4D TRAJECTORY MANAGEMENT IN THE EXTENDED TMA: COUPLING AMAN AND 4D FMS FOR OPTIMIZED APPROACH TRAJECTORIES

Bernd Korn*, Hartmut Helmke*, and Alexander Kuenz*
*** Institute of Flight Guidance**
German Aerospace Center, DLR
Braunschweig

Keywords: *DAG-TM, AMAN, FMS, 4D-CARMA*

Abstract

In order to meet the anticipated future demand for air travel DLR's Institute of Flight Guidance is investigating Distributed Air-Ground Traffic Management (DAG-TM) for arrivals in the Extended TMA. Based on the exchange of information between aircraft and ATC via data link, a trajectory based traffic management can take into account user preferred trajectories as well as make use of highly accurate prediction of aircraft movements. We here present results of flight trials and a concept to connect the on ground arrival manager with the on board flight management system. The concept also incorporates mixed traffic, i.e. 4D-FMS and data link equipped aircraft on the one hand and unequipped aircraft on the other hand.

1 Introduction

As traffic grows steadily, airport congestion and environmental impacts become a mounting problem and are already a limiting factor at some airports. Many of the international hubs and major airports are operating at their maximum throughput for longer and longer periods of the day. Some have already reached their operating limits as prescribed by physical as well as political and environmental constraints. This situation is expected to become more widespread and future traffic distribution patterns are likely to generate congestion at airports that currently do not experience capacity problems.

In order to meet the anticipated future demand for air travel many concepts e.g. as developed in European Research Projects like C-ATM [1] or OPTIMAL [2] propose a higher integration of aircraft capabilities in ATC operations, e.g. the capability of modern aircraft to precisely navigate along predefined routes. Here, major benefits can be expected especially in areas with a high traffic density like the TMA. Today, the air traffic in the TMA is still mainly controlled by ATC with means of radar vectoring which results in a high workload for the controllers and does not allow efficient aircraft trajectories to be followed.

Based on the exchange of information between aircraft and ATC via data link, a trajectory based traffic management can take into account user preferred trajectories as well as benefit from highly accurate prediction of aircraft movements. To achieve this, an early coordination between ATC and aircraft is required. Provided that the aircraft is equipped with a 4D capable Flight Management System the aircraft preferred 4D trajectory down to the threshold can be computed and downlinked to the respective ATC tools.

On the other hand, ATC has to make sure that this trajectory does not create any conflicts with other aircraft trajectories and respects the on ground optimization criteria, e.g. workload, flow, noise exposure. If necessary the ground planning system will generate appropriate constraints and uplink them to the on board FMS to ensure that the modified trajectory will be conflict free and meet the targeted time of arrival.

2 Trajectory Based Arrival Management

2.1 Present controller pilot communication

Fig. 1 shows the present situation concerning the air ground communication if an AMAN is used by the controller, e.g. the 4D Planer at Frankfurt Airport.

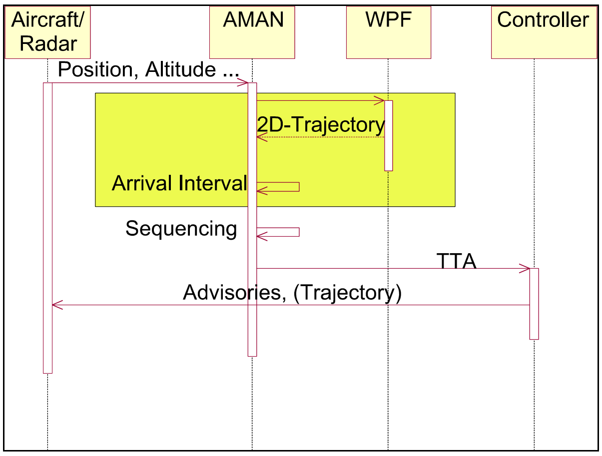

Fig. 1 Present Air Ground Communication

The radar units collect the aircraft positions, the transponders transmit the corresponding altitudes. The update rate is approx. every five seconds. Track information, horizontal and vertical speeds are derived and serve as primary input source for the arrival manager to derive a picture of the current traffic situation. Horizontal 2D profiles are predicted for each arriving aircraft by a module called waypoint finder (WPF) i.e. which route the aircraft may take from its present position to the runway threshold. The AMAN uses this to predict the earliest time of arrival for each aircraft in order to optimize the arrival sequence. Using the separation minima the AMAN assigns a runway and a target time of arrival (TTA) to each aircraft being displayed to the controller by a time scale. It is the controller's task to implement this sequence (or another one) with the assigned target times by adequate advisories via voice control.

