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Conflict pattern analysis under the consideration of optimal trajectories in the European ATM

Sergio Ruiz
Department of Telecom. and System Engineering
Universidad Autonoma de Barcelona (UAB)
Barcelona (Catalunya), Spain

Manuel Soler
Department of Bioeng. and Aerospace Engineering
Universidad Carlos III de Madrid (UC3M)
Leganés (Madrid), Spain

***Abstract*—In the future Air Traffic Management (ATM) system, the trajectory becomes the fundamental element of a new set of operating procedures collectively referred to as Trajectory-Based Operations (TBO). This has encouraged a renewed interest for the application of trajectory optimization techniques in commercial aviation, resulting in the so-called continuous operations that have shown significant benefits in terms of fuel savings and CO$_2$ emissions. Unfortunately, the real implementation of continuous operations is in turn still far to be possible. Its implementation must be also tested and compared against other key performance indicators such as safety and capacity. Therefore, the main contribution of this paper is to provide a preliminary analysis on how continuous operations might impact the traffic and subsequent conflict patterns (i.e, number and distribution of potential interactions among trajectories) at the European ATM network level. Conflict patterns serve as an indicator of the safety and capacity levels of the ATM system. The problem analysis has two scales, i.e., the mircroscale and the mesoscale. In the microscale analysis the optimal trajectories have been found for each flight, whereas in the mesoscale the conflict patterns have been analysed within a given volume of airspace (in this case, a big single sector representing the entire European airspace).**

***Index Terms*—4D Trajectory Optimization, Continuous Operations, Conflict Detection, Conflict Pattern Analysis.**

I. INTRODUCTION

Nowadays aircraft usually fly following predefined routes for the lateral profile and using flight level or isobars surfaces for the vertical profile according to ICAO rules [1]. In addition, operations rely on continuous tactical intervention from Air Traffic Control (ATC). As a result, flown trajectories are usually far from optimal, thus increasing operational cost and environmental impact [2, Section 3.5]. In the futurelly envisioned Air Traffic Management (ATM) system, the trajectory becomes the fundamental element of a new set of operating procedures collectively referred to as Trajectory-Based Operations (TBO) [3]. Improved capabilities in trajectory management, i.e., planning, sharing, agreeing, and updating (including real time revision of the trajectory and synchronization of airside and ground side systems), will result in enhanced ATM performances in terms of capacity, efficiency, safety, and environmental impact. Indeed, derived from the above mentioned TBO concept, new operational concepts are demanded to reduce the cost and environmental impact per flight as much as practicable.

Opposite to conventional procedures, it is widely known that the best aircraft performance is that resulting from continuous operations, i.e., Continuous Climb Departure (CCD), Continuous Climb Cruise (CCC), and Continuous Descent Approach (CDA). Extensive research related to the potential benefits derived from the application of continuous operations has been recently done both in simulation scenarios and real-trials. For the former, see for instance [4], [5], [6], and [7]. For the later, refer for instance to Project AIRE (Atlantic Interoperability initiative to Reduce Emissions) [8], including [9], [10], [11], or [12]. Some of the most relevant findings of these references are described in the following paragraphs.

Based on theoretical analysis and benchmark simulations, Soler et al. in [5] and more recently Dalmau and Prats in [13] provide both qualitative and quantitative measure of the potential benefits of continuous operations with respect to current procedures for a single flight. In [5] results showed that continuous profiles can achieve around 11% (short-haul flights) and 6% (medium-haul flights), i.e., between 220 and 380 [kg], of fuel savings and the corresponding CO$_2$ emissions when compared to current operations. In [7] results showed that the continuous cruise phase can lead to fuel savings between 1% and 2% of the total trip fuel for an Airbus A320 (also a reduction of trip times between 1% and 5%).

Within the framework of project AIRE [8], more than 1000 trial flights were performed with a global savings of 400 tons of CO$_2$ emissions (roughly 0.4 tones per flight). In [10] cruise climb, direct routing and variable speed were analyzed through Reykjavik Control Area (CTA). Estimation of benefits of cruise climb was around 0.1%-0.4% compared to 1000 [ft] step climb and around 0%-0.5% of total en-route fuel burn for variable speed. In [11] several trial scenarios in the Santa Maria Area Control Center (ACC) were studied. Results showed that a vertical profile based on steps in altitude of 1000 [ft] could save 29 [kg] of fuel compared to a 2,000 [ft] step climb or 12 [kg] if it is compared to two 1,000 [ft] step climbs. Additionally, several airlines have estimated from experience that cruise climb, in the case of B747-400, could save up to approximately 1% in fuel consumption in non RVSM (Reduced Vertical Separation Minima) airspace and a bit less in RVSM [10].

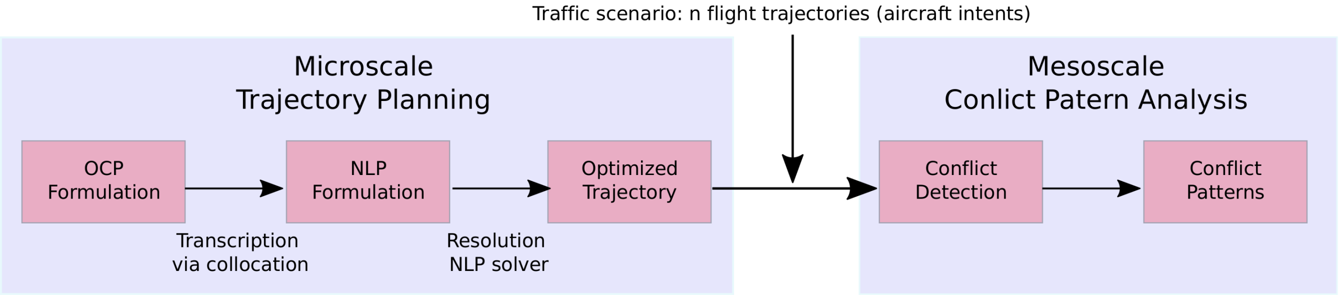

Figure 1. Block diagram of the simulation architecture.

