Conflict Resolution with Time Constraints in Trajectory-Based Arrival Management

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***Abstract*—The meet-time problem in arrival management is analyzed, that is, the problem of generating conflict-free trajectories that meet the scheduled times of arrival. The conflict-resolution algorithms developed are based on the parameterization of the aircraft intents, using predefined trajectory patterns that model the aircraft trajectories actually flown. The algorithms have three steps: avoidance, recovery and optimization. Two algorithms are presented: one in which the optimization step is applied globally (to all aircraft) after the other two steps are performed for all aircraft, and another one in which the optimization step is applied locally to each aircraft after the other two steps are performed for the same aircraft. This second algorithm is shown to be efficient when the scenario is very demanding (in which the global optimization of the first algorithm is not effective). Results are presented for two different scenarios in the TMA of Canarias.**

I. Introduction

Arrival management involves two high-level functions at the strategic level: traffic management and separation management, both in the en-route arrival transition, and in the terminal area. The traffic management function (TM) performs runway assignment, sequencing and scheduling, that is, it creates a strategic arrival plan, and the separation management function (SM) synthesizes intents that meet the traffic management schedule and ensures that the arrival plan is conflict free. For example, in the architecture of NASA CTAS (Center TRACON Automation System), the Traffic Management Advisor creates the traffic plan (sequences and schedules), and the EnRoute Descent Advisor (EDA) determines the intents that meet this plan and are deconflicted (see Coppenbarger et al. [1]).

The SM function relies on the iterative combination of Trajectory Prediction (TP), Conflict Detection (CD) and Conflict Resolution (CR) functions. How this iterative process is carried out depends strongly on the particular algorithmic solution used to implement the SM task. The TP function translates intent into a predicted trajectory; the CD function uses the predicted trajectories to determine whether conflicts exist; and, the CR function determines intents that meet the objectives and constraints. The primary hard constraint is to maintain safe separation throughout the conflict area; in addition to this, there are other constraints such as those arising from procedures, terrain and/or airspace avoidance. On the other hand, the primary objective is to stay close to the schedule provided by the TM function; secondary objectives can include for example fairness, operating cost, and environmental impact.

In this work we analyze the CR problem in arrival management with time constraints, that is the problem of generating conflict-free trajectories that meet the scheduled times of arrival (STAs); this is the so-called *meet-time problem*. A simplified version of this problem is solved, in which departing aircraft are not considered in the traffic, only arriving aircraft.

We develop a CR algorithm that has three steps: avoidance, which generates conflict-free trajectories that meet the given sequence of arrival; recovery, in which the resolution trajectories are modified to meet the STA; and, optimization, to minimize a combination of costs (secondary objectives). In fact, we develop two different algorithms, depending on whether the optimization step is applied globally (to all aircraft) or locally (to each aircraft). This second algorithm is shown to be efficient when the scenario is very demanding (in which the global optimization is not effective).

We consider CR algorithms based on the parameterization of the aircraft intents, using predefined *trajectory patterns*, which are in fact *flight intents*, that model the aircraft trajectories actually flown (see Valenzuela and Rivas [2]). The nominal (intended) trajectories and the operator preferences are supposed known. The resolution trajectory patterns take into account changes of the nominal waypoints (vectoring) and changes of the aircraft speeds.

Many methods have been developed to treat CR problems as, for example, those described in Refs. [3] and [4]. In particular, predefined trajectory patterns to treat CR problems have been used by the following authors. Vilaplana [5] defines a lateral shift maneuvre, as a sequence of straight lines connected by inside turns, to solve en-route conflicts. Vivona et al. [6] consider a CR algorithm based on predefined maneuver patterns (lateral offset, direct intercept path, path stretch, waypoint migration and cruise step climb/descent), designed to execute different types of user-acepted path modification. Coppenbarger et al. [1] describe the EDA tool of CTAS, that solves the meet-time problem, where the cruise and descent speeds are used as parameters, and a simple *dog-leg* maneuver is considered for lateral routing (path stretching to absorb large delays).

The CR algorithm must rely on a trajectory predictor, which can be of different levels of complexity. On one side, one has the case of kinematic trajectory modeling (see, for instance, Bilimoria [7]). On the other side, one has the general case of nonlinear point-mass dynamic trajectory modeling (see, for instance, Menon et al. [8]). The meet-time problem in the terminal area requires the use of a general nonlinear point-mass dynamic model, so that one has the accuracy required by this demanding traffic scenario. This is the case considered in this work. We consider a dynamic nonlinear trajectory predictor in which realistic aerodynamic and engine models (based on BADA 3.6 [9]) are used, such that the dynamic flight paths are handled with the required precision (see Ref. [2]).

Results are presented for two different scenarios in the TMA of Canarias: one with 3 entry points, 2 merging points and a traffic of 30 aircraft/hour, all of the same category; and another one with 4 entry points, 3 merging points and 35 aircraft/hour, with aircraft of different categories. The performance of the CR algorithms is evaluated applying a set of Key Performance Indicators (KPI) to the resolution trajectories generated (these KPI are defined in Appendix A).