2.2 Future Air Ground Cooperation

The colored part of Fig. 1 is the starting point to enhance air ground cooperation with data link. Within the C-ATM concept [1] it is designed that the planning computers on ground directly interact with the on board FMS. On board generated flight profiles are transferred to the ground systems via data link to incorporate them into a sector overall traffic planning. Flight plan conflicts are early detected. A negotiation process between aircraft and flight service provider is conceivable to get an optimal flight profile considering all present aircraft and ground constraints.

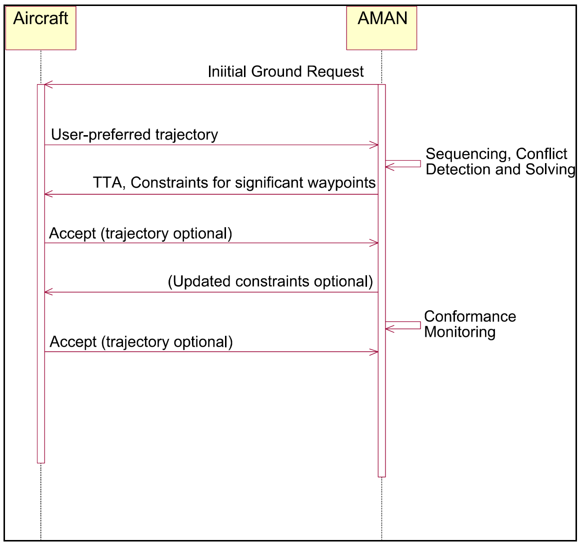

Fig. 2 Air Ground Cooperation

The air ground cooperation is initiated after radar contract by the AMAN. After the Initial Ground Request (Fig. 2), the on board FMS sends its flight intent (user-user-preferred trajectory) to the ground. The level of detail highly depends on the data link capacity.

During phases of high traffic demand the AMAN will normally not accept the exact user preferred trajectory due to conflicts with other aircraft. It is, however, possible to use the aircraft's target time for an update of the earliest time of arrival and the AMAN can extract parameters from the user preferred trajectory (e.g. descent rates, speeds) to trigger the ground trajectory generation process, after having updated the arrival sequence (see chapter. 3).

The ground generated conflict free trajectory is used to generate both advisories for unequipped aircraft for voice communication and to calculate appropriate ground constraints for the on board FMS for voice or data link communication.

Using the ground ATC constraints, the board FMS is generating a new trajectory. Depending again on the available data link capacity the new on board trajectory is transmitted to the ground (accepted trajectory in Fig. 2) and can replace the ground trajectory for detecting future planning conflicts and is used for conformance monitoring.

In both cases the FMS or the pilot have to send an acceptance message and the ground has to answer with a clearance if the accepted trajectory sufficiently meets all ground constraints. Then the pilot is allowed to activate the trajectory, which is transferred to the ground. If a ground update of the arrival sequence or an on board correction of the cleared trajectory is necessary a new air-ground negotiation cycle is started.

2.3 Requisites of the Concept

The presented concept highly depends on the ability of the AMAN to generate acceptable constraints for the board FMS, i.e. no real negotiation between air and ground is assumed.

Therefore it is indispensable that the trajectory engines used on board (i.e. the FMS) and on ground calculate approximately the same trajectories. The easiest way to meet this requirement would be to use the same software on board and on ground, but this is a nice requirement for simulations, but not for real life. It is very likely that the aircraft approaching an airport, using data link for air ground communication, will neither use a FMS of the same manufacturer nor the same FMS version. From today's view it is even unlikely, that an airline will publish its used FMS configuration parameters. Therefore it is necessary that all the relevant implicit on ground and on board assumptions are communicated, i.e. are made explicit.

