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Fuel Conservation Strategies for the Vertical Profile of Cruise Flight

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Abstract

Fuel conservation strategies are used by airlines with the objective of making their operations more efficient, whether it is from an economical or environmental point of view.

This dissertation focuses only on the vertical profile of the cruise phase of long haul commercial flights.

Covering legislation, operational standards, communications, surveillance, flight planning and performance aspects.

After a description of the previous aspects, the first case study is presented. This case study consists in a comparison between a usual vertical profile of a flight and an optimized one.

First a theoretical estimation of the results is presented and then the detailed calculations for the actual flight are described, continuing with an explanation of several factors associated with the results.

A summary of a second case study is presented to allow for a comparison between two vertical profile optimization procedures.

Keywords

Fuel Economy, Fuel Conservation Strategies, Cruise Climb, Step Climb, Vertical Profile Optimization, Emissions Reduction.

Resumo

Estratégias de otimização de combustível são utilizadas pelas companhias aéreas com o objectivo de tornar as suas operações mais eficientes, quer seja do ponto de vista ambiental, quer económico.

Existem diversas estratégias para tornar as operações mais eficientes, podendo ser aplicadas em qualquer fase do voo. Nesta dissertação o foco vai centrar-se na aplicação destas técnicas na fase de cruzeiro do voo e focando apenas o perfil vertical do mesmo.

É feita uma descrição da legislação aplicável à fase de cruzeiro do voo, falando de distâncias de separação mínimas, dos procedimentos operacionais, das ferramentas de comunicação e vigilância. É também apresentado o modo de construção de um plano de voo e por fim alguns pormenores sobre desempenho.

Depois da descrição destes pormenos importantes à realização de um voo, é apresentado o primeiro caso de estudo, descrevendo as ferramentas necessárias, tanto em terra como a bordo, à realização dos voos de teste.

Por fim são explicados vários factores que estão associados aos resultados, que são também apresentados e explicados.

Um resumo de um segundo caso de estudo é posteriormente apresentado de modo a permitir a comparação entre dois procedimentos de otimização de perfis verticais.

Palavras-chave

Economia de Combustível, Estratégias de Conservação de Combustível, Cruise Climb, Step Climb, Otimização de Perfil Vertical, Redução de Emissões.

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List of Acronyms

3D	Three Dimensions
4D	Four Dimensions
ACARS	Aircraft Communication Addressing and Reporting System
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-C	Automatic Dependent Surveillance - Contract
AIDC	ATS Interfacility Data Communication
AIP	Aeronautical Information Publication
AIRE	Atlantic Interoperability Initiative to Reduce Emissions
ANSP	Air Navigation Service Provider
AOC	Airline Operational Control
APM	Aircraft Performance Monitoring
ARINC	Aeronautical Radio, Incorporated
ASAS	Airborne Separation Assurance System
ATC	Air Traffic Control
ATCo	Air Traffic Control Officer / Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Services
ATSU	Air Traffic Services Unit
CAS	Calibrated Air Speed
CG	Centre of Gravity
CI	Cost Index
CPDLC	Controller-Pilot Data-Link Communication
DFE	Data-Link Front-End
DLCS	Data Link Communication System
DM	Down link Message
EC	European Commission
EPP	Extended Projected Profile
ETA	Estimated Time of Arrival

FAA	Federal Aviation Administration
FANS	Future Air Navigation Systems
FB	Fuel Burn
FBURN	Fuel Burn
FDPS	Flight Data Processing System
FDR	Flight Data Recorder
FIR	Flight Information Region
FL	Flight Level
FMC	Flight Management Computer
FMS	Flight Management System
FPA	Flight Path Angle
FPLN	Flight Plan
FPPS	Flight Plan Preparation System
FQTY	Fuel Quantity
GA	General Aviation
GNSS	Global Navigation Satellite System
GS	Ground Speed
GW	Gross Weight
HF	High Frequency
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ISA	International Standard Atmosphere
LAN	Local Area Network
LAT	Latitude
LON	Longitude
M	Mach number
MACH	Mach number
MCDU	Multifunction Control Display Unit
NextGen	Next Generation Air Transportation System
NM	Nautical Miles

OFDPS	Oceanic Flight Data Processing System
OFP	Operational Flight Plan
PEP	Performance Engineering Program
QN	Quality Number
QRH	Quick Reference Handbook
RTA	Required Time of Arrival
SAT	Static Air Temperature
SATCOM	Satellite Communications
SESAR JU	SESAR Joint Undertaking
SESAR	Single European Sky Air Traffic Management Research
SIGMET	Significant Meteorological Information
SSR	Secondary Surveillance Radar
TAS	True Air Speed
TAT	Total Air Temperature
TOC	Top Of Climb
TOD	Top Of Descent
TP	Trajectory Predictor
UM	Up link Message
VHF	Very High Frequency
VSM	Vertical Separation Minimum
WMO	World Meteorological Organization
WPR	Waypoint Position Report
WPT	Waypoint

1 Introduction

1.1 Motivation

Improving aircraft operational efficiency has become a dominant issue in air transportation, as the recent social and political climate has pushed for reduced environmental impact.

Scientific evidence of global climate change increased awareness on the importance of pollutant gases emissions such as CO_2, resulting in a significant pressure to reduce emissions. Air transport is responsible for 2% of man-made carbon emissions annually [1]. But the industry recognizes that it must work ever harder on behalf of the environment to achieve long-term sustainability, which will give the industry a license to grow. In 2009, therefore, the industry—comprising airlines, business aviation, airports, airplane manufacturers, and air navigation service providers (ANSP's)—committed to a united approach in reducing emissions that includes three carbon emissions goals [1]:

1. Improving fuel efficiency an average of 1.5% annually to 2020.
2. Capping net emissions through carbon-neutral growth from 2020.
3. Cutting net emissions in half by 2050, compared with 2005.

In 2014 the fuel impact on the operating costs of the global airline industry was $226 billion (accounting for 32.3% of operating expenses at $101.4/barrel of oil), which is near five times the fuel bill of 2003 at $44 billion (that accounted for only 13.6% of operating expenses at $28.8/barrel) [2]. For a better understanding of how much the fuel has been rising in the last few years, Figure 1 presents a graph with the evolution of fuel prices from 2000 to 2014.

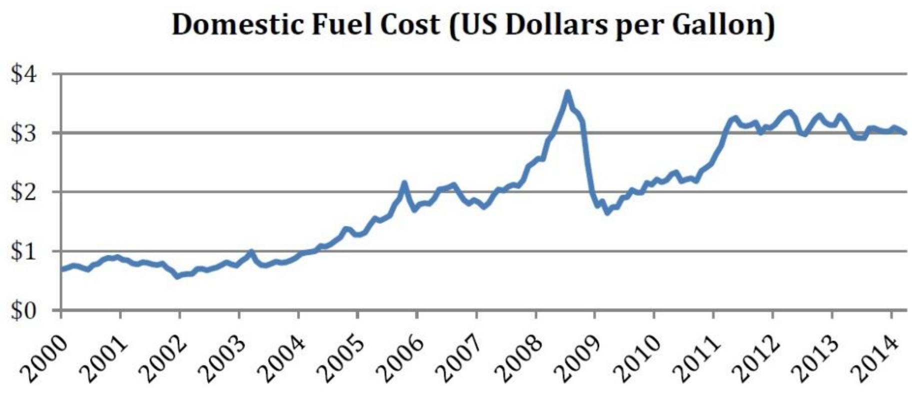

Figure 1. Average domestic US fuel price since 2000 [3].

Environmental concerns provide further motivation for fuel conservation as climate and air-quality impacts from hydrocarbon fuel combustion gain greater scientific and social prominence. There are various techniques to control fuel related environmental impact with varying implementation timelines and potential benefit. These include new aircraft technology, retrofits to existing aircraft technology, alternative jet fuel and propulsion technology, major infrastructure improvements and operational mitigation [3].

Efforts to modernize aircraft technology are limited by the extremely slow and expensive process of adopting new aircraft, which can take decades [4]. Major infrastructure improvements like the Single European Sky ATM Research (SESAR) in Europe or the Next Generation Air Transportation System (NextGen) in North America promise efficiency improvements but also face long implementation timelines. Operational mitigations are useful due to the potential for rapid implementation and low capital expenditure, although the long-term benefit is generally less than other technology-driven solutions. Prior work in academia and industry has identified many potential operational mitigations, including barriers to implementation and potential benefits.

Operational strategies for fuel conservation are those that involve the manner in which an aircraft is flown, handled on the ground or managed in the air traffic control (ATC) system. They are implementable without modification to aircraft structures or engines, but may require investment in avionics, infrastructure and training. These strategies can be implemented in all phases of flight.

1.2 Research Goals

The physics that define cruise performance are already well understood. Aircraft manufacturers provide detailed performance information with an aircraft upon delivery, including fuel burn dependencies on weight, altitude and speed. Airline dispatchers are able to calculate expected fuel consumption for a given flight using flight planning software and tables. Pilots have access to predicted fuel consumption from the flight plan and fine tuned projections through the onboard Flight Management Computer (FMC). Based on flight plan information, ATC can access total fuel load as well as initial altitude and speed assignments. Despite these shared trajectory planning mechanisms, most flights do not operate at fuel optimal altitudes. Thus, this study aims to accomplish the following objectives:

1. Quantify and characterize the aircraft fuel efficiency benefits that are achievable through improved altitudes in the cruise phase of flight;
2. Quantify the potential benefits of altitude trajectory improvement strategies; and
3. Compare the use of different profile optimizations.

As CO_2 emissions are directly related to the amount of fuel burned, reduction in fuel consumption yields a reduction in carbon emissions. Therefore, this analysis answers the question: How much can fuel burn and carbon emissions be reduced in cruise flight if aircraft are operated nearer to, or at their optimal altitude?

1.3 Study Scope

The scope of this study is limited to the vertical dimension of the cruise phase of long haul flights in the oceanic domain.

Airline operations are the intended focus of the research. General aviation (GA) and military operators account for only a small portion of the total fuel burned across airspaces, reducing the system wide environmental impact of optimization in those sectors. Additionally, cost drivers are different for GA and military operations - increased efficiency is often less important than speed and flexibility.

Airlines operate at a much larger scale with business pressures that favor minimized cost over raw performance. Therefore, efficiency studies are naturally well-suited for profit-maximizing airline operators.

In this research, a benefit is meant to imply a reduction in fuel burn due to an altitude optimization.

1.4 Dissertation Outline

The dissertation begins with an introduction to environmental aspects and fuel savings, then the objectives are set and the scope defined.

The second chapter covers legislation, the operational aspects for vertical trajectory management, communication and surveillance technology, flight planning and trajectory processing tools, performance computations and an overview of auto control modes towards the end of the chapter.

On the third chapter, the case study of NATCLM and all the technology needed to perform the flight trials are described.

The estimation of savings and related results from the flight trials are presented and explained in the fourth chapter. An overview of the needed enhancements to the Air Traffic Management (ATM) system and avionics systems is also made.

The fifth chapter presents another case study, the ISAVIA one, and its results.

On the sixth chapter, a comparison between the two case studies, NATCLM and ISAVIA, is presented.

As a conclusion, the seventh chapter contains an outline of the research, final considerations and future perspectives on the subject.

2 State of the Art

2.1 Introduction

This chapter covers the vertical aspects of the cruise phase management, i.e. the vertical profile from the top of climb (TOC) to the top of descent (TOD). The International Civil Aviation Organization (ICAO) regulations for vertical separation are presented first, followed by a description of Step Climb and Cruise Climb operations.

Then, the list of existing methods for the management of the vertical trajectory is given, focusing on existing communication and negotiation capabilities, as defined within ICAO regulatory specifications.

The trajectory computation and processing is explained, both for ground and airborne systems.

Finally, an overview of performance computations and auto control modes is made.

2.2 ICAO Rules for Separation and Minima [5]

2.2.1 Vertical Separation Application

Vertical separation is obtained by requiring aircraft using prescribed altimeter setting procedures to operate at different levels expressed in terms of flight levels (FL) or altitudes in accordance with the Altimeter Settings Procedures of ICAO.

2.2.2 Vertical Separation Minimum

The vertical separation minimum (VSM) shall be:

a. a nominal 300m (1000ft) below FL290 and a nominal 600m (2000ft) at or above this level, except for in b. below; and
b. within designated airspace, subject to a regional air navigation agreement: a nominal 300m (1000ft) below FL410 or a higher level where so prescribed for use under specified conditions, and a nominal 600m (2000ft) at or above this level.

2.2.3 Assignment of Cruising Levels for Controlled Flights

- Except when traffic conditions and coordination procedures permit authorization of cruise climb, an ATC unit shall normally authorize only one level for an aircraft beyond its control area, i.e. that level at which the aircraft will enter the next control area whether contiguous or not. It is the responsibility of the accepting ATC unit to issue clearance for further climb as appropriate. When relevant, aircraft will be advised to request en route any cruising level changes desired;
- Aircraft authorized to employ cruise climb techniques shall be cleared to operate between two levels or above a level;

- If it is necessary to change the cruising level of an aircraft operating along an established ATS route extending partly within and partly outside controlled airspace and where the respective series of cruising levels are not identical, the change shall, wherever possible, be effected within controlled airspace;
- When an aircraft has been cleared into a control area at a cruising level which is below the established minimum cruising level for a subsequent portion of the route, the ATC unit responsible for the area should issue a revised clearance to the aircraft even though the pilot has not requested the necessary cruising level change;
- An aircraft may be cleared to change cruising level at a specified time, place or rate;
- In so far as practicable, cruising levels of aircraft flying to the same destination shall be assigned in a manner that will be correct for an approach sequence at destination;
- An aircraft at a cruising level shall normally have priority over the other aircraft requesting that cruising level. When two or more aircraft are at the same cruising level, the preceding aircraft shall normally have priority;
- The cruising levels, or, in the case of cruise climb, the range of levels, to be assigned to controlled flights shall be selected from those allocated to IFR flights as specified in the Appendix 3 of Annex 2 to the Convention on International Civil Aviation (Rules of the Air) except that the correlation of levels to track as prescribed therein shall not apply whenever otherwise indicated in air traffic control clearances or specified by the appropriate ATS authority in AIPs;

2.2.4 Vertical Separation During Climb or Descent

- An aircraft may be cleared to a level previously occupied by another aircraft after the latter has reported vacating it, except when:
    a. severe turbulence is known to exist;
    b. the higher aircraft is effecting a cruise climb; or
    c. the difference in aircraft performance is such that less than the applicable separation minimum may result, in which case, such clearance shall be withheld until the aircraft vacating the level has reported at or passing another level separated by the required minimum;
- When the aircraft concerned are entering or established in the same holding pattern, consideration shall be given to aircraft descending at markedly different rates and, if necessary, additional measures such as specifying a maximum descent rate for the higher aircraft and a minimum descent rate for the lower aircraft should be applied to ensure that the required separation is maintained;
- Pilots in direct communication with each other may, with their concurrence, be cleared to maintain a specified vertical separation between their aircraft during ascent or descent.

2.2.5 Aircraft Climbing or Descending

2.2.5.1 Aircraft on the Same Track

When an aircraft will pass through the level of another aircraft on the same track, the following minimum longitudinal separation shall be provided:

a. 15 minutes while vertical separation does not exist;
b. 10 minutes while vertical separation does not exist, provided that such separation is authorized only where ground-based navigational aids or GNSS permit frequent determination of position and speed;
c. 5 minutes while vertical separation does not exist, provided that:
    1 the level change is commenced within 10 minutes of the time the second aircraft has reported over a common point which must be derived from ground-based navigation aids or by GNSS;
    2 when issuing the clearance through third party communication or CPDLC a restriction shall be added to the clearance to ensure that the 10 minute condition is satisfied.

2.2.5.2 Aircraft on Crossing Tracks

a. 15 minutes while vertical separation does not exist;
b. 10 minutes while vertical separation does not exist if navigation aids permit frequent determination of position and speed.

2.3 Standards for the Use of Vertical Airspace

The optimal vertical profile of a flight depends on several factors, the aircraft type, aircraft gross weight, environmental conditions (mostly the temperature and wind evolution), flight plan (FPLN) and ATC interventions.

All the phases of a flight are filled within the ICAO flight plan, including horizontal elements of the vertical profile expected/ preferred by the air user [5]. The OFP also contains all characteristics of the flight (airways, times of overfly of waypoints, distances between waypoints, tracks, FL's, fuel consumption, aircraft weights, air speeds, ground speeds, etc.) This operational flight plan (OFP) is the basis for the flight execution. Every ATS along the flight routes receives a copy of the ICAO FPLN so the ground services have full pre-flight information about the planned vertical profile of a flight [6].

In the ideal case, when an aircraft is not restricted by ATCo, the aircraft can then take-off and climb to the optimal altitude, i.e. to the top of climb. After reaching the TOC an aircraft can fly [6]:

- the same barometric altitude throughout the flight (Level Flight);

- a certain time at one flight level and later, when a current flight level is not the most efficient (after burning fuel off, better wind/temperature conditions at another flight level), can climb to a higher FL, i.e. follows the step climb procedure (Step Climb);
- or, where traffic is not an issue (and regulations do not forbid), it can continuously climb during the cruise (Cruise Climb).

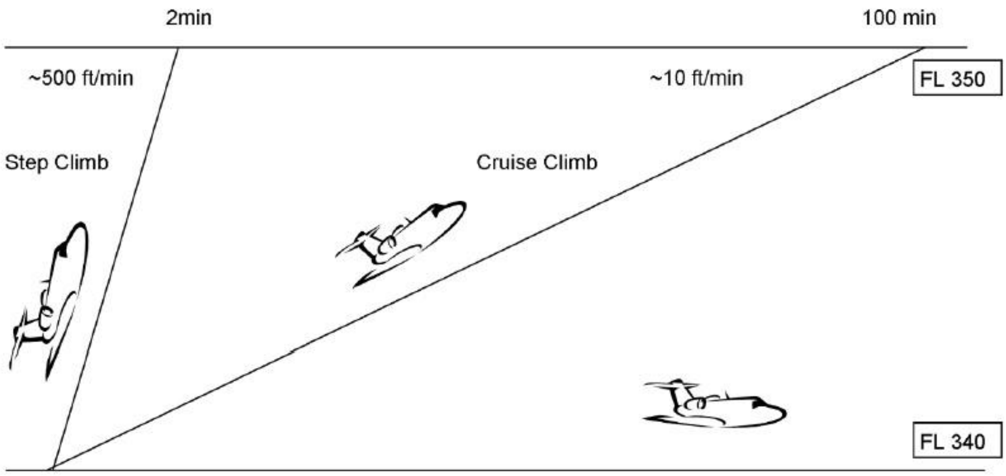

Figure 2. Difference between step climb, cruise climb and level flight [6]

As it can be seen in Figure 2, the main difference between a Step Climb and a Cruise Climb is the climb rate. Step Climbs usually have a high rate of climb, around 500ft/min. To approximate a step climb to a cruise climb, climb rates of 100ft/min are sometimes used, as that is the smallest automatic climb rate available on the FMS (Flight Management System). A climb at 100ft/min is usually called a Limited Cruise Climb [6].

2.3.1 Step Climb

A step climb is a technique currently used for fuel savings. It's a climb from one cruise altitude to another in fixed steps, which are intended to keep an aircraft flying for long periods of time at a fixed altitude, while still trying to maintain an efficient vertical profile. Although this technique is not optimal from the fuel consumption perspective, it is still more efficient than maintaining a single altitude during the whole cruise phase.

Modern commercial aircraft are equipped with flight management systems (FMS) that can calculate and execute the proper steps to increase the fuel efficiency.

The typical cruise phase for a commercial aircraft is described by a series of level segments which are increased in altitude as fuel is burned. The step climb is the climbing phase between two flight levels. ATC approval is always required to guarantee that the aircraft is flying at the cleared altitude [6].

