Enhancing operational efficiency of Terminal Maneuvering Areas through Continuous Climb Operations

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Abstract
Efficient continuous departure is an operational solution supported by global air navigation initiatives for future Air Traffic Management. In an effort to contribute for sustainable aviation, this work aims at presenting the efficiency enhancements at terminal airspace operation through the multi-objective trajectory optimisation of flight departures. This study put in place consolidated multi-objective models in terms of noise and fuel consumption for the calculations of optimised aircraft trajectories based on Continuous Climb Operations (CCOs) principles. The conclusions will bring the reader more relevant insights on determining the effects when ATC facilitates the performance of this type of operation.

1. Introduction

The growing global traffic demand of air transportation is translated into an increased number of aircraft movements. Despite aircraft have become more efficient along with quieter engines, aircraft's flight path can help on reducing noise levels through the performance a smooth climb towards the Controlled Terminal Airspace (CTA) rather than a standard stepped departure.
Aviation System Block Upgrades (ASBU) systems engineering modernization strategy, Global Air Navigation Plan (GANP) [2], the International Civil Aviation Organization (ICAO) prioritises the usage of CCOs among other initiatives. Along these lines, global air navigation initiatives for future Air Traffic Management like the Single Sky ATM Research (SESAR) [3] in Europe and The Next Generation Air Transportation System (NextGen) [4] in United States of America put in place innovative activities for the optimization of vertical trajectories. The departure phase of the flight has been identified as a key area where substantial environmental benefits could be achieved.
Single European Sky ATM Research (SESAR) targets up to 30% reduction in departure delays. On the other hand, its environmental expectation targets up to 10% reduction in CO_2 emissions including a positive impact on noise and air quality. Along with this key stakeholder expectations, the operational efficiency aims up to 6% reduction in flight time and up to 10% reduction in fuel burn.
The optimization of flight trajectories for terminal operating procedures has been a problem extensively tackled during years, particularly focused on arrival procedures. Limited research has been conducted in terms of 'pure' CCOs, as the benefits did not seem to be noteworthy. Considering engines usually run close to full throttle during climb phase, there exist potential for reducing the environmental footprint in living areas around the airports. In this regard, McConnachie et al. [5] presented the evidences for environmental performance change in case CCOs are applied at certain airports. Nevertheless, it was plausibly assumed that a CCO is just an uninterrupted climb. The successful application of a CCO should not be simplistically reduced to the operation of an uninterrupted climb procedure, which implies inexistent level-off segments. The importance of factors like aircraft, airport type, aircraft weight, runway, Standard Instrument Departure (SID) and operational constraints when identifying the CCO profile optimized to the performance of the aircraft, cannot be neglected.

CCO could lead to significant fuel economy and environmental benefits. The improvement of flight trajectories through the execution of a flight profile optimized to the performance of aircraft represents a significant enabler for Trajectory Based Operations (TBO), which is one of the four pillars (four-phase improvement) defined on SESAR [3]. The right climb strategy, particularly optimized CCOs, enables the aircraft to attain cruise flight levels at optimum configuration and improve the overall efficiency of operations at Terminal Manoeuvring Areas (TMAs) whilst ensuring the necessary safety of flight operations is ensured. Aircraft being able to select the most preferred CCO according to airlines' needs, allows advanced planning for departure phase of flight. The facilitation of users' preferences is aligned with current trends of SESAR, in particular with USER Preferred Routing concept (UPR).

This study has a significant leverage on actual surveillance data as well as Flight Data Recorder (FDR), as they have been analysed for characterisation of departure vertical profiles and optimisation of CCOs thereof. Regarding the former, it was possible to identify the existence of certain indicators (like level-off segments and aggressive vertical profiles) that manifested the fact that current flown departure trajectories are usually far from optimal. These imply the consequences like disproportionate fuel consumptions and excessive noise levels in the vicinity of airports. This challenge calls for researching on air navigation initiatives that improves the efficiency of terminal airspaces as well as contributing positively to the enhancement of the environment, in alignment with current international trends for future Air Traffic Management.

In order to tackle this, the combination of hand-tailored models through AMPL modelling language based on Pseudo-spectral methods was utilised as the platform for successfully optimising the CCOs as well as for further operational assessments. In this regard, the data sources gave also the capability to crunch and compare the simulated results against actual operational data. Cannot be disregarded the fact that the demanding Air Traffic Control (ATC) constraints have been considered and modelled within for the optimisation of CCOs. In alignment with global aviation initiatives, the findings bring interesting remarks for the promotion and dissemination of the importance of CCOs.

This document is organised as follows; Section 2 gathers the mathematical framework. Section 3 includes the optimisation model. Section 4 provides the case study along with the result that summarise the main finding of the analysis. And finally, section 5 concludes with the key remarks of the study.