Therefore we developed two different trajectory engines by two different teams – one for the ground trajectory calculation based on the BADA model and one for on board trajectory generation based on the FMS being developed during the PHARE project [3].

When connecting these two trajectory engines we had to consider the common use of data and models:.

- Air and ground have to use the same waypoint coordinate system (e.g. WGS 84).
- The same source for meteo data is necessary, e.g. air pressure, wind direction and speed (see ch. 5).
- Approach procedures (e.g. CDA, Low Drag Low Power (LDLP)),
- Speed profiles especially in the final approach phase,
- constraints are 2D waypoints with altitude, speed and curve restrictions (e.g. constant curve radius, but no constant CAS and altitude, bank angle may be used to compensate wind effects in order to maintain a constant curve radius),
- trajectory points are 4D waypoints with additional information concerning the waypoint type (e.g. start of descent, start of turn …), and
- tolerances, i.e. maximal and minimal values or exact values with allowed tolerance values have to be known.

The focal point, however, is that ground and board trajectory need not be sufficiently identical. Important, however, is that the board trajectory respects the constraints at the significant waypoints. Between these waypoints the aircraft is free, i.e. it can choose any user preferred profile, respecting the ground constraints. The challenge of the ground system is to minimize these constraints, so that still a smooth, efficient and conflict free inbound traffic flow is maintained.

The controller is still responsible for a safe and efficient guidance and control of the whole air traffic. The pilot is still responsible for his aircraft. Therefore both will stay the last arbitration in their decision area, i.e. the controller has to explicitly accept a clearance for a trajectory before it is sent to the pilot by the AMAN and the pilot has to explicitly activate a cleared trajectory. The rest of the air ground communication of Fig. 2 can be executed without explicit interaction of the controller resp. the pilot. This requires that the sequences, constraints and trajectories are accepted in most cases by the controller resp. the pilot, i.e. overruling the AMAN must be the exception.

3 The Arrival Manager 4D-CARMA

In this chapter we briefly describe the algorithm of DLR's latest arrival manager 4D-CARMA (four Dimensional Cooperative ARRival MAnager), a further development of DLR's previous arrival managers COMPAS [4] and the 4D Planner [5], being developed in close cooperation with the DFS, the German flight services.

Fig. 3 shows the basic algorithm of 4D-CARMA.

```
REPEAT FOREVER
...update = HandleMessages
...IF update
......Update previous sequence
......Calculate confilict free traject.
......Generate constraints
......Send constraints to aircraft
```

Fig. 3 Basic Algorithm of 4D-CARMA

3.1 Task HandleMessages

The *HandleMessages* task periodically receives radar data and performs a conformance monitoring with respect to the cleared board trajectory. If no on board trajectory is available due to data link restriction or aircraft equipment the corresponding ground trajectory is used. If the aircraft significantly deviates from its trajectory a replanning (update) of the sequence is necessary. *HandleMessages* also receives all aircraft related messages:

- *User Preferred Trajectory*:
  The parameters of the ground trajectory generator are initialized/updated for this aircraft.
- *Accept Constraints*:
  The ground trajectory is used for further conformance monitoring.
- *Reject Constraints*:
  New constraints have to be generated which might also cause a complete replanning of the arrival sequence and a position shift of the rejecting aircraft.
- *Accepted Aircraft Trajectory*:
  The parameters of the ground trajectory generator are updated. It is checked whether relevant deviations between ground and board trajectory exist which may cause a replanning. Otherwise a clearance is sent.
- *Trajectory activated:*
  The board trajectory, if available, is now used for conformance monitoring.

3.2 Task UpdatePreviousSequence

Depending on the reason for the update the whole sequence or only a subsequence is updated. The aircraft in the previous sequence not marked for an update are transferred without changes into the new sequence, i.e. no update of target times is performed. The subsequence, starting at the first aircraft marked for an update, is updated.

Different aircraft (sub-) sequences are tested in order to determine the approach sequence. These sequences are evaluated according to different evaluation criteria and the best evaluated sequence is chosen.

The following main evaluation criteria are considered in the context of the presented air ground communication concept.