After AIRE, AIRE-2 was launched seeking similar goals. Several projects an trial flights were performed. For instance, RETA-CDA project [12] realized trial flies to quantify CO_2 emissions and fuel consumption reduction, concluding that a CDA procedure from FL210 emits above 20% less CO_2 emissions than a non CDA procedure. In [14] a trajectory based night time CDA's at Schiphol airport were flown. This new procedure was very satisfactory with an approximated fuel consumption reduction of 74 [kg] per flight. For further insight on AIRE2 projects and reports, please refer to aire-2-reports.[1]

Despite discrepancies in the real benefits, all these results clearly illustrate that the implementation of continuous operation could bring benefits that are somehow aligned with some the main goals pursued by SESAR, i.e., 8-14 [min] gain per flight on average; 300-500 [kg] reduction in fuel per flight on average; 945-1575 [kg] reduction of CO_2 emissions per flight on average by 2020.[2] Unfortunately, the real implementation of continuous operations is in turn still far to be possible. Its implementation must be also tested in multi-aircraft scenarios at a traffic network level and compared against other key performance areas such as safety and capacity.

Approaches to quantitatively characterize the safety and capacity levels of the ATM system include different perspectives (e.g., human factors, human decision support tools, and levels of automation for the former; sectorization, flow analysis, and delays for the later) that go beyond the scope of this paper. However, it is under common agreement that both the number of potential conflicts and their distribution, i.e., the complexity, directly affect safety and capacity (understood as the maximum amount of aircraft a controller can safely handle within its assigned volume of airspace and with an acceptable level of workload). Indeed, recent work has been done related to strategic deconfliction of trajectories towards increasing the capacity of the system (number of flights) while augmenting or at least maintaining the current levels of safety (by reducing or at least maintaining the number of conflicts). See for instance [15], [16], [17], and the project STREAM (Strategic TRajectory de-confliction to Enable seamless Aircraft conflict Management), launched under the auspices of SESAR WP-E.[3] These works introduced different algorithmic approaches for strategic deconfliction, however none of these researches have considered continuous operations during the simulations (they only consider scenarios in which flights follow Flight Levels were considered).

Therefore, the main contribution of this paper is to provide a preliminary analysis on how continuous operations might impact traffic (i.e., number and distribution of potential interactions among trajectories) at the European ATM network level, since the resulting conflict patterns have a direct impact in the safety and capacity levels of the system. Based on simulations using realistic traffic demand scenarios and realistic flight performances, this paper provides insight on the conflict patterns (as an indicator of safety and capacity) under the consideration of continuous operations in the European ATM. The problem analysis has been divided in two scales: the microscale and the mesoscale. The microscale refers to single trajectories, whereas the mesoscale refers to a number of trajectories that may interact among them within a given volume of airspace (in this case, a big single sector representing the entire European airspace). Figure 1 sketches this architecture.

The microscale analysis will be tackled using optimal control techniques, solving a minimum fuel flight planning problem. Optimal control theory and its solution approach is analyzed in Section II. The mesoscale analysis (i.e., the impact of introducing continuous operations in the European ATM) in Section III will be tackled based on the execution of strategic conflict detection (i.e., predicting conflicts with a look-ahead time of 2 hours) and using a realistic European traffic demand pattern with thousands of flight trajectories (TBO environment with highly predictable 4D trajectories is assumed). The distribution of the conflicts (i.e., conflict patterns) will be analyzed and relevant conclusions about how the introduction of continuous operations may impact the safety and capacity will be provided, together with a preliminary analysis for the potential strategic de-confliction of the traffic at the mesoscale.

It is worth mentioning that the authors of this manuscript have proven experience in solving flight planning problems (at the microscale) [18], [19], [20], [21], [5], [22], [23], and solving strategic deconfliction problems (at the mesoscale) [24], [25], [26], [17], [27], respectively. However, for the former, the analysis has been always limited to a single flight,

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[1] http://www.sesarju.eu/newsroom/brochures-publications/aire-2-reports
[2] please refer to www.sesar.ju
[3] www.hala-sesar.net/projects

thus not considering any network effect (i.e., interactions with traffic at mesoscale level). Regarding the later, the mesoscale traffic analyses have been up to now done always considering flight operations subject to Flight Level Scheme (FLS) constraints, and thus not including continuous operations into the problem. The present paper represents a joint effort to tackle the problem from a more holistic perspective.

A case study is presented and discussed in Section IV using the real air traffic demand data of a yearly peak traffic day (July 1st 2011) provided by EUROCONTROL (uncertainty and stochastic events are not considered in this paper). At the microscale level, all flights are optimized according to the business interest of minimizing file consumption (and thus CO_2 emissions), resulting in a set of continuous operations' trajectories. This set of trajectories is shared and analyzed using a conflict detection tool [17] aimed at providing a descriptive analysis of the traffic patterns in terms of number and distribution of conflict generated, which will be related with the impact of continuous operations in the safety and capacity indicators of the ATM system.

II. Microscale: Trajectory Planning

Continuous operations result to the solution of a flight planning problem, which can be regarded as a trajectory optimization problem. The trajectory optimization problem can be studied as an optimal control problem applied to individual flights, in other words, applied to the microscale level and with no regarding about the potential network effects (mesoscale).

This Section describes the solution approach used to calculate the optimal (in terms of fuel cost) or near-optimal trajectories. Subsection II-A outlines the theoretical framework in which the model used is based (i.e., Optimal Control), and Subsection II-B presents the model of aircraft dynamics considered.

A. Optimal Control Problem

The goal of optimal control theory is to determine the control input that will cause a dynamical system (typically characterized by a set of differential-algebraic equations) to be steered from an initial state configuration to a final one, satisfying a set of path constraints, and at the same time optimize some performance criterion. Figure 2 illustrates it schematically.

