario files simultaneously in the same simulation session.

These scenarios are also defined in a way that is compatible with the EuroScope program, which will serve to create air traffic control sessions, both for teaching use and for training in air traffic control techniques.

The control of the traffic inside scenarios is exactly the same as in the simulation of individual traffic, through the pseudopilot interface.

4. Conclusions and future work

This project has allowed the creation of a new ATC simulation virtual laboratory in the Pedro Duque Laboratory of the School of Design Engineering of the Universitat Politècnica de València, which can be used by students and teachers in Aerospace Engineering Degree. This laboratory will have many pseudo-pilots, who through the interface developed will be able to respond quickly to the orders of the ATC controllers, thus allowing to create large simulations of air traffic control.

Although the initial objective of the project was focused on creating complex simulation scenarios, the possibility of executing individual simulations has been included, since its trajectory can be analyzed later, through the automatic saving of its trace.

In the field of research, this project has allowed to validate new designs and proposals of procedures, as well as to study and analyze situations of conflict between traffics.

It also opens a line of work that will continue during subsequent courses. Among the extensions of this project, one of them is to automate the updating of data sources of airports, waypoints, SID / STARs, nav aids, instrumental approaches, based on aeronautical databases, such as the European AIS Database (EAD) of EUROCONTROL, which consists of a single and centralized repository of aeronautical information. These data are: NOTAMS, all the aeronautical information published in the AIP (aerodrome information, including procedures and obstacles, information on routes, airspaces, nav aids and waypoints, and general information such as Organization and Authorities), as well as amendments, supplements, AIC and aeronautical charts.

In addition, the reproduction of historical traffic trajectories filtered by date could also be integrated into the program, from the EUROCONTROL DDR2 database. This will make it possible to simulate concrete situations between aircrafts, which would allow to study and analyze situations of possible conflicts.

Another possible improvement would be the incorporation in the simulator of new models of aircraft and remotely piloted aircraft systems (RPAS).

Finally, the simulator could be extended for a possible future study on the automatic management of ATC authorizations through Data Link communications, with the simulation of the automation of air controllers' orders.

5. References

For the development and implementation of this project, the following bibliography has been used:

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