EVALUATING THE LOCAL ENVIRONMENTAL IMPACT OF AIR TRAFFIC WITH IESTA: OUTPUTS AND VALIDATION WALKTHROUGH

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Abstract

IESTA (Air Transport Systems Evaluation Infrastructure) is a global evaluation facility for air transport systems that is currently being developed by Onera in Toulouse, France. The project aims at building a generic simulation platform, designed to ease the integration of new or existing models in order to assess air transport concepts. The first IESTA application, Clean Airport, allows for the assessment of the effects of innovative concepts with regard to air traffic noise and chemical pollution on the airports' surroundings. An effective simulation capability has been built and achieved by integrating Onera expertise in physical modelling. This paper overviews the resulting model toolbox architecture, the first outputs and the validation walkthrough.

1 The IESTA/Clean Airport platform

1.1 Overview

The worldwide air transport system is confronted with unprecedented environmental constraints, including energy crises. As new technologies and operational concepts are developed, a systems engineering approach is imperative to evaluate candidate solutions accurately prior to their implementation. The complexity of the air transport system makes it necessary to perform conceptual trade-off evaluations covering many criteria and metrics. While a myriad of simulation tools exist, the vast majority is designed for standalone operation and to meet specific needs.

IESTA aims at developing a generic simulation infrastructure [1] and an extensible toolbox of models [2], [3] in order to provide the aeronautical community with advances in modelling and simulation tools through a global evaluation facility. The model toolbox capability is built incrementally by improving existing models as well as developing new ones, thus providing an incentive for Onera and research partners investment into the platform.

IESTA consists of a fast-time simulation framework embedding a toolbox of compatible models to conduct high-fidelity assessments of concepts and technologies. The scope of the first application of IESTA, named Clean Airport, is the evaluation of the relative environmental impact of air traffic around airports.

1.2 Integrated modules

The IESTA/Clean Airport platform integrates (**Fig. 1**) previously existing Onera modules as well as some developed on purpose:

- a weather service
- a ground planning module to compute separated itineraries on the airport surface
- air and ground Aircraft modules to compute trajectories
- an aircraft Engine module to compute en-