II. Trajectory Patterns

As already indicated, the CR algorithms developed in this work are based on the use of *trajectory patterns*, which are predefined trajectories (in fact, flight intents) that can be described in terms of a small number of parameters (this is important in the CR algorithm). These trajectory patterns are defined in detail in Ref. [2]. Two different types are considered:

— **Nominal trajectory patterns**, which model the operator preferred trajectories.

— **Resolution trajectory patterns**, which model the resolution trajectories.

The operator preferences must be known, and, then, the trajectory patterns can be defined. It is assumed that all aircraft have the same nominal trajectory pattern. However, to resolve the conflicts different resolution trajectory patterns are considered (see Section II.B).

In order not to make the CR process too demanding computationally, the trajectory patterns are formed by rectilinear segments only, which means that turns, pull-ups or push-downs are not considered.

A. Nominal trajectory pattern

The nominal trajectory pattern (the same for all aircraft) considered for the cruise and descent phases is as follows:

Lateral profile: defined by waypoints, according to the operator preferred trajectory.

Vertical profile:

— constant Mach, constant altitude cruise,

— horizontal deceleration at cruise altitude, from the Cruise Speed Reduction (CSR) point to the TOD point,

— Mach/CAS descent, with IDLE engine rating, until 10000 ft,

— horizontal deceleration at 10000 ft, until 250 kt,

— constant CAS descent, with IDLE engine rating, until glide-path interception altitude,

— horizontal deceleration at glide-path interception altitude,

— glide path.

This vertical profile is quite similar to the flight profile used in the Experimental Flight Management System of the PHARE programme (see Ref. [10]).

The cruise speed reduction (CSR) point is the beginning of the last segment of the cruise phase. This segment is a deceleration at cruise altitude, that ends when the descent Mach number is reached. The CSR point (instead of the TOD point) is determined iteratively, and, then, the TOD point is just the end of the segment.

The aircraft can enter the TMA while flying any of the above segments above 10000 ft.

B. Resolution trajectory patterns

The resolution trajectory patterns are modifications of the nominal trajectory pattern both in the lateral and vertical profiles. In the lateral profile all the waypoints of the nominal trajectory pattern in the TMA, except the TMA entry point, the IAF and those after the IAF, may be changed, keeping fixed the total number of waypoints. The modification in the vertical profile consists in introducing speed changes, in cruise and in descent above 10000 ft (below 10000 ft the speed profile does not change).

In general, besides the coordinates of the waypoints (longitude λ and latitude φ), the parameters of the nominal trajectory pattern that can be modified are the following speeds: cruise Mach M_c, descent Mach M_d and descent CAS CAS_d.

Different resolution trajectory patterns are considered depending on the flight segment the aircraft is flying when it enters the TMA. These patterns introduce some constraints in the free parameters to ensure that 1) some flight segments do exist, 2) the waypoints lie within the TMA, and 3) to limit the speed variations. A complete description of the patterns and their constraints can be found in Ref. [2].

III. Trajectory Prediction

The CR algorithm relies on a trajectory predictor that solves the aircraft equations of motion. In this paper, a point mass model with 3 degrees of freedom, commonly used for trajectory prediction (see Ref. [11]), is adopted. The state vector is in general defined by the aircraft mass, velocity and position, and the control vector by thrust, lift and bank angle. The scalar equations of motion are formulated based on the following general assumptions: spherical, non-rotating Earth; rigid and symmetric aircraft; symmetric flight; and thrust parallel to the aircraft aerodynamic velocity. These assumptions are appropriate for subsonic, transport aircraft. An additional assumption is that there is no wind.

Additionally, some supplementary models are needed: Earth, aerodynamic and propulsion models. In this paper the aircraft models are based on BADA 3.6 [9], the atmosphere model is ISA, and the Earth has constant gravity.

The trajectory predictor is described in detail in Ref. [2].

TABLE I
SEPARATION MINIMA [NM] (ICAO DOC-4444)

		Preceding aircraft		
		Heavy	Medium	Light
Succeeding aircraft	Heavy	4	3	3
	Medium	5	3	3
	Light	6	5	3

IV. CONFLICT DETECTION

In the CD algorithm the horizontal distance d_{ij} between any pair of aircraft i and j is measured at discrete times $t_k = t_0 + k\Delta t$ during the time they both are in the TMA. The minimum distances $(d_{ij})_{min}$ are computed and compared with the corresponding separation minimum $d_{s,ij}$. In case $(d_{ij})_{min} < d_{s,ij}$ a conflict is detected between aircraft i and j. In this work, $\Delta t = 0.1$ s.

The CD algorithm considers the wake turbulence categories of aircraft (light, medium and heavy) and the wake turbulence separation minima, which are defined in ICAO DOC-4444 [12]. The separation minima used are shown in Table I. In this table it is considered that if aircraft i is succeeding aircraft j, then aircraft j is preceding aircraft i, or vice versa. This situation takes place in a nominal scenario in which all the aircraft fly predefined tracks. However, the aircraft trajectories proposed by the CR process allow the aircraft to be located at any point and with any heading. Therefore, to properly select the separation minimum between two aircraft it is necessary to determine at each time the relative position between them.