The optimal control problem can be stated as follows:

Problem 1 (***Optimal Control Problem***).

$$\textit{min}\ J(t,x(t),u(t),p) = E(t_f,x(t_f)) + \int_{t_0}^{t_f} L(x(t),u(t),p)dt;$$

subject to:

$$\begin{aligned}
&\dot{x}(t) = f(x(t),u(t),p),\ \textit{dynamic equations;}\\
&0 = g(x(t),u(t),p),\ \textit{algebraic equations;}\\
&x(t_0) = x_0,\ \textit{initial boundary conditions;}\\
&\psi(x(t_f)) = 0,\ \textit{terminal boundary conditions;}\\
&\phi_l \leq \phi[x(t),u(t),p] \leq \phi_u,\ \textit{path constraints.}
\end{aligned} \tag{OCP}$$

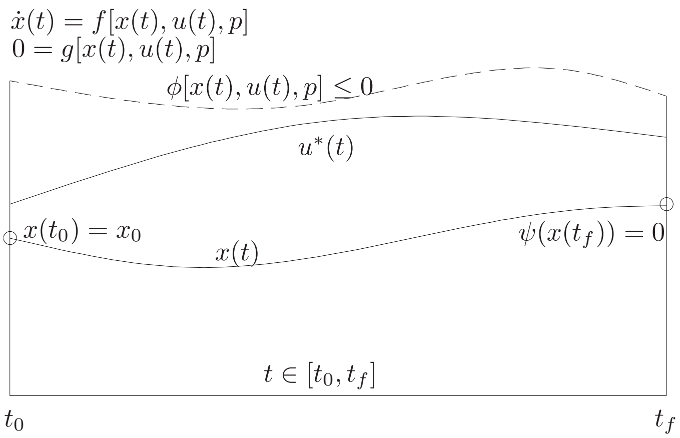


Figure 2. Optimal control problem.

Variable $t \in [t_0,t_f] \subset \mathbb{R}$ *represents time and* $p \in \mathbb{R}^{n_p}$ *is a vector of parameters. Notice that the initial time* t_0 *is fixed and the final time* t_f *might be fixed or left undetermined.* $x(t) : [t_0,t_f] \mapsto \mathbb{R}^{n_x}$ *represents the state variables.* $u(t) : [t_0,t_f] \mapsto \mathbb{R}^{n_u}$ *represents the control functions, also referred to as control inputs, assumed to be measurable. The objective function* $J : [t_0,t_f] \times \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}$ *is given in Bolza form. It is expressed as the sum of the Mayer term* $E(t_f,x(t_f))$ *and the Lagrange term* $\int_{t_0}^{t_f} L(x(t),u(t),p)dt$*. Functions* $E : [t_0,t_f] \times \mathbb{R}^{n_x} \to \mathbb{R}$ *and* $L : \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}$ *are assumed to be twice differentiable. The system is a DAE system in which the right hand side function of the differential set of equations* $f : \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}^{n_x}$ *is assumed to be piecewise Lipschitz continuous, and the derivative of the algebraic right hand side function* $g : \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}^{n_z}$ *with respect to* z *is assumed to be regular.* $x_0 \in \mathbb{R}^{n_x}$ *represents the vector of initial conditions given at the initial time* t_0 *and the function* $\psi : \mathbb{R}^{n_x} \to \mathbb{R}^{n_q}$ *provides the terminal conditions at the final time and it is assumed to be twice differentiable. The system must satisfy algebraic path constraints given by the function* $\phi : \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}^{n_\phi}$ *with lower bound* $\phi_l \in \mathbb{R}^{n_\phi}$ *and upper bound* $\phi_u \in \mathbb{R}^{n_\phi}$*. Function* ϕ *is assumed to be twice differentiable.*

1) Solving continuous time optimal control problems: Typically, optimal control problems are highly non-linear and it is very difficult to find an analytical solution even for the simplest cases. The common practice is to use numerical methods to obtain solutions. There are three fundamental approaches to numerically solving continuous time optimal control problems: Dynamic Programming (DP) methods, whose optimality criteria in continuous time is based on the Hamilton-Jacobi-Bellman partial differential equation [28]; indirect methods, that rely on the necessary conditions of optimality that can be derived from the Pontryagin's maximum principle [29]; direct methods, that are based on a finite dimensional parameterization of the infinite-dimensional problem [30]. Direct methods have been extensively used for solving aerospace trajectory optimization problems in spite of the fact that they present less accuracy than indirect methods [31]. Two comprehensive surveys analyzing direct and indirect methods for trajectory optimization are [32], [33]

2) Direct collocation methods: Collocation methods enforce the dynamic equations through quadrature rules or interpolation [34], [35]. A suitable interpolating function, or interpolant, is chosen such that it passes through the state values and maintains the state derivatives at the nodes spanning one interval, or subinterval, of time. The interpolant is then evaluated at points between nodes, called collocation points. At each collocation point, a constraint equating the interpolant derivative to the state derivative function is introduced to ensure that the equations of motion are approximately satisfied across the entire interval of time [36].

Collocation methods are characterized by the interpolating function and by the nodes and collocation points they use. One of the simplest methods of collocation is the Hermite-Simpson collocation method [34], [37]. In this method a third-order Hermite interpolating polynomial is used locally within the entire sequence of time subintervals, each solved at the endpoints of a subinterval and collocated at the midpoint. When arranged appropriately, the expression for the collocation constraint corresponds to the Simpson integration rule. A generalization of the method is obtained using the n-th order Hermite interpolating polynomial, and choosing the nodes and collocation points from a set of Legendre-Gauss-Lobatto points defined within the time subintervals. These choices give rise to the Hermite-Legendre-Gauss-Lobatto (HLGL) collocation method [36].

Another family of collocation methods is based on pseudospectral methods, which generally use global orthogonal Lagrange polynomials as the interpolants while the nodes are selected as the roots of the derivative of these polynomials, such as Legendre-Gauss-Lobatto (Legendre pseudospectral collocation methods), Chebyshev-Gauss-Lobatto (Chebyshev pseudospectral collocation methods), Legendre-Gauss (Gauss pseudospectral collocation methods), or Legendre-Gauss-Radau (Radau pseudospectral collocation methods). The reader is referred to [38], [39] and references therein for recent and comprehensive reviews of pseudospectral methods for optimal control.

In this article a Hermite-Simpson collocation method will be employed. Thus, the continuous optimal control problem is transcribed into a NLP problem. See, for instance, [40].