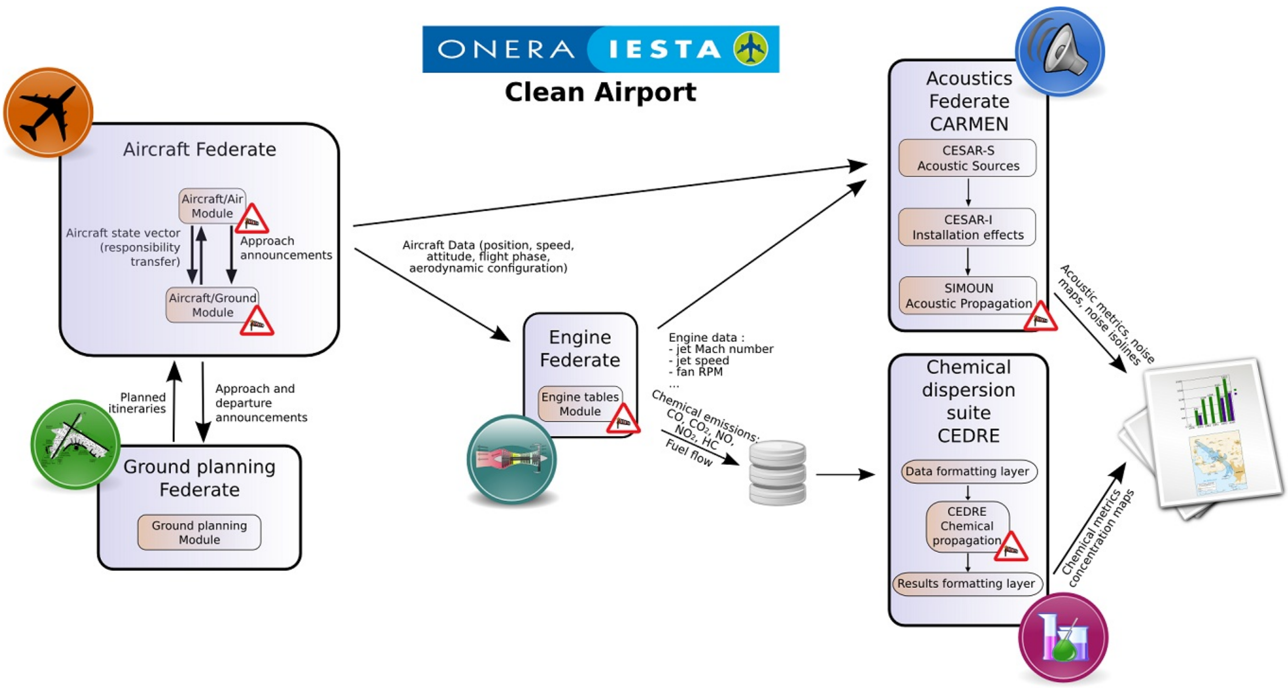

Fig. 1 Modules integrated into IESTA/Clean Airport

gine data such as fuel consumption, gas emissions, etc.

- *CARMEN* [3], an acoustic ray tracing software suite embedding:
  - the simulation of the aircraft noise sources (jet, fan, high-lift devices and landing gear)
  - the computation of the direct field and the installation effects, i.e. diffraction and reflection
  - the computation of the atmospheric propagation of acoustic rays
- *CEDRE* [3], a Computational Fluid Dynamics (CFD) code able to simulate turbulent combustion and multi-physics phenomena, which has been adapted for the large-scale chemical dispersion computations

IESTA modules can be launched in a standalone mode, with the adequate input data and also as part of the complete chain. Inputs are then either data retrieved from the scenario or the technological databases, or outputs from other modules.

In an IESTA/Clean Airport experimentation, the usual scheme is the following: the acoustic emission and propagation patterns, the engine thermodynamics tables and the airport circulation graph are computed off the simulation. Then, these permanent inputs and the specific scenario data (flight plan, weather, airport and aircraft characteristics, etc.) are used by the modules involved in the time-based simulation to compute the aircraft trajectories on the ground and in flight, the state of the engines including chemical emissions and the instantaneous noise levels. Finally, in a post-simulation phase, acoustic metrics are produced based on the grids of sound pressure values, and the chemical dispersion is computed, the engines' emissions being one of its inputs.

Some modules can be bypassed when they are not relevant to the experimentation context. For example, if the study is based on trajectories computed by another air traffic simulator, then the aircraft module is used in a mode which takes an aircraft type and mass, a trajectory and some weather conditions as inputs and only completes the state vector with the most likely Euler angles and required thrust. The rest of the chain (engine, acoustics, chemical emissions) is kept unchanged.

1.3 Example of input data: Engines

This section takes the modelling of a new turbofan engine as an example of input data preparation in IESTA/Clean Airport.

GSP[1] [4], [5] is NLR[2]'s primary tool for analyzing the performances of the gas turbine engines. It is a component-based modelling environment, using an object-oriented architecture that allows steady-state and transient simulation of any gas turbine configuration. It is primarily based on the 0D-modelling of the thermodynamic cycle of the gas turbine. **Fig. 2** provides an overview of a turbofan model in GSP.

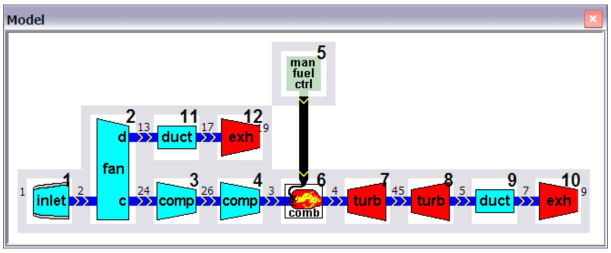

Fig. 2 Screenshot of GSP - turbofan model

This modelling enables to generate the thermodynamics tables covering the entire flight envelope and containing data such as thrust, fuel flow, gas emissions and valuables inputs for the calculation of the noise sources.