- Quality Of Longway Order q_1(seq):
  The criteria considers whether the aircraft are sorted according to the distance from their current position to the runway threshold.
- Quality Of Constancy q_2(seq):
  The criteria considers the number of target time and aircraft position changes with respect to the previous sequence. This criteria balances the adaptivity on the one hand and the sequence stability on the other hand.
- Quality Of Being Early q_3(seq):
  The criteria considers whether the aircraft are sorted according to their earliest time of arrival.
- Quality Of No Holding q_4(seq):
  The criteria considers whether aircraft

have to fly a holding to lose time in order to meet the required time of arrival.

- Quality Of Noise Exposure $q_5(seq)$:
  This criteria considers the population dependant noise exposure rate of the sequence, considering the trajectories which implement the assigned target times of the selected sequence.

Before the sequencing process is started, horizontal 2D profiles (arrival routes) are predicted for each arriving aircraft (sect. 2.1), they are the base for calculating an earliest time of arrival (ETA) for each aircraft. Each arrival route is split into segments, i.e. each aircraft has to fly along its present segment to the final segment ending at the runway threshold. Each segment except the first ones have one or more successors and one or more predecessors except the final segment. We get a segment hierarchy (Fig. 4). All sequences which require an overtaking of two aircraft being on the same segment or on a predecessor segment are invalid sequences, an idea being adapted from the work of Robinson [6]. The only exception is if the controller turns an aircraft from the downwind segment to the base leg. This is recognized by 4D-CARMA from the radar data and the sequence will be immediately updated.

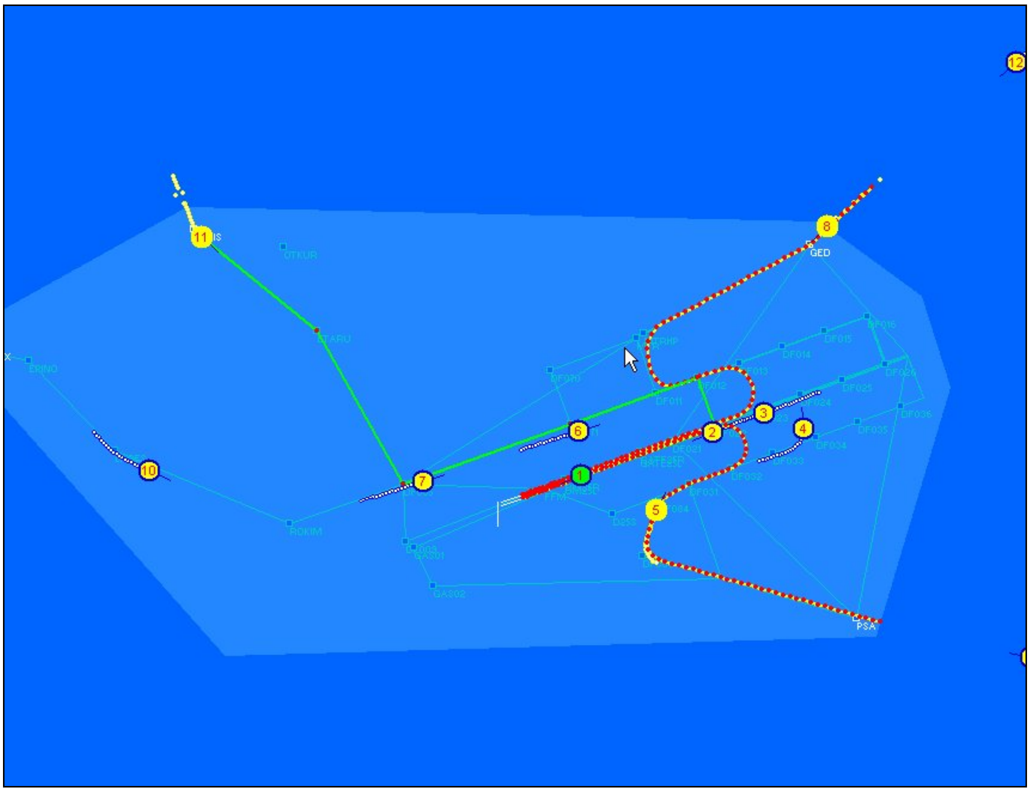

Fig. 4 4D-CARMA Segments of Frankfurt TMA

The planning of the arrival sequence is put down to an optimization task with multiple, mutually contradictive objective functions, which can be formally expressed by

$$seq^* = \arg \min_{seq \in SEQ} \{Q(\mathbf{a}, \mathbf{q}(seq))\}$$

where seq* is the optimal sequence, minimizing the quality function.