The horizontal distance between two aircraft is measured along a great circle (minimum distance) on the Earth surface, which is given by

$$d_{ij} = R_E \cos^{-1}\left[\sin\varphi_i \sin\varphi_j + \cos\varphi_i \cos\varphi_j \cos(\lambda_j - \lambda_i)\right] \quad (1)$$

where (λ_i, φ_i) and (λ_j, φ_j) are the geodetic coordinates of the aircraft horizontal positions and R_E is the Earth radius.

V. CONFLICT RESOLUTION

In the context of the CR process in a TMA scenario, the meet-time problem consists in generating conflict-free, on-time trajectories, that is, deconflicted trajectories that meet the scheduled times of arrival associated either to waypoints or runway threshold. Maintaining safe separation is considered as a *hard constraint* that must be always met. The scheduling requirement is a *primary objective* that has to be met as close as possible. Other objectives which should be met, called *secondary objectives*, are fairness (to attempt to distribute among all the aircraft the costs incurred in deviating from the user preferred trajectory), operating costs, and environmental impact.

The inputs to the CR algorithm are a set of n aircraft, described by their nominal trajectories or intents and their scheduled times of arrival; and the outputs are n deconflicted trajectories or intents and their arrival times. In case that there exist aircraft whose trajectories are fixed and cannot be modified, they can be introduced as additional constraints to the CR algorithm, as described in Ref. [2].

In the following, two CR algorithms are presented.

A. 2-step CR algorithm

This algorithm is divided into two phases: Phase 1 (with 2 steps) and Phase 2 (the structure of this algorithm can be seen in Fig. 1). Phase 1 deals with hard constraints and primary objectives (conflict-free, on-time trajectories) whereas Phase 2 deals with secondary objectives (fairness, cost optimization ...). According to this structure, Phase 2 is not performed until Phase 1 is completed.

1) Phase 1:

The objective of this phase is to generate conflict-free trajectories (hard constraint) that meet the scheduling requirement (primary objective). To achieve this goal, two steps are carried out: *avoidance* and *recovery* (using the nomenclature of Ref. [13]). These two steps are applied sequentially to each aircraft according to the arrival sequence. While aircraft i is processed (as it will be seen later), the only conflicts considered are those with the $i-1$ previous aircraft already processed (when the first aircraft is processed, no conflicts exist).

The two steps of this phase applied to each aircraft are carried out as follows:

a) Avoidance: In the avoidance step, two requirements are imposed: the trajectories must be conflict free and they have to meet a sequencing requirement (notice that the scheduled arrival times define an arrival sequence). The last requirement is imposed as a new constraint: the arrival time of a given aircraft must be greater than the scheduled arrival time of the previously processed aircraft. The output of this step is a set of conflict-free trajectories that comply with the pre-determined arrival sequence.

This step then consists in generating a trajectory for aircraft i that satisfies the following set of constraints:

$$\begin{array}{ll} \mathbf{c}_{TPi} \leq 0 & \\ (d_{i,j})_{min} \geq d_{s,ij}, & \forall j = 1, \ldots, i-1 \\ t_{ETA,i} > t_{STA,i-1} & \end{array} \quad (2)$$

where $\mathbf{c}_{TPi}$ is the set of constraints imposed by the resolution trajectory pattern assigned to aircraft i, $(d_{i,j})_{min}$ the minimum distance between aircraft i and j, $d_{s,ij}$ the separation minimum that corresponds to aircraft i and j, $t_{ETA,i}$ the estimated time of arrival of the aircraft i, and $t_{STA,i-1}$ the scheduled time of arrival of the previously sequenced aircraft.

Besides the constraints imposed by the resolution trajectory pattern, the second constraint refers to the conflicts between aircraft i and the $i-1$ previously processed aircraft, and the third constraint is the sequencing constraint: the arrival time of the aircraft i must be greater than the arrival time of the previously sequenced aircraft.

In the avoidance step, first, it is checked if all the given constraints are met by the nominal trajectory; if not, a random search is performed to obtain a first valid solution. Since the