When modelling a new turbofan in the simulation, the input of the model configuration is ideally the cycle design, or any known reference points of the engine. As most of the required inputs (especially turbine and compressor maps) are usually not available, in IESTA, the retained modelling method is adapted from [6]. The main sources of information, the engine manufacturer and the certification authorities: ICAO[3], FAA[4], EASA[5]. Among the data, one can note:

- take-off conditions: Overall pressure ratio (OPR), bypass ratio, take-off thrust, air flow and fuel flow, max Revolutions per minute (RPM), etc.
- max climb configuration: OPR, max climb thrust, Specific fuel consumption (SFC), etc.
- cruise configuration: OPR, cruise thrust, SFC, etc.

For example, this process was applied to model the GE-SNECMA CFM56-5C4 using the ICAO database [7] values of this engine. The adapted model accuracy can be appreciated in **Fig. 3**, where the predicted fuel flows at four thrust levels are presented versus the corresponding values of the ICAO data bank. One can note the very good agreement between model predictions and measurements.

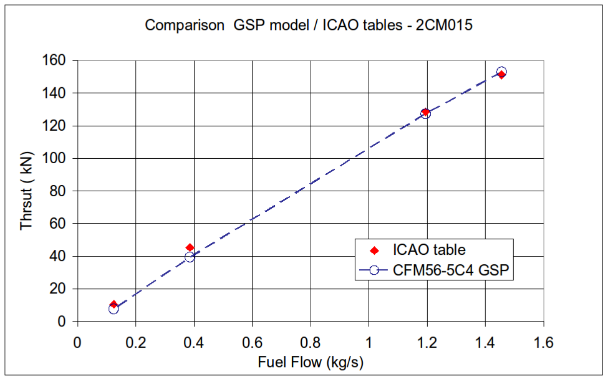

Fig. 3 Comparison of predicted (model) and ICAO data (thrust vs. fuel flow)

Concerning the chemical emissions, GSP uses the information contained in the ICAO database of aircraft engine emissions [7]. For each point of the flight envelope, an interpolation is done using the NLR emissions method (based on T3-P3 method). GSP also enables to use a more elaborate 'multi-reactor' modelling of emissions, that takes residence times and thermodynamic and chemical processes into account.

1.4 Infrastructure

The IESTA infrastructure [1] is designed for data preparation, execution process (time-based simulation, post-simulation treatment) and results

[1] Gas turbine Simulation Program
[2] National Aerospace Laboratory of the Netherlands
[3] International Civil Aviation Association
[4] United States Federal Aviation Administration
[5] European Aviation Safety Agency

analysis. In this perspective, its main components are databases, data preparation tools (environment and scenario), distributed simulation, visualization and analysis tools.

Databases ensure the capitalization of processes, input data and results. A process can thus be safely reused, ensuring that the behaviour of simulation components can be exactly repeated. Exact reproduction is important when one wants to compare different scenarios, for example, or carry out sensitivity tests.

Distributed time based simulation uses the HLA [8] interoperability standard. Among other advantages, it contributes to the capability of reproducing exactly a part of a simulation. In this perspective, IESTA provides logging/replay tools based on HLA. The post-simulation phase allows to run complex computations that are not compatible with run-time simulation.

Concerning results display, we distinguish online from off-line tools (**Fig. 4**).

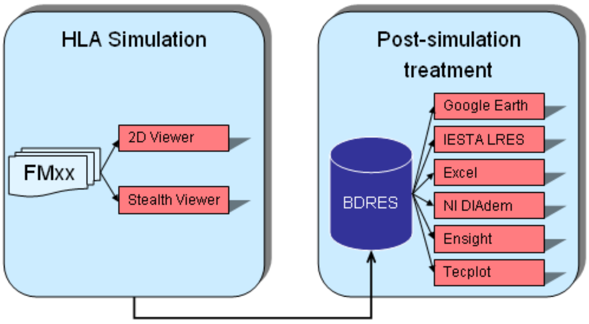

Fig. 4 Online and off-line results display

1.4.1 *Online tools*

Online display tools are launched during the HLA simulation.

The *Stealth Viewer* tool, based on the open source Delta3D simulation engine [9], offers a 3D dynamic perspective of the airport scene or of the selected aircraft, like a flight simulator visualization (**Fig. 5**).

The *2D Viewer* (**Fig. 6**) is a simplified radar view of the traffic. In complement to the Stealth Viewer, it provides the user with a 2D view of the aircraft paths.

