PERFORMANCE-BASED TMA HANDLING FOR MIXED TRAFFIC USING A GROUND BASED 4D-GUIDANCE FOR UNEQUIPPED AIRCRAFT

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Abstract

In order to meet the anticipated future demand for air travel, a trajectory based arrival and departure handling enables usage of aircraft optimized flight profiles and concurrent high airport throughput. DLR's Institute of Flight Guidance investigates a new concept based on 4D-trajectories for both modern aircraft equipped with a flight management system and unequipped aircraft. This paper introduces a navigation performance adapted concept that allows high throughput for airports dealing with mixed traffic. Furthermore, heaving already much experience with guidance of 4D-equipped aircraft, an example implementation of a ground based guidance module for 4D-uncapable aircraft is presented.

1 Introduction

New conflicting future demands in air travel like gain of capacity and coexistent reduction of environmental impact necessitate new airborne functions and a better integration of these capabilities in Air Traffic Management (ATM). Studies with the A330 Full Flight Simulator of ZFB Berlin and DLR's testing aircraft ATTAS both using DLR's Advanced Flight Management System onboard proved a highly accurate predictability of 4D-trajectories (see Chapter 4).

At least in high traffic situations, current terminal manoeuvring area (TMA) concepts do not support 4D-capable aircraft in flying fuel efficient and noise abating profiles. In contrast, equipped aircraft are frequently forced to early join the same lateral flight path flying all at the same speed to keep separation easy for the controllers and avoid a break-in of capacity. Thus, fuel and noise efficient approaches are currently performed in low traffic scenarios only.

A trajectory based TMA handling is necessary to combine aircraft optimized flight profiles with a high airport throughput. Based on new ATM concepts like time based late merging, this paper describes a possible solution for the current trade-off between green trajectories and airport capacity in high traffic scenarios.

Today's TMAs handle a mixture of 4D-capable and, due to long life cycles, also 4D-uncapable aircraft, that are not able to follow a 4D-trajectory autonomously.

In a trajectory driven TMA, every aircraft has to fulfil its 4D-contract with the controller. Depending on the equipment of an aircraft, the assigned area of tolerance from the trajectory should be smaller or bigger. While equipped aircraft are able to fulfil the contract on their own, unequipped aircraft are supposed to be integrated by means of a ground based 4D-guidance module.

2 Why 4D-Trajectories help – DLR's 4D Concept

Having a look at the key performance areas (KPA) of the European Operational Concept Validation Methodology (E-OCVM), safety and capacity are usually considered to be the most important ones. Environmental sustainability caught up in the last decade and is often thought of being KPA number three today. Frequently, a reduction of environmental impact even improves other KPAs like flight efficiency. For example, a reduction of CO_2 emissions can be achieved by minimizing fuel burn.

Focussing upon the TMA, environmental friendly procedures for arrival and departure feature

- efficient usage of engines,
- low drag aircraft configuration,
- and flying high altitudes

in order to reduce

- NOx and CO_2 emissions,
- noise emissions and immisions on ground,
- and fuel efficiency.

Especially concerning the approach, there exist some promising procedures like continuous descent approaches (CDA). A CDA allows

- fuel savings of 200-500 kg per landing aircraft
- reduction of CO_2 emissions of 500-1200kg per landing aircraft
- up to 5dbA less noise immissions on ground.

See Fig. 1 and Fig. 2 to get an idea of the difference between standard approach and idle CDA noise footprints. Both footprints were generated by an A320 aircraft landing on runway 25R in Frankfurt (in the lower left corner). The corresponding trajectories were generated with DLR's AFMS (see Chapter 3) and DLR's noise prediction tool SIMUL[1].

Unfortunately, since CDA aircraft are hardly touchable by Air Traffic Control (ATC) once the descent is commenced, implementation of CDA procedures results in larger slots and therefore lower airport throughput today. Thus, CDAs are currently not performed in high traffic situations.