2. Mathematical Framework

2.1 Optimal Control

Optimal Control Theory aims at determining the control input that will cause a system to achieve the control objectives, whilst satisfying the constraints and also optimizing some performance criterion. In this particular case, the trajectory optimisation problem is solved following an open loop terminal control problem that allows the constraints to act on the dynamical system to be considered in a way that the optimized trajectory will be admissible.
Despite commercial aircraft trajectory problem has been traditionally tackled through open loop optimal control techniques [6] [7] [8], optimal control problem is highly non-linear and thus, is difficult to determine the analytical solutions. In this regard, numerical methods are typically used for this purpose and in particular, direct methods have been selected for the resolution of this problem.
Direct methods translate the infinite dimensional problem into a problem with a finite dimensional parameterization, allowing solving the finite dimensional problem through optimisation. The approach could be defined with a strategy based on a first step for discretisation and a second step for optimisation, whilst not making use of the first-order necessary conditions of the continuous problem.
The Chebyshev pseudo-spectral Method has demonstrated advantages over indirect methods and is widely used, especially on trajectory optimization problems [9]. This spectral method utilises orthogonal polynomials instead of piecewise continuous polynomials when approximating state and control variables. F. Fahroo & I. M. presented at [10] the demonstration of the fact that Chebyshev-Gauss-Lobatto (CGL) method yields more accurate results than those obtained from the traditional collocation method. Recently, in [11], an intensive analysis on different direct collocation methods to solve a classical problem on ATM was presented. This study concluded with the fact that pseudospectral collocation method proves better results on accuracy and computational time but uncertainties in vertical trajectories during climb/descent.
In this investigation, the operational flight paths were obtained through multi-objective optimisation process based on CCO principles by a CGL pseudospectral method. The calculations were executed through a hand-tailored software tool implemented on AMPL modeling language [12] for Airbus A330 aircraft, using IPOPT as NLP solver. The latest Base of Aircraft Data (BADA 4.1 [13]) supported AMPL self-implemented optimisation model. AMPL is an algebraic modeling system for mathematical programming of large-scale optimisation problems. For sake of clarity, solver is defined as the number-crunching algorithm that computes optimal solutions.

2.2 Aircraft Performance

This section gathers the aircraft dynamics equations considered for this study. The considered representation of the aircraft is a dynamic model, which represents the point variable mass motion over a spherical flat non-rotating earth model besides neglecting wind components. The resulting set of differential equations of the aircraft is the following:

$$\dot{x} = V.\cos(\gamma) \tag{1}$$

$$\dot{h} = V.\sin(\gamma) \tag{2}$$

$$\dot{V} = \frac{T(h,V) - D(h,V,C_d) - m.g.\sin(\gamma)}{m(t)} \tag{3}$$

$$\dot{\gamma} = \frac{L(h,V,C_l) - m.g.\sin(\gamma)}{m(t).V(t)} \tag{4}$$

$$\dot{m} = -T(h,V).\ \eta(h,V) \tag{5}$$

where the state vector is comprised of the true airspeed V, the longitudinal position x, the aerodynamic flight path angle γ, the altitude h and the mass of the aircraft m. In addition to the states, there are other components like T, which represent the thrust, g the gravity acceleration (assumed as a constant value), D is the aerodynamic drag with the coefficient of drag C_d and, η is the thrust specific fuel flow. Furthermore, L that represents lift force, with C_l as the coefficient of lift.
In terms of the atmosphere, it has been considered the ICAO Standard Atmosphere (ISA) model [14], which presents pressure p(h), density ρ(h) and temperature τ (h). This model denotes p_0, ρ_0 and τ_0 for the standard values at sea level for pressure, density and temperature respectively.

3. Model

Traditionally, tactical air traffic controllers manage aircraft within their airspace domain and provide clearances to specific altitudes based on the characteristics of the traffic in terms of complexity and airspace layout. A conventional departure trajectory, which has been vertically limited, presents several level-offs before reaching the cruise level. There is a limit to the number of aircraft a controller can keep track of at one time, so as airspace has to be subdivided in airspace sectors, the flights require levelled segments. These levelled segments on the vertical profile penalize the aircraft efficiency and prevent the aircraft from flying its ideal trajectory. Conversely, the performance of an optimized CCO that allows the aircraft to attain initial cruise flight level at optimum air speed with optimal thrust settings brings noteworthy benefits to the flight efficiency. The Fig.1 illustrates the standard departure and an optimized CCO where can be appreciated the differences between their departure flight paths.