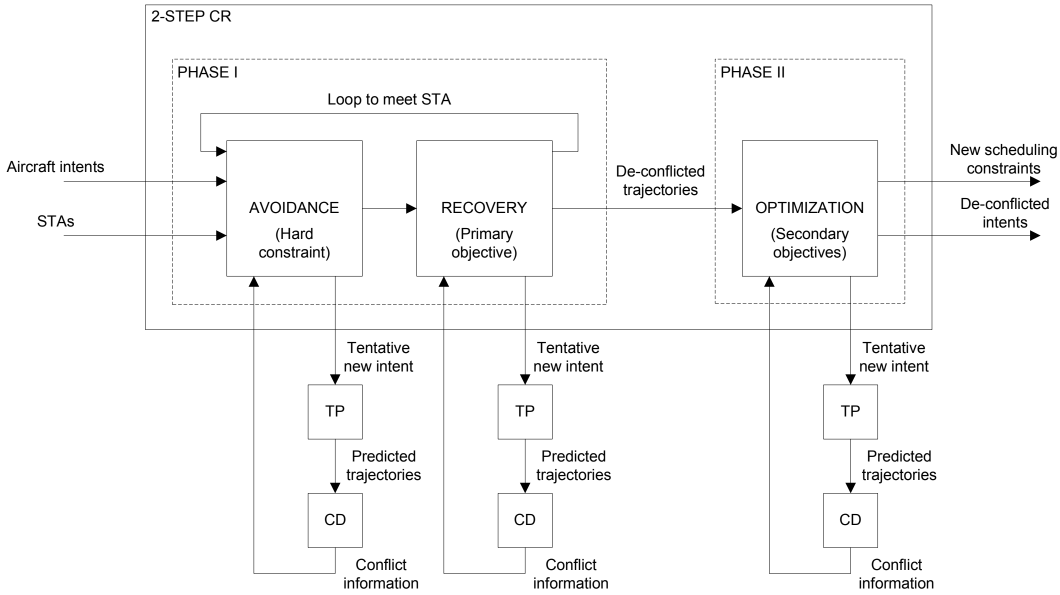

Fig. 1. Structure of the 2-step CR algorithm.

vector $\mathbf{x}_i$ contains the parameters that define the trajectory of aircraft i, this step reduces to iteratively generate random vectors $\mathbf{x}_i$ until one of them satisfy all the constraints. These vectors are generated around $\mathbf{x}_i^0$, which represents the nominal trajectory for aircraft i, using MATLAB's *randn*, a function that generates normally distributed pseudorandom numbers.

b) Recovery: In the recovery step, the conflict-free trajectories obtained in the avoidance step are modified in order to have arrival times as close as possible to the scheduled ones. The output of this step is a new set of conflict-free trajectories with arrival times very close to the scheduled ones.

To meet the scheduled arrival time, an optimization problem is formulated: minimize the deviation from the scheduled arrival time, $t_{STA,i}$, keeping the trajectory conflict free, that is,

$$\begin{aligned} &\text{minimize} \quad f = (t_{ETA,i} - t_{STA,i})^2 \\ &\text{subject to (2)} \end{aligned} \tag{3}$$

Note that deviations in both directions are penalized.

If after solving this optimization problem the scheduled arrival time is met, then the next aircraft is processed. Otherwise, the avoidance step is repeated in order to generate a new starting random trajectory. This process can be repeated up to 5 times if necessary. In case that after 5 repetitions it is not found any trajectory that meets $t_{STA,i}$, it is considered that the best solution is that trajectory with a $t_{ETA,i}$ closer to $t_{STA,i}$, and the next aircraft is processed.

2) Phase 2:

After executing Phase 1, all the trajectories are conflict-free with estimated arrival times very close to the scheduled ones. However, the resolution trajectories obtained may not meet the secondary objectives: have a high cost (for example, a high deviation from the nominal trajectories). Thus, this optimization phase aims at minimizing a combination of costs considering such secondary objectives; in this work only the lateral deviation from the nominal trajectories is considered. Starting from the trajectories found in Phase 1, a global optimization is performed. The modification of all the intents at once implies a high computational cost.

The following optimization problem is formulated:

$$\begin{aligned} &\text{minimize} \quad f = \frac{1}{n}\sqrt{\sum_{i=1}^{q}\left[\left(\lambda_i - \lambda_i^0\right)^2 + \left(\varphi_i - \varphi_i^0\right)^2\right]} \\ &\text{subject to} \\ &\mathbf{c}_{TPi} \leq 0 \;\; \forall i = 1, \dots, n \\ &(d_{i,j})_{min} \geq d_{s,ij} \;\; \forall i,j = 1,\dots,n, \;\; j \neq i \\ &t_{ETA,i} - t^1_{ETA,i} = 0 \;\; \forall i = 1,\dots,n \end{aligned} \tag{4}$$

where $\left(\lambda_i^0, \varphi_i^0\right)$ are the nominal location of the waypoints, q the total number of waypoints that can be changed, and $t^1_{ETA,i}$ is the estimated time of arrival of the aircraft i obtained in Phase 1. Notice that the last constraint represents that the arrival time obtained in Phase 1 is to be maintained.