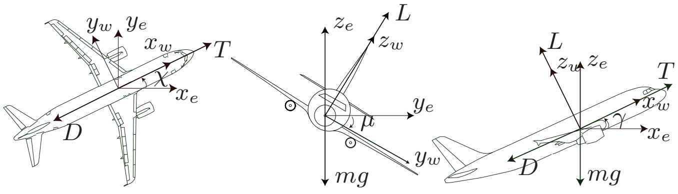
3) Interior point nonlinear solver IPOPT: For the NLP problem to be solved, the NLP solver IPOPT (Interior Point Optimizer) is one of the most suitable ones because it handles properly large-scale, sparse, non-convex problems, with a large number of equality and inequality constraints. Moreover it is open source. IPOPT can be used to solve general nonlinear programming problems. IPOPT implements an interior point line search filter method. The mathematical details of IPOPT algorithm can be found in [41]. Source and binary files can be found at COIN-OR (www.coin-or.org).

B. Aircraft dynamics

In order to plan optimal aircraft trajectories, it is common to consider a 3 degree of freedom dynamic model that describes the point variable-mass motion of the aircraft over a spherical Earth model. We consider a symmetric flight, that is, we assume there is no sideslip and all forces lie in the plane of symmetry of aircraft. Wind must be considered due to its tremendous impact in fuel consumption and flight time. However in the preliminary case study to be discussed in the forthcoming sections has been removed for the sake of simplicity.

1) Equation of motion: The equations of motion of the aircraft are:

$$\frac{d}{dt}\begin{bmatrix} V \\ \chi \\ \gamma \\ \lambda_e \\ \theta_e \\ h_e \\ m \end{bmatrix} = \begin{bmatrix} \frac{T(t)-D(h_e(t),V(t),C_L(t))-m(t)\cdot g\cdot \sin\gamma(t)}{m(t)} \\ \frac{L(h_e(t),V(t),C_L(t))\cdot \sin\mu(t)}{m(t)\cdot V(t)\cdot \cos\gamma(t)} \\ \frac{L(h_e(t),V(t),C_L(t))\cdot \cos\mu(t)-m(t)\cdot g\cdot \cos\gamma(t)}{m(t)\cdot V(t)} \\ \frac{V(t)\cdot \cos\gamma(t)\cdot \cos\chi(t)}{R\cdot \cos\theta_e(t)} + W_x(\lambda_e(t),\theta_e(t),h_e(t)) \\ \frac{V(t)\cdot \cos\gamma(t)\cdot \sin\chi(t)}{R} + W_y(\lambda_e(t),\theta_e(t),h_e(t)) \\ V(t)\cdot \sin\gamma(t) + W_z(\lambda_e(t),\theta_e(t),h_e(t)) \\ -T(t)\cdot \eta(V(t)) \end{bmatrix} \quad (1)$$



(a) Top view (b) Front view (c) Lateral view

Figure 3. Aircraft state and forces

In the above, the three dynamic equations are expressed in an aircraft-attached reference frame (x_w, y_w, z_w) and the three kinematic equations are expressed in a ground based reference frame (x_e, y_e, z_e) as shown in Figure 3. The states are: V, χ, γ referring to the true airspeed, heading angle, and flight path angle, respectively; λ_e, θ_e, h_e referring to the aircraft 3D position (longitude, latitude, altitude); and m referring to the aircraft mass. R is the radius of earth, η is the speed dependent fuel efficiency coefficient. Lift $L = C_L S\hat{q}$ and drag $D = C_D S\hat{q}$ are the components of the aerodynamic force, S is the reference wing surface area and $\hat{q} = \frac{1}{2}\rho V^2$ is the dynamic pressure. A parabolic drag polar $C_D = C_{D0} + KC_L^2$, and an International Standard Atmosphere (ISA) model are assumed. C_L is a known function of the angle of attack α and the Mach number. The aircraft position in 2D (x_e, y_e) is approximated as $x_e = \lambda_e \cdot (R + h_e)\cdot \cos\theta_e$ and $y_e = \theta_e \cdot (R + h_e)$. The bank angle μ, the engine thrust T, and the coefficient of lift C_L are the control inputs, that is, $u(t) = (T(t), \mu(t), C_L(t))$. W_x, W_y, and W_y denote the components of the wind vector, $W = (W_x, W_y, W_z)$, expressed on an Earth reference frame $F_e(O_e, x_e, y_e, z_e)$.[4]

Note that the herein presented framework is not only valid for set of equations (1). Yet, it is suitable for more accurate

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[4] Recall that wind is considered null in the case study to be presented. We keep in the model for the sake of completeness.

models, e.g.: a drag curve considering compressibility effects; an Earth model based on the World Geodetic System 84 (WGS84), standard in aviation; more accurate aircraft dynamics considering, for instance, sideslip, angle of attack, and the effects of wind in the force equations; more realistic models for the atmosphere (different from ISA); etc.

2) Flight envelope constraints: These constraints are derived from the geometry of the aircraft, structural limitations, engine power, and aerodynamic characteristics. We use the BADA 3.9 performance limitations model and parameters [42]:

$$\begin{array}{ll}
0 \leq h_e(t) \leq \min[h_{M0}, h_u(t)], & \gamma_{min} \leq \gamma(t) \leq \gamma_{max}, \\
M(t) \leq M_{M0}, & m_{min} \leq m(t) \leq m_{max}, \\
\dot{V}(t) \leq \bar{a}_l, & C_v V_s(t) \leq V(t) \leq V_{Mo}, \\
\dot{\gamma}(t) V(t) \leq \bar{a}_n, & 0.1 \leq C_L(t) \leq C_{L_{max}}, \\
T_{min}(t) \leq T(t) \leq T_{max}(t), & \mu(t) \leq \bar{\mu}.
\end{array}$$

In the above, h_{M0} is the maximum reachable altitude, $h_u(t)$ is the maximum operative altitude at a given mass (it increases as fuel is burned); $M(t)$ is the Mach number and M_{M_0} is the maximum operating Mach number; C_v is the minimum speed coefficient, $V_s(t)$ is the stall speed and V_{M_0} is the maximum operating calibrated airspeed; $\bar{a}_n$ and $\bar{a}_l$ are respectively the maximum normal and longitudinal accelerations for civilian aircraft. $T_{min}(t)$ and $T_{max}(t)$ correspond to the minimum and maximum available thrust, respectively. $\bar{\mu}$ corresponds to the maximum bank angle due to structural limitations.

Note that both the ordinary differential equation system (1) and the set flight envelop constraints are nonconvex.