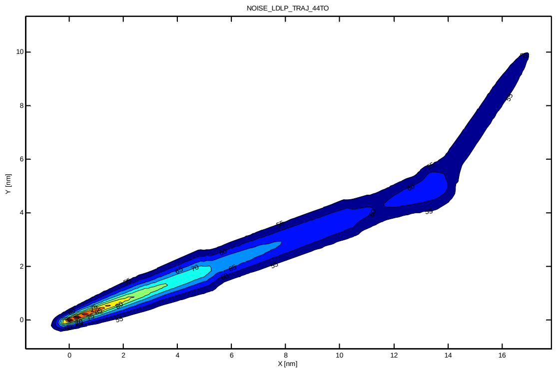

Fig. 1: Noise footprint standard LDLP approach

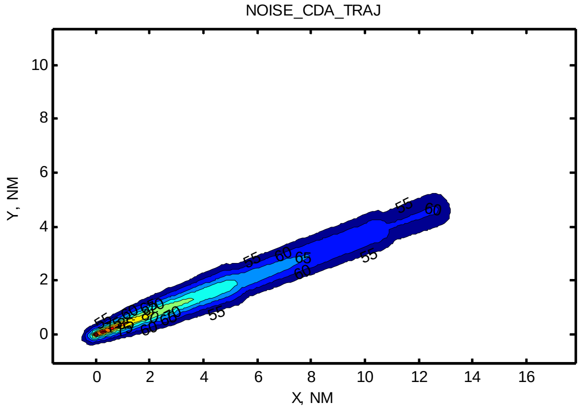

Fig. 2: Noise footprint for CDA approach

Denying equipped aircraft to fly their user preferred trajectory leads too higher noise immissions around airports, longer approach routes in terms of distance and time and higher fuel consumption. The mixture of traffic with different capabilities of single aircraft necessitates a concept dealing with both FMS equipped and unequipped aircraft. Provided the traffic mixture of today there are very few aircraft equipped with highly advanced systems like the AFMS described in this paper, if there is another apart from ATTAS at all.

Nevertheless, there are a lot of aircraft today capable of guiding along 3D-trajectories with one time constraint to fulfill. These FMS-equipped aircraft are not really capable of flying DLR's idle CDA but can also fly very efficient by performing standard CDAs.

A trajectory based TMA handling approach seems to be an efficient solution for a traffic mixture of unequipped and FMS equipped aircraft [2].

Fig. 3 depicts an exemplary route structure for trajectory based TMA handling. All arrival traffic is merged at a late merging point lying late on the center line. Every approaching aircraft has to fulfill a time constraint at this point. Many of today's aircraft are capable to meet the time constraint board-autonomously, unequipped aircraft are supposed to be integrated by means of a ground based guidance module that is also 4D-trajectory based.

Before merging, arriving aircraft are separated procedurally by staggering them laterally in an extended TMA (E-TMA). Time constraints are assigned when entering the E-TMA. Since fulfilling a time constraint is more efficient using speed variation than detouring, the extended TMA has to be rather big (80-120NM radius) to allow adequate time deviations by means of speed variations. Strategic path stretching areas (see the dotted lines) are provided if speed variation is not enough to meet the desired constraints. Static E-TMA entries help to keep the TMA structured and clearly arranged.

