ABSTRACT
High precision 4D flight path predictions are crucial for reliably optimizing the complex ATM/ATC system. The presented enhanced jet performance model provides a significant improvement over currently applied trajectory prediction methods. The use of purely analytical methods allows a high level of adoption of the real physical aircraft environment. This paper presents the model and applies the findings to predict fuel flow characteristics as fundamental parameter for trajectory planning. Further the model was implemented in an agent-based simulation to consider stochastic atmospheric boundary conditions for flight path optimization. Thus, our presented research is a preliminary development considering the targets of the UTOPIA project within the SESAR Long-term and Innovative Research.

Keywords
Automation, flight efficiency, 4D trajectory prediction, analytical performance model

APPLICATION AND DATA TRIALS OF THE EJPM
Calculating the instantaneous fuel flow requires all corresponding EJPM input parameters such as state parameters or environmental. The pre-processing inside the Speed Determination Module (SDM) and the Lift and Drag Module (LDM) delivers preliminary results, on which further processing within the Thrust Wanted Module (TWM) refers. The High Precision Fuel Flow Calculation Module (HPFFC) finally supplies the EJPM solution parameters initiating the high precision fuel flow determination model. A first test of the EJPM algorithms were performed in 2010 with real time data of standard airline operations. The reference aircraft model was an Airbus A320-214. The affected flight crew of this test trial was asked to collect the following data from cockpit instrumentation for some stationary flight segments according to table 1. The cockpit instrumentation gets the data from the aircraft Air Data and Inertial Reference System computer (ADIRS).
Column 2 stands for “Pressure Altitude (PA)”, column 3 “(Current) Mass”, column 4 “Calibrated Air Speed (CAS)”, column 5 “Flight Path Angle (γ)”. The current state parameter are imported to compare the results of EJPM modules with column 6 “True Air Speed (TAS)”, column 7 “Mach (Number)” and column 9 “(Total) Fuel Flow”. Column 8 “Static Air Temperature (SAT)” is an environmental parameter. Column 10 shows under “Remarks (Rm.)” the current flight phase.

Each requested value and column is well selected to test the respective modules SDM, LDM and FFCM. TWM could not be tested, yet because all data were selected from steady cruise flight phases. Of course this validation campaign is so far of provisional character, only: Another huge data acquisition and evaluation phase in cooperation with Lufthansa Cargo is scheduled for spring 2011, as the validation methodology was shown to be mature.

<table>
<thead>
<tr>
<th>Type</th>
<th>PA</th>
<th>Mass</th>
<th>CAS</th>
<th>TAS</th>
<th>Mach</th>
<th>SAT</th>
<th>Fuel Flow</th>
<th>Rm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320-214</td>
<td>110,000.00 ft</td>
<td>5,396,000 kg</td>
<td>220 kt</td>
<td>0°</td>
<td>258 kt</td>
<td>0.406</td>
<td>7 °C</td>
<td>2,080,000 kg/hrs</td>
</tr>
<tr>
<td>A320-214</td>
<td>9,000.00 ft</td>
<td>5,166,000 kg</td>
<td>250 kt</td>
<td>0°</td>
<td>285 kt</td>
<td>0.448</td>
<td>4 °C</td>
<td>2,280,000 kg/hrs</td>
</tr>
<tr>
<td>A320-214</td>
<td>110,000.00 ft</td>
<td>5,420,000 kg</td>
<td>250 kt</td>
<td>0°</td>
<td>293 kt</td>
<td>0.461</td>
<td>7 °C</td>
<td>2,200,000 kg/hrs</td>
</tr>
<tr>
<td>A320-214</td>
<td>29,000.00 ft</td>
<td>5,700,000 kg</td>
<td>263 kt</td>
<td>0°</td>
<td>414 kt</td>
<td>0.651</td>
<td>-35 °C</td>
<td>2,240,000 kg/hrs</td>
</tr>
<tr>
<td>A320-214</td>
<td>5,000.00 ft</td>
<td>5,950,000 kg</td>
<td>242 kt</td>
<td>0°</td>
<td>428 kt</td>
<td>0.673</td>
<td>-51 °C</td>
<td>2,200,000 kg/hrs</td>
</tr>
<tr>
<td>A320-214</td>
<td>5,000.00 ft</td>
<td>5,470,000 kg</td>
<td>253 kt</td>
<td>0°</td>
<td>443 kt</td>
<td>0.697</td>
<td>-53 °C</td>
<td>2,080,000 kg/hrs</td>
</tr>
</tbody>
</table>

Test of the Speed Determination Module (SDM)
During this first evaluation, the SDM tests refer to a comparison of the sampled data with the behavior according to equation (1). The necessary environmental parameters from the EPC are generated with standard ISA equations based on column 2 (PA) and column 8 (SAT). The corresponding “CAS to TAS” algorithm complied perfectly with the measured data as figure 6 depicts.