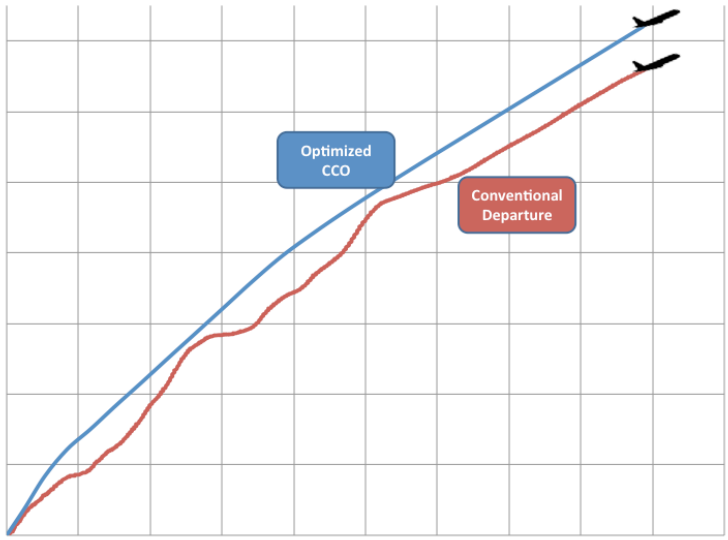

Figure 1: Departure flight paths: Optimized CCO vs. standard departure

3.1 Optimization Criteria

Whether lateral adjustments are not possible or a trajectory is constrained by the requirement of overflying certain points, the vertical flight path has potential to improve the departing/arriving trajectory.
Several studies have been presented during years with the objective of improving the noise annoyance impact around airport neighbours [15], [16], [17]. This is due to the fact that acting on the vertical flight profile is an efficient method to mitigate aircraft environmental footprint on the vicinity of airports. Thus, considering the importance of noise factor, it has been selected as one of the main factors for CCO optimisation. Modelling aircraft noise became a global priority with the objective of providing reliable aircraft noise prediction tools. In this regard, those semi-scientific methods based on certain empiricism have gained better acceptance by industry, airports and aviation regulators for predicting aircraft method relying on physical model of noise production and propagation. As a result, Federal Aviation Authority (FAA) promoted in 1978 the Integrated Noise Model (INM), [18].
The noise model utilized on this paper is based on the methodology employed by the INM that has been adopted as the standard package for noise evaluations in several countries. The core of this methodology relies on the Noise-Power-Distance (NPD). Noise levels are calculated at a particular point through interpolation of noise values obtained from a NPD table. This data, which is based on empirical measurement for each aircraft type, is collected on the table whose values are A-weighted decibel levels for the different combinations of distance and thrust. The maximum A-weighted sound level (L_max) has been selected as the optimisation parameter for this study.
As a performance related component, the consumed amount of fuel needs to be considered as a noteworthy criteria on optimising aircraft operations. This is not only to its relationship regarding the operating cost but also, regarding the negative effects the emissions produce on the air quality. There is a direct coupling between emissions and fuel consumption. Despite the effort some studied put on emission calculations, Hartjes concluded within [15] that the optimisation in terms of gaseous pollutants did not led to significant results. Taking this into account and considering

the availability of data source that allows direct comparison of fuel consumption, it was decided to consider the fuel as the optimisation parameter for this study.
Aiming at supporting this multi-parameter optimization, the weighted combination of the aforementioned factors have been implemented as follows,

$$J' = Fuel\ Consumption + k.\sum_{i}^{n} Noise \qquad (6)$$

where k is an adjustable weighting constant. The value of this constant are directly related to the trade-off between noise exposure and fuel consumption / emissions. In this study, the weighting has been applied in order to avoid the prioritisation of one of them. Is important to note that the different weight of the constant will have consequences on the results. The Pareto frontier for this particular problem is presented later in this document, but it is out of the scope to determine the most convenient solution.

3.2 Optimisation model

As identified at international level, the performance of continuous operations brings environmental benefits, whereas the necessary safety of flight operations is ensured. Aircraft can therefore be enabled to fly the most preferred vertical trajectory according to their business' needs. This facilitation that is allowed by ATC is in compliance with current international trends towards the provision of excellence Air Traffic Services.
In this study, the optimisation problem has been solved based on Chebyshev Pseudospectral Method. The optimisation problem was hand tailored and implemented in AMPL modelling language for Airbus A330 aircraft using IPOPT as NLP solver.
The characteristics that portray the optimisation of CCOs are the following; First of all, the algorithm, for a given length needs to determine the best departure that complies with the associated priorities. Regarding this, levelled segments do not take place as expected for a continuous climb path. Moreover, it is important to highlight that this method of operation allows the aircraft to attain the desired altitude at optimum air speed and engine thrust settings. Accordingly, the model has to determine the most convenient thrust settings as a result of a trade-off between noise and fuel consumption, considering the effects of the altitude. The AMPL self-implemented optimisation model is based on the latest Base of Aircraft DAta (BADA 4.1 [13]). The optimization has been applied to several operational Gross Weight (GW) values covering thus, the most representative operational variability.