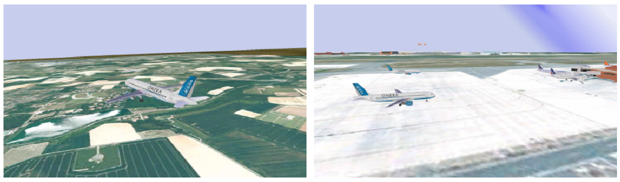

Fig. 5 Stealth Viewer

Fig. 6 2D Viewer

1.4.2 *Off-line tools*

The *IESTA Results presentation tool (LRES)* allows to retrieve relevant data from the results' database using multi-criteria search.

Since the IESTA platform uses well known file formats for data storage, experts may use off-the-shelf (OTS) software. For example: spreadsheet (e.g. OpenOffice.org [10]) and data analysis and reporting tools for tables, graphs, 2D and 3D surfaces (e.g. NI DIADEM [11], **Fig. 8**), and Geographic Information Systems (e.g. Ensight [12], **Fig. 7**) for cartographic views.

IESTA enables to merge different kinds of results (e.g. trajectories with noise carpet) with scenario or environment data (for instance, weather data, population, aeronautical information such as navigation points or airspace classes, etc.)

1.5 First outputs

In the frame of Clean Airport, intermediary results include aircraft primary parameters over time (position, attitude, speed, required thrust, mass, flight phase, etc.), while final results are the computed results (such as acoustics metrics) that can be shown to the platform user.

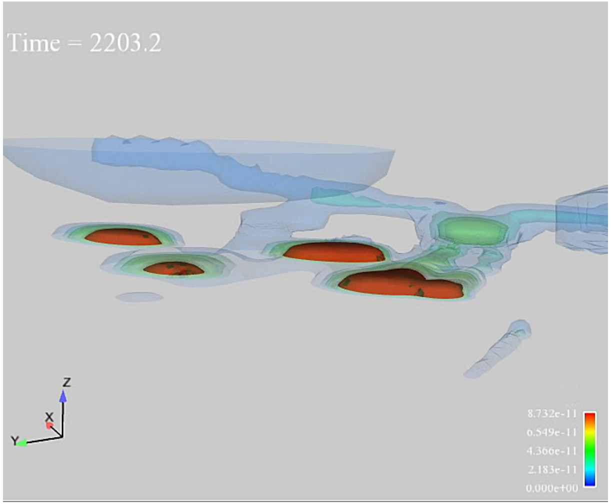

Fig. 7 Display of the chemical concentrations of a given pollutant using Ensight

During the simulation, the Stealth Viewer provides a preliminary visual validation means. Indeed, aircraft deviations to planned trajectory or spurious behaviours can be detected (wrong path on a taxiway, etc.) and the Aircraft Module can be corrected or improved if needed.

In complement to the 3D real time visualization of the traffic, the radar view is of most interest for conflict detection, especially during the approach phases. The next phase of IESTA will lead to the development of a model automatically building conflict-free trajectories (LGC4D).

If the preliminary visual validation is successful, the results provided by the IESTA models are then processed and analyzed. They belong to three domains, and include the following metrics:

- Traffic: aircraft trajectories, aircraft parameters, capacity figures (airport and runways capacity, delays) and fuel consumption
- Acoustics: instantaneous noise, L_{den}, $L_{A_{Eq}}$, $L_{A_{Max}}$ and Effective Perceived Noise Level (EPNL)
- Chemistry: chemical species emissions, Local Air Quality (LAQ) metrics

The IESTA acoustic chain allows for the production of tables showing the relation between the above-mentioned noise metrics, their iso-contour surfaces, the number of points of interest (hospitals, schools) and the number of inhabitants within the contours. These metrics can also be represented on 2D static maps. One can compare scenarios using a sensitivity analysis (the same aircraft flying at a higher speed should create more noise), while the display of colored isolines enables an intuitive validation of the models by the domain experts.

The concentrations of pollutants can be displayed with graphs showing the evolution over time of emissions vs. fuel consumption for direct pollutants, i.e. engine emissions (CO, CO_2, NO, NO_2, H_2O, SO_x, UHCs), **Fig. 8**) or tables (aggregated, peak or average concentrations).