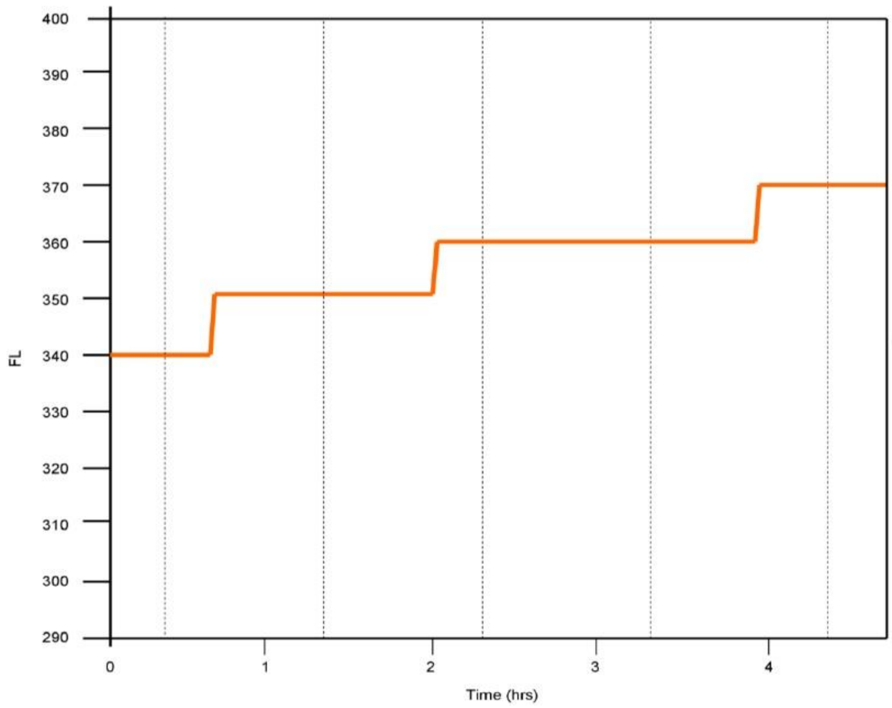

Figure 3. Step climb profile [6]

2.3.1.1 Choice of Profile

There are several ways to approximate the step climbs to the optimum altitude profile [7]:

- The low profile initiates the step climb at the weight where the next available flight level is also the optimum flight level at that weight. Consequently, the flight levels are always at or below the optimum. This has the advantage of better maneuverability margins;
- The high profile initiates the step climb at the weight where the next available flight level is also the maximum flight level at that weight. The flight levels are mainly above the optimum and the aircraft will have decreased maneuverability and fly slower;
- The mid profile initiates the step climb at the weight where the specific range at the next available flight level is better than that at the current flight level. This enables the flight profile to remain as close as possible to the optimum flight level. This technique is recommended for best fuel economy, and is very close to that required for best economy.

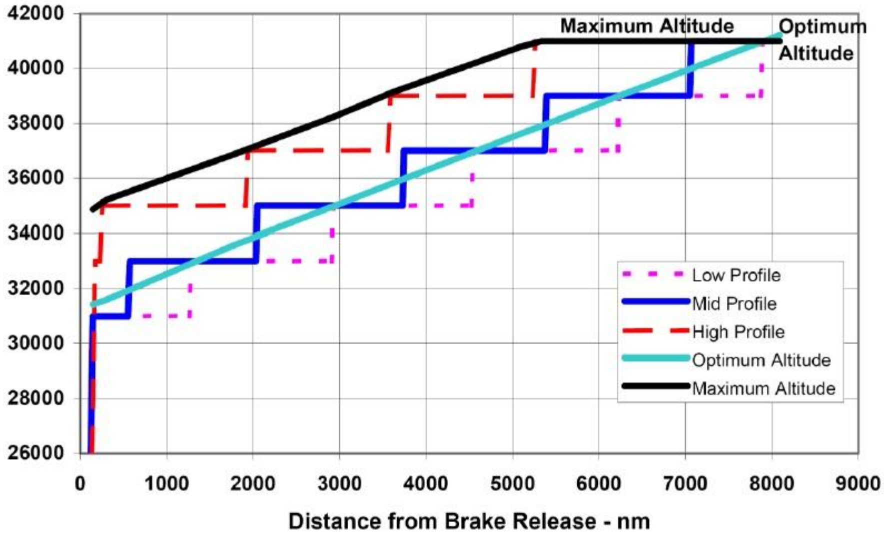

Figure 4. Step climb profiles at odd flight levels for RVSM [7]

2.3.2 Cruise Climb

The altitude that provides the most fuel efficient cruise at the start of a long flight, when the aircraft is fully loaded with fuel, is not the same as the altitude that provides the best efficiency at the end of the flight. As the flight proceeds fuel is burned and the aircraft becomes lighter. This change may be very significant; up to half the total weight on a long-haul aircraft. With the aircraft becoming lighter, the required lift becomes lower. In order to operate at the best lift coefficient we need to reduce the dynamic pressure. There are two options to reduce the dynamic pressure, by reducing the speed or by climbing to a higher altitude. If the aircraft is powered by a gas turbine we do not wish to reduce speed, or the engine efficiency will suffer. So, the air density is reduced by climbing gradually throughout the cruise phase [6].

The Concorde flights, for example, used a continuous cruise climb over the Atlantic, benefiting from rare situations where traffic at the same altitude (nearly 60000ft), in the same direction, and at the same time of the day was scarce or inexistent. According to ICAO rules [5], the procedures for cruise climb operation and coordination are still valid and can be used.

With the increase of air traffic since the Concorde days, and the assignment of distinct flight levels to specific flights, airways, and directions of flight, it is generally no longer possible to climb continuously. Even though low traffic regions are able to authorize cruise climbs, it is not practical from a traffic control standpoint.

When traffic conditions and coordination procedures, allow the clearance of a cruise climb, an ATC unit shall normally authorize only one level for an aircraft beyond its control area, i.e. the level at which the aircraft will enter the next control area whether contiguous or not. It is the responsibility of the accepting ATC unit to issue clearance for further climbing. When relevant, aircraft will be advised to request, en route, any cruising level changes.

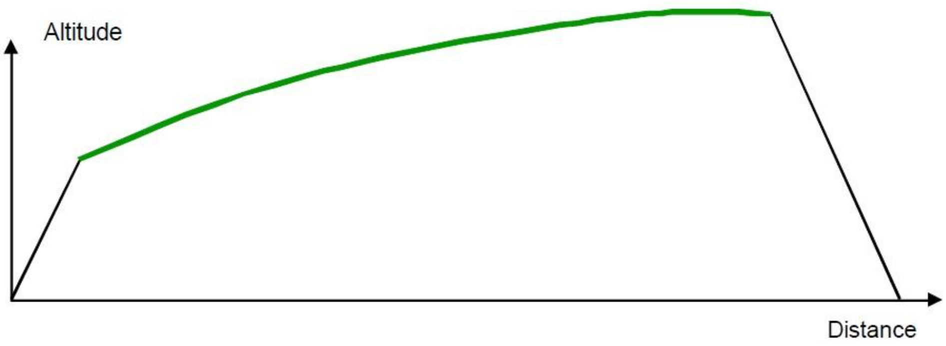

Figure 5. Cruise climb profile [8]

Given that modern avionics do not have an automatic cruise climb function, which is a barrier to the implementation of the technique, when an aircraft flies a cruise climb, what is actually happening is that the aircraft is performing a Limited Cruise Climb or some other technique of approximation [8].

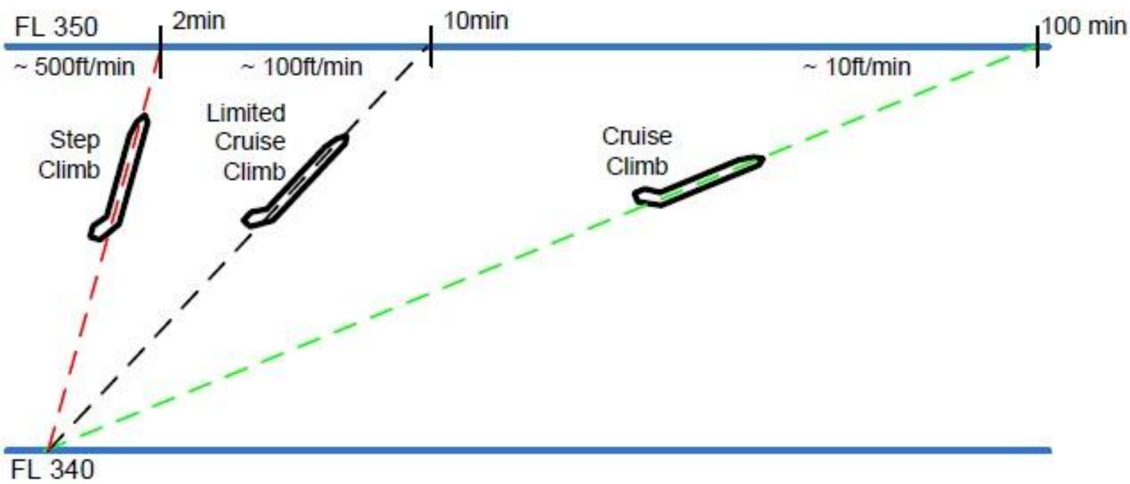

Figure 6. Different climb profiles [6]

A visual explanation of the different climb profiles is introduced on Figure. 6, showing the approximate climb rates, as well as the average time needed for a 1000ft level change in each of the modes.

2.4 Data-Link Services Considered for Vertical Airspace Management [6]

2.4.1 Automatic Dependent Surveillance - Contract (ADS-C)

The ADS-C is a tool used by air traffic services (ATS) in which aircraft automatically transmit, via a data link, data derived from on-board navigation systems. According to the ICAO Doc. 4444 [5] the ground systems shall provide for:

- the transmitting, receiving, processing and displaying of ADS-C messages related to flights equipped for and operating within environments where ADS-C services are being provided;

- the display of safety-related alerts and warnings;
- position monitoring (the aircraft's current position as derived from ADS-C reports is displayed to the controller for air traffic situation monitoring);
- conformance monitoring (the ADS-C reported current position or projected profile is compared to the expected aircraft position, which is based on the current flight plan. Along track, lateral and vertical deviations that exceed a pre-defined tolerance limit will permit an out-of-conformance alert to be issued to the controller);
- flight plan update (i.e. longitudinal variations that exceed pre-defined tolerance limits will be used to adjust expected arrival times at subsequent fixes).

There are four ways in which the information is passed from the ADS-C airborne system to the ground air traffic services unit (ATSU):

- on demand;
- on a periodic basis;
- when triggered by an event; and
- in an emergency and/or urgency condition.

2.4.1.1 Data Structure

As defined within the ICAO Doc. 9694 [9] each downlink starts with the Basic ADS-C frame and contains the information listed below:

a. Basic ADS-C information:
    - the 3D position of the aircraft (latitude, longitude, and altitude);
    - the time; and
    - an indication of the accuracy of the position data (figure of merit).
b. The Optional information could be included to the report, as an addition and on request. This optional information could be:
    - aircraft identification;
    - ground vector;
    - air vector;
    - projected profile;
    - meteorological information;
    - short-term intent;
    - intermediate intent; and
    - extended projected profile (EPP).

2.4.1.2 ADS-C in Multi-sector Airspace

A ground ATSU is expected to establish a connection with, and issue a contract request to an aircraft about to enter the airspace under its control. As an aircraft passes from one airspace management area to another, the ATSU handing over control may transmit coordination information to the accepting ATSU at some predetermined time before the aircraft reaches the boundary. The accepting center can initiate a connection. Contracts to the new and old ATSU's may be in effect simultaneously for some time period so that both centers can receive reports while the aircraft is in the vicinity of the border. The ATSU passing on the control of the ADS-C equipped aircraft may cancel its contract when the aircraft moves an ATS-specified distance away from the airspace management area boundary.

2.4.2 Automatic Dependent Surveillance - Broadcast (ADS-B)

This surveillance system is based on the ability of the aircraft to periodically and automatically broadcast a set of data, its state vector as minimum. This data can be received by any user, either aircraft or ground-based, within range of the broadcast that choose to receive and process the ADS-B information. It is Automatic because there is no need for human (crew member) intervention, Dependent because the data broadcasted is based on onboard equipment, and Broadcast because data is sent without previous interrogations from an air traffic controller or any other partner. Its principle is to send as many reports as possible to a greater number of receptors able to capture its signal. The ADS-B system was deployed primarily in areas with poor radar coverage (primary and/ or secondary) and for airborne separation assurance systems (ASAS) application in the future. Areas with expected usage of ADS-B can be used by any other systems (even ground based ATM systems), it can also be used for Cruise Climb operations. Moreover, future ASAS operations enabled by ADS-B should be considered as an influencing factor for the design of Cruise Climb operations as well.

2.4.3 Controller-Pilot Data-Link Communication (CPDLC)

Controller-Pilot data link communication (CPDLC) is an ATC communication tool that uses a data link to establish communication between air traffic controllers (ATCo) and pilots.

CPDLC has three primary functions:

- The exchange of controller-pilot messages with the current data authority;
- the transfer of data authority involving current and next data authority; and
- downstream clearance delivery with a downstream data authority.

The CPDLC should supplement the primary role of traditional voice communication. As such, the CPDLC predefined message set follows the existing phraseology with some specifics for non-verbal communication. Inside this predefined message set there is an option for free text messages.

The full set of messages can be consulted in ICAO Doc. 9694 [9].

2.5 Trajectory Processing in Ground Systems

2.5.1 Before Departure

Airspace Users plan and operate their flights, normally, in accordance with the IFR rules. It implies that the airline/ crew requests all air traffic services providers for confirmation of prepared ICAO flight plans.

The prepared flight plan is sent to the ATS flight data processing system (FDPS). After receiving the FPLN, each FPLN item is carefully controlled. Attention is specially paid to the item 15- route. The route must be continuous and correct. Then, the FPLN is sent to the flight data record (FDR) database system. Nevertheless, before departure (usually an agreed period of time before take-off) it is still possible to modify, delay or cancel it.

However, since the preparation of the FPLN, all airlines normally include in item 15- route, proposed changes for the duration of the flight. There are modifications of the requested 4D trajectory [6].

(FPL - ….. – **N0450F310** G1 UG1 STU **RTF/M082F330** UG1 52N015W 52N020W 49N050W… - …)

Figure 7. Item 15 of the prepared FPLN with route and information about FL change [6]

The information in Figure 7 describes the situation in which an aircraft at 450kts of speed at FL310 intends to make a FL change at waypoint RTF to the new FL330 at 0.82M of speed. Adding information about the time, to the information on the flight plan defines the planned 4D trajectory.

2.5.2 After Departure (En Route)

At this period of the flight, the aircraft has been cleared/ authorized as close as possible to the planned FPLN route, depending on traffic conditions.

If a discrepancy, like a sudden change in meteorological conditions, occurs, the crew has to inform the ATCo of the new 4D trajectory. The ATCo then includes this new data and recalculates the ground trajectory prediction, which is done by extrapolating an aircraft's current speed along the current route. The new generated trajectory is then sent to all ATSU's along the path of the aircraft (Ground-Ground coordination). New route data, like waypoints, FL's or times of overfly, is displayed (printed) on strips and used as a new trajectory.

The ground Trajectory Predictor (TP) module is used by the ATC to manage the traffic and to anticipate potential conflicts. The implementation of the Cruise Climb procedure would probably have an impact on the ground models. In fact, the ground tool should have a good knowledge of the cruise climb procedure and the aircraft capabilities in order to perform an accurate prediction and avoid raising false alarms [6].

2.5.3 Atmospheric Model

The most recent FDPS, use an atmospheric model, that includes forecasted wind and temperature information for the areas of jurisdiction of the ANSP, during agreed time periods [6].

This data, which is broadcasted as the result of an agreement between ICAO and the World Meteorological Organization (WMO), is used by the ground system to calculate the user requested trajectory and allows the comparison with the information provided by the pilot.

2.6 Trajectory Computation in the FMS

The flight crew selects flight planning data on the Multifunction Control Display Unit (MCDU), on the navigation display or by data-link, from the airline's operational control.

The flight plan can be modified at any time, whether from a crew decision, from an airline operational communication or by air traffic control due to a tactical situation. An edition of the flight plan creates a temporary modified version that is a copy of the active flight plan plus all the changes made to it. To allow the crew to assess the impact of the flight plan changes, trajectory predictions are calculated for every edit on the modified FPLN and periodically updated. When all the changes are in accordance with the crew's will, a FPLN change approval from the ATCo is needed is order to make it an active FPLN. During the negotiation phase, the ATCo will assess the consequences of the proposed FPLN changes, the ATCo can then accept or reject the required modifications. When the FPLN modification is accepted by the ATCo, the modified flight plan is activated by the crew in the FMS.

The trajectory prediction function then computes the predicted four dimensional flight profile of the aircraft based on atmospheric data inputs and in accordance with the flight plan constraints and aircraft performance limitations. The flight profile is continuously updated to account for non-forecasted environmental conditions and tactical diversions from the specified flight plan [10].

2.6.1 Weather Forecast

An important part of the flight planning process is to consider temperature and wind forecast conditions for the path and altitude of the flight. These forecast conditions help the FMS improve the trajectory predictions to provide more accurate determination of estimation times of arrival (ETA's), fuel burn, rates of climb/ descent and leg transitions construction.

Wind models used in the cruise segment usually allow the input of wind speed for multiple altitudes at en route waypoints. To achieve wind parameters between waypoints an interpolation between entries is made. It is also possible to propagate an entry forward until the next waypoint entry is encountered. Forecast winds are merged with current winds obtained from sensors in a method that gives a heavier weighting to sensed winds close to the aircraft and converges to forecast winds as each waypoint-related forecast wind is sequenced.

The forecast temperature used for the extrapolation of temperature is based on the International Standard Atmosphere (ISA) with an offset (ISA deviation) obtained from pilot entries and/or the actual sensed temperature [10].

2.6.2 On-board Construction of the Flight Plan

The flight trajectory is divided in lateral profile (the flight profile as seen from above) and vertical profile (the flight profile as seen from the side). The lateral profile and the vertical are interdependent as they are coupled to one another through a parameter, the ground speed. An example of a typical flight plan with lateral and vertical profiles is shown in Figure 8.

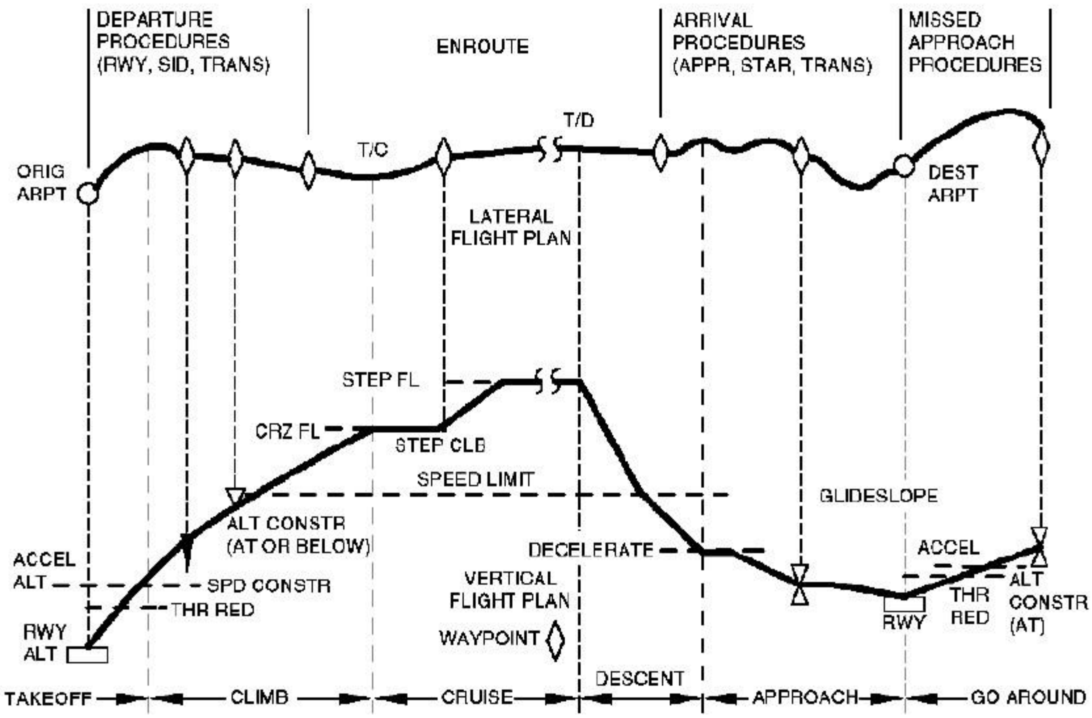

Figure 8. Typical lateral and vertical profiles on a flight plan [10].