III. MESOSCALE: CONFLICT DETECTION AND PATTERN ANALYSIS

This Section argues the importance of considering the traffic trajectories and their potential interactions at mesoscale level and also details the importance of performing a conflict pattern analysis for the European traffic as a preliminary step prior to tackle the problem of global strategic de-confliction of the traffic under the consideration of full continuous operations.

One of the key aspects of the new ATM concept proposed by the SESAR Concept of Operations is the management and utilization of the airspace as a continuous mean (with as less restrictions as possible), so that the planning and execution of trajectories can be as close to optimum as possible. It is understood that such paradigm shift will bring as a consequence more complex traffic patterns that may require of extra operational capacity to preserve the same safety levels.

Therefore, the SESAR concept considers the deployment of tools to assist the controllers with involved situations and to reduce complexity by strategic deconfliction measures where necessary to increase capacity (note that extra capacity is also already required because an increment of the current air traffic levels is forecasted).

The term Strategic De-confliction is often used in the SESAR context to define separation actions taken when the flight takeoff time is known with sufficient accuracy (e.g., after push-back) or even after the flight is airborne but with sufficient time to allow a Collaborative Decision Making (i.e., Collaborative Flight Planning) process to occur. This term excludes tactical instructions and clearances that require an immediate response but includes activities such as dynamic route allocation.

Strategic conflict management and traffic synchronization would lead to pre-deconflicted 3D routes subject to dynamic refinement or adjustment during flight (i.e. 4D contracts). This constitutes a quantum leap with respect to the current airspace structure, which consists of a set of predefined airways depending on a ground-based infrastructure of navigation aids and relying on the subdivision of airspace into Flight Levels (FLs) aimed at facilitating the management of flights.

Because safety cannot be reduced, the trajectories will be strategically deconflicted even prior to the take-off of the flights. In this context, the introduction of automation support to conflict detection, situation monitoring and conflict resolution will be one of the principal changes for increasing airspace capacity, safety and efficiency in the period up to 2020.

The STREAM (Strategic TRajectory de-confliction to Enable seamless Aircraft conflict Management) project, launched under the auspices of SESAR WP-E,[5] developed innovative and computationally efficient Conflict Detection and Resolution (CD&R) algorithms for strategic de-confliction of thousands of trajectories within a few seconds or minutes by taking into consideration the Airspace Users (AUs) preferences and network constraints. This system may enable air traffic to be de-conflicted over wide airspace regions and may permit large look-ahead times on the order of hours (e.g., 2-3 h).

The strategic de-confliction STREAM algorithms can contribute to the achievement of Network Manager (NM) goals through the development of a proper traffic micro-model framework in which all the traffic at European airspace scale can be represented and managed as a (large) set of individual 4D business trajectories (i.e. microscale), and by suggesting strategically de-conflicted trajectories which closely match AUs preferred ones in a free-flight environment, i.e., ideally not constrained by pre-structured routes and/or by Flight Level Schemes as occurring today (note that this approach is congruent and could contribute to the *Integrated Network management and ATC Planning*, INAP, function defined in the SESAR Concept of Operations Step 2 [43]).

However, the capability of the causal algorithms to provide efficient conflict-free scenarios is limited by the conflict patterns found in the scenarios (i.e., number and distribution of interactions among the traffic trajectories) [25]. Thus, the insights obtained through the conflict pattern analysis performed in the simulation of this paper could contribute to assess the possibilities of performing strategic de-confliction under the consideration of applying continuous operations for all traffic, a research topic that has not received sufficient attention by the ATM scientific community.

STREAM algorithms are available through the TPAS tool

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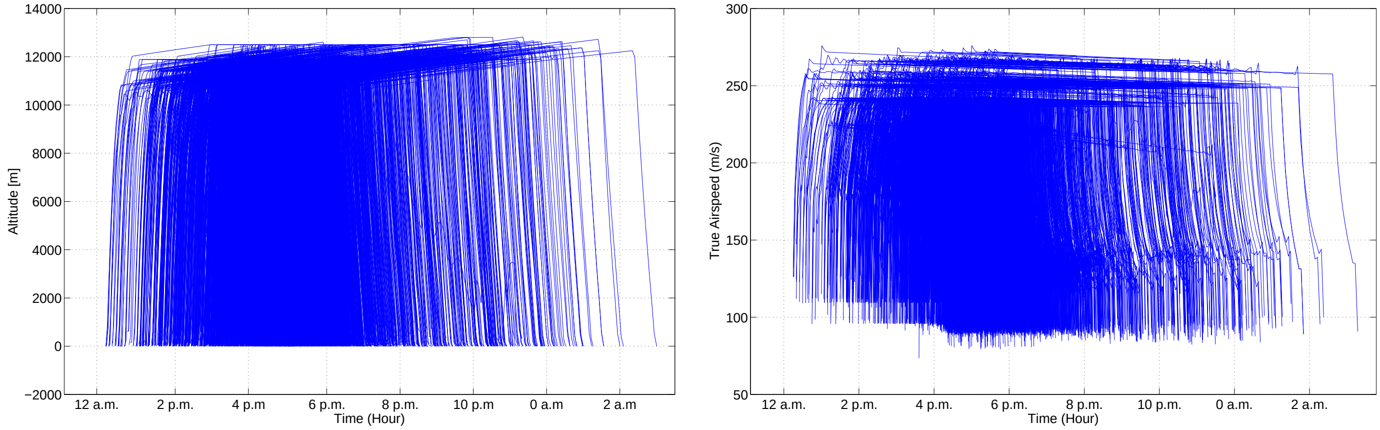
[5] www.hala-sesar.net/projects



(a) Altitude Profiles

(b) Speed Profiles

Figure 4. Set of optimal trajectories.

[17], which has been used in this paper for the traffic simulations and conflict analyses.

IV. CASE STUDY

A. Scenario

Real air traffic demand data of a yearly peak traffic day (July 1st 2011) provided by EUROCONTROL are considered. The intended flight have been simulated to obtain optimal trajectories according to Section II. Trajectories have been computed without any ATM constraint (e.g., no flight level scheme or route structure have been considered) and under no weather conditions, thus the horizontal profile of each trajectory corresponds to a Direct Route between origin airport and destination airport (orientation of runways have been also not considered for the sake of simplification) and the vertical profile corresponds to a continuous operations (BADA 3.11 models assumed). The resulting 4D trajectories have been cropped to fit within a spatial region covering most of the European airspace as defined with latitudes in the interval [30, 70], longitudes in the interval [-20, 30] and flight levels from FL50 to FL430. A time-window filter corresponding to 2 h of maximum airspace demand during the day (i.e., from 16.00 to 18.00) has been also applied to the computed trajectories. The resulting scenario included close to 3700 trajectories with an average length of 51.6 min.