$$Q(\mathbf{a}, \mathbf{q}(seq)) = \mathbf{a}^T \mathbf{q}(seq)$$

is the scalar optimization function for the vector optimization problem, and

$$\mathbf{a}^T = [a_1 \quad a_2 \quad \dots \quad a_5], \quad a_i \geq 0 \, \forall i, \sum_{i=1}^{5} a_i, \quad \|\mathbf{a}\| > 0$$

is a weight vector for the five criteria functions.

Normally some ten thousand sequences are tested before the best sequence is selected. Therefore the evaluation of a sequence must be considerably faster than one millisecond. Especially for q_5 (Quality Of Noise Exposure) this is a very ambitious requirement, because this criteria is based on trajectories. However, 4D-CARMA uses an approximation of the population dependant noise exposure rate which can be calculated from the target time without explicitly calculating the corresponding trajectory.

As 4D-CARMA uses only monotonous evaluation functions $q_j(t)$ with respect to the assigned target time, the optimization of the sequences can be performed independent from the assignment of target times, i.e. it can be performed easier by investigating all possible, minimum staggered arrival sequences. So planning is now reduced to a tree-search problem.

However, since this is a NP-hard problem, a more sophisticated search algorithm is required for larger sets of arrivals to solve the problem in due time. The planner uses an A*-algorithm, which on average reduces the calculation time by about 40 percent. Furthermore, some heuristics are applied, which however cannot guarantee to find the global optimum solution. In particular, a so-called take-select strategy is implemented, which optimizes the arrival sequences for a subset several times by sliding a “selection-window” over a pre-sorted sequence [7], [8].

3.3 Task CalculateConflictFreeTrajectory

This task calculates a new trajectory for each aircraft whose target time has significantly changed. Fig. 5 shows the basic algorithm and Fig. 6 shows the subtask to create a conflict free trajectory from the aircraft’s current position to the metering fix (MF) / initial approach fix (IAF).

```
FOR all metering fixes (MF)
...Create conflict free traj. to MF
FOR all aircraft of main sequence
...Calculate traj. from MF to runway
...Merge 2 trajectories
```

Fig. 5 Trajectory Generation

So we use a commonly agreed technique of algorithm development – *divide and conquer*: We split the big problem into two separate smaller problems and claim that they are independent. We deconflict the aircraft before the metering fixes. Therefore the aircraft trajectories produce no conflicts from their present position to the metering fix and they have no conflicts at the runway threshold, because they are separated by time there. Between metering fix and final approach fix (FAF) we either can control the aircraft on separate routes, we can assure homogeneous speed profiles or we have to separate the aircraft at the merging points in the terminal maneuvering area (TMA).

```
Create subsequence for MF
FOR all aircraft ai of subsequence
...Assign target time for MF to ai
...Calculate traj. for ai to MF
...Check for conflict with prev. traj.
...Solve conflicts if necessary
```

Fig. 6 Trajectory Generation to MF

4 The Advanced Flight Management System AFMS

For the onboard part, the strategic trajectory generation as well as the automatic guidance along this trajectory according to schedule is the domain of the Flight Management System (FMS). As today’s FMS suffer from the poor interfacing with the aircrew and ATC an ***Advanced Flight Management System (AFMS)*** is being developed based on the Experimental FMS developed within the Programme for Harmonized Air traffic management Research in Eurocontrol (PHARE) [9], [10].

The conventional Flight Management functionality is extended by co-operative elements, which connect traffic planning modules on the ground to flight planning systems on board the aircraft via data link.