2.6.2.1 Waypoints

Waypoints can have associated speed, altitude and time constraints.

A waypoint speed constraint is interpreted as a "cannot exceed" speed, or speed limit. If the waypoint is in the climb phase, the speed constraint applies at that specific waypoint and at all waypoints prior to it. If the waypoint is in the descent phase, it applies to all waypoints after it [10].

A waypoint altitude constraint can be of four types: "at", "at or above", "at or below" and "between".

A waypoint time constraint can be of three types: "at", "at or after" and "at or before".

2.6.2.2 Vertical Profile Flight Planning

Vertical profile flight planning consists of a selection of speed, altitude, time constraints at waypoints (if required or desired), cruise altitude selection, aircraft weight, forecast winds, temperatures, and barometric pressure at the destination, as well as altitude levels for planned use of aircraft anti-icing. The construction limits of the flight plan are stored in the performance database in the form of fuel flow, drag and thrust models. A variety of optimized speed schedules for the various phases of the flight is usually available. Several aircraft performance-related crew selections may also be provided. All these selections affect the predicted aircraft trajectory.

The cruise flight phase starts from the top of climb (TOC) to the top of descent (TOD), where the TOC is the computed transition from the climb phase to the cruise phase and TOD is the computed point, where the planned descent flight phase begins. During the cruise phase several climbs and descents can occur.

The vertical part of the cruise flight phase is usually very simple. It consists of a segment in which the climb speed mode is switched to the cruise speed mode. The cruise phase is typically flown at a cruise altitude level that was predicted during the flight planning phase. The vertical profile is computed based on the energy balance equations including variable weight, speed and altitude. The computed steps are constrained by the flight plan which comprises ATM restrictions and aircraft limitations [10].

2.7 Performance Computations

The pilot is provided with information to help optimize the flight by the FMS performance unit, which implements a variety of performance functions, some of them regarding fuel consumption optimization.

2.7.1 Cost Index

The FMS includes a functionality allowing the setting of preferred economy aspects of a flight in terms of a ratio between fuel related costs and time related costs. The selected cost index (CI) impacts mainly the speed of the flight [10].

2.7.2 Speed Schedule Computation

Part of the vertical flight planning process is the selection of performance modes for each phase of the flight based on mission requirements and preferences. The selection of a flight phase specific performance mode results in the computation of an optimized speed schedule (with respect to the selected preferences). The performance parameter that is optimized is different for each performance mode selection [10].

2.7.3 Cruise Speeds

For the cruise phase of the flight the following speed preferences are used [10]:

- Economy (Cost Index based)- speed selection to minimize the overall cost;
- Maximum endurance- speed selection to minimize burnt fuel;
- Long range cruise- speed selection to maximize the flight range;
- Required time of arrival (RTA)- speed selection to arrive at a waypoint at required time; and
- Manual setting of speed.

2.7.4 Optimal Altitude

The algorithm estimating the optimal altitude for the aircraft considers the given aircraft weight, atmospheric conditions, engine settings and the other set parameters. The optimal altitude algorithm computes the cost-effective operational altitude based solely on aircraft performance and forecasted environmental conditions. Fundamentally, the algorithm searches for the altitude that provides the best fuel range taking into account the weight reduction caused by fuel burn, the speeds according to the selected performance mode and prediction of wind and temperature. The optimum altitude is always limited by maximum altitude [10].

2.7.5 Maximum Altitude

The maximum altitude is the highest attainable altitude considering solely the aircraft performance margins within the predicted weather conditions, while allowing for a specified rate of climb margin [10].

2.7.6 Trip Altitude

The computation of the altitude for a specified route, called trip altitude allows the pilot to request an altitude clearance to optimize the flight with respect to their preferences.

This altitude may be different from the optimum altitude in that for short trips the optimum altitude may not be achievable because of the trip distance. This algorithm searches for the altitude that satisfies the climb and descent while preserving a minimum cruise time [10].

2.7.7 Step Climb, Step Descent

For long haul flights, the achievable cruise altitude is initially lower than the optimal altitude because of the heavy weight of the aircraft. As fuel is burned off and the aircraft weight reduced, it becomes advantageous to step climb to a higher altitude for more efficient operation. The step descents can be considered by the FMS for example in the case when the temperature of the surrounding air does not allow the optimal engine performance.

The FMS provides a prediction of the optimum points at which a step climb/ descent maneuver may be initiated to provide a more efficient operation. The step altitude is limited by the current ATM rules. This algorithm considers all the vertical flight planning parameters, particularly the downstream weight of the aircraft, as well as forecasted wind data. The time and distance to the optimum step point for the specified step altitude is displayed to the pilot.

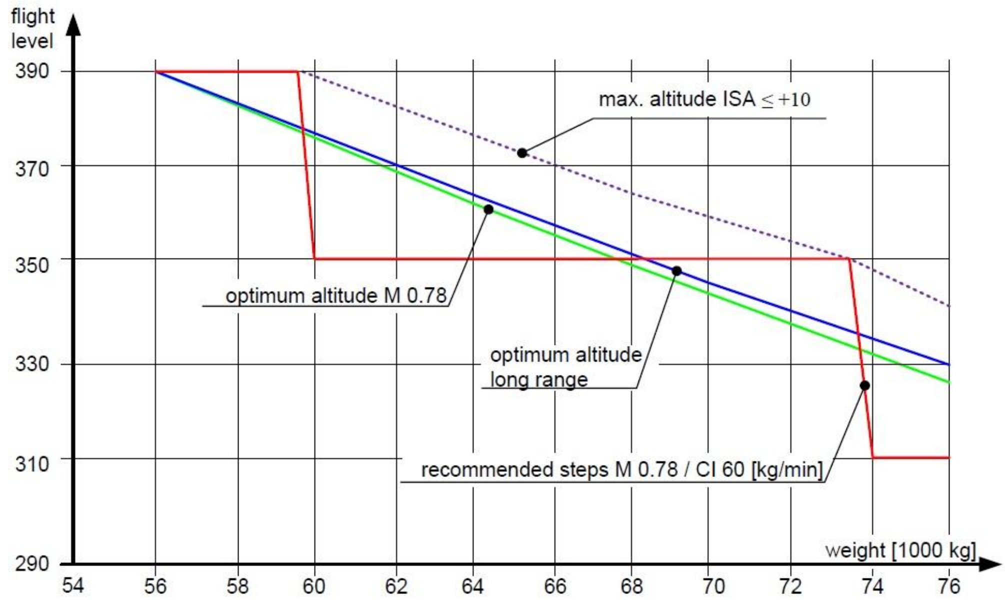

Figure 9. Optimum altitudes for different weights at M0.78 [10].

For transoceanic flights the trajectory prediction function assumes that the steps will be performed as a part of the vertical profile, this way the fuel predictions will have a greater degree of reliability.

The FMS computes the aircraft's along-path speed, along-path distance travelled and fuel burned based on the projected aircraft target speed, wind, drag, and engine thrust in a repetitive manner. The projected aircraft true airspeed or MACH is derived from the pilot-selected cruise speed schedule. Drag is computed as a function of the aircraft speed and flight path angle. For level flight thrust must be equal to drag. Given the required thrust, the engine power setting is computed and becomes the input for throttle control algorithms and fuel burn estimation.

Because of the jet engine efficiency it is more efficient to fly at a higher altitude as the fuel is burned and the aircraft weight slowly decreases.

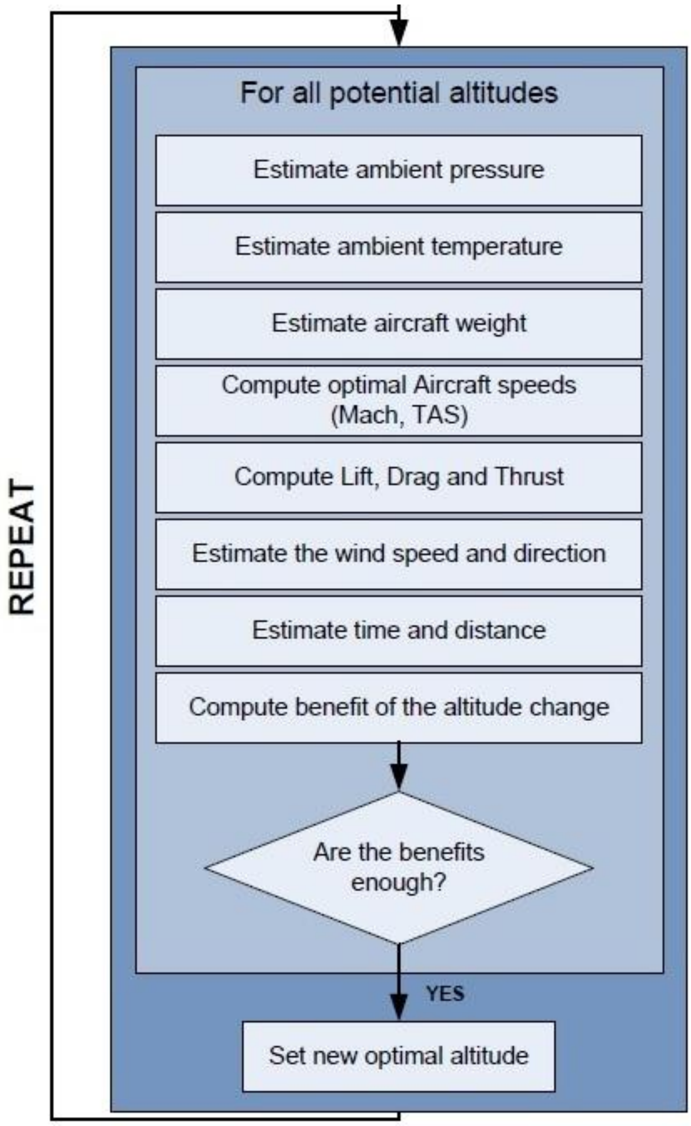

Figure 10. Flowchart of the necessary steps for estimation of optimal altitude [10].

The FMS provides the computation of the point in the trajectory where the change of the altitude is convenient. The optimal step altitude is computed regarding restrictions of ATM, estimated aircraft weight, speed setting and surrounding environmental conditions. Figure 10 presents a flowchart of all the steps necessary to determine optimal altitude. The step maneuver is then executed either automatically or by the pilot [10].

2.8 Overview of Auto Control Modes

The automatic flight of an aircraft is attained through predefined control objectives. While the objectives of the lateral profile are more navigation-oriented, the vertical profile is more oriented to the aircraft's performance control. Within the vertical profile of a flight three basic sets of control parameters exist and to specify the vertical motion it is enough to select two of the three control objectives. The control objectives are chosen to be coherent with the ATC and pilots procedures.

The selection of control objectives has a significant impact on the sensitivity and accuracy of the trajectory prediction. In fact, a disturbance of a parameter controlled by an active control objective will initiate immediate corrective action of the guidance system and the sensitivity to this parameter is thus smaller than to the other errors [10].

2.8.1 Airspeed Control Objectives

The flight crew can control the airspeed by using the following modes accessible from the flight control panel or from the FMS users interface [10]:

- Calibrated airspeed (CAS);
- Calibrated airspeed profile (FMS descent path);
- MACH;
- MACH profile (FMS descent path or cruise economy mode); and
- FMS RTA - the algorithm controls the speed schedule to fulfill a requested time of arrival (RTA) (at a given waypoint).

2.8.2 Throttle Control Objectives

The flight crew can select the manual or the automatic mode. The automatic mode is controlled by the FMS and it's selectable on the flight control panel [10]:

- Constant throttle - the control law is tracking the desired throttle setting; and
- FMS throttle profile - the throttle is controlled on the basis of the variable desired throttle settings in order to achieve the desired descent path profile.

2.8.3 Vertical Control Objectives

The flight crew selects the vertical profile by using the following modes accessible from the flight control panel [10]:

- Constant pressure altitude - the control law tracks a constant pressure altitude;
- FMS pressure altitude profile - Similar to constant pressure altitude but dependence on distance is added to follow the desired profile, as in a descent path;
- Constant baro-corrected altitude - the control law tracks a constant baro-corrected altitude;
- FMS baro-corrected altitude - similar to constant baro-corrected altitude but dependence on distance is added in order to follow the desired profile;
- Constant pressure altitude rate - the algorithm controls a constant change of pressure altitude;
- Constant inertial Flight Path Angle - the algorithm controls a constant Path Angle with an inertial system; and
- Constant air-mass Flight Path Angle - the algorithm controls a constant Path Angle with air-mass.

2.9 Conclusion

The main goal of this chapter was to describe the operational aspects of the fuel optimization techniques for the vertical profile of the cruise flight phase. The two main methods for cruise vertical profile optimizations were described in detail, the cruise climb technique and the step climb technique. A reference to the concept of limited cruise climb is also included. These methods are described in a way that covers the airborne as well as the ATC's point of view.

A description of the vertical path itself is made, from the construction of the flight plan, update and revision of the airborne trajectory while considering the actual conditions, to the ground system trajectory prediction synchronization.

There is also an overview of the current networking technologies, data-link services and applications as a support for the considered cruise climb concept, as well as the actual operations, which normally consists of step climbs.

3 The Case of NATCLM

3.1 Introduction

The Atlantic Interoperability Initiative to Reduce Emissions (AIRE) is an agreement between the European Commission (EC) and the Federal Aviation Administration (FAA) of the United States of America. It is a project that aims to reduce CO_2 emissions by taking advantage of ATM best practices and new technologies, it expects to accelerate the implementation of environmentally friendly procedures for all flights and to validate the benefits of these improvements. The SESAR Joint Undertaking (SESAR JU) is responsible for the management of AIRE from an European perspective [11].

The project includes a set of activities for aircraft vertical trajectory optimization in the oceanic domain.

The results of the project expect to bring a valuable contribution to the removal of constraints that prevent aircraft from flying as close as possible to their most efficient altitude.

3.2 Description of Trials

Several flights between Europe and North, Central and South America provided data and derived results for the project. The demonstrations were carried out inside one of the Oceanic Flight Information Regions (FIR) that compose the North Atlantic Region defined by ICAO (Figure 11).

Some flights were supported by the Air Navigation Service Provider (ANSP) that manages the FIR that follows the FIR where the trials were taking place to allow for an extension of the flight profile optimization.

Data link communications were used to support the flight trials. So, it was required for the execution of the optimization commands that all aircraft taking part in the trials were equipped with Future Air Navigation Systems (FANS).

All flight trials were conducted exclusively with ADS-C / CPDLC certified flights and were handled expeditiously by the operators involved regarding all current standards and practices. None of the flight trials were constrained by any reason other than safety or ICAO regulations.

In total, fifty flights, by the several airlines involved in the project were optimized.

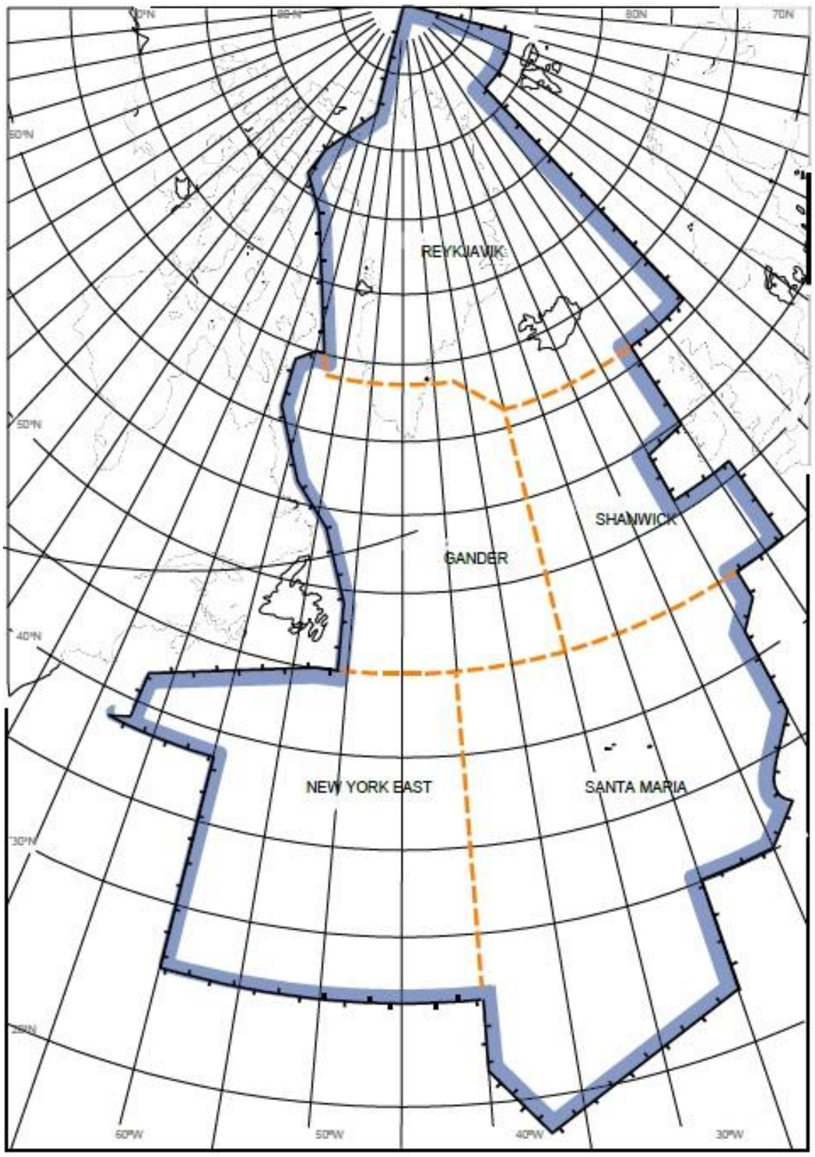

Figure 11. Flight information regions of the North Atlantic [12]

3.2.1 Flight Profile Description

To approximate the vertical profile optimization to a real cruise climb, the flight trials were flown at Mach 0.80, over a distance of around 1600NM, in a sequence of twenty 100ft climbs with an average rate of climb of 250ft/min from FL370 to FL390 (Figure 12).

To be able to estimate how much savings were obtained, the results from the optimization were confronted with values from usual step climb procedures. In this case - a 2000ft step climb at maximum climb rate.