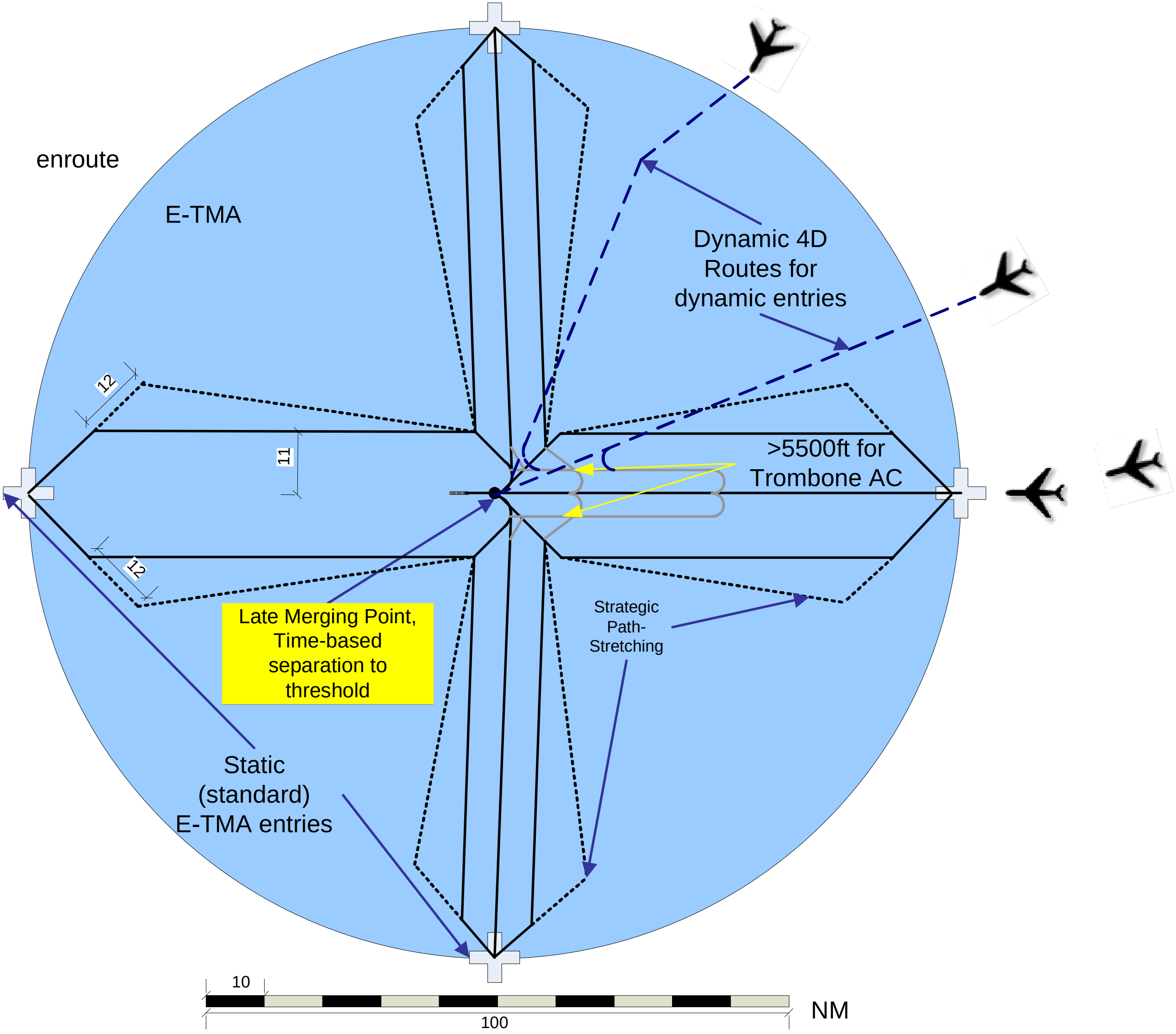

Fig. 3: DLR's Route Structure for a Trajectory Based TMA Handling

Aircraft not entering near a static E-TMA entry are guided by means of dynamic routing. Different equipage of aircraft will lead to different navigation precision. Aircraft with high navigation precision will be directed directly to the late merging point while unequipped aircraft are supposed to fly the trombone approach (see Fig. 4). The trombone allows readjusting the time of arrival just before landing by moving the turn-to-final point.

Aircraft pretending to fly precise but cannot meet their promised constraints in the end can also be redirected to the trombone approach until crossing the trombone path.

Aircraft flying the trombone can be delayed to allow insertion of short term departures and simplify handling of emergency situations.

Having a time-based separation at the late merging point anyway, the separation between late merging point and touchdown is supposed to be time-based too. In high head wind conditions this should not only ensure a high capacity of the airport, but even increase it.

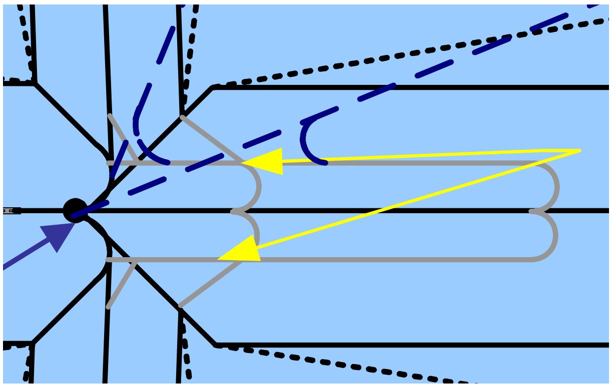

Fig. 4: Unequipped Aircraft are directed to the Trombone

In order to implement the concept above, we need:

- Equipped aircraft capable to generate and fulfill 4D trajectories board-autonomously. Chapter 3 explains the features of modern FMS by describing DLR's Advanced Flight Management System. Chapter 4 explains how DLR's FMS proved high accuracy in simulations and flight trials.
- Ground based trajectory generation supporting unequipped aircraft in following 4D trajectories. Chapter 5 describes rather fundamental flight trials done with the ATTAS degraded to an unequipped aircraft. Chapter 6 explains the design of a ground based guidance tool that gives recommendations to fulfill 4D contracts.

3 The Advanced Flight Management System

Within the Programme for Harmonized Air traffic management Research in Eurocontrol (PHARE), an Advanced Flight Management System (AFMS) with a high level human machine interface has been developed and since then continually improved by the Institute of Flight Guidance, DLR. By means of strategic trajectory planning and a corresponding guidance module the AFMS allows planning of highly accurate 4D-trajectories and following them with little deviations autonomously.

Fig. 5 shows the in- and output data of the AFMS. Generation of 4D-trajectories is performed based on a list of waypoints describing the route from actual position to the destination, altitude and time constraints, the aircraft's performance data and an accurate weather forecast. An accurate weather forecast is a main driving factor for a high quality trajectory. Aircraft's performance data is published by Eurocontrol in the Base of Aircraft Data (BADA, current version 3.6 with 295 aircraft) [3]. The AFMS implements three different descent profiles (see Fig. 6):

- Low drag low power (LDLP) approach with an intercept level,
- Continuous descent approaches (CDA) without intermediate level on descent
- and Segmented continuous descent approaches (SCDA) with a steep descent segment caused by early gear and flaps extraction. This results in higher altitudes and therefore higher damping of noise but increases airframe noise.

All implemented descent procedures can be adjusted by a set of parameter (altitudes and lengths of levels).