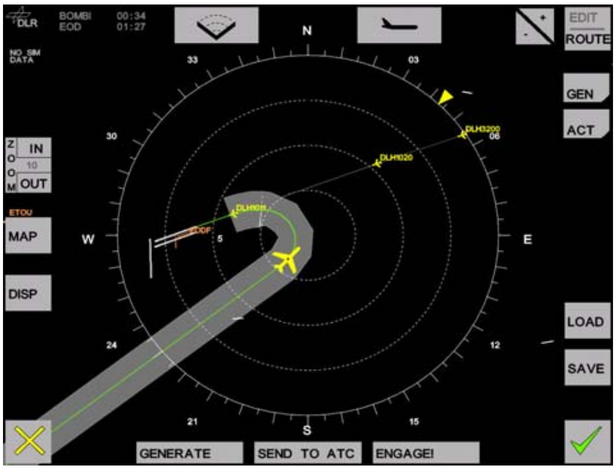

Fig. 7 Navigation Display as interface to the AFMS during a continuous descent approach

The main features of the AFMS are:

- Computation of 4D-trajectories on board considering
  - constraints received via data link from ATC,
  - aircraft performance parameters,
  - meteo conditions
  - economical criteria, etc.
- negotiation of the flight plan with ATC/ATM by means of data link connection, and
- 4D-guidance capabilities along the engaged negotiated trajectory.
- interactive navigation display as human machine interface
- FLS (FMS based Landing System) approaches including noise abatement approach procedures like Low Drag Low Power or (Segmented) Continuous Descent Approaches

5 Results Experiments and of Flight Trials

With our Traffic Simulator we generated the inbound traffic for a typical day of the Frankfurt extended TMA. The messages described in sect. 2.2 were exchanged between air and ground. In general, the a/c trajectories calculated by the FMS and the predicted trajectory calculated by the ground tool match satisfactorily. As only the significant waypoints of the board trajectory are downlinked, the 2D profiles do not match exactly in the curve segments. This results in small differences in the altitude over time diagram, but at important waypoints like e.g. the waypoint, where the aircraft is leaving the downwind segment, both trajectory calculations result in the same altitude value.

In 2005/2006 DLR has conducted flight trials with its test aircraft ATTAS and ZFB's A330-300 simulator in Berlin to prove that with the help of an advanced FMS an aircraft is capable to exactly predict its future 4D trajectory down to the threshold including complex approach procedures like e.g. Advanced Continuous Descends (ACDA) (see Fig. 8 for more details about the flown vertical profiles). This is a pre-requisite for introducing (A-)CDAs even in high-density airspace. A typical example of an approach flown during these trials is depicted in Fig. 9.

Descents were flown with variable CAS and flight path angle, engines idle. We measured the deviation between original estimated time of arrival (ETA) and real approach time for different descent procedures starting at FL70/80. The results were very satisfying:

Approach Type	Altitude-Error	ETA-Error
Low Drag Low Power	+/- 50 feet	+/- 3 sec.
Continuous Descent Approach (Idle)	+/- 50 feet	+/- 3 sec.
Segmented Continuous Descent Approach	+/- 100 feet	+/- 12 sec

Even if the values above sound great you have to consider that they are only achievable with proper knowledge of the aircraft performance, engines and last but not least the wind information available. All flight trials were performed with a meteo forecast not older than two or three hours.