3.3 Pareto Optimal

A solution of the optimization problem is said to be Pareto optimal (or Pareto frontier). In mathematical terms, every Pareto optimal solution is an equally acceptable solution of the optimization problem. However, it is highly recommended to select one point as a solution. The selection of one out of the set of Pareto optimal solutions brings the opportunity to influence in the decision making of what needs to be prioritised at a particular scenario and is not a straightforward task. Selecting a Pareto optimal is linked to the environment of the scenario that is subject to be studied as well as the operational needs.
The priorities of the objectives are reflected by the weight associated to the constant that is a real number and normalized. The decision makers will have the capability to adjust the weighting of the constant. It is out of the scope of this study to evaluate the decision-making on the most suitable Pareto frontier for a particular TMA.

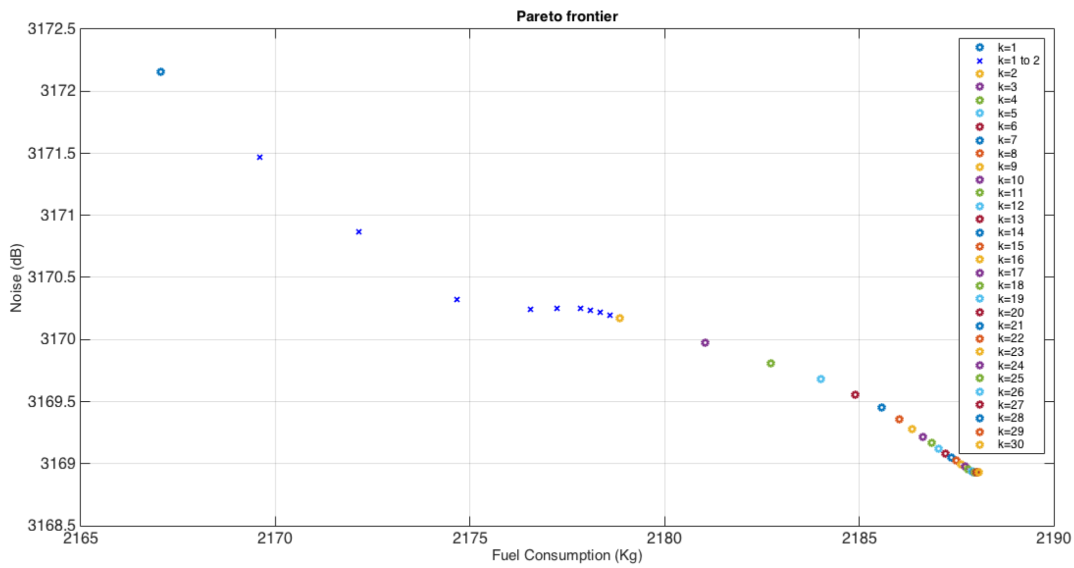

Figure 2: Pareto frontier in terms of Noise (dB) and Fuel Consumption (Kg)

The diagram represents the effects of the weights of the constant k, in terms of noise and fuel-consumption for the optimized CCOs. It can be appreciated that with higher weights for k, the importance of Noise factor increases, the solutions of the optimization problem presents higher values of fuel consumption and therefore lower fuel savings.

4. Case Study

4.1 Departures at Adolfo Suárez Madrid Barajas

Adolfo-Suárez Madrid Barajas is the largest airport in Spain with 409,832 total operations in 2018. Considered as one of the largest airport in Europe by physical size, it is the country's busiest airport in Spain, and Europe's sixth busiest. The airport is predominantly operated in North configuration and runway (RWY) 36L was selected as the preferred option for this study. In particular, the chosen flight segments go from ground to waypoint (WPT) AVILA.