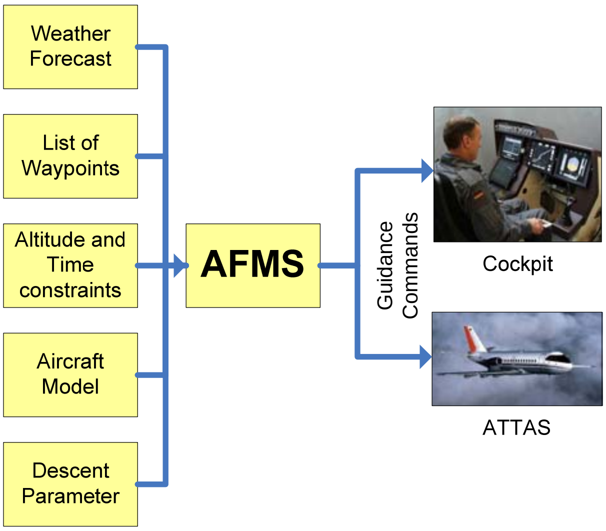

Fig. 5: Input and Output of the AFMS

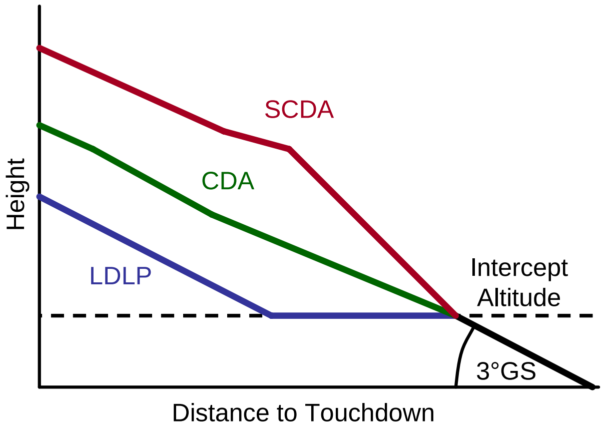

Fig. 6: Descent profiles implemented in AFMS

All three descent profiles have in common that

- Descents are performed with engines idle. Thus, sink rate and flight path angle are not necessarily constant while descending. Idle thrust does not only reduce noise emissions of the engines but also reduces noise immissions on the ground and fuel consumption due to higher and therefore more economical flight profiles.
- The vertical profile can be specified independently of the lateral path. This enables the implementation of special procedures like curved approaches.

Once generated a 4D-trajectory, consisting of a lateral route with altitude and time information for each waypoint, the AFMS provides guidance commands to fly along the calculated route. If an appropriate connection to the autopilot is available these commands are directly forwarded to the aircraft that will automatically follow the trajectory. If such a connection is not available the guidance commands can be displayed as instructions to be carried out by the pilot [4].

The AFMS guidance commands control the aircraft in all 4 dimensions (2D-lateral, vertical and time).

4 Trials with Equipped Aircraft

DLR’s Institute of Flight Guidance proved high accuracy of the AFMS in several simulation trials with the A330 full flight simulator located at the ZFB Berlin and in real flight trials with DLR’s test aircraft ATTAS, a VFW614 twin engine jet modified for research purpose.

Fig. 7 depicts a typical CDA profile flown with the A330 simulator. The Top of Descent (TOD) is in FL80 flying 250 knots, where the aircraft starts its descent in clean configuration (i.e. flaps and gear in).

Since the aircraft decelerates to reach a glideslope intercept speed of 170 knots, the descent is rather smooth. The trajectory generated by the AFMS also incorporates the aircraft configuration by predicting the times where flaps and gears have to be extracted.