B. Results

Fig. 4 shows the set of optimal trajectories. The characteristic altitude and speed profiles of continuous operations, i.e., continuous climb and slightly decreasing cruise speed, can be readily observed. This set is thereafter processed to analyze conflict patterns.

Fig. 5 shows a snapshot of the retained trajectories after the Conflict Detection (CD) processing, which resulted in a total of 1496 conflicts detected among the set of optimal trajectories (CD algorithm's computational time employed is less than 4 sec.). The conflict regions are represented in red. These results can be compared with those obtained in [25], in which a similar traffic pattern was simulated with the consideration of FL constraints and only 311 conflicts were found in the en-route phase of the flights[6]. Overall, these results suggest that the introduction of continuous operations may notably increase the number of potential conflicts during the trajectory execution by a factor of 4 to 5, yet the complexity of the traffic (flying continuously changing altitudes). Thus, continuous operations would be affecting negatively the levels of safety and capacity in the ATM. It also suggests that the current mechanism for strategic separation of traffic based on the application of FL constraints is performing reasonably well on the separation and simplification of vertical traffic patterns.

Fig. 6 shows the distribution of conflicts along the different Flight Levels (barometric altitude FL=0 has been assumed equal to MSL for all the regions of the scenario). It can be observed that most of the conflicts occur in altitudes between FL290 and FL390, while also a relevant number of conflicts can be found at altitudes from FL80 and below. The results are congruent with the fact that flights tend to find their optimum flight levels for the cruise phase at higher altitudes, while the conflicts below FL80 can be explained due to the natural increase of traffic density near airports. This high number of conflicts in FL80 and below also confirms the importance of having special air traffic management rules and procedures near highly-demanded airports (e.g., dynamic route allocation with specific constraints to separate departing and arriving flights).

Fig. 7 shows the distribution of trajectories with a certain number of conflicts (the maximum number of conflicts that has been found in a single trajectory is eight). Note that the total number of trajectories that are involved in the 1496 predicted conflicts is 1677, which represents the 44% of the traffic scenario. It means that the remaining 56% of the traffic could fly their optimal trajectories without any constraint (no

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[6] Notice that in [25] only flights flying above FL200 were considered. A fair comparison would require thus to consider in the present simulations only those conflicts above FL200, resulting in 1211 conflicts (about four times more conflicts)

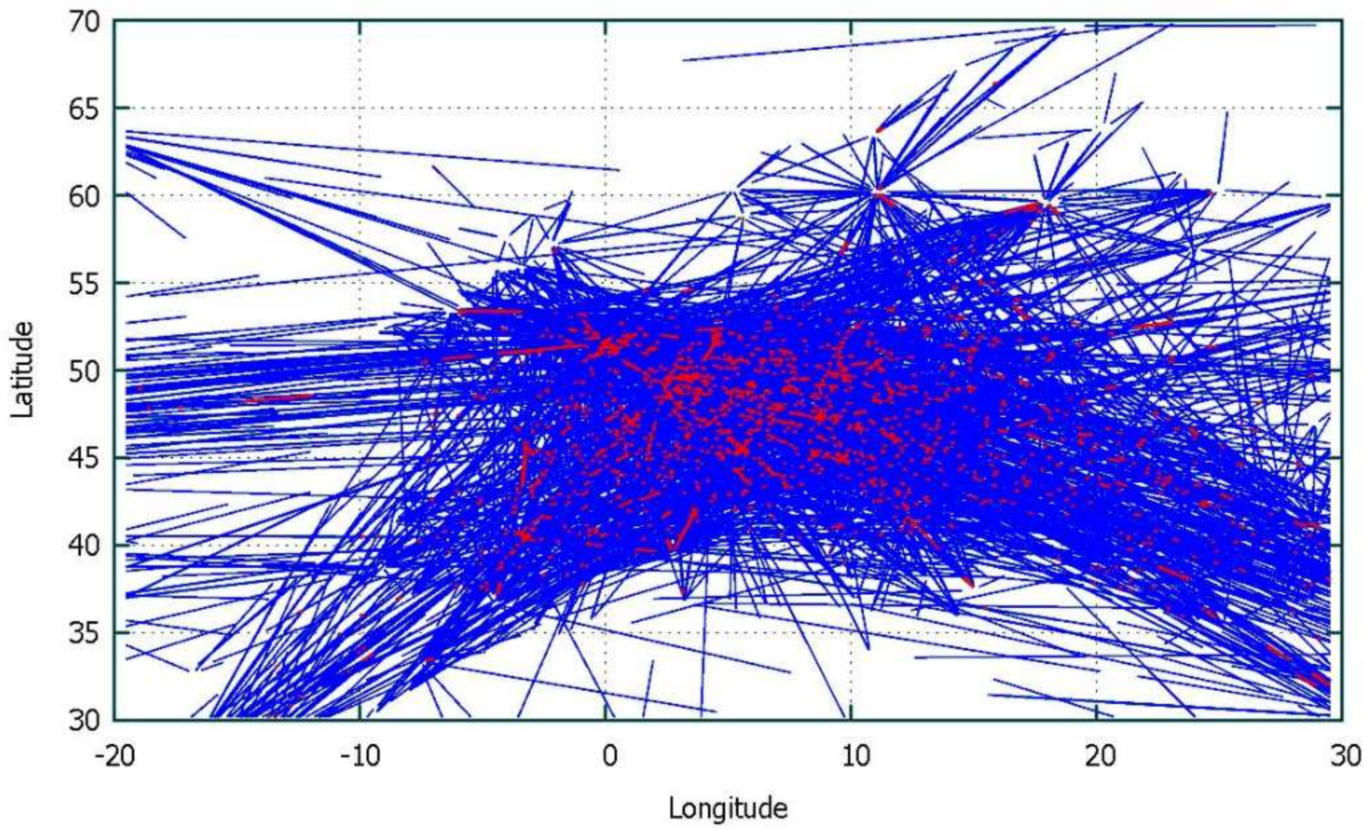

Figure 5. European airspace with 4010 trajectories following Direct Routes and Continuous Climb and Descent Operations; 1496 conflicts detected.