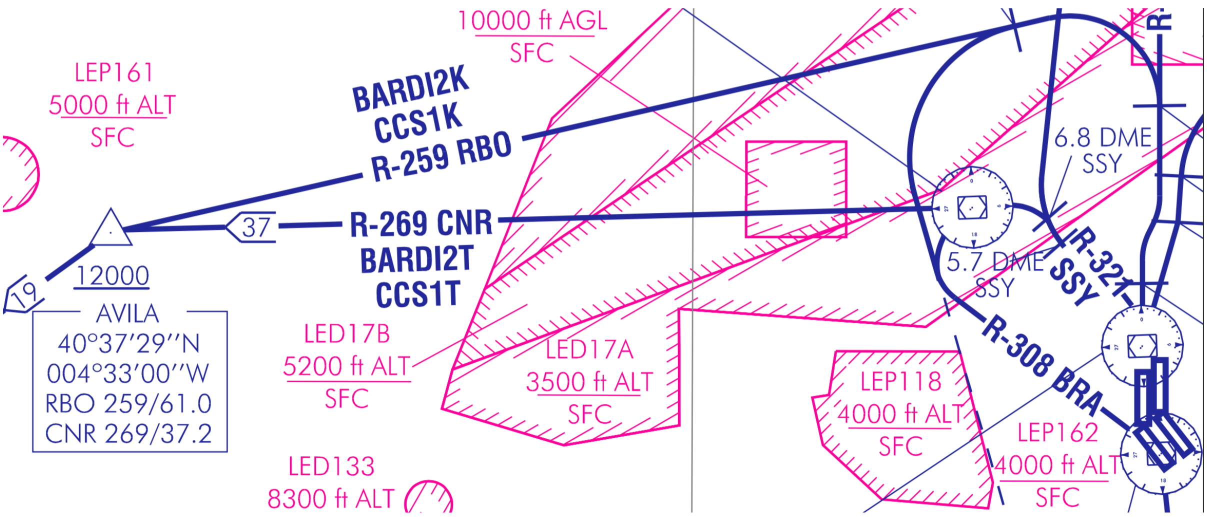

Figure 3: SIDs RWY 36L: Detailed view of selected flight segments associated to BARDI2T/ CCS1T & BARDI2K/CCS1K SIDs

Fig. 2 shows a zoom view of the published chart, which includes the SIDs for RWY 36L, usable at daytime. SIDs BARDI TWO TANGO (BARDI2T) & CÁCERES ONE TANGO (CCS1T), are only allowed to authorized aircraft and thus, BARDI TWO KILO (BARDI2K) SID & CÁCERES ONE KILO (CCS1K) SID become mandatory to listed aircraft due to noise restrictions. Published noise abatement procedures are applicable to all take-offs, unless exceptionally cancelled due to an event that cannot be reasonably anticipated. The facilitation of CCO when performing these departure segments must satisfy the airspace restrictions and operational constraints. The BARDI2K/CCS1K SID corresponds to the tackled departure flight segment.

4.2 Operational Constraints

The complexity of the problem is higher when applied to a real environment due to the necessary compliance of operational constraints. The initial conditions on the studied procedure are taken from ground. Is important to note that the departure segment before attaining 1000ft altitude is operationally quite restrictive and there are no many degrees of freedom for a potential optimization.

Table 1: Boundary conditions

Variables and states	Initial values	Final values
Distance s [NM]	0	S_f
Time t [s]	0	Unconstrained
Velocity V [Kt]	V_i	V_f
Altitude h [ft]	0	h_f
Rate of Climb ROC [fpm]	0	Unconstrained
Flight path angle γ [rad]	0	Unconstrained
Thrust Level Percentage (TLP) [0-1]	0.8	Unconstrained
Gross Weight [Kg]	M1	Unconstrained

The CCO was modelled enforcing the boundary conditions described on the indicated table. In terms of speed; No deceleration was permitted, as this is the trend observed in actual data. The initial climb speed corresponds to the sample mean of the analysed FDR data. The final climb speed has been set according to the data analysed. Analytics of real departures for this specific scenario unmasked a typical operational constraint for departures. This operational constraint refers to the limitation of 250 Kt. below FL 100 [19]. In this regard, the optimisation of this departure has been forced to comply with this operational limitation up to the crossover altitude.

4.3 Numerical results

Once the CCOs have been optimized, it is of paramount importance to compare the optimized departure against the conventional departure. In this case, we have selected a historic actual aircraft with a representative value regarding the actual Take-off Weight considering the FDR database. In other words, the stored database includes a different variety of actual operational Take-off Weights, and the selected one is illustrative. Unfortunately, The value of this parameter has not been disclosed in purpose. This actual conventional departure is also consistent in terms of level-off segments and do not present significant level-off segments, particularly at low level altitudes. This actual departure corresponds to a departure trajectory operated in North configuration and runway (RWY) 36L and SID BARDI2K/CCS1K.