B. 3-step CR algorithm

The poor performance shown by the optimizer in the lateral optimization of the 2-step CR algorithm (Phase 2) with a very demanding scenario, as it will be shown in Section VI.B, makes it necessary to modify the optimization procedure. We consider a modification in which smaller optimization problems are solved. To that end, Phase 2 is eliminated and a third optimization step is added after the avoidance and recovery steps, as can be seen in Fig. 2. The three steps are performed sequentially for each aircraft. The first two steps are as before (Section V.A). Once these two steps have been executed an optimization of the lateral deviation of aircraft i is performed keeping fixed its $t^1_{ETA,i}$ (as in Phase 2 before). In this third step, while aircraft i is processed, the only conflicts

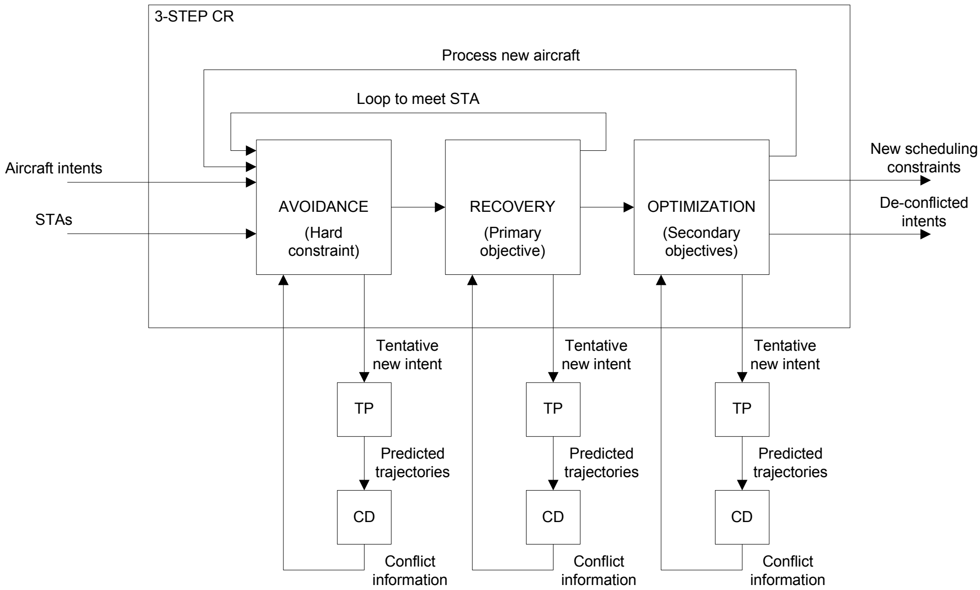

Fig. 2. Structure of the 3-step CR algorithm.

considered are those with the $i-1$ previous aircraft already processed, as in the two first steps. Once this last step is executed, the next aircraft is processed.

The optimization problem solved in the third step while aircraft i is processed is formulated as:

$$\begin{aligned} \text{minimize} \quad & \sqrt{\sum_{j=1}^{q_i}\left[\left(\lambda_j-\lambda_j^0\right)^2+\left(\varphi_j-\varphi_j^0\right)^2\right]} \\ \text{subject to} \quad & \mathbf{c}_{TPi} \leq 0 \\ & (d_{i,j})_{min} \geq d_{s,ij} \qquad \forall j=1,\dots,i-1 \\ & t_{ETA,i}-t^1_{ETA,i}=0 \end{aligned} \tag{5}$$

where only the waypoints of aircraft i are considered, being q_i the total number of waypoints that can be changed for this aircraft.

VI. Scenarios

Two scenarios are considered: one in which the 2-step CR algorithm is efficient, and another, more demanding, in which the 3-step CR algorithm must be used to meet the secondary objectives.

A. Scenario 1

Scenario 1 corresponds to the TMA of Canarias with three entry points (TERTO, RUSIK and WPT1), and two merging points (FAYTA and CANIS). The waypoint WPT1 is placed South-East of FAYTA, at (φ,λ)=(27°40'00"N,13°30'00"W). In this scenario one has 30 aircraft arriving in one hour, with the scheduled arrival times equally spaced 120 seconds. All aircraft are of the same category (medium): 12 CRJ, 12 Airbus A320 and 6 Boeing 737-400.

The general properties of this scenario are: number of aircraft, 30; mean aircraft mass at TMA entry point, 41372 kg; maximum deviation time, 148.0 s; mean deviation time, 61.3 s; and conflicts between nominal trajectories, 12.

In this scenario a separation minimum of 3 NM has been considered. The nominal trajectories are represented in Fig. 3. Each aircraft is bounded by a circle of radius 1.5 NM.

B. Scenario 2

The scenario 2 is a modification of Scenario 1 with an additional entry point (WPT2). Now it has four entry points (TERTO, RUSIK, WPT1 and WPT2), and three merging points (FAYTA, BETAN and CANIS). The arrival procedure that starts at WPT2 is composed of the following waypoints: WPT2 (φ,λ)=(30°15'34"N,14°30'11"W), WPT3 (φ,λ)=(29°19'07"N,14°25'51"W), BETAN, CANIS, ENETA, and RWY. The aircraft have different categories (medium and heavy).

In this scenario 35 aircraft arrive in one hour: 9 CRJ (medium aircraft), 9 Boeing 737-400 (medium aircraft), 8 Airbus A320 (medium aircraft), and 9 Boeing 777-300 (heavy aircraft). The scheduled arrival times are equally spaced 120 seconds. Thus, the deviation time (difference between the nominal ETA and STA) of the last landing aircraft is at least 600 seconds.