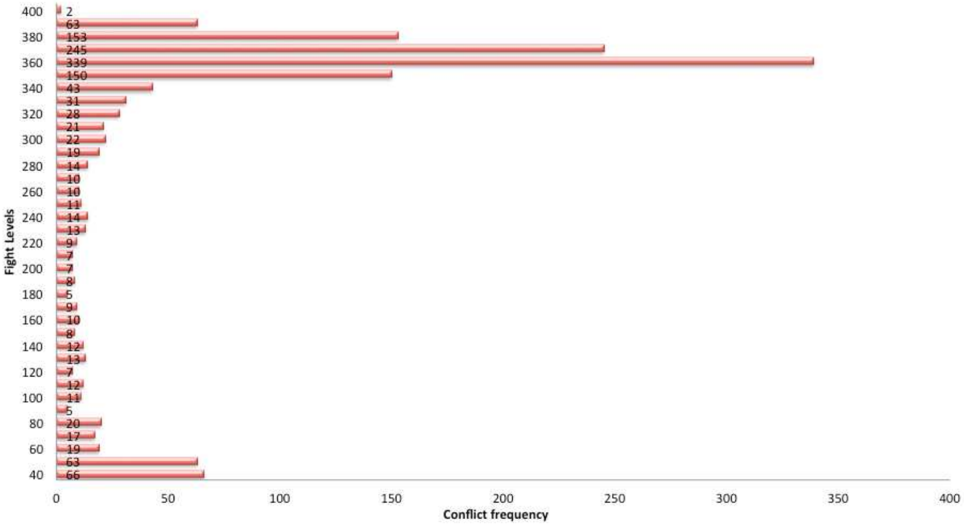

Figure 6. Distribution of conflicts per Flight Levels

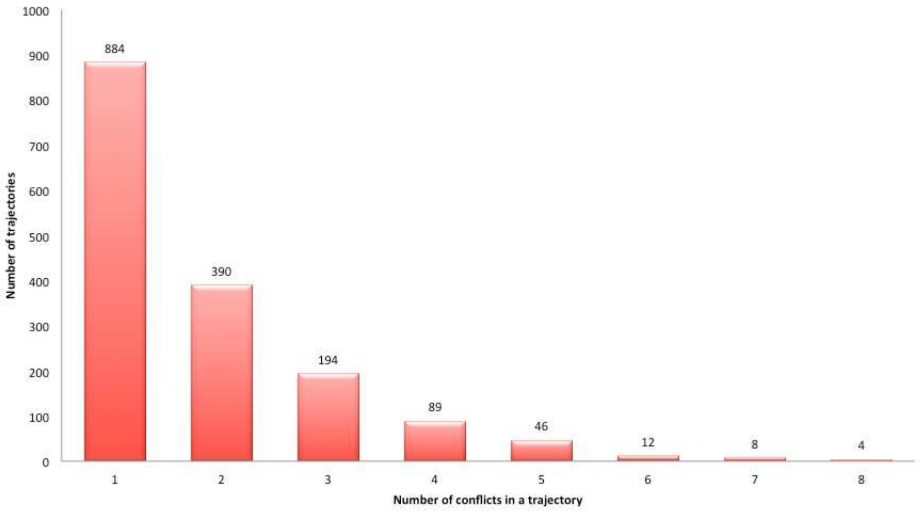

Figure 7. Distribution of trajectories per number of conflicts. 884 trajectories with 1 conflict; 390 trajectories with 2 conflicts; 194 with 3 conflicts; etc.

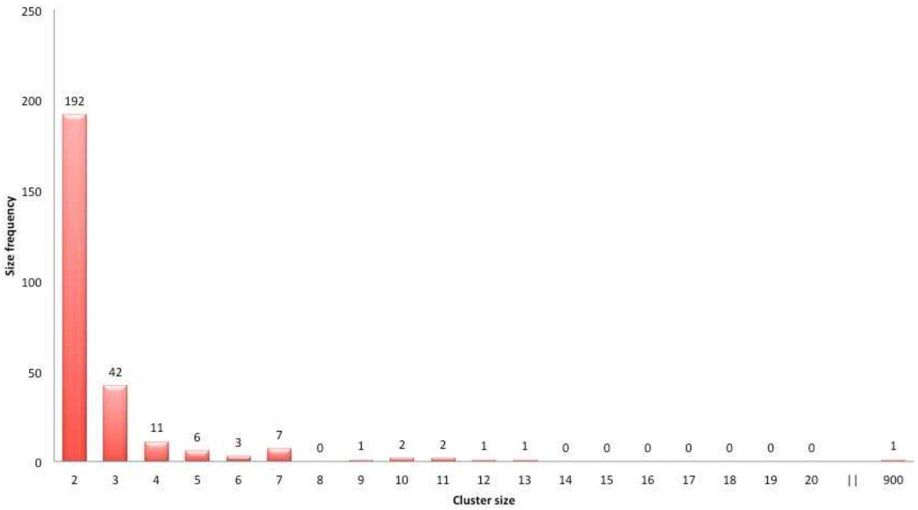

Figure 8. Cluster size distribution

conflicts are foreseen). Therefore, as already argued, current airspace design succeed at strategically de-conflicting the traffic at the expense of increasing flight inefficiencies and environmental impact.

These results (i.e., increased number of predicted conflicts should continuous operations be introduced) do not necessarily imply degradation of ATM safety and capacity: since these (potential) conflicts are predicted in a strategic phase, an effective traffic separation strategy could be introduced by using adequate strategic de-confliction algorithms. In [25] an efficient strategic de-confliction algorithmic framework was developed. It can be continuously executed in real-time (in a few minutes), and provides a globally optimized conflict-free solution for all trajectories. This in turn may lead to a higher degree of safety (traffic shall be separated earlier, while still preserving the tactical separation provided by controllers if needed) and a higher capacity (traffic shall be de-conflicted most of the times prior to be handled by controllers, thus reducing their workload).