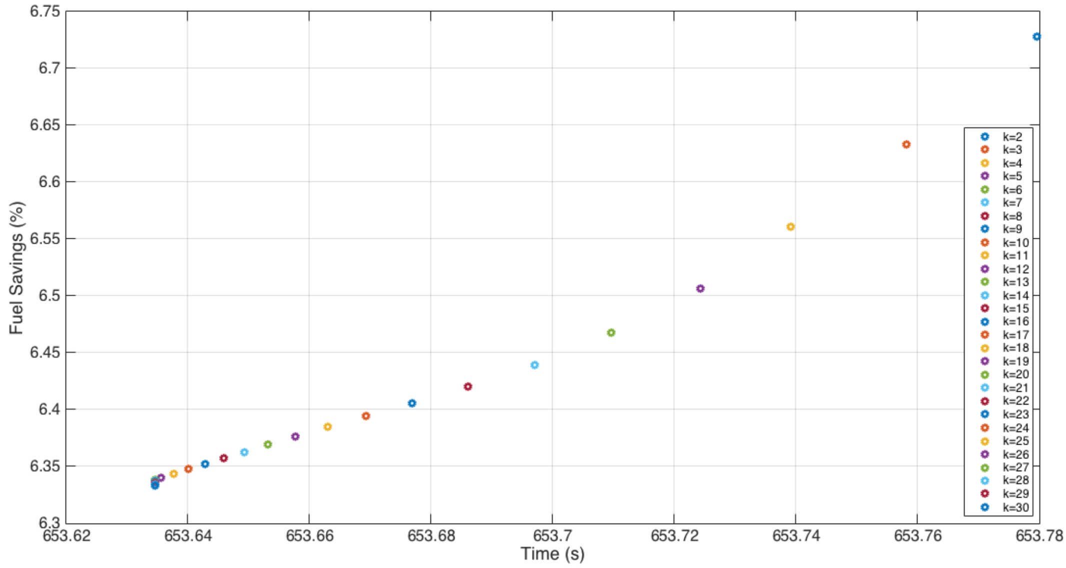

Figure 4: Conventional departure compared to Optimized CCO - Fuel Savings (%) vs. Time (s)

The Fig.4 gathers the information regarding the Fuel Savings (%) versus the time required to perform the optimal CCO. The values regarding the fuel savings represent the reduction of fuel consumption when comparing the optimal CCO against the actual departure. The effects of the constant value "k" can be appreciated and the higher is the weight of the noise (higher k), the lower is the time required. It can be observed that the fuel savings achieved goes between 6.3% and 7.3%. Thus, considering the time requirements and fuel consumption, the decision makers could identify the most convenient solution depending on the operational situation.

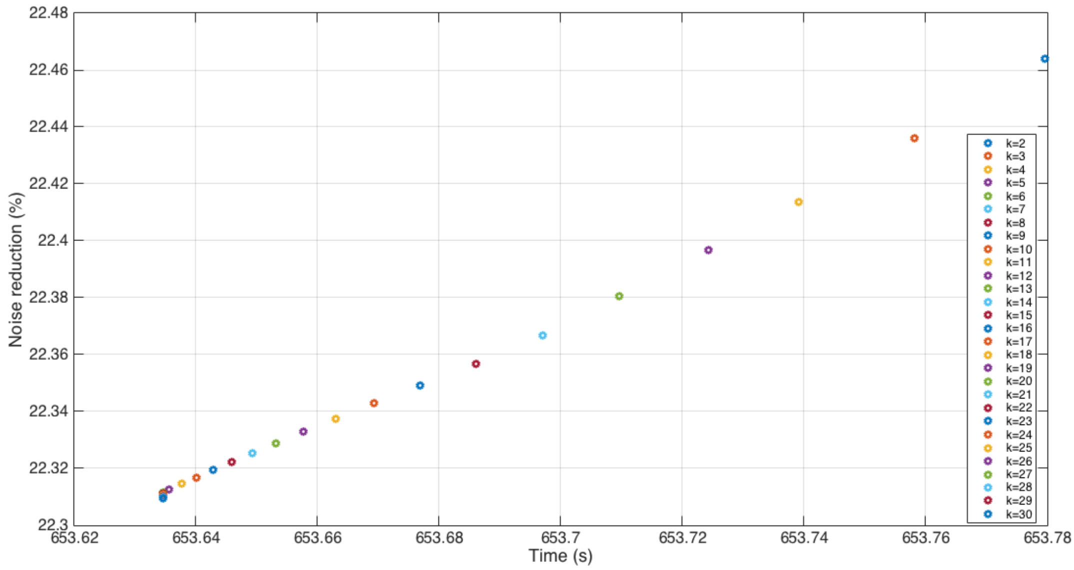

Figure 5: Conventional departure compared to Optimized CCO – Noise reduction (%) vs Time (s)

The Fig.5 includes the information regarding the Noise reduction (%) versus the time required to perform the optimal CCO. The values regarding the fuel savings represent the reduction of noise when comparing the optimal CCO against the actual departure. The effects of the constant value "k" can be appreciated and the higher is the weight of the noise (higher k), the lower is the time required. It can be observed that the noise reduction achieved goes between

22.3% and 22.5%. Thus, considering the time requirements and fuel consumption, the decision makers could identify the most convenient solution depending on the operational situation.