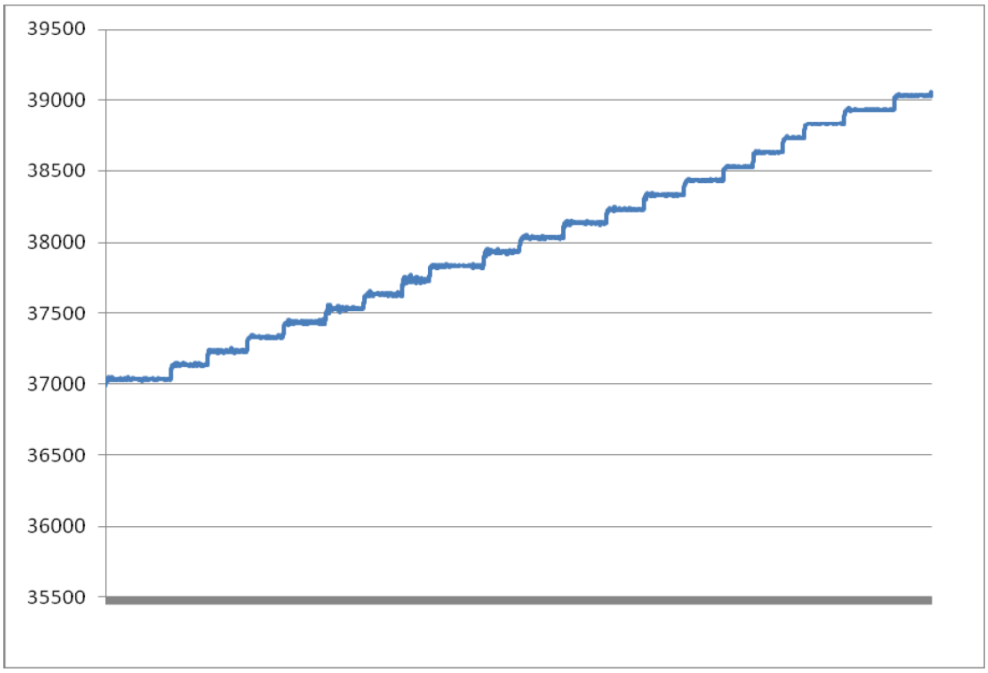

Figure 12. Vertical profile optimization in 100ft step climbs [11].

In order to determine the right time to step climb, crews follow the information from Figure 13 which was made available in the customized Quick Reference Handbook (QRH) for the flight trials.

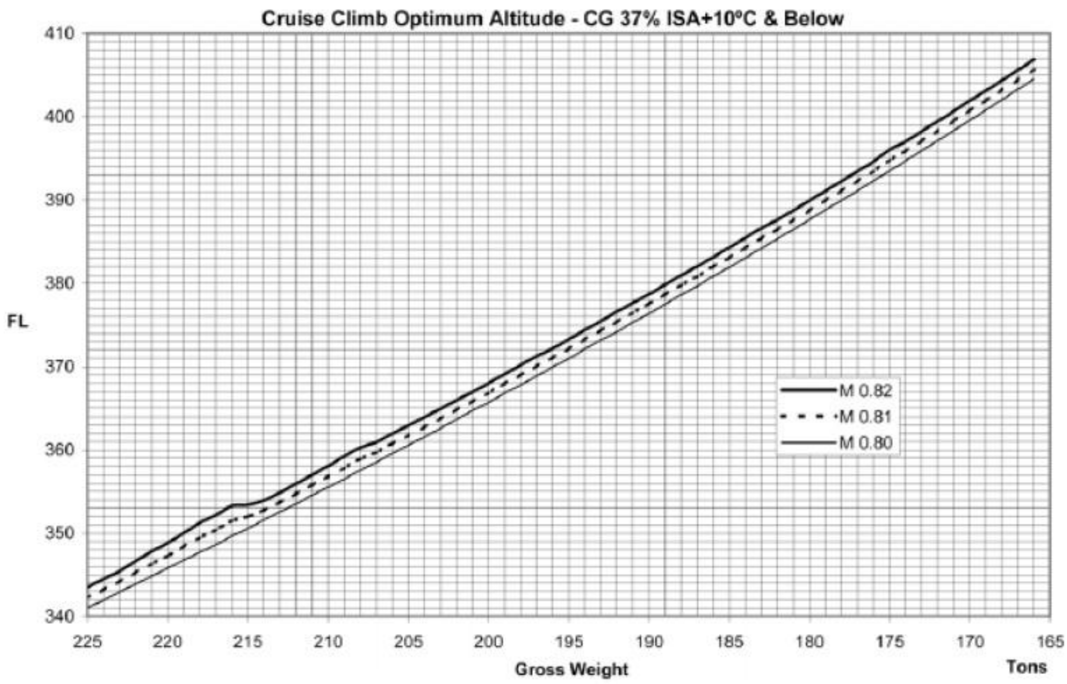

Figure 13. Cruise climb optimum altitude [11]

Figure 13 presents the optimum altitude vs. gross weight of the aircraft for M0.82 and M0.80, the values for M0.81 were interpolated. Considering the Centre of Gravity (CG) of the aircraft at 37% and at ISA +10°C & below.

3.3 Facilities and Equipment

3.3.1 Oceanic Control Centre

The facilities and equipment used for the demonstration flight trials are owned and operated by an ANSP that has to fulfill its State delegated responsibilities of providing ATM services in its FIR.

It is required by ICAO that the ATM service provision has a minimum set of facilities, equipment and functional capabilities. All these requirements are audited by the national regulatory agency.

This particular control centre provides Air Traffic Control, Flight Information Service, Alerting Service, Airspace Management, Air Traffic Flow Management (ATFM), Radio Navigation and Radio Communication Services, for the FIR under its control, to around one hundred thousand flights every year [11].

The surveillance and communications applied within the FIR are based on a mixed mode environment using the certified systems for surveillance and communication. Voice, ADS-C position reports and radar for surveillance and, for communications, voice over HF, VHF and satellite communications (SATCOM) as well as CPDLC.

3.3.1.1 Systems Architecture

The service provision is supported by redundant systems for flight data processing and data and voice recording for all communications and surveillance.

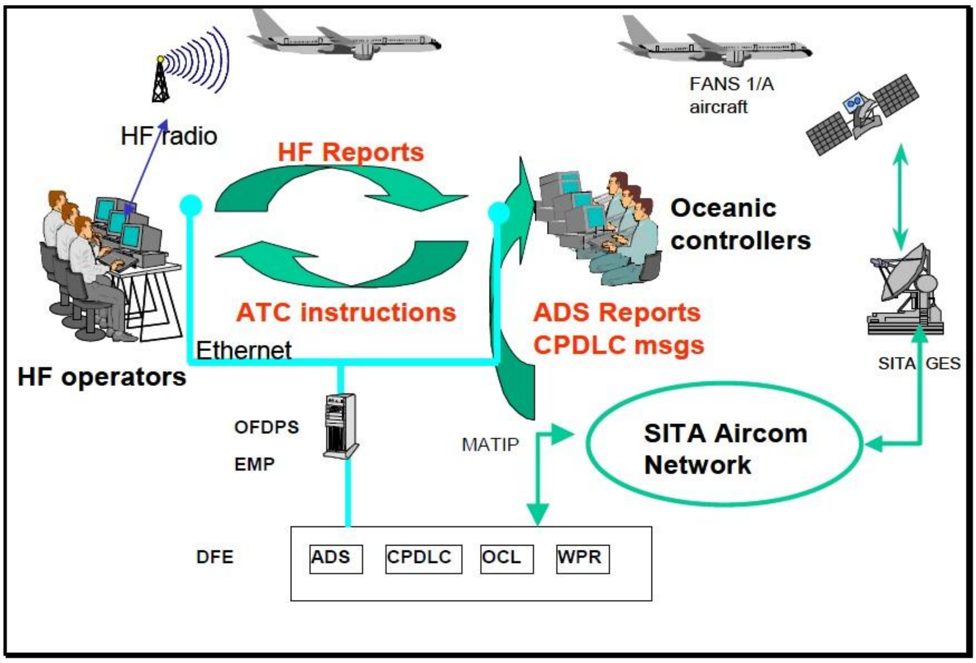

Figure 14. General systems architecture [11]

The redundant flight data processors are responsible for processing all ATS relevant information, flight plans, ATS messages, voice and data link reports, radar data, ADS-C data, or CPDLC.

All the internal workstations are connected to the main processors via a redundant LAN (Local Area Network) and each sector has proper software interfaces for the provision of the respective services, which is shown in Figure 14.

In order to access the data link services the Oceanic Flight Data Processing System (OFDPS) interfaces with a redundant DFE (Data Link Front-End) that is connected to the SITA Network. This allows the staff to exchange messages with the aircraft.

3.3.1.2 ATM System

Description of the ATM - OFDPS functionalities used for the flight trials [11]:

- Extrapolated Traffic Graphical depiction;
- Electronic flight strips;
- Advanced processing of flight progress, both for conventional surveillance, FMC waypoint position report (WPR) and ADS-C WPR;
- Automatic Conflict detection and analysis;
- Advanced Conformance monitoring;
- Air/Ground communications interface and integration;
- Automatic On-line Data (AIDC) interchange with adjacent centers; and
- Real time integration of SSR Radar data with FDPS and appropriate display of correlated (conformant or not) and non correlated radar tracks in oceanic sectors.

Figure 15 presents a display of an ATM system, with information on the status of every aircraft on the sector being controlled by the ATCo.

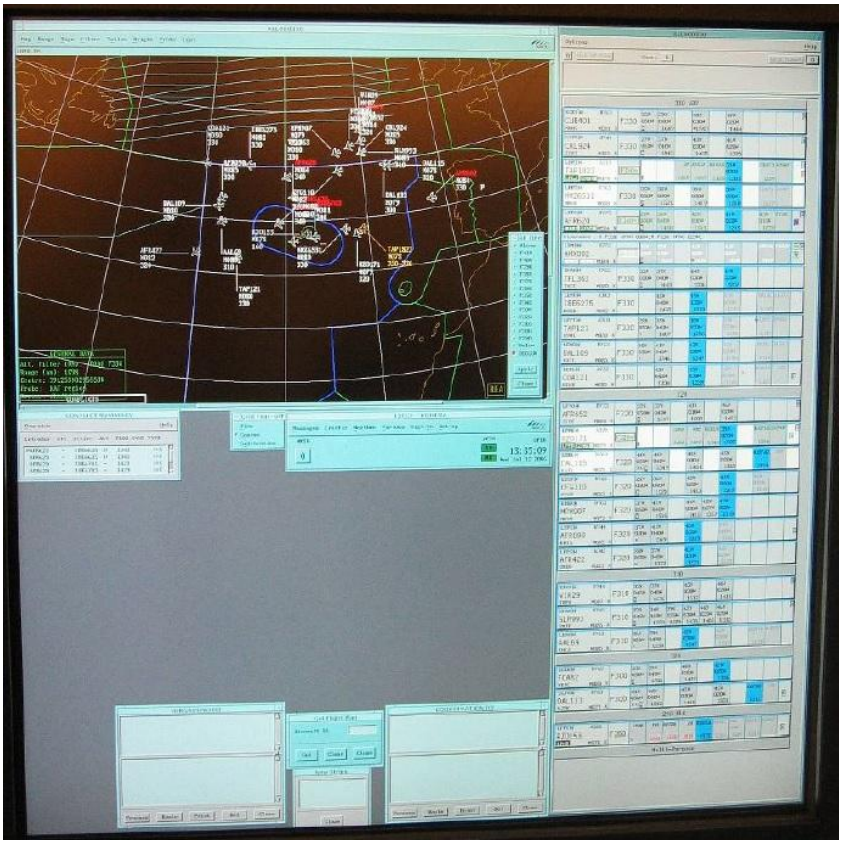

Figure 15. Display of the ATM System [11]

3.4 Data Gathering and Processing Systems

3.4.1 ANSP System

All the aircraft flight data was recorded by the FDPS database. This database collected data from every flight trial as well as from other similar flights to support the gathering of flight data.

3.4.2 Airline A

3.4.2.1 Airline Operational Control (AOC) System

A flight plan preparation system (FPPS) is used by the staff in order to calculate an optimized FPLN based on the daily conditions for their flights. This system receives a weather update valid for the next 36 hours twice a day at 4am and 4pm local time of the airlines headquarters.

When dispatch receives a crew request or an ATC request to re-route the flight, they use the FPPS to update the Flight Plan during the flight.

The dispatch staff also uses a Long Haul Flight monitoring system to monitor Long Haul flights. This system offers a graphical interface where routes, tracks, weather forecast and weather observation can be displayed. In the past, long haul flights were monitored based on the Flight Plan estimated times on the several waypoints along the route, starting with the actual time of take off. Nowadays, thanks to these new systems, long haul flights can be monitored based on their actual flight position.

Airline A also has a system based on its country's National Meteo Agency that helps the dispatcher analyze weather events with more precision. This system also includes significant meteorological information (SIGMET) that displays en route weather information that is provided by the ATC.

The Aircraft Communication Addressing and Reporting System (ACARS) allows the dispatcher to exchange information with the flight crew via data link communication.

3.4.2.2 Flight Analysis Database

The Flight Analysis Database stores flight data parameters, like speed, position, heading or fuel flow. These parameters are recorded every second of the flight for flight analysis purposes and are available a few days after the flight. Once it becomes available, it is possible to extract just a desired amount of flight data, or all of it, if needed.

The fuel consumption of the flight trials was extracted from this database. Because all flight parameters are recorded every second, it was possible to focus solely on the cruise phase of the flight.

For confidential reasons, it is not allowed to use this information without the agreement of the crew, unless if it is not possible to identify the actual flight from the information extracted.

Confidentiality was assured since the day of the flight analyzed was not extracted and the flight trials took place in several different days.

3.4.3 Airline B

3.4.3.1 Airline Operational Control (AOC) System

The FPPS used by Airline B works in the same way as the one used by Airline A. It takes the daily conditions and plans an optimized flight plan based on them. This system differs from Airline's A system in that it receives a weather update every six hours.

Airline A uses a ground server responsible for forwarding messages to and from the airplane via ARINC. This server integrates the AOC messages in their information systems.

The availability of this server is controlled by ARINC Control Centre and also by Airline A Line Control 24h a day.

Via ACARS, the dispatcher can exchange information with the cockpit crew through data link communication.

3.4.3.2 Flight Analysis System

For the purpose of flight analysis, Airline B used a SAGEM Flight Analysis System which allows the extraction of all the relevant flight parameters.

3.5 Conclusion

This chapter presents the project that was studied and whose results will be presented in the next chapter.

Starting with the description of the flight trials and the on-board equipment necessary for the execution of the flights. The chapter proceeds with an overview of the ATM system and ATC facilities that accompanied the flight trials.

To conclude the chapter, the data gathering and processing systems are described for the ANSP that controlled the flights and for both of the airlines that took part in the flight trials.

4 Analysis of the NATCLM Results

4.1 Introduction

In this chapter it will be presented an estimation of savings, as well as the detailed calculations of the flight trials results.

During any commercial flight, the air temperature, air density and wind velocity can be recorded. As these values are not known before the flight and they are needed for filling the flight plan, forecast values, given by the meteorology are used instead. Other important parameters like the exact weight of passengers, luggage and remaining fuel, are never certain.

To reduce the uncertainty of the results, the specific range deviation was determined for different segments of the flight, which makes it possible to determine an average performance factor to apply to all predictive performance calculations.

For all trials the actual fuel consumption was compared with the predicted fuel consumption for the prevailing conditions and with predicted fuel consumption in the cases where the current techniques were used.

To determine the actual fuel consumption the data extracted from the flight data recorders was used, integrating it in time instantaneous readings of the relevant parameters. The fuel consumption figure was compared with the fuel quantity readings, which allowed to determine how much fuel was used between the initial and final instants considered.

4.2 Estimation of Savings

The prediction of fuel consumption for the prevailing conditions was made using the manufacturers Performance Programs [3]. Calculations were performed in a sequence of 100ft climbs plus cruise segments at increasing flight levels, from the initial weight at a given level, until the optimum weight to climb another 100ft is attained.

For the prediction of fuel consumption for the current climb technique, it was used Performance software, by calculating a cruise segment from the start of the cruise until the point where optimum weight for a 2000ft step climb is attained, plus a climb of 2000ft, plus a cruise segment until the same point where the cruise climb would be finished [11].

For the estimation of savings, an A330-202 aircraft was used. And the steps were calculated at a weight that leads the aircraft to be at the optimal weight for the average altitude of the altitude between the steps. This yields results that are expected to be valid for other aircraft types in a qualitative way.

Three different optimization strategies were tested, besides the current operational situation:

- Case 0, was a step climb of 1000ft, from FL360 to FL370 followed by a cruise segment at FL370 and then a step climb from FL370 to FL380;
- Case 1, was a 2000ft step climb from FL360 to FL380;
- Case 2, was a series of 100ft steps each followed by a cruise segment;
- Case 3 was a continuous climb at a rate as close as possible to the one that makes the aircraft follow the path of optimum altitude versus weight (in this case 10ft/min). This, in theory, could be called the actual Cruise Climb Technique, although it proved to be far from ideal.

Table 1 summarizes the results obtained, considering the following conditions:

- Cruise at Mach 0.80;
- Climb at maximum rate;
- Initial weight: 205300 kg, which is close to the optimum weight for FL360 (205270kg);
- Final weight: 186400 Kg, which is the optimum weight for FL380.

Table 1 - Estimation of savings - Summary [11]

	Case 0 (1000ft step)	Case 1 (2000ft step)	Case 2 (100ft steps)	Case 3 (Slow climb)
Distance from 205300kg to 186400 kg (NM)	1596.8	1595.3	1597.9	1565.8
Extra distance to case 2 (NM)	1.1	2.6	0	32.1
Extra fuel for distance 2 (kg)	12	29	0	360
Final weight (kg)	186388	186371	186400	186040
Fuel increase with respect to case 0 (kg)	0	17	-12	348
% increase with respect to case 0	0.00%	0.09%	-0.06%	1.84%
Fuel increase with respect to case 1 (kg)	-17	0	-29	331
% increase with respect to case 1	-0.09%	0.00%	-0.15%	1.75%
Fuel increase with respect to case 2 (kg)	12	29	0	360
% increase with respect to case 2	0.06%	0.15%	0.00	1.90%

From Table 1 it can be concluded that there are potential savings of 0.06% when flying as specified in Case 2 comparing to Case 0. If a comparison is made to Case 1 the potential fuel savings reaches 0.15%.

4.2.1 Detailed calculations

The detailed calculations for Case 2 - twenty 100ft climbs are presented in Table 2.

Table 2. Detailed calculations for 100ft step climbs [11]

		Cruise					Climb				
FL	Optimum Weight (kg)	Initial Weight (kg)	Final Weight (kg)	Fuel (kg)	Distance (NM)	Time (min)	Initial Weight (kg)	Final Weight (kg)	Fuel (kg)	Distance (NM)	Time (min)
36000	205270	205300	204761	539	43,8	5,72					
36050	204750										
36100	204245	204740	203751	989	80,6	10,55	204761	204740	21	1,3	0,18
36150	203740										
36200	203230	203730	202730	1000	81,9	10,71	203751	203730	21	1,3	0,18
36250	202720										
36300	202190	202709	201710	999	82,2	10,75	202730	202709	21	1,3	0,17
36350	201700										
36400	201200	201689	200786	903	74,7	9,77	201710	201689	21	1,3	0,17
36450	200775										
36500	200275	200765	199786	979	81,3	10,63	200786	200765	21	1,3	0,17
36550	199775										
36600	199275	199765	198882	883	73,7	9,64	199786	199765	21	1,3	0,17
36650	198872										
36700	198350	198861	197860	1001	83,9	10,97	198882	198861	21	1,3	0,17
36750	197850										
36800	197401	197840	197010	830	69,9	9,14	197860	197840	20	1,3	0,17
36850	197000										
36900	196520	196990	196050	940	79,5	10,39	197010	196990	20	1,3	0,17
36950	196040										
37000	195575	196030	195130	900	76,5	10	196050	196030	20	1,3	0,17
37050	195120										
37100	194660	195110	194220	890	76	9,94	195130	195110	20	1,3	0,17
37150	194210										
37200	193610	194200	193165	1035	88,8	11,61	194220	194200	20	1,3	0,17
37250	193155										
37300	192695	193145	192240	905	78	10,2	193165	193145	20	1,3	0,17
37350	192230										
37400	191790	192220	191335	885	76,7	10,03	192240	192220	20	1,3	0,17
37450	191325										
37500	190870	191315	190441	874	76,1	9,95	191335	191315	20	1,3	0,17
37550	190430										
37600	190012	190421	189525	896	78,3	10,24	190441	190421	20	1,3	0,17
37650	189515										
37700	189070	189505	188629	876	76,9	10,06	189525	189505	20	1,3	0,18
37750	188620										
37800	188180	188609	187735	874	77,1	10,08	188629	188609	20	1,3	0,18
37850	187725										
37900	187290	187715	186860	855	75,8	9,91	187735	187715	20	1,3	0,18
37950	186850						186860	186840	20	1,3	0,18

38000	186400	186840	186400	440	39,1	5,11					
			Cruise	18493	1570,8	205,4			407	26	3,46
			Climb	407	27,1	3,46					
			Total	18900	1597,9	208,9					

In Table 2, the distances presented have a precision of tenths of a nautical mile. It was observed that the actual distance for each 100ft step was somewhere between 1.3NM and 1.4 NM. By using the same total distance as the one found for one single step of 2000ft, 27.1NM, the error would decrease, as shown in the detailed calculations of Table 3.