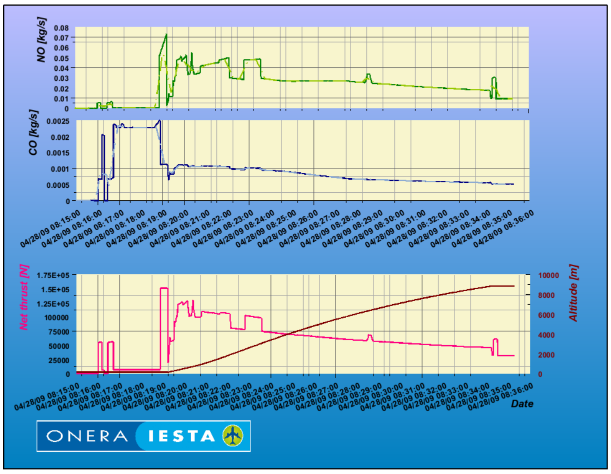

Fig. 8 Evolution of the CO and NO emissions of an engine vs. net thrust vs. elevation over time during a take-off

Thanks to some measured or predictive weather data, it will also be possible to compute the secondary pollutants around the study airport, meaning the atmospheric background reacting with engine emissions, taking into account advection, convection and chemical reactions. One way to depict the consequences of a flight on the atmosphere background is to display dynamically 2D slices at a given altitude showing the pollutant iso-concentrations on a map (**Fig. 9**).

2 Verification and validation tests

2.1 Purpose

The goal of IESTA/Clean Airport is to evaluate the environmental impact of the air traffic at the

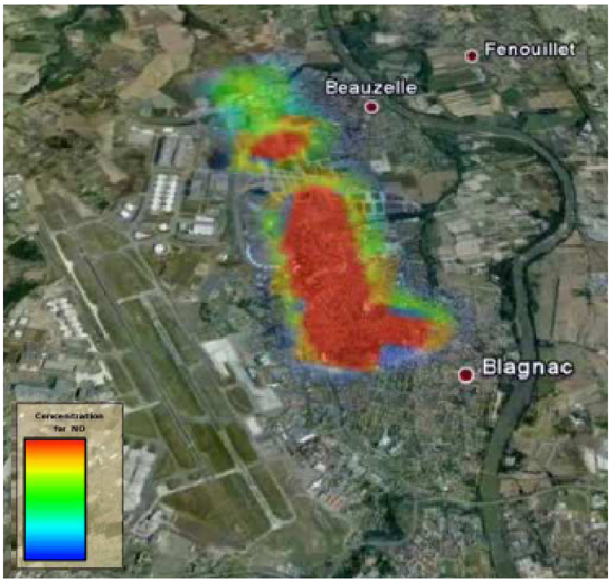

Fig. 9 Test simulation of the dispersion of a passive tracer in the atmosphere around the Toulouse-Blagnac airport with IESTA/Clean Airport

airport platform level, but it should not be confused with a predictive or measuring tool; to expect for an exact prediction of the results of a real experimentation would be unrealistic as too many external factors would have to be modelled down to an unreachable level of detail. However, thanks to the precision of the physical models it implements, it will be able to assess the potential impact improvement brought by different technologies, such as new motorizations, aircraft architectures, airport configurations or procedures. This is achieved by comparing simulations of reference and candidate scenarios according to given criteria, which implies that the modelled phenomena are correctly rendered in terms of trends.

2.2 Test plan

The IESTA/Clean Airport validation tasks include different methods and scopes:

- separate validation and limits of usage of each of the models
- qualitative validation of the behaviour of the modules
- sensitivity to the input data
- validation of the complete platform by comparison with output data: from “other software” or simulators (positioning); from “recognized databases”; or “measured”.

As an exhaustive presentation of these tests cannot be made within the space of this paper, only examples of the carried out ones will appear in the following parts.

2.3 Automated testing

One of the bases of software verification in IESTA is automated testing.

Each component of the platform (physical model, technical component) is associated to a set of tests. Apart from static verification (coding rules and reviews, defensive coding, static code analysis), we also consider dynamic tests. They include both white box tests (testing while knowing the inside of the component) and black box tests (examining the response of a component to an input that varies according to time). The complete test process also covers integration and system testing. Regression tests are particularly important: each time a malfunction is identified, a new unit test is written and capitalized together with the corrective patch.