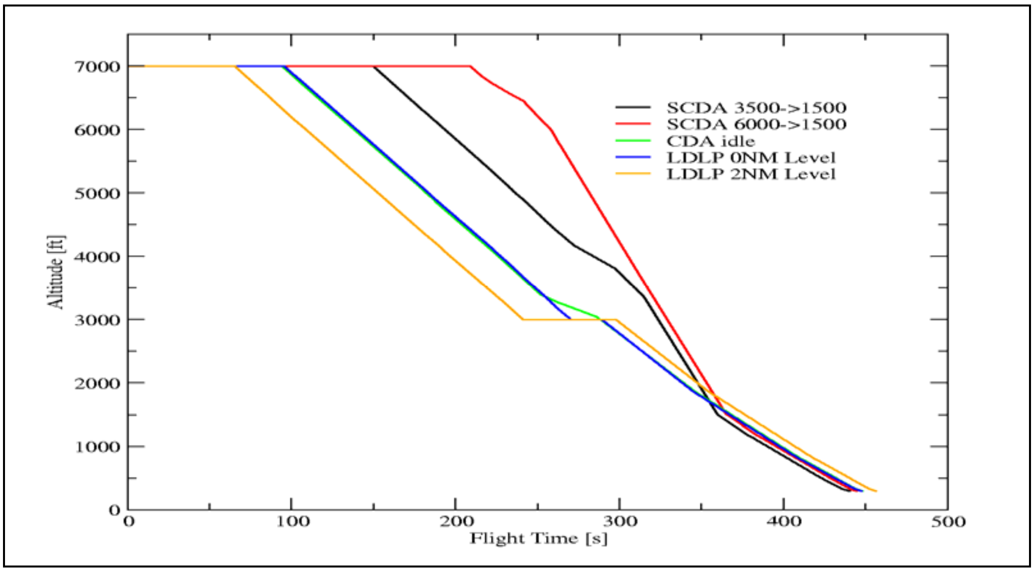

Fig. 8 Different Approach Types flown with FMS

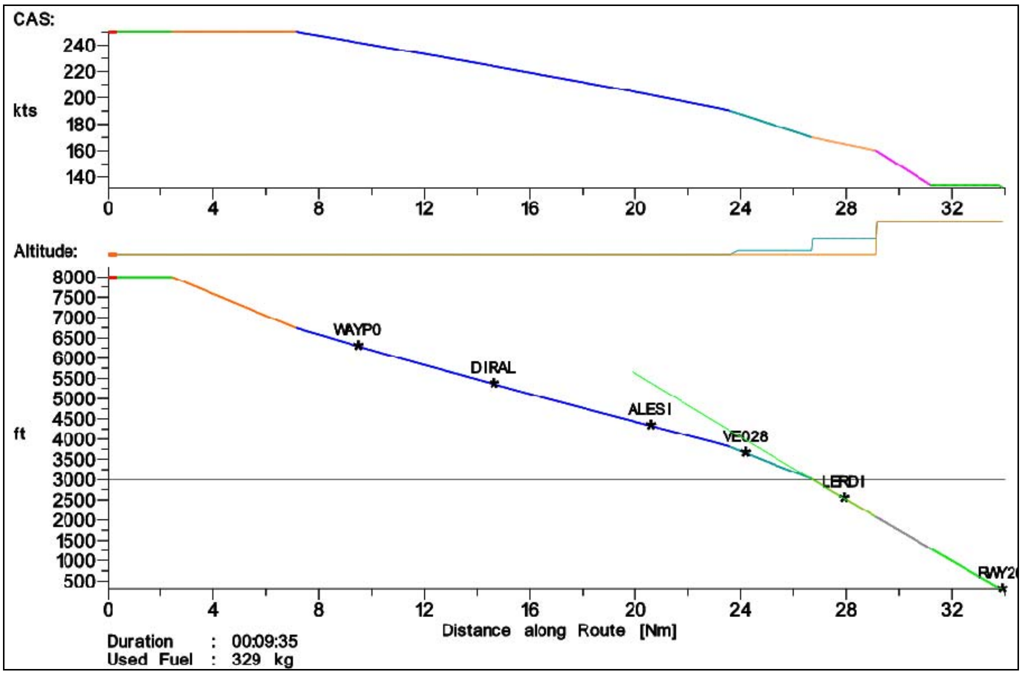

Fig. 9 CAS and altitude profile of CDA for A330-300

It is very important to ensure ground and air working on the same reliable wind data. Otherwise the ground constraints may lead to trajectories with conflicts or they will even be rejected by the board FMS.

An altitude error, e.g. due to an improper meteo forecast, initiates a re-planning of the active FMS trajectory. A positive altitude error will result in an earlier flaps extraction for a higher descent rate; a negative altitude will lead to a subphase insertion with reduced flight path angle to ensure low altitude errors.

6 Expected Benefits

Regarding the today's situation of major airports the following benefits can be expected:

- Reduction of flight time in TMA (including reduction of holdings due to a better traffic synchronization).
- Reduction of controller workload due to assistance in planning and implementing the arrival sequence and due to the reduction of voice communication.
- Integration of noise abatement procedures like continuous descent approaches (CDA) even in high density traffic situations.
- Improved use of landing capacity due to more precise aircraft navigation and higher trajectory predictability.