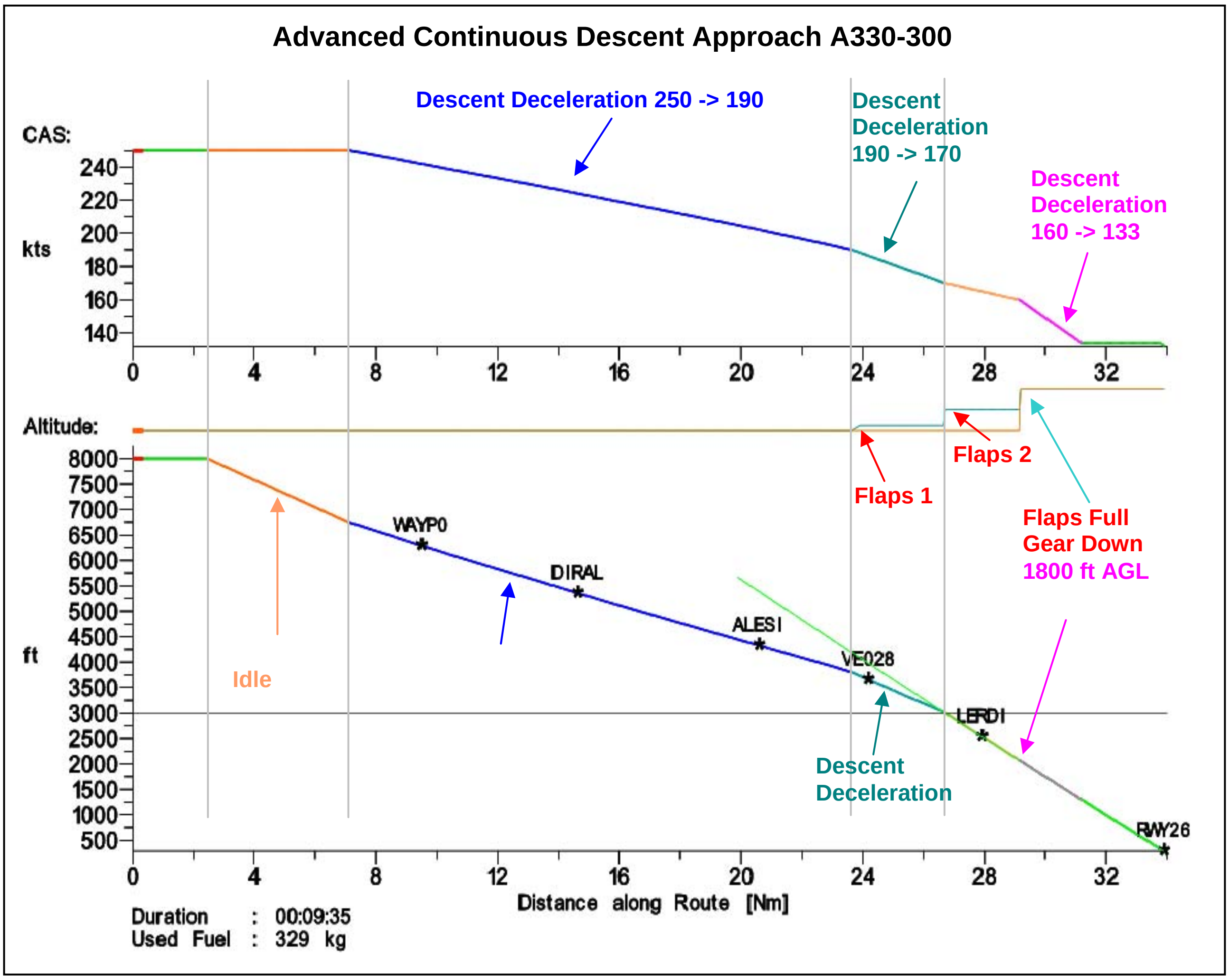

Fig. 7: ACDA for Airbus A330-300

In 1800ft above ground level the aircraft is supposed to be in landing configuration (full flaps, gear down).

When flying along the calculated trajectory, deviations may occur due to

- Insufficient or imprecise aircraft performance data
- Jitter in the configuration points
- Bad quality of weather forecast
- …

Forced to deviate from the predicted trajectory because of unforeseen influence as described above, the AFMS guidance functionality tries to hold the time deviation at minimum and accumulates an altitude error. This behavior helps to fit in the concept described in Chapter 2. The altitude error is compensated when intercepting the glideslope. This type of readjustment depends on whether the aircraft is too high or too low.

Being in time and having a positive altitude (too high) error means that the aircraft has too much energy left. Since the engines are idle in descent there is no way out by means of changing the thrust. Therefore, the AFMS reacts by increasing the drag and preponing dynamically the configuration times for flaps and gear.

A negative altitude (too low) error implies a lack of kinetic energy and is corrected by insertion of a less steep segment. Only in extreme cases this segment will be a level segment. In order to get rid off the missing energy, the AFMS brings forward the point of leaving idle thrust. Thus, there is no new phase of closed loop low power control but a small extension of the thrust phase just before landing.

DLR did various flight trials with ATTAS to Braunschweig airport and A330 simulator to Munich airport, each covering the last 20 minutes before landing. Typical precision for more than 30 approaches with ATTAS was a maximum of +/-150ft altitude error and +/-5s time deviation at the touchdown point.

Typical maximum altitude errors of 100ft and time deviations of up to 3 seconds at touchdown have been evaluated with the A330 full flight simulator. The higher precision with the A330 compared to ATTAS can be attributed to the missing realistic weather.

However, both campaigns proofed a high and reliable predictability for the whole descent segment. The concept proposed in Chapter 2 takes advantage of the early predictability of high-precision arrival times. Chapter 5 and 6 will discuss the approach for unequipped aircraft.

5 Trials with Unequipped Aircraft

To get a general idea of how to guide an aircraft along a 4D trajectory without FMS functionality onboard, test-flights with the Advanced Technologies Testing Aircraft System (ATTAS) were carried out.