Table 3. Detailed calculations for Case 1 [11]

	FL	Initial GW (kg)	Final GW (kg)	Fuel (kg)	Distance (NM)	Time (min)
Cruise	360	205300	195762	9538	791,1	81,34
Climb	360-380	195762	195350	412	27,1	3,55
Cruise	380	195350	186400	8950	777,1	101,62
			Total	18900	1595,3	186,51
Cruise	381	186400		29	2,6	0,34
			Total	18929	1597,9	186,85

The total distance for a 2000ft step climb from FL360 to FL380 (1595.3NM), as can be seen from Table 3, is 2.6NM shorter than the distance used for twenty 100ft step climbs (1597.9NM). Thus, an additional distance of 2.6NM needs to be flown at FL380 in order to cover the same distance as before, as shown in Table 3.

It is shown in Table 4 a comparison of fuel consumption between a level flight at FL360 (and FL380) and performing 100 ft step climbs between FL360 and FL370 (and between FL370 and FL380).

Table 4. Fuel consumption between FL360 and FL380 [11]

FL (100ft)	Initial Weight (kg)	Final Weight (kg)	Fuel (kg)	Distance (NM)	FL(100ft)	Fuel (kg)	Delta Fuel (kg)
360	205300	204761	539	43.8	360	539	0
361	204740	203751	989	80.6	360	989	0
362	203730	202730	1000	81.9	360	1000	0
363	202709	201710	999	82.2	360	999	0
364	201689	200786	903	74.7	360	904	1
365	200765	199786	979	81.3	360	979	0
366	199765	198882	883	73.7	360	884	1
367	198861	197860	1001	83.9	360	1001	0
368	197840	197010	830	69.9	360	831	1
369	196990	196050	940	79.5	360	941	1

370a	196030	195575	455	38.6	360	455	0
370b	195575	195130	445	37.9	380	448	3
371	195110	194220	890	76	380	895	5
372	194200	193165	1035	88.8	380	1039	4
373	193145	192240	905	78	380	907	2
374	192220	191335	885	76.7	380	888	3
375	191315	190441	874	76.1	380	876	2
376	190421	189525	896	78.3	380	897	1
377	189505	188629	876	76.9	380	877	1
378	188609	187735	874	77.1	380	875	1
379	187715	186860	855	75.8	380	856	1
380	186840	186400	440	39.1	380	440	0
			Total:	1570.8			27

For a better understanding of the values in Table 4, take the case of the 100ft step climb from FL363 to FL364, 903kg of fuel were used for that distance, 74.7NM. By flying the same distance, starting at the same weight, but at FL360, over the same distance, 904kg of fuel were used, resulting therefore in savings of 1kg of fuel over a segment of 74.7 NM. By doing the same exercise for all other FL's and summing up all the savings, we obtain the 27kg of fuel savings for the flight segment of 1570.8NM mentioned in Table 4.

From Table 4, the cruise segments explain 27 kg of the total of 29 kg (presented in the estimation of Table 1) difference obtained between one 2000 ft step climb and twenty 100 ft step climbs. Between each cruise segment there is a small distance flown in climb mode for each of the 100 ft steps of Case 2 and in cruise mode for the one 2000 ft step of Case 1. On the right side, the whole climb portion is concentrated at near the optimal weight for FL370, whereas on the left side, climb segments are evenly distributed along the weight interval. The total difference in fuel consumption of these small segments would account for the other 2 kg of the estimated fuel savings of Table 1.

The optimum altitude is given by the performance program as a function of gross weight, it is not the GW that is given in function of altitude. This means that the GW had to be iterated and used as input until the desired altitude was obtained.

In order to minimize errors for all the cruise calculations, final weights were used as input to obtain the cruise distance of each segment. With this new distance, the performance program would be run again. If a different final weight was yielded, this would be the weight retained.

4.3 Savings Results from Trials

4.3.1 Gross Weight Estimation

A detailed analysis is presented for one flight, an excel file (with the values extracted from the flight parameters database) is used to display the several parameters that were recorded (Table 5).

Table 5. Recorded flight parameters [11]

TIME	21:44:58	22:23:06	22:33:22	22:45:54	22:56:26	00:12:06
MACH	0,804	0,804	0,804	0,8042	0,8057	0,808
TAT	-27,195	-24,3	-24,3	-24,12	-23,45	-25,3
ALT	38436	38836	38936,6	39035,8	39134,4	39933,8
N11C	82,5	82,465	82,925	82,9	83	82,8
N12C	82,6	82,6	83,01	83	83,1	82,925
N21C	85,8	85,97	86,24	86,29	86,305	86
N22C	85,79	85,9	86,11	86,1	86,3	85,97
IASC	251,9125	249,7625	249,025	249	248,5625	244,8
GSC	473	461	466	465	464	441
ROLL	-0,665	-0,56	-0,63	-0,63	-0,42	-0,385
GW	182718,7	179260,9	178411,5	177418	176532,6	170088
FPAC	0,00045	-0,0005	0,00005	-0,00005	0,0001	-0,00005
IVV	-12	4	-6,4	-6,4	2,4	-3,2
HEAD_MAG	264	258	257	256	255	237
LATP	24,9	22,5	21,8	20,945	20,2	13,8
WIN_SPD	21,2	29,95	22,45	18	11,8	24,55
WIN_DIR	11,1	324,8	335	329,6	322,5	244,05
FF1C	2649,95	2564,05	2598,35	2594,75	2582,4	2496,9
FF2C	2692,8	2616,65	2642,45	2632,15	2621,5	2527,6
EGT1C	382	385,8	389,6	390	392	388
EGT2C	396	402	406	406	408	404
PF1	1,0318	1,025	1,02425	1,02125	1,0235	1,0128
PF2	1,02725	1,02425	1,02275	1,02125	1,0205	1,012
VRTG	0,978	0,979	0,9795	0,98	0,9795	0,9785
LATG	-0,02	-0,02	-0,02	-0,02	-0,02	-0,02
LONG	0,038	0,03	0,0315	0,03	0,03	0,03
PITCH	2,5	2,5	2,5	2,5	2,5	2,5
TAS	461,1	464	464	465	466	465,4
FBURN	31191,15	34523	35423,65	36514,3	37423,65	43790,5
FQTY	24015,7	20559,7	19708,5	18715	17831,4	11385,9
LONGPC	-47,9509	-52,6784	-53,8827	-55,3416	-56,5495	-63,9682
QN	0,516363	0,157713	0,203074	0,233428	0,29139	0,18136

In Table 5 the times at which periods of one hundred seconds of greater stability were identified, are displayed. The quality number (QN) gives an indication of the level of stability, it can be read in the last row of Table 2.

The analysis starts by determining the specific range degradation for this particular flight. It will vary from the average used value (for the case of the aircraft whose flight is being analyzed, it is -2.5%) from one flight to another. This is due to unavoidable errors that occur while estimating the aircraft's GW.

The stability periods are analyzed to look for 100 seconds intervals during which the maximum variation of each parameter does not exceed a certain specific limit value. When the stability check is satisfied, the points with the lowest quality numbers are selected. To find the corresponding input for the Aircraft Performance Monitoring program (APM), the central 20 seconds period of each 100 seconds stability period is used to determine the average value for each parameter. Table 5 shows these average values for each of the parameters included therein.

The APM printed deviation data is shown in Figure 16.

```
* A I R B U S   C R U I S E   P E R F O R M A N C E   *   A I R C R A F T   P E R F O R M A N C E   M O N I T O R I N G *
*  ==================================================================================================================== *
*                               ***  PROGRAM:  A P M - Version 2.9.4 -          ***                                    *
*                                                                                                                      *
*  ------  AIRCRAFT TYPE:    A330-223               ENGINE TYPE:    PW4168A            ----------------------------    *
*                                                                                                                      *
*  ------  DATABASES:  AERODYN. :  A330223.BDC                                        DATE:              ------        *
*          ----------  ENGINE   :  MPW4168A.BDC                                       DATE:              ------        *
*                      GENERAL  :  GB223A02.BDC                                       DATE:              ------        *
*                                                                                                                      *
*  ------  JOB-INFORMATION:                                                            ----------------------------    *
************************************************************************************************************************
AIRCRAFT TAIL-NO.:                      DIRECT ANALYSIS OUTPUT (INPUT BY ADIF)                DATA BLOCK/FLEET:   1/ 1

                                          A P M   D E V I A T I O N   D A T A
```

NO.	DEPR1	DEPR2	DFFA1	DFFA2	DFFB1	DFFB2	DEGT1	DEGT2	DEPRM	DFFAM	DFFBM	DEGTM	DSR
	*100.	*100.	%	%	%	%	%	%	*100.	%	%	%	%
1	0.718	0.718	0.911	0.911	1.559	3.199	0.732	2.885	0.718	0.911	2.379	1.808	-3.206
2	-0.017	-0.017	-0.022	-0.022	1.558	3.660	0.821	3.311	-0.017	-0.022	2.609	2.066	-2.521
3	1.496	1.496	1.923	1.923	1.330	3.049	0.819	3.313	1.496	1.923	2.189	2.066	-3.989
4	1.054	1.054	1.361	1.361	2.616	4.096	1.098	3.538	1.054	1.361	3.356	2.318	-4.546
5	0.173	0.173	0.220	0.220	1.964	3.508	1.053	3.484	0.173	0.220	2.736	2.269	-2.877
6	1.771	1.671	2.276	2.148	1.444	2.820	0.793	3.269	1.721	2.212	2.132	2.031	-4.206
MV	0.866	0.849	1.112	1.090	1.745	3.389	0.886	3.300	0.857	1.101	2.567	2.093	-3.558
SD	0.712	0.687	0.916	0.885	0.478	0.461	0.151	0.230	0.699	0.900	0.452	0.183	0.806
NR	6	6	6	6	6	6	6	6	6	6	6	6	6

```
*  VALUES OUT OF RANGE (MARKED BY A TRAILING "*") ARE NOT INCLUDED IN MEAN VALUES (MV) AND STANDARD DEVIATIONS (SD).
   SO NUMBER OF CASES MAY BE REDUCED TO NUMBER OF READINGS (NR). ".---" MEANS FAILED OR NOT CALCULATED.
```

Figure 16. APM deviation data [11]

The APM program yields a specific range degradation of -2.521 % for point number two (Figure 16). As this value is very similar to the one that is published for this aircraft (-2.5%, as was said before), it will be used as the reference for the calculation of the GW, since the fuel burn (FBURN) figures are more reliable than determining the GW from the indications of fuel quantity (FQTY).

The stable cruise points at time 22:22:15 are presented in Table 6. This particular time was chosen by inspecting the excel file regarding the values presented previously.

Table 6. Stable Cruise Points [11]

TIME_R	22:22:15
MACH	0,804
TAT	-24,3
ALT_STDC	38836
N11C	82,5
N12C	82,6
N21C	86
N22C	85,9
IASC	249,75
GSC	461
ROLL	-0,7
GW	179260
CG	
IASC	8

HEAD_MAG	258
WIN_SPD	29
WIN_DIR	325
FF1C	2566
FF2C	2624
EGT1C	386
EGT2C	402
SATR	
LONPC	-52,6736
LATP	22,5
VRTG	0,98
LATG	-0,02
LONG	0,03
PITCH	2,5

TAS	464
FLIGHT_NO1	
FLIGHT_NO2	
DATE	
AC_TAIL123	
AC_TAIL456	
AC_TAIL7	
ORIGIN	
DESTINATION	
FBURN	34519
FQTY	20557
FPAC	-0,001
PF1	1,031
PF2	1,031

The values presented in Table 6 allow for a good precision in determining the GW of the aircraft.

For the 4D position of the aircraft characterized by an altitude of 38836ft, latitude of 22.5º, longitude of -52.6736º and time of 22:22:15, the estimated GW of the aircraft on the excel file is 179260kg with a fuel burn (FB) of 34519kg.

This position and respective flight parameters will be considered the reference point for the calculation of the initial weight (IW) of the aircraft:

$$IW = GW_{RP} + FB_{RP} \quad (1)$$

Where IW is the initial weight of the aircraft, GW_{RF} is the gross weight of the aircraft at the reference point and FB_{RP} is the fuel burn at the reference point.

From (1) it yields an initial weight of 213779kg (which is the result of 179260+34519).

As the fuel burn figures are more reliable than the fuel quantity figures present on the excel file, the estimation of GW for three other positions will now be presented for further clarification:

$$GW_x = IW - FB_x \quad (2)$$

Where GW_x is the desired gross weight at any random point, IW is the initial weight that was calculated previously from the information about the reference point and FB_x is the fuel burn at that random point, which can be extracted with precision from the excel file.

Table 7. Excel file sample with gross weight and fuel burn at points P, Q and R [11]

P		Q		R	
GW (kg)	196079	GW (kg)	186590	GW (kg)	177518
FB (kg)	17572	FB (kg)	27243	FB (kg)	36418

In Table 7 the values extracted from the excel file for points P, Q and R are presented.

Equation (2) will be used to obtain a better estimation of the GW at each point.

$$GW_P = IW - FB_P = 213779 - 17572 = 196207kg \quad (3)$$

$$GW_Q = IW - FB_Q = 213779 - 27243 = 186536kg \quad (4)$$

$$GW_R = IW - FB_R = 213779 - 36418 = 177361kg \quad (5)$$

With the more precise estimation of the gross weight it shows that the aircraft is 128kg heavier in point P than what it was when taking the weight from the excel file, 54kg lighter in point Q and 157kg heavier in point R.

4.3.2 Vertical Profile Details

It is worth mentioning that the period being analyzed (Figure 17) corresponds to about 3h 50min. This kind of flight profile, when flown manually, imposes a great burden on flight crews. The average cruise time of each step (climb plus cruise) is about 11m 30s [11].

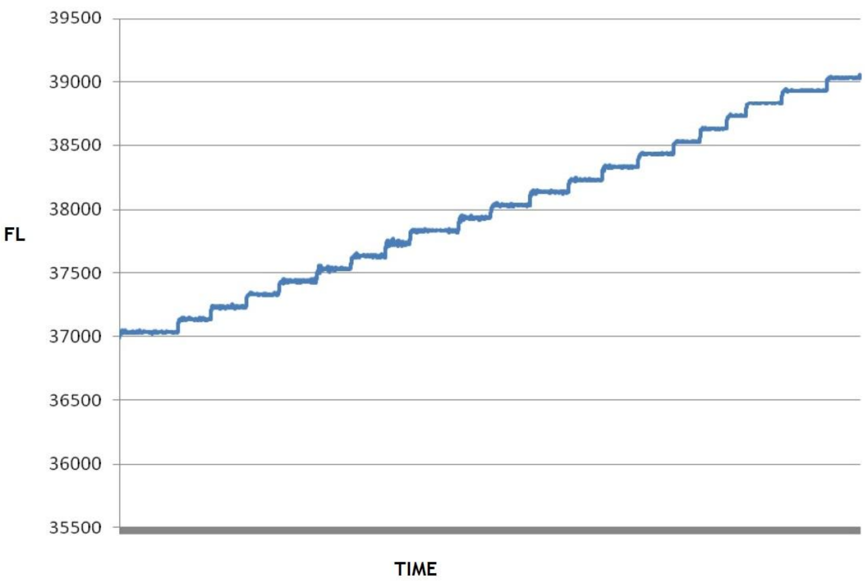

Figure 17. Vertical profile analyzed [11].

In order to determine the exact moment to initiate the step climb, pilots follow the performance information present in the Flight Performance Manuals of the aircraft.

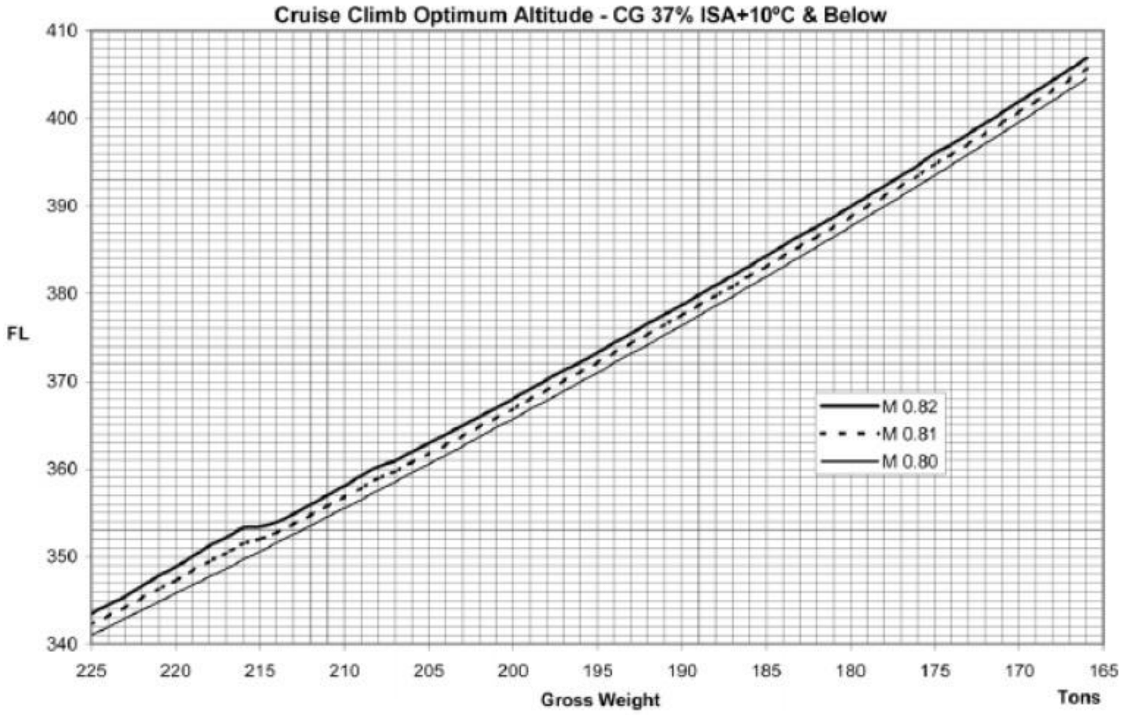

Figure 18. Cruise climb optimum altitude profile graph [11]

The lines in Figure 18 describe the most efficient vertical profile at MACH 0.80, 0.81 and 0.82, subject to the values specified in the image:

- CG at 37%; and
- Atmospheric conditions at ISA + 10ºC & below.

The profile described in Figure 17 is the better approximation to the cruise climb optimum profile that was possible to make.

Optimum altitudes are also affected by the status of several equipments as is shown in Figure 19:

	ENGINE ANTI ICE ON	TOTAL ANTI ICE ON	PACK FLOW HI OR/AND CARGO COOL ON
≤ ISA + 11	- 1000 FT	- 2000 FT	- 400 FT
ISA + 15	- 2000 FT	- 2700 FT	- 1200 FT
ISA + 20	- 3000 FT	- 3600 FT	- 1800 FT

Add 60 FT per each 1% below CG of 37%.

Figure 19. Effect of equipment on optimum altitude [11]

On Figure 20, the numerical values used to build the graph on Figure 18 are presented.