Considering the large amount of software, it has been necessary to automate testing as much as possible using CppUnit [13] and CDash [14]. Every night, the whole base of tests is run, and each failure is notified to the developers of the corresponding components. Nightly tests also cover integrated sets of components, as well as automatic memory checking and the generation of coverage metrics.

This test framework allows to carry out a validation process with complete confidence in the technical base of IESTA.

2.4 Sensitivity testing - example: the Engine module

Observing of the dependence of outputs on the input data through systematic coverage of the input space has several benefits. First, it completes the verification tests described in part 2.3, as it shows the module's limits and the soundness of its behaviour on the extent of its scope. If supplemented by a numerical analysis (e.g. of partial point elasticity as explained below), it also helps determining the inputs which act primarily on the outputs, that have to be as accurate as possible, and those on which good approximations are sufficient. Last, it gives precise indications on how the uncertainties propagate throughout the platform computations.

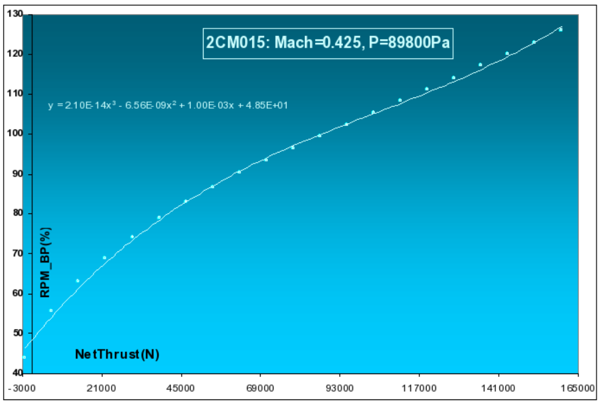

Fig. 10 Fan speed (*RPM_BP*) as a function of the requested net thrust, at a given aircraft Mach and local pressure

The IESTA Engine module is initialized with the thermodynamic tables produced by GSP during the simulation, each engine's state being characterized by the aircraft airspeed in Mach, the local atmospheric pressure, and the requested net thrust. Fixing 2 of those 3 inputs, one can trace the module's response on one significant output in a given region of its input 3D space (**Fig. 10**). In the case at hand, the fan speed *RPM_BP* is approximated by a polynomial function of the thrust T, $P_{rpm}(T)$, and the point elasticity of the fan speed with respect to the thrust is thus $\frac{T}{P_{rpm}(T)} \times \frac{\partial P_{rpm}(T)}{\partial T}$ (**Fig. 11**).

Reading this figure, one can then say that a 1 % uncertainty on the thrust around the 45000 N mark yields in itself about 0.3 % uncertainty on the fan speed.

According to **Fig. 12** and **13**, one can state that among the inputs, the thrust variations impact the fan speed more than the others. Note that