The general properties of this scenario are: number of aircraft, 35; mean aircraft mass at TMA entry point, 96657 kg; maximum deviation time, 630.83 s; mean deviation time, 274.15 s; and conflicts between nominal trajectories, 30. Note that this scenario is more demanding than Scenario 1: all the properties are significantly greater.

The nominal trajectories are represented in Fig. 4. Each aircraft is bounded by a circle of radius 1.5 NM. The medium aircraft are bounded by red circles and the heavy ones by blue circles.

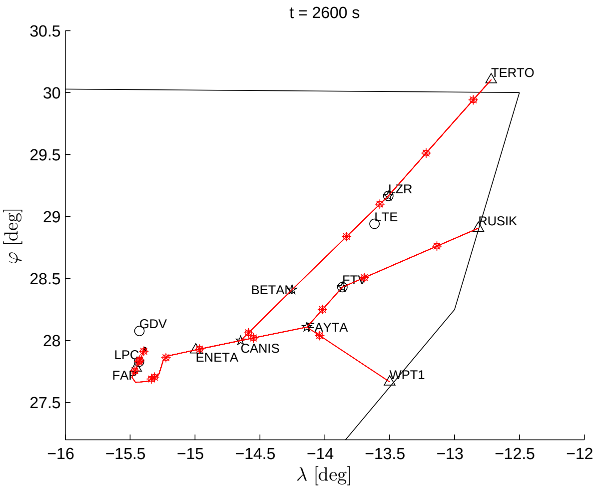

Fig. 3. Scenario 1, nominal trajectories at $t = 2600$ s.

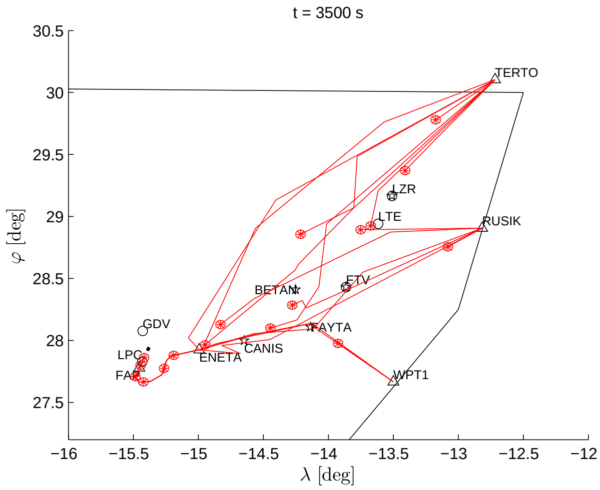

Fig. 5. Scenario 1, 2-step CR resolution trajectories at $t = 3500$ s, Phase 1.

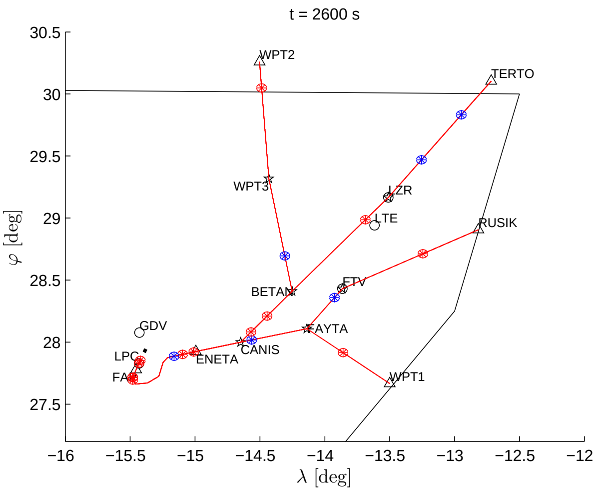

Fig. 4. Scenario 2, nominal trajectories at $t = 2600$ s.

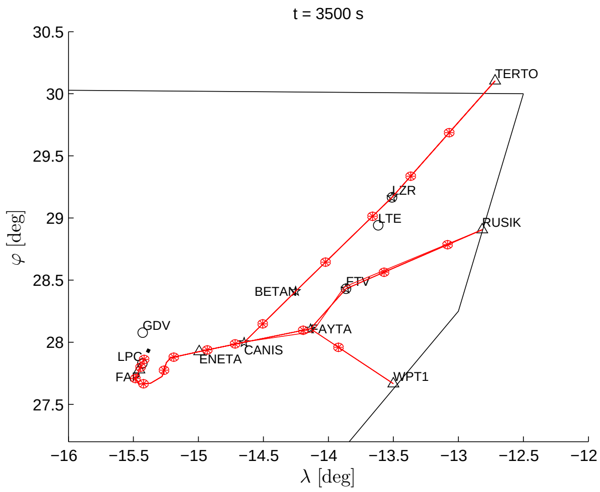

Fig. 6. Scenario 1, 2-step CR resolution trajectories at $t = 3500$ s, Phase 2.

VII. Results

In this section the results obtained in the generation of conflict-free, on-time trajectories are presented. Both algorithms, 2-step and 3-step, are used in Scenarios 1 and 2.