CG Position 37% Air Cond.: NORM Anti-Ice: OFF ISA + 10ºC & Below

GROSS WEIGHT [ton]	Pressure Altitude [ft]														
	M 0.80					M 0.81					M 0.82				
	0.0	1.0	2.0	3.0	4.0	0.0	1.0	2.0	3.0	4.0	0.0	1.0	2.0	3.0	4.0
165	-	40456	40330	40205	40081	-	40571	40446	40321	40196	-	40686	40561	40436	40311
170	39958	39835	39713	39592	39471	40077	39952	39830	39708	39587	40195	40068	39946	39824	39703
175	39351	39232	39113	38996	38885	39479	39348	39229	39112	38998	39606	39464	39345	39227	39110
180	38764	38648	38533	38419	38304	38879	38763	38647	38541	38425	38993	38877	38761	38662	38545
185	38190	38087	37965	37864	37750	38310	38201	38083	37981	37867	38429	38315	38200	38097	37983
190	37634	37535	37416	37317	37211	37752	37650	37538	37433	37326	37869	37765	37660	37548	37440
195	37094	36997	36886	36777	36682	37212	37108	37006	36897	36797	37329	37218	37125	37016	36911
200	36568	36474	36365	36259	36155	36685	36584	36481	36376	36275	36802	36694	36597	36492	36395
205	36058	35957	35851	35756	35649	36175	36077	35972	35893	35785	36292	36196	36092	36029	35921
210	35553	35457	35349	35256	35160	35681	35578	35471	35372	35277	35808	35698	35593	35487	35394
215	35058	34966	34862	34771	34677	35199	35147	35040	34948	34840	35339	35328	35217	35124	35003
220	34578	34486	34388	34296	34192	34731	34634	34527	34420	34321	34883	34782	34665	34543	34450
225	34108	-	-	-	-	34229	-	-	-	-	34349	-	-	-	-

Figure 20. Table with numerical values for optimum altitude [11]

4.3.3 Detailed Calculations

4.3.3.1 Case 2 VS Case 1

To calculate the fuel savings, the actual fuel burn from the flight is compared with the fuel estimated considering an aircraft specific range degradation of 2.5% and one single 2000ft step, divided in two consecutive steps, before and after point Q, for a greater convenience.

Taking points P, Q and R once again, and the information stored in the excel file it takes that:

Point P:

- Pressure altitude of 37004ft;
- M0.802;
- TAT = -23.8ºC (249.35K);
- SAT= -52.2ºC (249.35/(1+0.2M^2)-273.15);
- ISA temperature for 37004ft is -56.6ºC, which corresponds to an ISA deviation of +4.3ºC;
- Point P is over flown at 19:15h;
- LAT= +35.8; and
- LON=-30.302.

Point Q:

- FL380;
- SAT = -58.4ºC;
- ISA deviation of -1.9ºC;
- Over flown at 21:00h;

- LAT= 27.2; and
- LON= -42.1436.

Point R:

- FL390;
- SAT= -52.8ºC;
- ISA deviation of +3.7ºC;
- Over flown at 22:44h;
- LAT= 21.0; and
- LON= -55.2137.

The ground distance between P and Q is 794.62NM and it takes the aircraft 6300s to cover that distance.

From point Q to point R it takes the aircraft 6240s to cover the 806NM that divide the two points.

The air distance (ADist) between P and Q is found by multiplying the average TAS (460.50kts, according to the excel file) by the time interval:

$$ADist_{P-Q} = 460.5kts \times 6300s/(3600s/h) = 805.88\ (NM/h)\ s\ (s/h) = 805.88NM \quad (6)$$

The climb from FL370 to FL380, which is the segment right before Q is calculated assuming an ISA deviation of -1.9ºC.

The climb at maximum rate leads to an initial GW of 186717kg, an air distance of 11.6NM, a TAS of 460.3kt, an average rate of climb of 658.75ft/min and a mach number of 0.799, as shown in PEP output (Figure 21).

CLIMB AT MAXIMUM RATE SPEED

ALT. (FT)	ALTG (FT)	WGHT (KG)	MACH ( )	CAS (KT)	TAS (KT)	WIND (KT)	TIME (MN)	FUEL (KG)	DIST (NM)	RATE (FTMN)
37000.	37296.	186717.	0.798	258.9	459.8	0.0	0.00	0.	0.0	704.0
38000.	38306.	186536.	0.800	253.6	460.8	0.0	1.52	181.	11.6	613.5

Figure 21. PEP output for the segment between P and Q at maximum climb rate [11].

Running the PEP with conditions that are closer to the climb segments performed, for Mach 0.804, and an average rate of climb of 250ft/min. Yields an initial GW of 186939kg, an air distance of 30.9NM and a TAS of 463.3kt (Figure 22).

CLIMB AT GIVEN RATE

ALT. (FT)	ALTG (FT)	WGHT (KG)	MACH ( )	CAS (KT)	TAS (KT)	WIND (KT)	TIME (MN)	FUEL (KG)	DIST (NM)	RATE (FTMN)
37000.	37296.	186939.	0.804	261.1	463.3	0.0	0.00	0.	0.0	250.0
38000.	38306.	186536.	0.804	255.1	463.3	0.0	4.00	403.	30.9	250.0

Figure 22. PEP output for the segment between P and Q at 250ft/min rate of climb [11]

The air distance between the weight at point P (196207kg as was previously calculated) and the weight at the point where the climb is initiated (186717kg for maximum climb rate and 186939 for a climb rate of 250ft/min) can be calculated by running the PEP program.

Assuming an ISA deviation of +4ºC, Mach 0.8045 and maximum rate of climb, running the PEP (the PEP has to be run twice, once for Mach 0.804 and another for Mach 0.405, to interpolate the value for Mach 0.8045) yields a distance of 791.9NM, from point P to the point where the climb was initiated.

Adding the 11.6NM flown during the climb at maximum rate (shown in Figure 21) gives a total flown distance from point P to point Q of 803.5NM.

By proceeding in the exact same way for the 250ft/min climb rate, the PEP program yields a distance of 773.1NM.

Adding the 30.9NM flown during the climb at 250ft/min (shown in Figure 22) gives a total flown distance from point P to point Q of 804NM. This distance is approximately 1.9NM less than the actual distance flown of 805.88NM (calculated before).

The weight of fuel needed to cover the extra distance (1.9NM) at FL370 with a weight of 186536kg, is the equivalent to the amount of fuel saved.

Running the PEP for this conditions yields savings of 22kg between point P and point Q.

CRUISE AT 0.804 MACH NUMBER

WGHT (KG)	MACH ( )	CAS (KT)	TAS (KT)	TIME (MN)	FUEL (KG)	DIST (NM)	SR (NMKG)	WFE (KG/H)	EPR ( )
186536.	0.804	261.1	463.3	0.00	0.	0.0	0.08538	5426.	1.307
186514.	0.804	261.1	463.3	0.25	22.	1.9	0.08539	5426.	1.307

CRUISE AT 0.805 MACH NUMBER

WGHT (KG)	MACH ( )	CAS (KT)	TAS (KT)	TIME (MN)	FUEL (KG)	DIST (NM)	SR (NMKG)	WFE (KG/H)	EPR ( )
186536.	0.805	261.5	463.8	0.00	0.	0.0	0.08533	5436.	1.307
186514.	0.805	261.5	463.8	0.25	22.	1.9	0.08533	5436.	1.307

Figure 23. PEP output with the savings from the segment between P and Q [11].

To calculate the savings for the segment between points Q and R, the process used for the segment between P and Q was repeated.

Between Q and R, the average TAS (from the excel file) is 462.13 kts, which yields an air distance (ADist) of:

$$ADist_{Q\text{-}R} = 462.13 \times 6240/3600 = 801.03 \text{ NM} \quad (7)$$

With Mach 0.804 and a rate of climb of 250ft/min, a final GW of 186135 kg and an air distance of 30.9NM are obtained.

CLIMB AT GIVEN RATE

ALT. (FT)	ALTG (FT)	WGHT (KG)	MACH ( )	CAS (KT)	TAS (KT)	WIND (KT)	TIME (MN)	FUEL (KG)	DIST (NM)	RATE (FTMN)
38000.	38306.	186536.	0.804	255.1	463.3	0.0	0.00	0.	0.0	250.0
39000.	39315.	186135.	0.804	249.3	463.3	0.0	4.00	401.	30.9	250.0

Figure 24. PEP output for the segment between Q and R for a climb rate of 250 ft/min [11]

Calculations for the cruise segment flown at 39000ft (after the climb) between the weight of 186135kg and the weight at R (177361kg that was previously calculated):

With an ISA deviation of +6.8ºC and Mach 0.8042 the PEP program outputs a distance of 769.48NM, from the point where the climb was terminated (at the weight of 186135kg) to point R (where the weight is 177361kg).

Adding the climb distance from Figure 24 to the 769.48NM yields a total distance of 800.4NM.

This distance of 800.4NM is roughly 0.6NM less than the 801.03NM that were actually flown. The equivalent weight of fuel saved is the amount of fuel needed to fly the extra distance at 39000ft. Running the PEP program for the conditions specified yields savings of 7kg.

CRUISE AT 0.805 MACH NUMBER

WGHT (KG)	MACH ( )	CAS (KT)	TAS (KT)	TIME (MN)	FUEL (KG)	DIST (NM)	SR (NMKG)	WFE (KG/H)	EPR ( )
177361.	0.805	249.6	471.8	0.00	0.	0.0	0.08959	5267.	1.338
177354.	0.805	249.6	471.8	0.08	7.	0.6	0.08959	5266.	1.338

Figure 25. PEP output showcasing the savings between point Q and point R [11]

The total fuel savings during the 2000ft step climb from FL370 to FL390 was 29kg, 22kg from the first segment between FL370 and FL380 or between points P and R. And 7kg from the second segment between points Q and R and FL380 and FL390. This is in accordance with Table 1 that estimates the savings, between Case 1 (one single 2000ft step) and Case 2 (twenty 100ft steps) to be 29kg.

4.4 Other Factors Affecting the Results

Table 8 presents the difference in fuel consumption that is expected by varying the values of several parameters by the specified amount. It is then possible to see how sensitive fuel savings results are. A cruise segment of 800NM was considered in order to approach the distance flown in average between the optimum weights for 2000ft difference in altitude.

Table 8. Sensitivity of savings relative to several variables [11]

Variable	Variation	Difference in fuel consumption (kg)
Temperature (ISA deviation)	5ºC	42
GS, TAS, Wind componente	1kt	21
Estimated Gross Weight	1ton	47
Performance Degradation	1,00%	93

CG position	5%	24
Air conditioning packs	Cargo cooling ON	47
Air conditioning packs	Econ/Norm	36

Several other parameters also affect fuel consumption. Flight path acceleration, inertial vertical velocity or the direction of flight and its impact on Coriolis acceleration, amongst others. The impact of these variables on fuel consumption whether positive or negative could have an influence on the savings attributed to the climb technique.

4.5 Enhancements for Ground Systems

This section identifies and details enhancements that would optimize the support to these advanced operational procedures, highlighting the functionality enhancements that apply to the ATM system, as well as identifying specific changes to other entities, such as AIDC protocols and CPDLC message set, that would enhance the usability and benefits of these advanced operational procedures.

4.5.1 ATM System Enhancements

Enhancements for vertical optimization consist mainly of improved 4D trajectory modeling and improved conflict probe processing related to the Cruise Climb clearance, to better represent the unrestricted cruise climb profile. The 4D trajectories and conflict probe are key ATM functionalities for the ATM system.

The improvements that should be made to the ATM System were identified as a result of the flight trials [11]:

1. The Aircraft Performance database should be augmented to store the FMS automatic cruise climb capabilities for the most common aircraft type that is to be flown automatically by the FMS, regarding current gross weight;
2. The system should allow the controller to enter the current weight for the optimized cruise climb;
3. When probing an optimized cruise climb, the Conflict Probe module should reserve only the airspace effectively occupied by the aircraft, buffered by appropriate tolerances (e.g. +/- 3 minutes for each FL crossed). The entered aircraft weight should be used to look up the cruise climb capabilities when modeling the optimized cruise climb. This would define a center line around which the system should add a buffer to account for tolerances. The reserved vertical airspace should then be defined by providing an envelope consisting of a stepped climb and a stepped release of airspace around the buffer. The calculations should also consider the last reported level as a new start point for the envelope;
4. When generating the clearance for this new optimal cruise climb, the system should add information transmitting to the pilot the vertical level constraints that the

system has assumed. This can be done using the currently defined CPDLC set using a free text uplink. Alternatively, if a dedicated CPDLC downlink message is used to transmit the vertical level constraints applicable to a cruise climb, the system should use this information for 4D Trajectory modeling and Conflict Probe;

5. The system should extract the cruise climb information that may exist in the FPLN and present that information automatically to the controller on the flight strip;
6. Airspace should be released as level reports are received as normally done; and
7. The processing of AIDC coordination messages should be enhanced to extract the Cruise Climb information in coordination.

4.5.2 CPDLC message set enhancements

Dedicated CPDLC messages should be defined to exchange the information regarding the vertical level constraints that apply to the cruise climb. An uplink message can transmit to the pilot the system applied constraints upon a cruise climb clearance. A downlink message can transmit to the system the aircraft vertical level constraints to be applied for the cruise climb.

In addition a dedicated uplink message should be defined to request the aircraft current weight and a dedicated downlink message should be defined to report the aircraft current weight. This enhancement would be paired with an ATM System enhancement to handle sending the uplink and automatically processing the downlink.

4.5.3 AIDC protocol enhancements

The AIDC coordination messages should be improved to add in field 14 or 15 the Cruise climb information when the cruise climb spans across FIR boundaries. This also would be paired with an improvement in the AIDC module of ATM system to process the cruise climb information in the coordination messages.

4.6 Enhancements for Avionics Systems

4.6.1 Flight Management System

The FMS should allow for the:

- Computation of impact of the cruise climb maneuver (fuel economy, time economy, etc);
- Computation and execution of optimal vertical profile including altitude, time and speed profile computation;
- Computation of optimum cruise climb step point for minimum selectable vertical rate; and
- Preparation of visualization of computed cruise climb relevant information in the display unit.

4.6.2 Display Unit

The display unit should allow the visualization of:

- Active and temporary FPLN;
- Performance information; and
- General messages.

4.7 Operational Feedback [11]

4.7.1 Pilots feed-back

The feedback from the pilots, whom volunteered for the flight trials, was positive. The following conclusions were drawn from there:

- The procedure was clear enough and was followed without any problem;
- The cooperation Pilot- Air Traffic Controller was excellent;
- Usage of free text messages must be done with caution. Even with limited use and content well defined in the procedure, they can be interpreted in a different way causing confusion; and
- Finally, today the auto-pilot does not implement the cruise climb. For these flight trials, pilots were asked to manually step climb every 100ft, to stay as close as possible to a true cruise climb. Consequently, pilots had to change the FL every 6 to 10 minutes instead of every hour. These manual actions could only be handled in the framework of these flight trials. It is absolutely not foreseen to use them on a daily basis. If the benefits are significant and stakeholders decide to implement the technique, then the future autopilot must include a cruise climb function.

4.7.2 Air Traffic Controllers Feedback

- The procedures applied on this evaluation were transparent to the ATC in general.
- Air Traffic controllers did not raise any particular issue during the evaluation. The additional workload compared to current was accepted.
- The evaluation was performed during low-medium traffic conditions. With the current ground system tools the cruise climb optimization has limited clearance chances on high traffic situations.
- They reported the excellent cooperation between the ATC and the pilots during evaluation that allowed demonstrating significant benefits and strong interest in this new cooperative procedure.

4.8 Conclusion

The fact that there are so many changes in some of the variables during any flight and that these savings are of such a low magnitude, precludes the use of a methodology based in global parameters like the fuel spent per flight, even if it is corrected for payload and meteorological differences.

In order to make an analysis based on the factors referred in section 4.4, it would be necessary to have data from a larger number of flights, during a very long period of time and this is simply not feasible due to the current state of on-board equipment and to the burden it would impose on pilots. Such a burden would increase risks in terms of operational safety.

The methodology used, changing from climb to cruise modes and back, was validated through this analysis, which proved that the estimation of savings was in line with the actual data obtained from the flight trials.

Enhancements to the ATM system can be done quickly and easily, under the control of the local ANSP and would allow for immediate benefits. Changes to the AIDC protocol would require coordination within the NAT region and would allow for the continuation of the optimized trajectory across FIR boundaries.

Changes in the avionics systems could also help a faster implementation of more efficient vertical profiles in large scale.

5. ISAVIA's Case Description and Results

5.1 Introduction

As a part of the AIRE project, the case of ISAVIA also aims to demonstrate, through simulation and flight trials, the benefits that can be obtained if more efficient flight profiles are used.

The flight trials performed for this project had the goal of validating practical actions that could be employed in the present or in the near future that would lead to fuel savings.

5.2 Description of Flight Trials

5.2.1 The Procedure

The typical cruise flight of a jet aircraft involves a sequence of level segments increasing in altitude as fuel is burned. The steps in altitude are typically 1000ft, 2000ft, or 4000ft depending on the constraints of the airspace where the aircraft is flying. A step climb is typically made when the flight efficiency between two candidate altitudes is approximately the same. At that point, the optimal altitude is approximately at the mid-point between the two altitudes [13].

There is a potential for increased fuel savings by allowing aircraft to continuously fly their optimal cruise altitude. This is known as cruise climb and is a continuous climb in the cruise phase of a flight that optimizes the vertical profile in terms of fuel consumption. The flight altitude is continually increased to ensure that the aircraft is at its optimum altitude as its weight decreases due to fuel burn. The Cruise Climb procedure is compared to the 1.000 ft and 2.000 ft step climb in Figure 26.

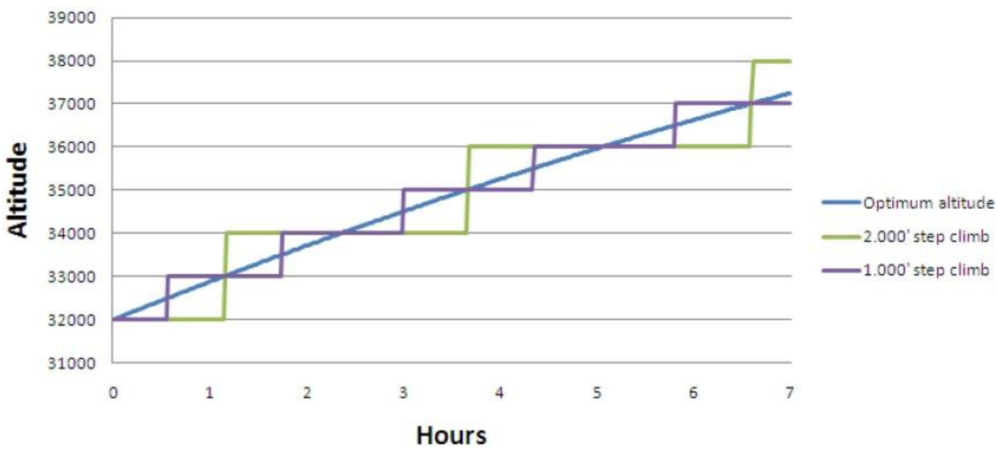

Figure 26. Comparison of a cruise climb with 1000ft and 2000ft step climbs [13].

Because of limitations in the current avionics systems, flying a Cruise Climb is an arduous process of continuous configuration while climbing and so, making it an option that is not feasible for the flight trials. The cruise climb rate of climb of approximately 10 to 15ft/min was approximated by a climb rate of 100 ft/min. This approximation is named Limited Cruise

Climb. Figure 27 shows how a reduced climb rate is used to approximate a Cruise Climb. After the ATC clearance, the pilot sets the climb rate of 100 ft/min instead of the standard 500 ft/min. For all the 14 flights trialed, the climbs were performed at a fixed Mach speed of M0.80 in a B757-200 [13].