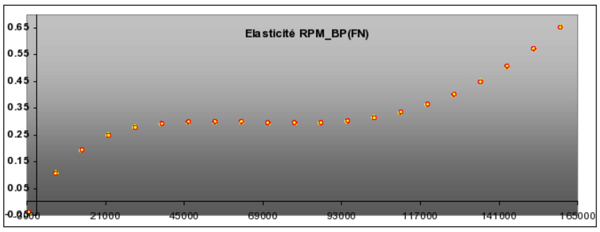

Fig. 11 Elasticity of the fan speed w.r.t. the thrust

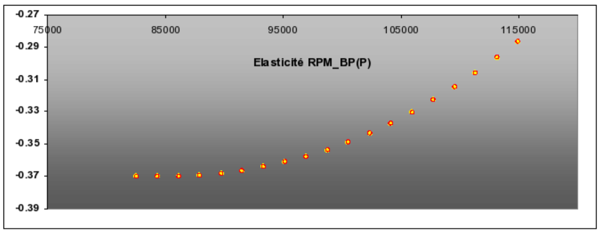

Fig. 12 Elasticity of the fan speed w.r.t. the local pressure

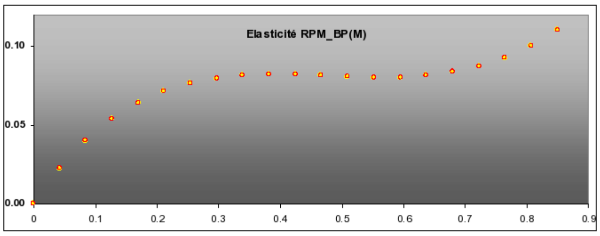

Fig. 13 Elasticity of the fan speed w.r.t. the aircraft Mach

the moduli of the partial elasticities add up, so for instance, around the (95000 N, 89800 Pa, 0.4 M) state, errors of 5 % on each of the 3 inputs will lead to an uncertainty of $5 \times (0.3 + 0.36 + 0.08) =$ 3.7 % on the fan speed. The same errors have a 13.25 % uncertainty impact on the *NO* flow, and about 7.3 % on the primary jet speed.

As mentioned above, this method also allows for assessment of the uncertainty propagation throughout the chain of modules. The resulting elasticity is the product of the local ones. This analysis performed on the IESTA fan noise model, then on the aircraft-to-ground atmospheric noise propagation model, gives the uncertainty on the sound pressure received, with respect to those on the engine inputs.

2.5 Comparison with simulated data - example: the Aircraft module

Trajectory calculation test The testing of the trajectory calculation is fundamental to the credibility of all the IESTA outputs. One phase of the validation of the Aircraft Module was to compare its outputs with the ones of a Flight Management System (FMS) which was used on a simulation platform with no human in the loop. The collected data are of various types, but include all the basic data expected for such a test, such as speed values, aircraft attitude, configuration and position, mass, etc.

Scenario The flight plan includes:

- take-off from runway 14L of the Toulouse-Blagnac airport,
- Standard Initial Departure (SID) procedure FISTO 5A,
- en-route phase made of the PERIG, FOUCO, ADABI, BOKNO, DEVRO and VANAD navigation points,
- landing on the runway 06 of Paris-Orly

The simulation is done under international standard atmospheric (ISA) conditions.

Tests The FMS data have been compared to those produced on the IESTA platform by the Aircraft Module. The same scenario (airspace, weather, aircraft type and flight plan) was used. Two tests have been selected:

- the comparison between the trajectories generated by the FMS and the IESTA Aircraft Module;
- the comparison between the attitude and thrust data generated by the FMS on one side, and by the IESTA Aircraft Module using the trajectory generated by the FMS as an input on the other side.

Analysis of the results These comparisons could theoretically be used to heighten the realism of the Aircraft Module by fine-tuning its parameters and improving its calculation algorithms to match the industrial, state-of-the-art models better. On the opposite, these results cannot be used as a perfect trajectory comparison tool: the trajectories generated by the models are not unique, and the same set of input parameters can lead to several different trajectories. This comparison could only help to enhance the module if some obvious computation errors were found out.

First test The first test compares the raw trajectory produced by the FMS to the one produced by the IESTA Aircraft Module, which relies on the Eurocontrol BADA database [15]. It helps to check for differences in fundamental values such as variation in the position in the horizontal plan, caused, for instance, by a different calculation of turn angles by the model or tuning mistakes in the thrust model. As long as the variation between the two calculated trajectories stays in the flight domain of the simulated aircraft type (**Fig. 14**), the model should not be updated in any way.

Second test The main objective of the second test was to analyse the capability of the IESTA Aircraft Module to use an existing trajectory, here calculated using the FMS, as input data, to compute the required thrust and the Euler angles in order to compare them to the FMS values. Like