The special shape of the graph refers to the different environmental conditions (pressure, temperature, density) of each node point along the above mentioned test trial. The Real Data from the ADIRS was tracked discretely, whereas the EJPM is calculating continuously based on an analytic algorithm. On average, the error between discrete CAS/TAS Real Data from Airbus ADC and analytic EJPM CAS/TAS Data was found to be less than 0.1%.

Test of the Lift and Drag Module (LDM)
The current lift and drag can’t be measured and listed directly in flight like the parameter of the SDM. But with the knowledge of the flight path angle according column 5 and the current stationary flight situation (usually cruise flight, Remarks in column 10) the lift equals the current weight according “Current Mass” from column 3. With knowledge of the lift coefficient according (10) we can calculate the respective drag amount according to (16). The authors have access to real first principle data of the selected aircraft type A320-214 (polar graph) and took this data into consideration as master for evaluating the LDM.

Figure 7 depicts the result and again the real first principle data are discrete, whereas the EJPM calculates a continuous function due to its analytic approach.

Test of the Fuel Flow Calculation Module (FFCM)
During the test of the Fuel Flow Calculation Module we took the fuel flow data from the real time test trial of column 9 and compared these values with the predicted fuel flow of EJPM. We used the above mentioned empirical approach which is based on the BADA setup according to equation (20).

Figure 8 shows the corresponding results. The data line composed of diamonds shows the results taken from BADA with an error of approximately 5%. The cross line of data is the modified empiric EJPM FFCM with compressibility considered reducing the error below 1.8%.
The superior level below 1% will be reached with the new analytic fuel consumption model, which is expected to be functional until spring 2011. As already mentioned, this test trial is not fully representative because of the large number of unknown input errors, but it shows the current trend of the EJPM tool for flight path prediction. The left bunch of supporting points is at lower altitudes and the right at higher flight levels.

OUTLOOK AND ADDED VALUE
The enhanced jet performance model developed could demonstrate a significant increase in accuracy to predict all fundamental flight parameters and so the fuel flow of modern commercial aircraft. Even though the validation based on operational flight data is seen as preliminary, only, a clear added value for the ATM sector could be recognized: The prediction of optimized four-dimensional aircraft trajectories complying with complex target functions and dynamic boundary conditions according to realistic ATM system behavior seems a realistic goal, implementable in both airborne, or ground based systems.

The next iteration prediction capability will be based on an agent based simulation [15] for the movement of the aircraft in space; this will allow defining the optimum flight path under uncertain boundary conditions (as it is typically true for weather parameters). The routine is called Jet Performance Optimization Routine (JPOR). The simulated aircraft (agent) gets the physical intelligence through the enhanced jet performance model (EJPM). The JPOR is based on a four-dimensional grid environment, where the agent moves from one grid cell to one of the adjacent, neighboring cells (according to Moore relationship). The decision of the agent on where to move next is triggered first by both the agent’s operational envelope and generated optimized parameter from the EJPM, second by the evaluation of the boundary conditions like emission rates and probabilities, weather constraints [9], varying pre-set air traffic control (ATC) operational procedures (assuming increasing automation levels) and by the level of uncertainty in the input data [7]. The agent may be subject to Monte-Carlo simulations to reflect the stochastic nature of the constraint parameters.

The trajectory using least resources, inducing the lowest amount of pollutions and/or the shortest flight time needed at best trajectory handling comfort may be selected based on pre-set target functions. The trajectory will be fitted through a set of analytic trajectory functions for easy implementation into onboard or ground based decision support and flight management functions.

Further on, the trajectory prediction process is also influenced by several stochastic factors which produce discrepancies between the real trajectory flown by an aircraft and the predicted trajectory used by the decision support tools (DST) to evaluate the traffic flow. The current DSTs need to understand and handle the uncertainty associated to the trajectory data to provide a proper decision to a human who has the last responsible role. The objective UTOPIA project is to perform a qualitative and quantitative analysis of the effects of those stochastic factors on the behavior of a fully automated control environment and how it is able to take decisions considering non deterministic information ensuring continuously the safety of operations, based on a large set of previous studies done in the context of full automation in ATC.

References

Figure 3. Result of comparison between Airbus real time fuel flow measurement and EJPM FFCM prediction