The optimization problems are solved using the *Sequential Quadratic Programming* (SQP) method, see Ref. [14], implemented in MATLAB's *fmincon*.

A. Scenario 1

The conflict-free, on-time trajectories obtained with the 2-step CR algorithm after Phase 1 are represented in Fig. 5, and those obtained after Phase 2 in Fig. 6 (in these figures, some aircraft have already landed, and some others have not yet entered the TMA). After Phase 1 the value of the objective function is 0.1324 deg and after Phase 2 it reduces to 0.0048 deg. This objective function measures the deviation of the resolution waypoints from the nominal waypoints (see Section V.A.2). The improvement obtained after executing Phase 2 is notorious. After the CR execution call, the number of conflicts is 0 and all aircraft are on time, with a mean deviation time of 0.04 seconds. These and other indicators of the solution are provided in Table II.

TABLE II
2-STEP CR RESOLUTION INDICATORS (SCENARIO 1).

Indicator	Value
Objective function value after phase 1, f_1 [deg]	0.1324
Objective function value after phase 2, f_2 [deg]	0.0048
Maximum deviation time, T [s]	0.10
Mean deviation time, $\overline{T}$ [s]	0.04
Mean fuel cost, $\overline{C}$ [kg]	-16.71

The resolution trajectories obtained with the 3-step CR algorithm are represented in Fig. 7. It can be seen that the deviation from the nominal trajectories is small, but for some aircraft it is greater than the deviation obtained with the 2-step

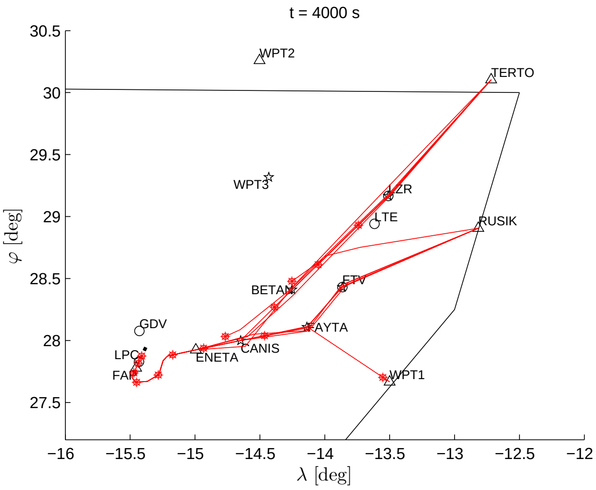

Fig. 7. Scenario 1, 3-step CR resolution trajectories at $t = 4000$ s.

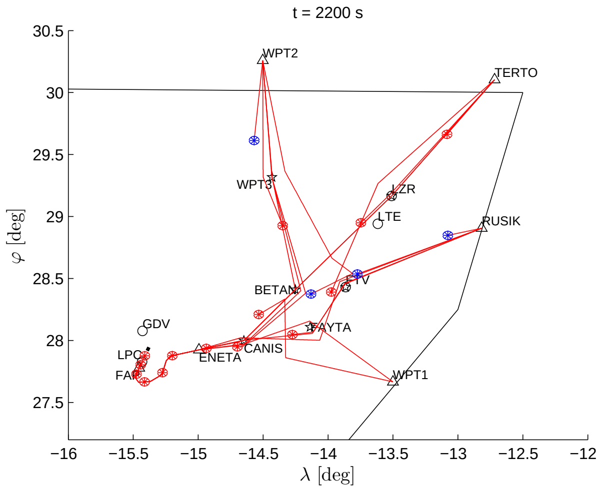

Fig. 8. Scenario 2, 3-step CR resolution trajectories at t=2200 s.

TABLE III
3-STEP CR RESOLUTION INDICATORS (SCENARIO 1).

Indicator	Value
Objective function value, f [deg]	0.0488
Maximum deviation time, T [s]	0.2783
Mean deviation time, $\overline{T}$ [s]	0.1003
Mean fuel cost, $\overline{C}$ [kg]	-7.45

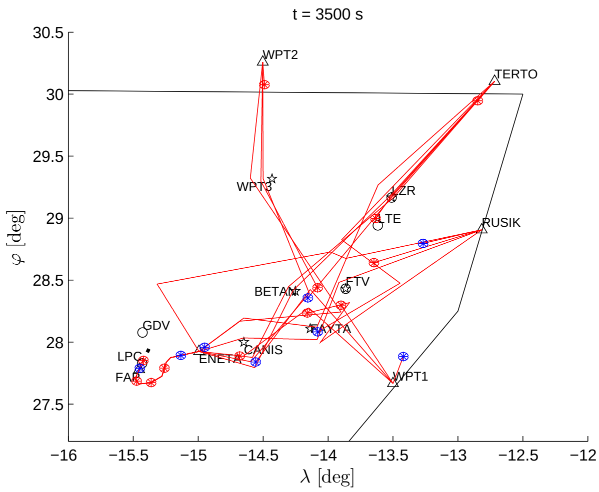

Fig. 9. Scenario 2, 3-step CR resolution trajectories at t=3500 s.

algorithm. Quantitatively, the value of the objective function is 0.0406 deg, as opposed to 0.0048 deg obtained with the 2-step algorithm. These results indicate that the global optimization is more efficient. Other indicators of the solution are provided in Table III.