The ATTAS is equipped with a measurement system providing Global Positioning System (GPS), Inertial Reference System (IRS), Air-Data, Very high frequency Omni directional Radio range (VOR), Distance Measuring Equipment (DME) and Instrument Landing System (ILS). The Fly-By-Wire-system in the ATTAS includes an experimental autopilot similar to an Airbus A320 autopilot.

During test-flights it is possible to generate 4D-Trajectories from a workstation in the cabin and have “radio communication” via intercom with the pilot in the cockpit. The idea of this test flights with ATTAS degraded to an unequipped aircraft was to have a controller in the cabin with all information of a 4D trajectory including guidance-information not visible to the pilot. The pilot received radar vectors from the controller out of the cabin via intercom and activates them on the Flight Control Unit (FCU).

Three different levels of automation were executed:

- For reference purposes all three axes were controlled by the AFMS outer-loop-guidance-vector to the experimental autopilot.
- Next lower level of automation was to select airspeed, heading and altitude on the FCU and engage the approach mode on final.
- The lowest level of automation for the pilot was to fly the aircraft manually. Thrust was fully manual and a Control-Wheel-Steering-Law (CWS) on a sidestick supported the pilot lateral and vertical.

New for the pilot was to get expected times for the top of descent and, pretending to have an exact aircraft model and actual speed, even times for the configuration of flaps and gear.

The other commands of the controller were standard like heading, airspeed and altitude commands. Before intercepting the ILS a target-heading was given.

Following general problems occurred during flight:

- There were only engineering readouts provided to the controller onboard the ATTAS on the FMS operator’s workstation. Thus, he had to take into account the wind for track/heading and groundspeed/airspeed conversions.
- Flying in a real ATC environment, the handover of advisories to the pilot sometimes were delayed by a blocked real ATC communication channel.

The routing started about 20 NM north of Braunschweig EDVE and a LDLP and CDA were performed as vertical profile during the approaches. Flight time for one approach was about 15 minutes starting at FL 70.

The number of advisories for one approach ranged from 6 to 10, most of the advisories being heading commands.

The time error from initially predicted time of the route to 500 ft above ground level on the final was about 5 to 10 seconds. This time error was at maximum 2 seconds in the reference flight with fully automatic control under FMS. The reference flight had results as described in Chapter 4. Fig. 8 shows time error, speed profile, configuration and altitude profile with all axes in a selected mode and guidance commands given by the airborne controller. Note that time error gets a sudden increase after 30 NM distance along the route because of heading changes at waypoint LENDI. While the AFMS plans a routing with constant radius turns, the autopilot turned with a constant standard bank angle of 25 degrees.

Due to heading changes of about 100 degrees the exact start point for the initiation of the turn was hard to figure out without assistance tools.

As expected, the controller claimed much better support tools assisting with the calculation of instructions.