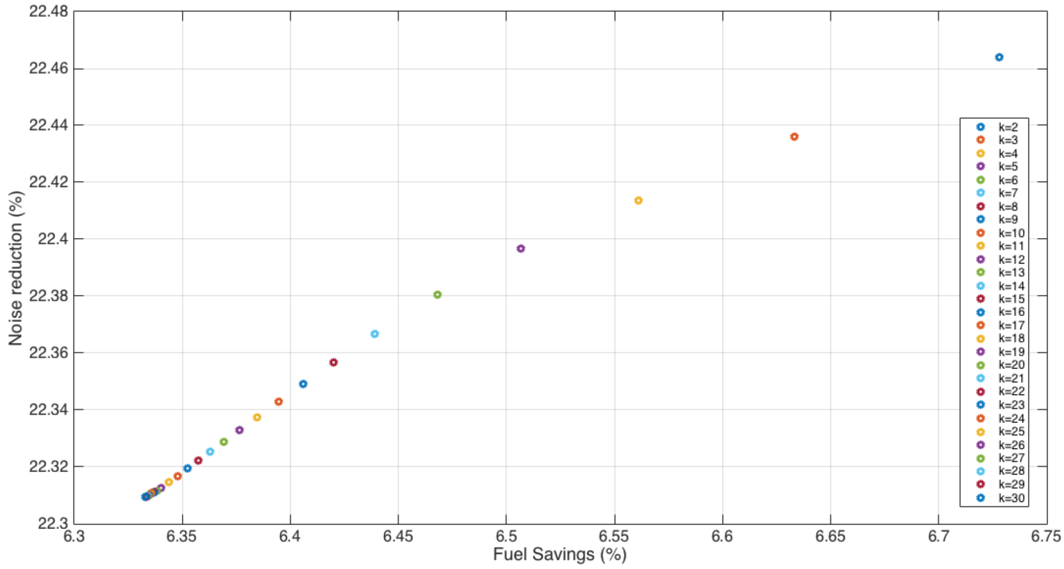

Figure 6: Conventional departure compared to Optimized CCO - Noise Reduction (%) vs. Fuel Savings (%)

The Fig.6 reveals the information regarding the Noise reduction (%) versus Fuel Savings (%) between optimal CCOs and the actual conventional departure. The effects of the constant value "k" can be appreciated and the higher is the weight of the noise (higher k), the higher is the noise reduction and the lower is the higher is the fuel saving for this particular case. This is due to the fact that the represented noise reduction value is for the entire trajectory and at lower altitudes the noise reduction is significantly higher than at higher altitudes. Thus, considering the time requirements and fuel consumption, the decision makers could identify the most convenient solution depending on the operational situation.

5. Conclusion

In view of the results of this study, optimised CCOs in terms of noise and fuel consumption brings benefits when integrated at terminal airspace operation through trajectory optimisation by means of Chebyshev-Gauss-Lobatto (CGL). The application of a consolidated mathematical method was not only applied to multiple operational factors but also reflected restrictions of actual Air Traffic Control (ATC) operational constraints.
Unlike Standard Arrival Routes where aircraft are tactically guided by air traffic controllers, SID routes tend to follow fixed flight paths. Thus, the optimization of the vertical profile may be considered as an appropriate initiative for departure efficiency.
The benefits are presented through 6.3% - 7.3% of fuel savings and 22.3% - 22.5% of noise reductions for the studied flight segment when comparing an optimised CCO with a representative actual departure. These results bear out the advantages to the communities around the airports when optimized CCOs are facilitated by ATC.
From operational point of view, facilitating uninterrupted climb flight operation allowing the aircraft to attain initial cruise flight level at an optimum air speed with optimal thrust settings will lead to more consistent flight paths whilst reducing the number of required radio transmissions. As a consequence, this may be traduced on lower pilot and air traffic controller workload.
This study reinforces the idea of transmitting the importance of CCOs and furthermore, promotes the usage of this operating technique in TMAs.
Despite the benefits presented in this paper, the integration of a CCO operating technique in a Terminal Manoeuvring Area (TMA) requires the analysis of one of the most important parameters on airport planning, which is capacity. In order to allow the reader to gain further insights regarding the effects on capacity please, see [20].

Nomenclature

C_d= coefficient of drag

C_l= coefficient of lift

D = drag force

g = gravity acceleration

h= altitude

L = lift force

L_{max}= maximum A-weighted sound level

m = mass

p = atmospheric pressure

p_0= standard value at sea level for atmospheric pressure

t = time

T = thrust

V = true airspeed

x = longitudinal position

η = thrust specific fuel flow

γ = flight path angle

ρ = atmospheric density

ρ_0= standard value at sea level for atmospheric density

τ = temperature

τ_0= standard value at sea level for temperature

References

References must be numbered in the text in the following style [3] and listed at the end of the paper in the following way.