B. Scenario 2

If one uses the 2-step CR algorithm in the second scenario, the value of the objective function after Phase 1 is 0.2053 deg, but Phase 2 does not provide any improvement: the global optimization (considering all the aircraft) is not effective. One possible explanation to this poor performance of Phase 2 is that Scenario 2 is more demanding than Scenario 1 due to: 1) the higher number of aircraft (35 opposed to 30), which determines the number of free parameters and constraints; 2) the mean deviation time (274.2 s opposed to 61.3 s), which indicates that the aircraft have to spend more time flying inside the TMA; and 3) the number of conflicts among nominal trajectories (30 opposed to 12), which suggests a greater interaction among trajectories.

The resolution trajectories obtained with the 3-step CR algorithm are plotted at two different times in Figs. 8 and 9. It can be seen that the horizontal deviation at the larger time is greater because the differences between the ETA and the STA of the last aircraft are much bigger than the differences of the first aircraft, and have to spend more time flying inside the TMA.

The indicators of the resolution trajectories obtained are shown in Table IV. After the CR execution call, the number of conflicts is 0 and the mean deviation time is 4.84 seconds. It can be shown that all the medium aircraft that arrive after heavy aircraft are not on time. This deviation arises because a separation of 2 minutes at the runway threshold is not compatible with the separation minimum applied of 5 NM (Table I) and with the evolution of the speeds during the long common approach. Therefore, in this scenario, bigger separation between STA should be used between medium and heavy aircraft. In addition, proper separation can save computational time because the CR tries to meet the STA although it is physically impossible.

The mean fuel cost is significantly greater than in Scenario 1. This is due to: the higher deviation time of the scenario (the delay is absorbed in the TMA) and to the increase in the mean mass (the fuel consumption is larger).

TABLE IV
3-STEP CR RESOLUTION INDICATORS (SCENARIO 2).

Indicator	Value
Objective function value, f [deg]	0.0873
Maximum deviation time, T [s]	38.47
Mean deviation time, $\overline{T}$ [s]	4.84
Mean fuel cost, $\overline{C}$ [kg]	323.96

VIII. CONCLUSIONS

In this paper a method to solve the meet-time problem in arrival management has been presented. The method is based on the parameterization of the aircraft intents. To perform this parameterization, predefined trajectory patterns have been considered. The resolution trajectory patterns take into account changes of the nominal waypoints (vectoring) and changes of the aircraft speeds.

The resolution method is formed by 3 steps. First, the avoidance step, in which the objective is to obtain resolution trajectories that are conflict free and meet the sequencing constraint; second, the recovery step, in which these resolution trajectories are modified to meet the scheduled arrival times as close as possible; and, third, an optimization step in which the goal is to minimize a given combination of costs (secondary objectives).

Two algorithms have been presented. One in which the 3rd step (optimization) is applied globally (to all aircraft) after steps 1 and 2 are performed (for all aircraft), and another one in which the 3rd step is applied locally to each aircraft after steps 1 and 2 are performed for the given aircraft. The results have shown that the first algorithm is adequate for scenarios which are not very demanding, in which the global optimization is effective (that is, it improves the results obtained with the avoidance and recovery steps). On the other hand, for very-demanding scenarios, the global optimization is not effective and the 2nd algorithm must be used. The performance of the algorithms has been evaluated using a set of key performance indicators, which have been applied to the resolution trajectories generated.

Departing aircraft and aircraft whose trajectories cannot be modified have not been considered in this work. They represent new constraints in the optimization problems, increasing the difficulty of the resolution process. The inclusion of these aircraft is left for future work, as well as the study of other scenarios with different route structures, and other traffic conditions, for instance, a mixture of early and late aircraft, or schedules with more incoming aircraft.

APPENDIX A. KEY PERFORMANCE INDICATORS

Maximum deviation time

This is an efficiency indicator that measures the maximum absolute value of the difference between the ETA of the resolution trajectory and the STA. It is given by

$$T = \max_i \left(|t_{ETA,i} - t_{STA,i}|\right) \quad (6)$$

Mean deviation time

This is also an efficiency indicator that is computed adding the absolute values of the differences between ETA given by the resolution trajectory and the STA and dividing the result by the number of aircraft. It is given by

$$\overline{T} = \frac{1}{n}\sum_{i=1}^{n} |t_{ETA,i} - t_{STA,i}| \quad (7)$$

Mean fuel cost

This is a cost-effectiveness indicator that is computed as the sum of the fuel costs for all aircraft, divided by the number of aircraft. It does not take into account how the costs are distributed among the aircraft. It is given by

$$\overline{C} = \frac{1}{n}\sum_{i=1}^{n} \Delta m_{F,i} \quad (8)$$

where $\Delta m_{F,i}$ is the extra fuel consumption due to the resolution trajectory of aircraft i.

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