Fig. 8 shows the distribution of the identified clusters (i.e., independent sub-scenarios of trajectories with conflicts among them). This distribution is important since affects the performance of the strategic de-confliction algorithm. In the case study under analysis, the 1496 conflicts were distributed among 269 clusters and 97% of the clusters did not involve more than seven aircraft. It should be noted that for clusters with less or equal than seven aircraft the strategic de-confliction algorithm could provide solutions in less than 10 seconds due to the application of a reduced set of horizontal restrictions to a few flights [25] (usually in about a 50% of the set of trajectories with conflicts). For the present scenario this means that only the 22% of the traffic (approximately the half of the traffic in conflict) is expected to require strategic flight restrictions, while the other 22% could fly their optimal trajectories. In STREAM algorithms, restrictions were applied usually in the horizontal plane (although also vertical and temporal restrictions can be applied in some complex regions), which means that most of the flights could be still operated following its optimal vertical profiles. Thus, these restricted trajectories shall remain as business preferred over the alternative flight profiles constrained by FLs structure.

A very large cluster with 900 flights is shown in Fig. 8. Since global-optimal conflict resolution is a highly combinatorial problem, such big cluster must be re-clustered and reduced to several sub-clusters with a maximum size (e.g., of seven flights). The re-clusterization could be only possible after the identification of those tightly coupled trajectories that contribute more to the generation of the big clusters, whose number is expected to be between 10 trajectories (since $2^{10} = 1024 > 900$) and no more than 30 (based on the conflict patterns found in Fig. 7 and Fig. 8 that denotes a relatively low level of multi-interactivity among the trajectories; further research will confirm that number). Therefore, for a number of flights between 10 and 30 (which represent 0.8% of the total traffic scenario) some particular restrictions or resolution maneuvers that might be more penalizing than the horizontal restrictions (e.g., altitude transitions) could be applied in the regions in which they are predicted to encounter a conflict with another certain trajectory of the cluster, thus contributing to avoid the emergence of a too large cluster. Again, the resulting restricted trajectories might be preferred over the traditional profiles, since out of the constrained regions the flights could operate with continuous operations.

V. CONCLUSIONS AND FUTURE WORK

This manuscript represents a first approximation to the cost-benefit analysis of considering the airspace as a continuous mean to allow flights to be planned and executed with the minimum constraints in the horizontal and vertical planes, i.e., free route and continuous climb and descent operations. Simulations to calculate optimal flight trajectories for each individual flight (i.e., microscale analysis) have been performed based on the utilization of advanced optimal control techniques and accurate aircraft flight dynamic models. Traffic simulations have been also performed to observe the interactions among the individual optimal trajectories across the European airspace (approximated) region (i.e., mesoscale analysis).

Results suggest that the introduction of continuous operations may notably increase both the number of conflicts during flight execution (by a factor of 4 to 5 compared to flights under current ATM) and the complexity of traffic. Thus, air traffic controllers' workload would be potentially raised and, as a consequence, a notable safety and capacity degradation shall be expected. However in a TBO context these conflicts could be predicted at strategic phase (2 hours in advance), and thus this safety and capacity degradation could be prevented with effective early traffic separation provided by sophisticated decision support tools for strategic trajectory de-confliction [25]. Such system (complemented with the proper equipment to allow controllers to re-synchronize the traffic in case of deviations during flight execution) would be capable of increasing safety and capacity to the required levels while still taking advantage of a notable enhancement in the flight efficiency (fuel burnt and emissions) due to continuous operations: a 78% of the flights would be able to fly their optimal trajectories, whereas only the 22% of the traffic would be constraint (however still flying a flight profile that would be more efficient than those constraint by FLs).

Future work is threefold:

- A detailed comparison of fuel consumption metrics between the scenario flown in this paper (continuous operations) and a scenario based on the same air traffic demand but simulated with the application of FL constraints.
- An enhancement of existing tools [25], seeking new strategies for re-clustering the traffic more efficiently to add the less constraints as possible to the trajectories, and thus finding better global de-conflicted solutions..
- The addition of uncertainty to the algorithms for strategic de-confliction, i.e., the consideration of uncertainty at micro level (e.g., wind affecting individual trajectories) and its propagation effects from the microscale level to the mesoscale (de-confliction robustness), and vice-versa, i.e., with the consideration of uncertainty at meso level (e.g., thunderstorms dropping the capacity of some airspace volumes) and its propagation effects from the mesoscale level to the microscale (flight planning robustness).

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AUTHORS BIOGRAPHIES

Sergio Ruiz received the B.Sc. in Economics and Bussiness Administration in 2007 form Universitat Pompeu Fabra, Barcelona, Spain, the B.Sc. in Telecommunications Engineering in 2009 form Universitat Oberta de Catalunya, Barcelona, Spain, the M.S. in Industrial Informatics in 2010 form Universitat Autonoma de Barcelona, Barcelona, Spain, and the PhD in Telecommunication and System Engineering by the same university in 2013. From 2008 to nowadays he has been a Researcher and Assistant Professor of the B.S in Informatics and the B.S. in Aeronautical Management in Universitat Autonoma de Barcelona. His main research has been focused on tactical management and control of air traffic flows. He was awarded with the SESAR Young Scientist Award 2012 because of his contributions to the SESAR WP- E project STREAM, the 1st SWIM Master Class challenge and several publications in JCR journals and congresses related to the ATM field.

Manuel Soler received a 5-year Bachelor's Degree in Aeronautical and Aerospace Engineering and a Master's degree in Aerospace Science and Technology, both from the Universidad Politćnica de Madrid. In 2013, he completed a Doctorate Degree in Aerospace Engineering from the Universidad Rey Juan Carlos, Madrid. He has been a visiting scholar in the Automatic Control Laboratory at the Swiss Federal Institute of Technology, ETH Zürich, Switzerland, and in the Institute of Transportation Studies at University of California Berkeley, USA. Since January 2014, Manuel Soler is Assistant Professor in the area of Aerospace Engineering at the Universidad Carlos III de Madrid. His research interests focus on optimal control, hybrid systems, and stochastic processes with application to aircraft trajectory planning in Air Traffic Management (ATM). He is member of the SESAR WP-E research network HALA! (Higher Levels of Automation in ATM). He has been awarded with the SESAR young scientist award 2013.