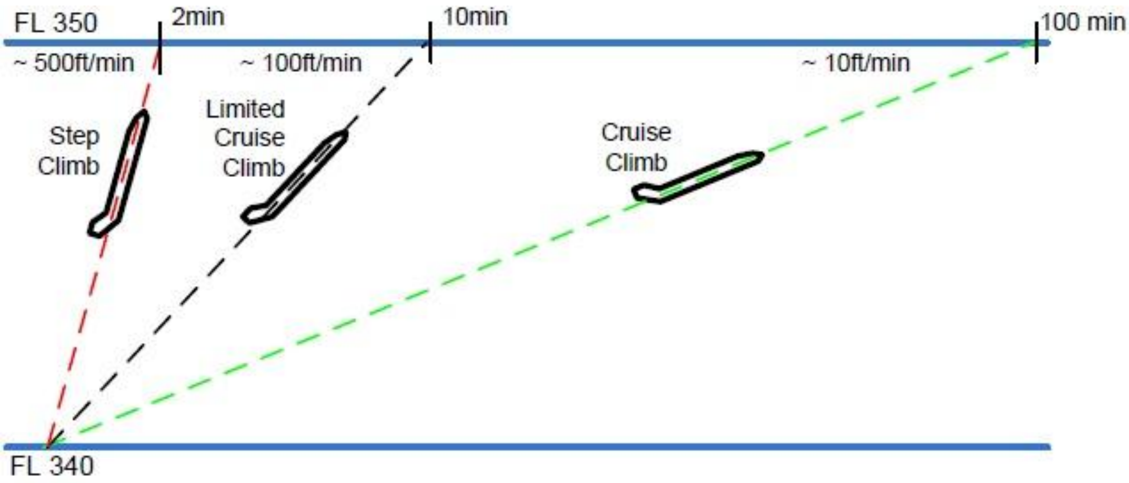

Figure 27. Difference between cruise climb, limited cruise climb and a regular step climb[6]

5.2.2 Execution of the Flight Trials

For the execution of the flight trials, the airline pilots were given instructions on how to perform the desired flight profile. ATC shift supervisors distributed memos to the ATCo's on duty during the flight trials [13].

To allow for a smooth execution of all the flight trials, several actions from both pilots and ATCo's were needed [13].

From the airborne side, pilots must:

- Monitor the optimal altitude on the FMC carefully;
- Request cruise climb clerance when the optimal altitude is 300ft above the current altitude;
- Choose the target FL and 100ft/min climb rate after being cleared to do so; and
- Report maintaining the cleared FL when the level is reached.

On the ground, ATCo's must:

- Perform a conflict check on the clearance request;
- Grant the cruise climb and block the FL's involved, if no conflict is found; and
- Through the FDPS unblock the lower FL when the cleared FL is reached.

By combining the actions from the airborne and ground sides into a flowchart (Figure 28), a better understanting of when the actions are performed by ATCo's or pilots is obtained.

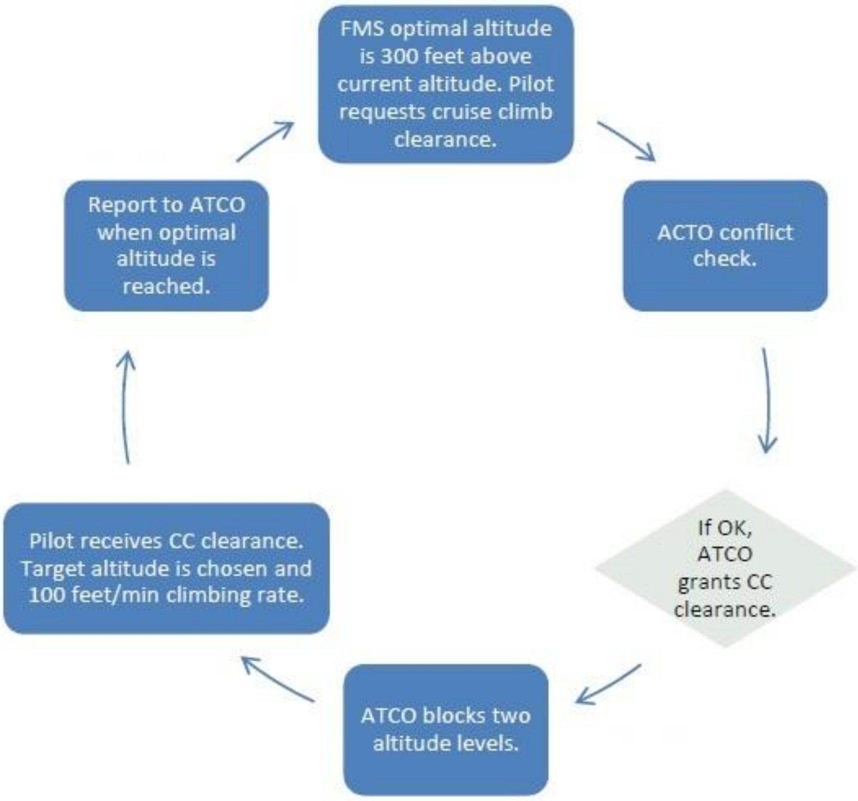

Figure 28. Flowchart of the flight trials actions from pilots and ATCo's [13].

5.3 Results

The benefit from the limited cruise climb technique is calculated at around 330kg of fuel.

Table 9 shows the the average fuel savings and total fuel savings from the 14 flight trials.

Table 9. Summary of the results obtained [13].

	Number of flights	Average savings (kg)	Total savings (kg)
Limited Cruise Climb	14	330	4260

5.4 Findings

The (FDPS) is capable of maintaining an overview of flights in cruise climb and calculate possible conflicts. The Integrated Situational Display System (ISDS) however, is not capable of identifying aircraft in cruise climb. Thus, the system would have to be enhanced to give indication that an aircraft is climbing at a slower climb rate than usual.

The Data Link Communication System (DLCS) is responsible for ADS-C and CPDLC communications. The downlink messages which are not supported are messages which include "expect" (Figure 29) [13] .

#	Downlink Message	Supported
DM 8	REQUEST CRUISE CLIMB TO [altitude]	☑
DM 54	WHEN CAN WE EXPECT CRUISE CLIMB TO [altitude]	☑

#	Uplink Message	Supported
UM 12	EXPECT CRUISE CLIMB AT [position]	☒
UM 17	AT [time] EXPECT CRUISE CLIMB TO [altitude]	☒
UM 18	AT [position] EXPECT CRUISE CLIMB TO [altitude]	☒
UM 34	CRUISE CLIMB TO [altitude]	☑
UM 35	CRUISE CLIMB ABOVE [altitude]	☑

Figure 29. CPDLC messages

These messages are not supported due to decisions at ICAO level that "expect" messages can be misinterpreted if communication fails. This is due to the fact that American crews understand an "expect" clearance as something which should be followed. While European crews will wait for confirmation. DM54 is supported, but how DM54 is answered is up to the ATCo. From the experience of the ANSP, it comes that DM8 is often used to ask for climbs during the cruise phase, that are not cruise climbs. If a cruise climb is not supported because of separation issues, DM8 is answered with, “cruise climb not supported, did you want a normal climb?” [13].

The UM35, CRUISE CLIMB ABOVE [altitude] was designed for Concorde, thus it is very rarely used.

Furthermore, it is recommended that ADS-C is used to monitor aircraft performing cruise climbs.

From the pilot perspective, the Limited Cruise Climb procedure did not increase the workload of the pilot [13].

5.5 Conclusion

From the results obtained by the flight trials performed by ISAVIA, another technique that can be used to further optimize the vertical profile of a flight was validated.

This technique can be employed with the current state of the systems (ground and airborne), and is only dependent on traffic conditions and clearance from the ATC.

6. Flights Profiles Comparison

6.1 Introduction

For a comparison of case studies we need to find some common ground where comparing would make sense and contribute to the development of the state of the art. Thus, three main points of comparison where chosen:

- Flight profile;
- Results; and
- Operational Feedback;

6.2 Flights Profiles

The flight profile tested for NATCLM was a division of a 2000ft step climb into twenty 100ft steps climbs, climbing at a 250ft/min climb rate.

By doing this, the goal was to remain as close as possible to the theoretical most efficient flight profile.

From Figure 30 the average cruise climb rate for an A330 like the one used in the flight trials can be obtained.

Type	*Distance between 2000 foot altitude step [NM]*	*Rate of climb Mach 0.80 [Feet per minute]*
A300	*1000 - 1100*	*16.8*
A310	*1150 – 1250*	*14,7*
A320	*1200 - 1300*	*14,1*
A330	*1500 - 1650*	*11,2*
A340	*1500 - 1650*	*11,2*
A340-500/600	*1600 - 1700*	*10,7*

Figure 30. Cruise climb rate of climb for several aircraft [13]

With the information on the cruise climb rate from Figure 30 and the information already presented in the results chapter (Chapter 4), the graph from Figure 31 was built. Using a climb rate of 500ft/min for the step climb, 11.2ft/min for the cruise climb and 250ft/min climb rate plus a 11.1m cruise segment for the 100ft step climbs.

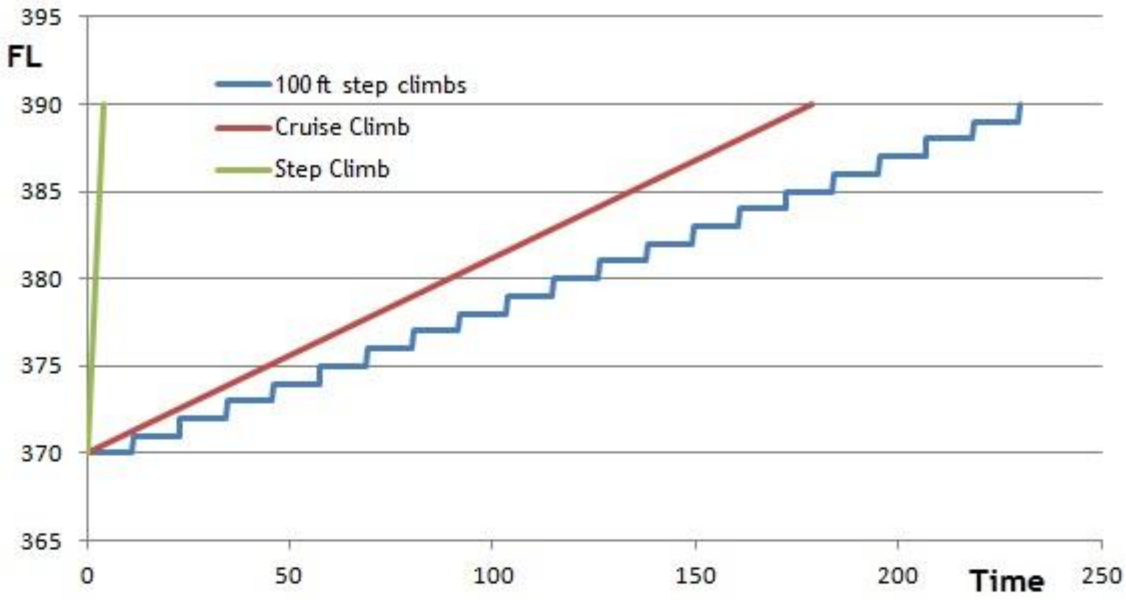

Figure 31. Time needed for a 2000ft altitude change for an A330.

From Figure 31, it can be observed that the approximation of the cruise climb by 100ft steps, although a good approximation, it stays below optimal altitude at all times.

For the ISAVIA flight trials, a step of 1000ft was performed at 100ft/min.

Altough information of the actual cruise climb rate for the B757 is not given, it is estimated at between 10 and 15 ft/min [13].

Taking advantage of Figure 27 and modifying it for another cruise climb rate, Figure 32 was obtained.

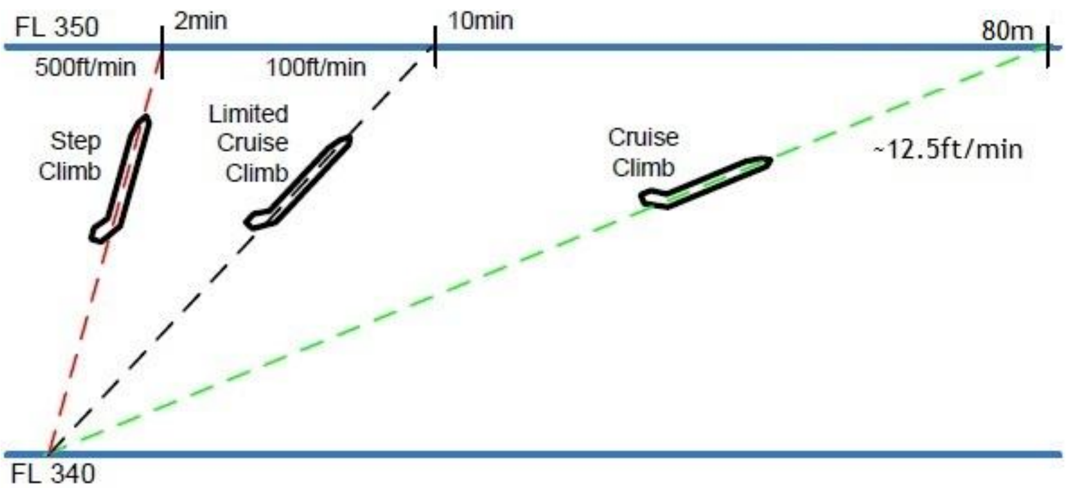

Figure 32. Time needed for a 1000ft altitude change for a B757.

It is observed from figures 31 and 32 the times spent climbing for the two techniques trialed.

Performing a 2000ft altitude change by climbing in 100ft step climbs at a climb rate of 250ft/min, takes 50min more than if the same climb would have been done in a cruise climb mode. It takes more time because of the cruise segments between the climbs.

The 1000ft climb at 100ft/min is around 70min faster than if the same altitude change would have been performed in a cruise climb.

For a better understanding of why all flights should be performed at or the closer possible to optimum altitude, Figure 33 is presented.

Aircraft	+2000ft	-2000ft	-4000ft	-6000ft
A300B4-605	2.0%	0.9%	3.4%	9.3%
A310-324	1.9%	1.4%	4.4%	9.3%
A318-111	0.7%	1.6%	5.0%	10.0%
A319-132	1.0%	3.0%	7.2%	12.2%
A320-211	**	1.1%	4.7%	9.5%
A320-232	1.4%	2.1%	6.2%	12.0%
A321-112	2.3%	1.4%	4.6%	15.2%
A330-203	1.8%	1.3%	4.2%	8.4%
A330-343	3.0%	1.0%	3.2%	7.2%
A340-212	1.4%	1.5%	4.0%	8.0%
A340-313E	1.5%	1.6%	5.2%	9.5%
A340-642	1.6%	0.6%	2.2%	5.1%

** Above Maximum Altitude

Figure 33. Specific range penalty for not flying at optimum altitude [7].

6.3 Results

All in all, 29kg of fuel savings were obtained in the NATCLM project, while 330kg were obtained from the ISAVIA flight trials.

Besides the differences in the aircraft used for the flight and the flight profile, it is also important to note that the NATCLM results account for only a segment of 1600NM. The results yielded from ISAVIA account for the whole flight.

Even if it is not expected that fuel savings work in the same way for every aircraft, it is expected that the penalties for not flying at the optimum altitude might be similar.

6.4 Operational Feedback

From the pilots point of view, as it was already presented in the results section of each case study, it was considered that the procedure from ISAVIA requires less workload from the pilots.

Although, pilots from both cases agree that if a real cruise climb is to be flown, avionics systems should include a function for automatic execution of the cruise climb.

ATC did not raise any particular issue with the procedures in any of the cases, although with the current ATM system, the optimization of the vertical profile in the way of these case studies has limited clearance opportunities.

6.5 Conclusion

From this sixth chapter, we conclude that the procedure tested by ISAVIA:

- Yields better savings;
- Has an easier implementation if compared to the procedure from NATCLM, given that it can be executed automatically by the current state of flight instruments; and
- Requires less workload from the pilots, as, once again, it can be executed automatically, while for the NATCLM, every climb had to be performed manually.

Thus we conclude that given the current state of equipment, whether on board or on the ground, the limited cruise climb technique is a better approximation of a cruise climb, then the 100ft step climbs at 250ft/min plus cruise segment.

5 Conclusion

5.1 Dissertation Overview

The main purpose of this dissertation was to quantify the fuel efficiency benefits achievable through a better altitude profile management during the cruise phase of flight. This was achieved through the development of a strategy that would approximate a vertical profile to the theoretical most efficient profile. Which is to fly as close as possible to a cruise climb.

It was defined in the NATCLM case that the cruise climb would be approximated by a series of 100ft step climbs during a FL change of 2000ft. For the estimation of the savings that resulted from the optimization, the fuel burn from the twenty 100ft step climbs that were actually flown was compared to the predicted 2000ft climb that would have been flown in the same conditions.

This vertical profile chosen for these flight trials, while not being the most efficient from a theoretical point of view, turned out to be a decent approximation, yielding savings in the order of 0.15% which for the segment analyzed translates into 29kg of fuel saved.

With the introduction of the ISAVIA's case, which yielded savings of around 330kg, it became possible to perform a comparison between the two procedures. Through this comparison it was concluded that a limited cruise climb profile is a better approximation of a cruise climb than 100ft steps at 250ft/min of climb rate.

Even if the savings obtained don't look like much, we would like to reinforce that everyday there are thousands of long haul flights with cruise segments of over five hours. If these fuel savings are looked at from an industry wide point of view and this kind of optimization starts being applied more often, the benefits would add up to very significant savings.

5.2 Final Considerations

The initial plans for this dissertation were to count with the collaboration of an Airline in designing and testing several different approximations to the real cruise climb, and then studying the results. Through a collaboration with an airline our work would have been facilitated, as we would have been involved in the flight tests, gathering the data in first hand and discussing the results with the performance engineers. As none of the airlines that we contacted were interested in being a part of this project, we had to search for another solution.

Instead of trying to develop a new study, we started asking airlines for flight data on fuel conservation strategies that they might already have. Once again, we received nothing that we could use.

Finally, NAV Portugal, the Portuguese ANSP, provided a report of the NATCLM project [11] with data and results from a set of flight trials in which they were involved.

Through a careful examination of all the flight data and results presented in the report we were able to extract enough information to write chapter three and explain the results of chapter four from our own point of view.

As a study of the NATCLM case was not enough, it was decided that we should include another study, the case of ISAVIA [13], which was also a part of AIRE.

5.3 Future Perspectives

The approximation of flight profiles to the theoretically most efficient profiles is well known and well documented.

Airlines have been performing step climbs for a very long time to try to stay as close as possible to their optimum altitude throughout the flight.

For a future research, we believe that a combination of the two procedures presented in this dissertation would be very interesting. As the two techniques were already tested, it proves that the current state of the on-board and ground systems, would not impose a problem to test this possibility.

The combined technique would be to perform the twenty 100 step climbs, just like it was presented in the dissertation but at the limited cruise climb rate of 100ft/min, and with a shorter cruise segment between climbs, to maintain the aircraft even closer to its optimum altitude at all times.

By combining two techniques that already proved to be good approximations of an optimum vertical profile, it is expected that the savings associated with this new technique would increase the savings already observed from the flight tests performed.

Furthermore, slight changes to the on-board and ground systems would allow a system wide optimization of flight profiles in the near future.

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Annex 1. Scientific Paper Submitted for Publication at ICEUBI2015

Fuel Conservation Strategies for the Vertical Profile of Cruise Flight

1. Introduction

This paper examines the potential fuel burn benefits of altitude optimization in the cruise phase of long-haul flights. With small modifications in how the cruise phase of a flight is operated, Airlines can achieve cost reductions and mitigate environmental impacts. The efficiency of the airspace can be improved with coordination between pilots, air traffic controllers and airline dispatchers.

Improving aircraft operational efficiency has become a dominant issue in air transportation, as the recent social and political climate has pushed for reduced environmental impact.