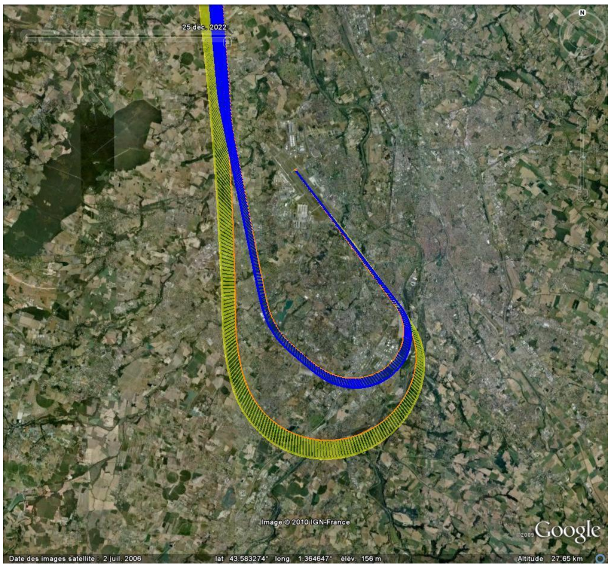

Fig. 14 Trajectory comparison results example

the first test results, these could be used to correct the module. For instance, a difference in the pitch angle could be caused by an erroneous value of the lift coefficient in the aircraft performances database.

Conclusion The state vectors generated using the IESTA Aircraft Module are in the domain of the possible trajectories and flight parameters regarding the input data. The differences which can be observed do not allow to dismiss one trajectory predictor or the other one: they both generate realistic trajectories and BADA is considered by the operational experts as able to generate some acceptable trajectories from the Air Traffic Management (ATM) point of view. The fact is that the set of inputs described above does not capture the way the FMS is used: for instance, airlines usually tune the cost index (minimization of the flight duration vs. minimization of the fuel consumption). Thousands of flight data recordings would be necessary to enhance the behaviour of the IESTA Aicraft Module.

2.6 Comparison with real data - example: Thermodynamics

In the frame of the validation of GSP software for IESTA applications, three tracks were followed:

- a bibliographical validation using the various papers written by NLR and others research centers or universities ([16], [17]),
- an internal validation using the database of engine performance data available in Onera,
- a collaboration with the Department of Aerodynamics, Energetics and Propulsion (DAEP) of the ISAE[6] for the theoretical and experimental validation of GSP.

About this collaboration, the theoretical validation mainly concerns the map scaling factors used in GSP (and based on GasTurb assumptions [18]). For the experimental part, the objective is to model the Price Induction DGEN 380 dual-flow turbofan (**Fig. 15**) of the ISAE/DAEP test bench.

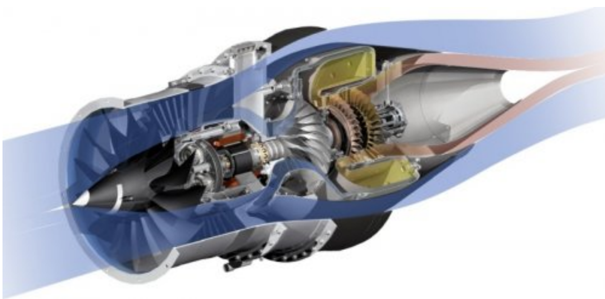

Fig. 15 Overview of DGEN 380 engine (courtesy of Price Induction)

This fully instrumented test bench enables to compare, component by component, the accuracy of GSP models for off-design conditions. Up to now, the first GSP model managed to reproduce almost perfectly the two design conditions (take-off and cruise) and experienced around 5 to 7 % accuracy for off-design conditions (exhaust gas temperature for example).

3 Conclusion

The IESTA/Clean Airport system integrates a simulator of air traffic operations and some physical engine, noise and chemical emissions simulators. The typical set of results of an evaluation

[6] Institut Supérieur de l'Aéronautique et de l'Espace, France

includes some data usually computed by the air traffic simulators, as well as acoustic and chemical emissions metrics.

The verification tests of the system helped to ensure that the intermediate and final results are compliant with the specifications of the system.

The validation tests of this system included sensitivity to input data tests, as well as comparisons with simulated and real data; the air traffic operations part cannot be validated in an absolute manner, since it embeds the modelling of some human behaviour. It can at most render these operations in a realistic way.

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The activities described in this paper reflect a collective work carried out by the whole team of the IESTA programme. Moreover, this programme owes its existence to a federative and close collaboration between several Onera scientific departments that gather a multidisciplinary team of experts of a wide range of domains (DCSD, DMAE, DMPH, DSNA and DPRS).

Finally, the IESTA team would like to thank Eurocontrol for its kind authorization to use its aircraft performance database BADA.

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6 Copyright Statement

[7] European Regional Development Fund (ERDF), French State, French Civil aviation authority (DGAC), French Midi-Pyrénées region, Urban community of Greater Toulouse

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