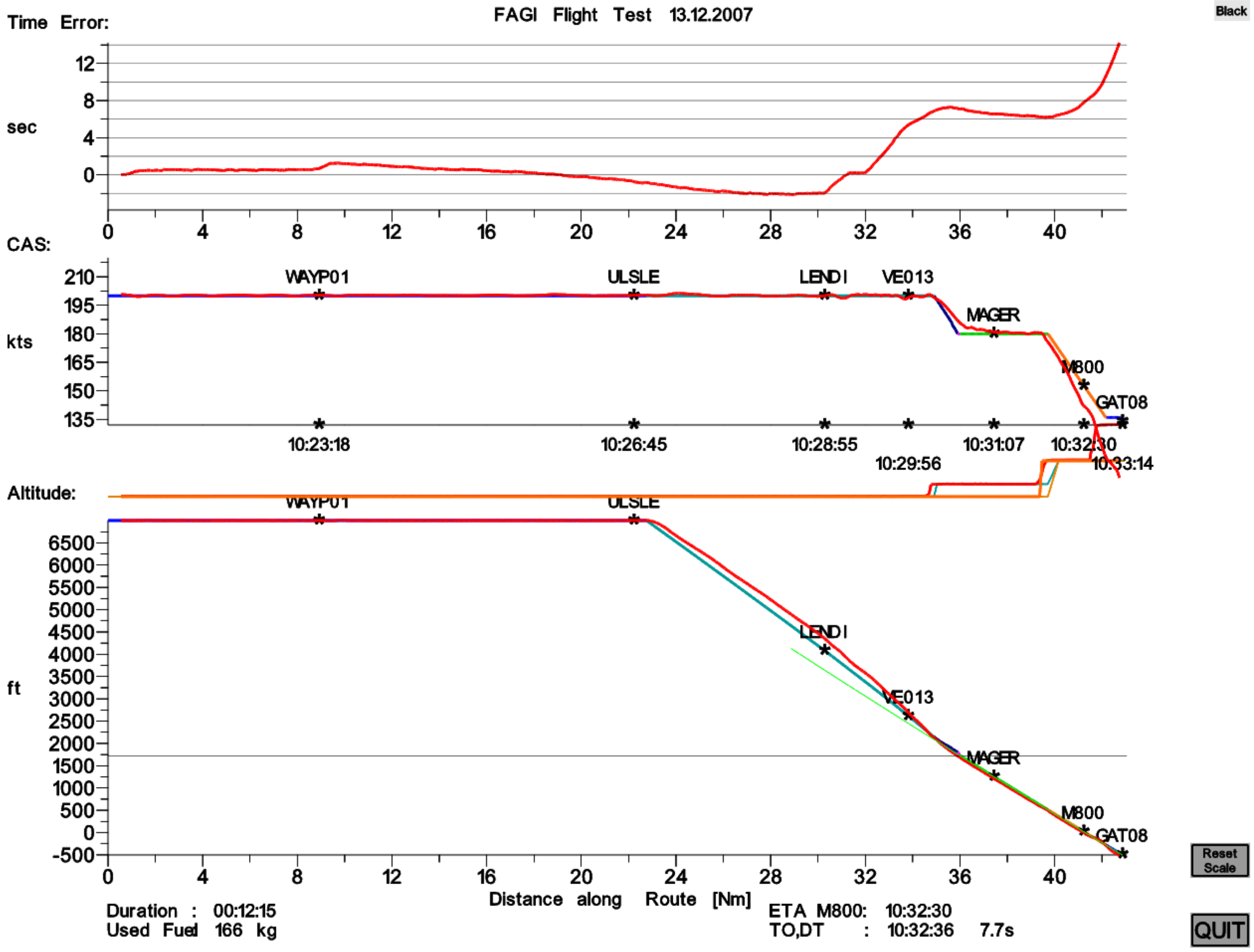

Fig. 8: Manual selected mode

6 Ground Based 4D-Guidance

The main problem concerning unequipped aircraft is the absence of an onboard 4D-capable FMS (indeed this is how the term “unequipped aircraft” is defined in the scope of this document).

This paper proposes to substitute the missing onboard FMS by a 4D FMS on the ground. Having a second look at Fig. 5, following data is essential to feed the FMS:

- Weather Forecast: A weather forecast is provided by several forecast services. This could even be improved by landing aircraft collecting wind data while approaching, but that should not be necessary.
- List of Waypoint/Altitude and Time constraints: In an ATC-centred TMA handling, the list of waypoints and corresponding altitude and time constraints are ground based anyway.
- Aircraft Model: The aircraft model can be derived from BADA for almost every commercial aircraft. Even if the model is not

available, conservative estimation should help.
- Descent Parameter: The descent parameter can be set to a standard LDLP. The improvements listed in Chapter 2 are mainly derived from equipped aircraft.

Thus, just checking the necessary data for the prediction, there are no problems. Even the task of the guidance module can be quite similar on the ground:
- No action if there are no deviations.
- If there are small deviations, guide the aircraft back to the designated route (4D).
- If there are big deviations, generate a new 4D trajectory fulfilling all the recent constraints. Having in mind the concept proposed in Chapter 2, these constraints are especially the lateral route and the time constraint at the late merging point.

The heading/track and airspeed/groundspeed conversion mentioned in Chapter 5 is solved automatically by the FMS. Based on the forecasted wind data, the FMS calculates both heading and track respectively airspeed and groundspeed for every point of the 4D trajectory. Another advantage of using the AFMS is automatic reduction of time deviations by calculating the appropriate path stretching length.

Of course, there is one big difference between ground based and onboard FMS concerning the guidance module: the ground based FMS has no direct, high frequency, connection to the autopilot.

```
17:29:38  DLH4685  [0.2NM,  3s,  -9ft]1

01:06:24>  Aircraft  generated
17:32:29>  <=  Flight  Plan  Message
17:32:29>  =>  Ground  init  message
17:22:12>  <=  Ground  init  message
17:22:12>  =>  Generate  local  traj  Message
17:22:13>  <=  Generate  local  traj  Message  [17:47:12]
17:22:13>  =>  Vector  [161°,  25000ft,  300kt  (1)]
17:22:19>  =>  Vector  [  70°  (2)]
17:23:20>  xtrack  17073/13802  ->  16/1
17:23:20>  =>  Generate  local  traj  Message
17:23:21>  <=  Generate  local  traj  Message  [17:47:13]
17:23:21>  =>  Vector  [  90°  (3)]
17:23:27>  =>  Vector  [280kt  (4)]
17:24:19>  =>  Vector  [152°  (5)]
17:29:32>  =>  Vector  [  6200ft  (6)]
```

Fig. 9: Ground based 4D guidance for one aircraft

Assuming no available data link, every guidance command has to be transmitted via voice communication. The pilot has to activate the guidance commands in the aircraft and read it back to the controller. In the worst case, the controller and pilot even have to wait for a free communication channel.

Therefore, unequipped aircraft have to be guided with very few instructions. While an airborne guidance module generates lots of commands to guide an aircraft around a curve, a ground based guidance module should preferably send only one command (the final heading). The same applies to altitude and speed commands – only the target values should be transmitted.