All these benefits depend on the availability of a highly reliable data link with sufficient capacity in order to downlink a complete trajectory. Furthermore the on board FMS must be able to handle time constraints with sufficient accuracy, e.g. DLR's advanced FMS. These requirements together will be fulfilled in 2020 at the earliest. However, a trajectory based guidance and control is also possible with restricted data link capacity.

Therefore, ground based AMAN and on board FMS planning are converging in three steps: Advisories based on conflict free AMAN trajectories are transmitted via voice control or CPDLC. Parameters of a published approach procedure are transmitted to the aircraft. If data link capacity allows it a full constraint list is sent by the AMAN and the FMS is transmitting the resulting 4D trajectory.

Using predefined TMA arrival routes and standardized arrival procedures reduces the amount of information being exchanged between air and ground. The ground system only defines the constraints at significant waypoints (time, speed, altitude and tolerances), see Fig. 10.

On the other hand the on board FMS has to downlink trajectory data (time, altitude, speed) at significant waypoints of the vertical profile, i.e. start and end of descent segments are relevant.

Already today it is possible, however, to vector the aircraft based on advisories derived from ground generated trajectories. The advisories are uplinked to the pilot via voice. Data link is not necessary, but CPDLC (controller pilot data link communication) may be helpful.

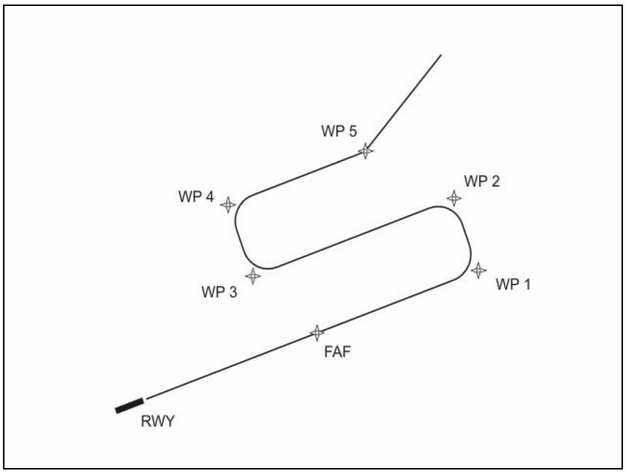

Fig. 10 Typical Arrival Route with Significant Waypoints

7 Summary

We presented a concept for air ground cooperation based on the exchange of ATC grounds constraint and aircraft board trajectory via data link. The concept enables user preferred trajectories as well as makes use of highly accurate prediction of aircraft movements.

Ground based AMAN and on board FMS planning can converge in three steps: Advisories based on conflict free AMAN trajectories are transmitted via voice control or CPDLC. Parameters of a published approach procedure are transmitted to the aircraft. If data link capacity allows it, a full constraint list is sent by the AMAN and the FMS is transmitting the resulting 4D trajectory.

This concept is open for integrating complex approach procedures like (A-)CDA even in high density traffic situation. For ACDA to be carried out efficiently, the vertical profile will be specific and won't be easily modifiable. Also, the lateral path has to be kept constant in order to guarantee a constant length; for those reasons, it is important to have a smooth flow of arriving traffic as there are fewer options for the controller to control the arrival sequence without too much interference. This requires an early planning of the arrival traffic and the early and reliable co-ordination of expected/required arrival times between arriving aircraft and ATC (particularly with the AMAN). Both requirements are fulfilled with the presented concept and tools (AMAN, FMS). The already very precise trajectory prediction capability of the AMAN allows for an optimized traffic flow in the (extended) TMA. The subsequent refinement of the trajectories by FMS-AMAN coordination and the capability of the FMS to exactly fly the trajectory ensure as well the implementation of the planed traffic flow.

Flight trials with DLR's ATTAS test aircraft as well as with the A330 full flight simulator in Berlin demonstrated that accurate flight prediction is possible provided precise wind information is available.

Time is ready to start or saying it with Albert Schweizer:

It is better to have high principles,
which are obeyed,
than to have even higher ones
which are disregarded.

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