[1] ICAO, Continuous Climb Operations (CCO) Manual, International Civil Aviation Organization, 999 University Street Montréal, Quebec, Canada, 1st Edition (2013).
[2] ICAO, Global Air Navigation Plan 2016-2030, International Civil Aviation Organization, 999 University Street, Montréal, Canada (2013).
[3] SESAR, Single sky atm research (2016) [cited Sep. 2016]. URL http://www.sesarju.eu.
[4] NextGen, The next generation air transportation system (2016). URL https://www.faa.gov/nextgen/.
[5] D. McConnachie, P. Bonnefoy, and A. Belle, "Investigating benefits from continuous climb operating concepts in the national airspace system," in 11th USA/Europe, 2015, pp. 1–11.

[6] P. Bonami, A. Olivares, M. Soler, E. Staffetti, Multiphase mixed-integer optimal control approach to aircraft trajectory optimization, Journal of Guidance, Control, and Dynamics 36 (5) (2013) 1267–1277. doi:10.2514/1.60492. URL https://doi.org/10.2514/1.60492.

[7] A. Franco, D. Rivas, Optimization of multiphase aircraft trajectories using hybrid optimal control, Journal of Guidance, Control, and Dynamics 38 (3) (2015) 452–467. doi:10.2514/1.G000688. URL http://dx.doi.org/10.2514/1.G000688

[8] D. González-Arribas, M. Soler, M. Sanjurjo-Rivo, Robust aircraft trajectory planning under wind uncertainty using optimal control, Journal of Guidance, Control, and Dynamics 41 (3) (2017) 673–688. doi:10.2514/1.G002928. URL https://doi.org/10.2514/1.G002928.

[9] R. Z. Jiang Zhao, X. Jin, Reentry trajectory optimization based on a multistage pseudospectral method, The Scientific World Journal vol. 2014 (878193) (2014) 13.

[10] F. Fahroo, I. M. Ross, Direct trajectory optimization by a chebyshev pseudospectral method, Journal of Guidance, Control, and Dynamics 25 (1) (2002) 160–166. doi:10.2514/2.4862. URL http://arc.aiaa.org/doi/abs/10.2514/2.4862

[11] J. García-Heras, M. Soler, F. J. Sáez, A comparison of optimal control methods for minimum fuel cruise at constant altitude and course with fixed arrival time, Procedia Engineering 80 (2014) 231–244. doi:http://dx.doi.org/10.1016/j.proeng.2014.09.083. URL http://www.sciencedirect.com/science/article/pii/S187770581401176X

[12] AMPL, Ampl modeling language (2013) [cited Sep. 2016]. URL http://ampl.com

[13] Eurocontrol, User Manual for the Base of Aircraft Data (BADA) family 4, European Organisation for the Safety of Air Navigation, EUROCONTROL Agency Rue de la Fusee, 96 B -1130 BRUXELLES (2014).

[14] ICAO, Manual of the ICAO Standard Atmosphere, International Civil Aviation Organization, 999 University Street, Montréal, Canada, 3rd Edition (1993).

[15] S. Hartjes, H. G. Visser, S. J. Hebly, Optimization of rnav noise and emission abatement departure procedures, in: 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS), 2009, p. 6953

[16] D. Mitchell, H. Ekstrand, X. Prats, T. Gronstedt, An environmental assessment of air trac speed constraints in the departure phase of flight: A case study at gothenburg landvetter airport, Sweden, Transportation Research Part D: Transport and Environment 17 (8) (2012) 610–618. doi:http://dx.doi.org/10.1016/j.trd.2012.07.006. URL http://www.sciencedirect.com/science/article/pii/ S136192091200079X.

[17] A. Filippone, Aircraft noise prediction, Progress in Aerospace Sciences 68 (2014) 27 – 63. doi:http://dx.doi.org/10.1016/j.paerosci.2014. 02.001. URL http://www.sciencedirect.com/science/article/pii/S0376042114000311.

[18] E. R. Boeker, E. Dinges, B. He, G. Fleming, C. J. Roof, P. J. Gerbi, A. S. Rapoza, J. Hemann, Integrated noise model (inm) version 7.0 tech- nical manual, FAA-AEE-08-01 NSN 7540-01-280-550 , U.S. Department of Transportation, Federal Aviation Administration, Oce of Environment and Energy 800 Independence Avenue, S.W. Washington, DC 20591 (January 2008).

[19] ICAO, Procedures for Air Navigation Services - Aircraft Operations (PANS-OPS), International Civil Aviation Organization, 999 University Street Montreal, Quebec, Canada, 5th Edition (2006).

[20] Manuel Villegas Díaz, Fernando Gómez Comendador, Javier García-Heras Carretero, and Rosa María Arnaldo Valdés, “Analyzing the Departure Runway Capacity Effects of Integrating Optimized Continuous Climb Operations,” International Journal of Aerospace Engineering, vol. 2019, Article ID 3729480, 10 pages, 2019. https://doi.org/10.1155/2019/3729480.