Another drawback of a ground based FMS, compared to the onboard one, is the inaccurate position data of the aircraft. The actual aircraft position is needed for the trajectory prediction (the trajectory should start at the actual position) and conformance monitoring. Considering the proposed concept, both problems can be solved by being less demanding on the navigation precision of unequipped aircraft.

A high accuracy of the transmission times and activation points is essential to obtain a good guidance quality. When the voice channel is blocked target values (especially heading) may vary. To prevent control delays, the guidance module has to look ahead.

For simulation trials, an exemplary implementation of a ground based guidance module has been implemented. The module is based on the AFMS described in Chapter 3 and, compared to the flight trials in Chapter 4, is expected to make things much easier for the controller.

The system was linked to a simulation tool performing a motion simulation of multiple aircraft. On default, the tool simulates FMS-equipped aircraft. When sending vectors to a specific aircraft it will be degraded to a 4D incapable one.

For an E-TMA radius of 100NM the guidance module needs in average 14 instructions if the aircraft initially is not on track. See the blue box in Fig. 9 for an exemplary communication plot. Entries with “=>” stand for send/request, “<=” for receive/answer.

Summarizing, the aircraft gets a flight plan from the arrival manager and initializes. The ground module generates a first trajectory and sets the aircraft (just for simulation purpose) to vectored mode.

The first vector is a heading of 70°, followed by a regenerate triggered by a too high cross track error. The arriving time changed by one second only, which is in the limits. Two heading commands and one speed command (280 knots) guide the aircraft along the cruise flight segment. Just before reaching the TOD, the aircraft is told to descent to 6200ft. The implemented module has a look ahead time of 30 seconds. The last instruction always is sent on the final just before glideslope intercept. It clears the aircraft for an ILS approach.

Trials showed that beginning the descent too early is less critical than too late because even LDLP approaches have few route left to descend down to the touchdown point. The same applies for speeds because high speeds necessitate reduction phases with low descent rates.

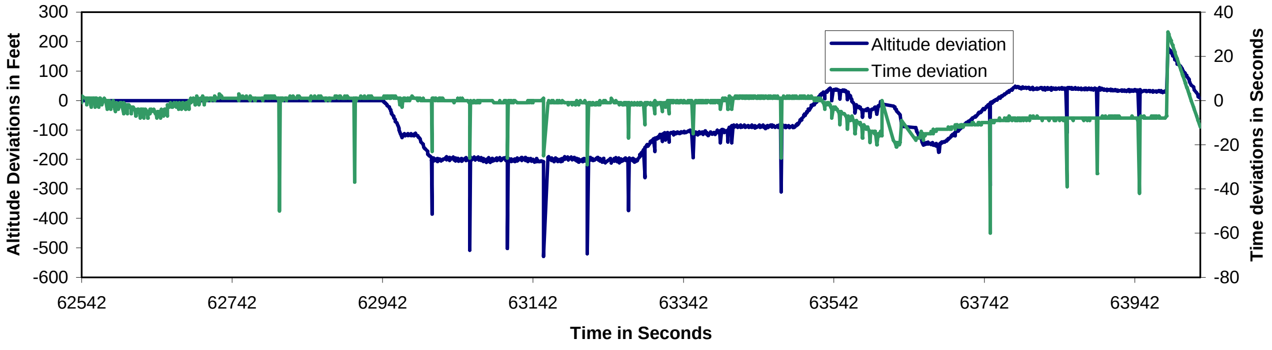

Fig. 10: Altitude and Time Deviations with Ground Based Guidance

The headline of the blue box informs about actual cross track, altitude and time deviations. Reference for the deviations is the trajectory point being closest to the actual aircraft position in terms of distance and time, normalizing the time to a distance using the airspeed. Currently, typical deviations are up to 150ft altitude error, 15s time error and 0.2NM cross track error (see Fig. 10). The outliers in the figure are caused by a jump of the reference position, especially in curves.

Future work regarding the ground guidance module will concentrate on implementing a simulation of the radio communication channel and typical response times of the pilot to get more realistic results.

7 Summary

This paper proposes a new concept for 4D-trajectory based TMA handling incorporating equipped and unequipped aircraft. It enables 4D equipped aircraft to fly environmental friendly trajectories even in high traffic situations. The performance of modern FMS has been described based on DLR's AFMS.

A concept for dealing with unequipped aircraft has been introduced that allows guiding 4D incapable aircraft by means of a ground based guidance module. First results of an implementation are promising regarding accumulated deviations and usage of radio communication channel. In average, 14 instructions are enough to have a time deviation less than 15 seconds for an E-TMA size of 100NM.

Using the ground based guidance functionality for unequipped aircraft, future research at DLR will prove that the proposed E-TMA concept enables equipped aircraft to fly environmental friendly without today's break-in of capacity within a mixed high traffic scenario.

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