Scientific evidence of global climate change increased awareness on the importance of pollutant gases emissions such as CO_2, resulting in a significant pressure to reduce emissions. Air transport is responsible for 2% of man-made carbon emissions annually [1]. But the industry recognizes that it must work ever harder on behalf of the environment to achieve long-term sustainability, which will give the industry a license to grow. In 2009, therefore, the industry—comprising airlines, business aviation, airports, airplane manufacturers, and air navigation service providers— committed to a united approach in reducing emissions that includes three carbon emissions goals [1]:

1. Improving fuel efficiency an average of 1.5% annually to 2020;
2. Capping net emissions through carbon-neutral growth from 2020;
3. Cutting net emissions in half by 2050, compared with 2005.

Efforts to modernize aircraft fleets are limited by the extremely slow and expensive process of adopting new aircraft, which can take decades [2]. Major infrastructure improvements like those within the Single European Sky Air Traffic Management Research (SESAR) promise efficiency improvements but also face long implementation timelines. Operational improvements, however, remain a viable means of improving environmental performance in the near term.

2. State of the art

2.1 Introduction

This chapter covers the vertical aspects of the cruise flight phase, i.e. a vertical profile from the top of climb (TOC) to the top of descent (TOD). First, the general principles for vertical separation are presented. Then, the list of existing operations and methods for vertical trajectory management is given. A description of Step Climbing and Cruise Climbing is also included.

2.2 ICAO Rules for Separation and Minima

2.2.1 Vertical separation application

Vertical separation is obtained by requiring aircraft using prescribed altimeter setting procedures to operate at different levels expressed in terms of flight levels or altitudes in accordance with the Altimeter Settings Procedures of ICAO.

2.2.2 Vertical separation minimum

The vertical separation minimum (VSM) shall be [3]:

c. a nominal 300m (1000ft) below FL290 and a nominal 600m (2000ft) at or above this level, except for in b. below;
d. within designated airspace, subject to a regional air navigation agreement: a nominal 300m (1000ft) below FL410 or a higher level where so prescribed for use under specified conditions, and a nominal 600m (2000ft) at or above this level.

2.2.3 Standards for the Use of Vertical Airspace

The optimal vertical profile of a flight depends on several factors, the aircraft type (design, engines, etc.), aircraft gross weight, environmental conditions (mostly the temperature and wind evolution), flight plan (FPLN) and ATC interventions.

All phases of a flight are filled within the ICAO flight plan, including horizontal elements of the vertical profile expected by the air user [9]. The flight plan is completed on the basis of the operational impact on the flight's economy, i.e. aicraft performance data and weather forecast (deviation of temperature from ISA as well as wind vector at flight levels). It contains all characteristics of the flight (airways, times of overfly of waypoints, distances between waypoints, tracks, FL's, fuel consumption, aircraft weights, air speeds, ground speeds, etc.) This operational flight plan (OFP) is the basis for the flight execution. Every Air Traffic Service (ATS) along the flight routes receives the OFP so the ground services have full pre-flight information about the planned vertical profile of a flight.

In the ideal case, when an aircraft is not restricted by ATCo, the aircraft can then take-off and climb to the optimal altitude, i.e. to the top of climb. After reaching the TOC an aircraft can fly:

- the same barometric altitude throughout the flight (Level Flight);
- a certain time at one flight level and later, when a current flight level is not the most efficient (after burning fuel off, better wind/temp conditions at anoter flight level), can climb to a higher FL, i.e. follows the step climb procedure (Step Climb);
- or, where traffic is not an issue (and regulations do not forbid), it can continuously climb during the cruise (Cruise Climb).

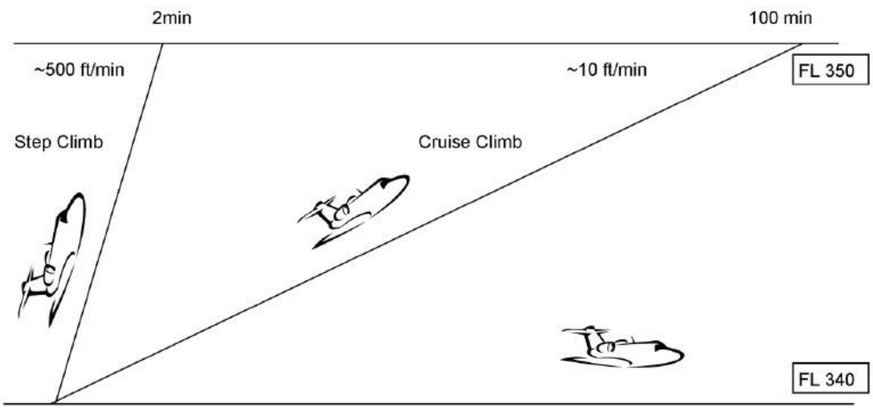

Fig. 1 – Difference between Step Climb, Level Flight and Cruise Climb [4]

As it can be seen in Fig. 1, the main difference between a Step Climb and a Cruise Climb is the climb rate. Step Climbs usually have a high rate of climb, around the 500ft/min. To approximate a step climb to a cruise climb, climb rates of 100ft/min are sometimes used, as that is the smallest automatic climb rate available on the FMS (Flight Management System). A climb at 100ft/min is usually called a Limited Cruise Climb, Fig.2 [5].

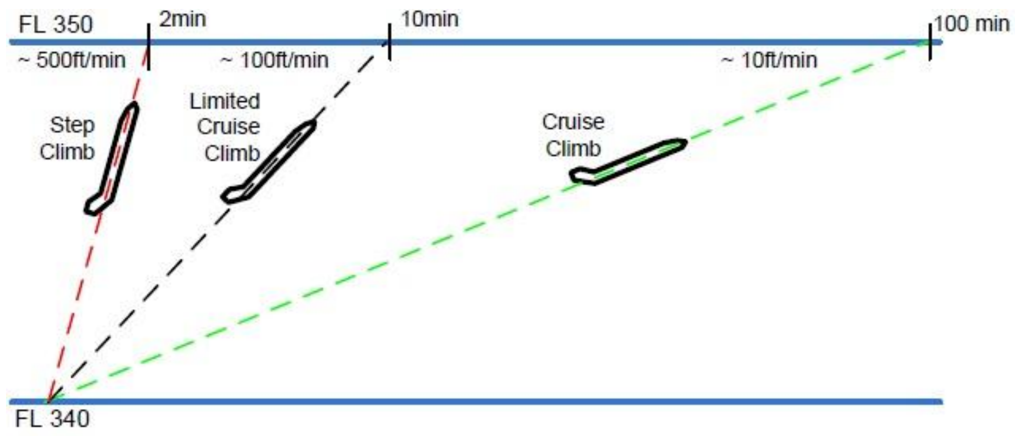

Fig. 2 - Different climb profiles [5]

2.2.3.1 Step Climb

A step climb (Fig.3) is a technique currently used for fuel savings. It's a climb from one cruise altitude to another in fixed steps, which are intended to keep an aircraft flying for long periods of time at a fixed altitude, while still trying to maintain an efficient vertical profile. Although this technique is not optimal from the fuel consumption perspective, it is still more efficient than maintaining a single altitude during the whole cruise phase.

Modern commercial aircraft are equipped with flight management systems (FMS) that can calculate and execute the proper steps to increase the fuel efficiency.

The typical cruise phase for a commercial aircraft is described by a series of level segments which are increased in altitude as fuel is burned. The step climb is the climbing phase between two flight levels. ATC approval is always required to guarantee that the aircraft is flying at the cleared altitude.

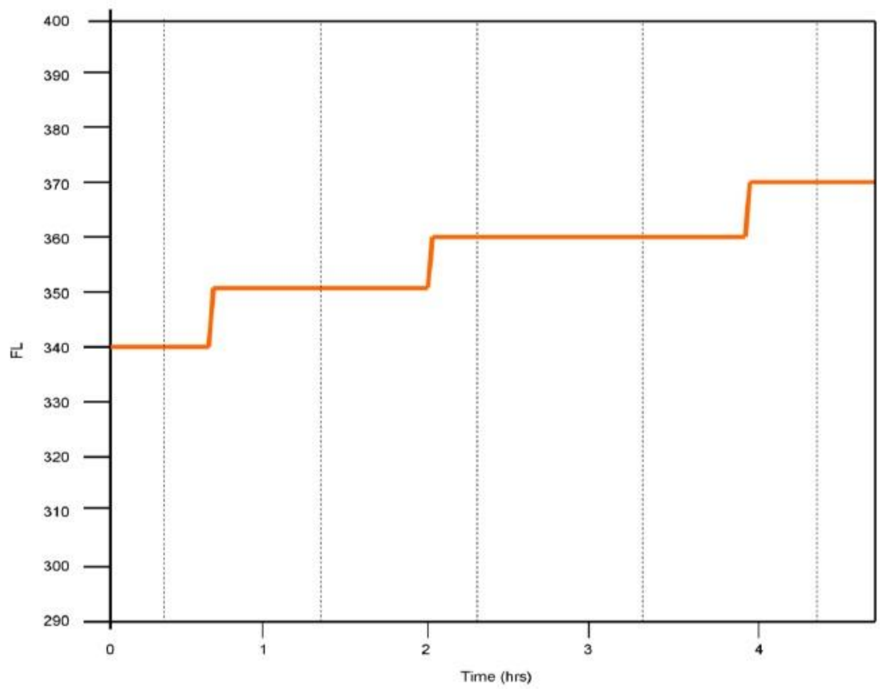

Fig. 3 - Step climb profile [4]

2.2.3.1.1 Choice of Profile

There are several ways to approximate the step climbs to the optimum altitude profile:

- The low profile initiates the step climb at the weight where the next available flight level is also the optimum flight level at that weight. Consequently, the flight levels are always at or below the optimum. This has the advantage of better manoeuverability margins;
- The high profile initiates the step climb at the weight where the next available flight level is also the maximum flight level at that weight. The flight levels are mainly above the optimum and the aircraft will have decreased manoeuverability and fly slower;
- The mid profile initiates the step climb at the weight where the specific range at the next available flight level is better than that at the current flight level. This enables the flight profile to remain as close as is practically possible to the optimum flight level. This technique is recommended for best fuel economy, and is very close to that required for best economics.

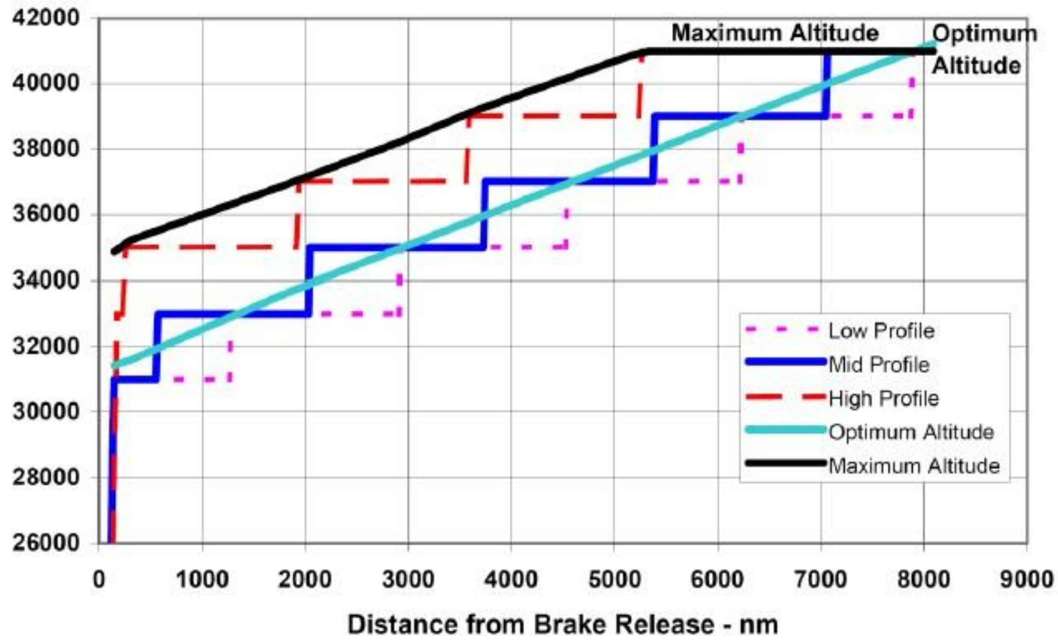

Fig. 4 - Example of Step Climb Profiles

2.2.3.2 Cruise Climb

The altitude that provides the most fuel efficient cruise at the start of a long flight, when the aircraft is fully loaded with fuel, is not the same as the altitude that provides the best efficiency at the end of the flight. As the flight proceeds fuel is burned and the aircraft becomes lighter. This change may be very significant; up to half the total weight on a long-haul aircraft. With the aircraft becoming lighter, the lift will become lower. In order to operate at the best lift coefficient we need to reduce the dynamic pressure. There are two options to reduce the dynamic pressure, by reducing the speed or by climbing to a higher altitude. If the aircraft is powered by a gas turbine we do not wish to reduce speed, or the engine efficiency will suffer. So, the air density is reduced by climbing gradually throughout the cruise phase.

The Concorde flights, for example, used a continuous cruise climb over the Atlantic, benefiting from rare situations where traffic at the same altitude (nearly 60000ft), in the same direction, and at the same time of the day was scarce or inexistent. Although this technique used by Concorde is not in operational use today, according to ICAO rules [3], the procedures for cruise climb coordination are still valid and can be used.

With the increase of air traffic since the Concorde days, and the assignment of distinct flight levels to specific flights, airways, and directions of flight, it is generally no longer possible to climb continuously. Even though low traffic regions are able to authorize cruise climbs, it is not practical from a traffic control standpoint.

When traffic conditions and coordination procedures, in those low traffic regions, allow the clearance of a cruise climb, an ATC unit shall normally authorize only one level for an aircraft beyond its control area, i.e. that level at which the aircraft will enter the next control area whether contiguous ot not. It is the responsability of the accepting ATC unit to issue clearance for further climbing. When relevant, aircraft will be advised to request en route any cruising level changes desired.

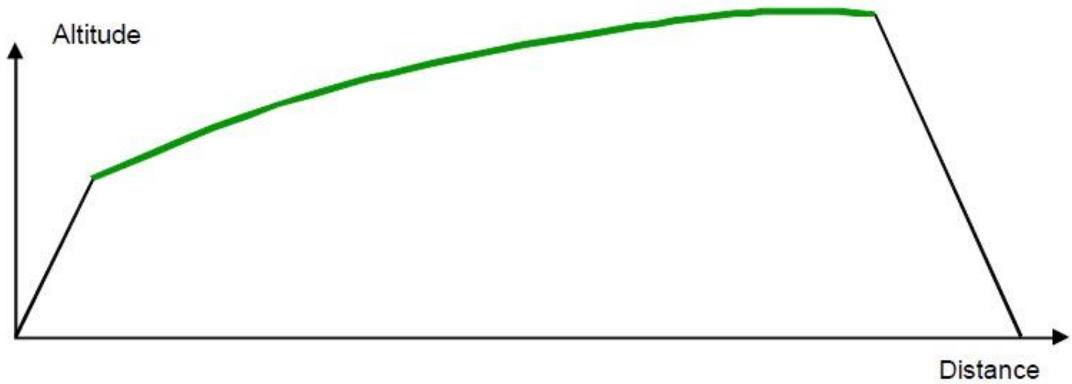

Fig. 5 - Continuous Cruise Climb profile

3. Case Study

3.1 Project Context

The Atlantic Interoperability Initiative to Reduce Emissions (AIRE) is an agreement between the European Comission (EC) and the Federal Aviation Administration (FAA) of the United States of America. It is a programme which aims to reduce CO_2 emissions by taking advantage of air traffic management best practices and new technologies, it expects to accelerate the implementation of environmentally friendly procedures for all phases of a flight, and to validate the benefits of these improvements. The SESAR Joint Undertaking is responsible for the management of AIRE from an European perspective [6].

3.2 Estimation of Environmental Benefits

3.2.1 Vertical Optimization

The prediction of fuel consumption for the prevailing conditions was made using the manufacturers Performance Programs [6]. Calculations were performed in a sequence of 100ft climbs plus cruise segments at increasing flight levels, from the initial weight at a given level, until the optimum weight to climb another 100ft is attained.

For the prediction of fuel consumption for the current climb technique, it was used Performance software, by calculating a cruise segment from the start of the cruise until the point where optimum weight for a 2000ft step climb is attained, plus a climb of 2000ft, plus a cruise segment until the same point where the cruise climb would be finished [6].

3.2.1.1 Estimation of Savings

For the estimation of savings, an A330-202 aircraft was used. And the steps were calculated at a weight that leads the aircraft to be at the optimal weight for the average altitude of the altitude between the steps. This yields results that are expected to be valid for other aircraft types in a qualitative way.

Three different optimization strategies were tested, besides the current operational situation:

- Case 0, the reference of the current operation in the Atlantic, will be a step climb of 1000ft, from FL360 to FL370 followed by a cruise segment at FL370 and then a step climb from FL370 to FL380;
- Case 1, still valid in some areas of operation, will be a 2000ft step climb from FL360 to FL380;
- Case 2, will be a series of 100ft steps each followed by a cruise segment;
- Case 3 will be a continuous climb at a rate as close as possible to the one that makes the aircraft follow the path of optimum altitude versus weight (in this case 10ft/min). This, in theory, could be called the actual Cruise Climb Technique, although it proved to be far from ideal.

Table 1 summarizes the results obtained, considering the following conditions:

- Cruise at Mach 0.80;
- Climb at maximum rate;
- Initial weight: 205300kg, close to optimum weight for FL360 (205270kg);
- Final weight: 186400, optimum weight for FL380.

Table 1 - Estimation of savings - Summary [6]

	Case 0 (1000ft step)	Case 1 (2000ft step)	Case 2 (100ft steps)	Case 3 (Slow climb)
Distance flown between 205300kg and 186400 kg (NM)	1596.8	1595.3	1597.9	1565.8
Extra distance to case 2 (NM)	1.1	2.6	0	32.1
Extra fuel for distance 2 (kg)	12	29	0	360
Final weight (kg)	186388	186371	186400	186040
Fuel increase with respect to case 0 (kg)	0	17	-12	348
% increase with respect to case 0	0.00%	0.09%	-0.06%	1.84%
Fuel increase with respect to case 1 (kg)	-17	0	-29	331
% increase with respect to case 1	-0.09%	0.00%	-0.15%	1.75%
Fuel increase with respect to case 2 (kg)	12	29	0	360
% increase with respect to case 2	0.06%	0.15%	0.00	1.90%

From Table 1 it can be concluded that there are potential savings of 0.06% when flying as specified in Case 2 instead of flying the current operational procedure.

It is shown in table 2 a comparison of fuel consumption between a level flight at FL360 (and FL380) and performing 100 ft step climbs between FL360 and FL370 (and between FL370 and FL380).

Table 2 - Fuel consumption between level 360 and 380 [6]

FL (100ft)	Initial Weight (kg)	Final Weight (kg)	Fuel (kg)	Distance (NM)	FL(100ft)	Fuel (kg)	Delta Fuel (kg)
360	205300	204761	539	43.8	360	539	0
361	204740	203751	989	80.6	360	989	0
362	203730	202730	1000	81.9	360	1000	0
363	202709	201710	999	82.2	360	999	0
364	201689	200786	903	74.7	360	904	1
365	200765	199786	979	81.3	360	979	0
366	199765	198882	883	73.7	360	884	1
367	198861	197860	1001	83.9	360	1001	0
368	197840	197010	830	69.9	360	831	1
369	196990	196050	940	79.5	360	941	1
370a	196030	195575	455	38.6	360	455	0
370b	195575	195130	445	37.9	380	448	3
371	195110	194220	890	76	380	895	5
372	194200	193165	1035	88.8	380	1039	4
373	193145	192240	905	78	380	907	2
374	192220	191335	885	76.7	380	888	3
375	191315	190441	874	76.1	380	876	2
376	190421	189525	896	78.3	380	897	1
377	189505	188629	876	76.9	380	877	1
378	188609	187735	874	77.1	380	875	1
379	187715	186860	855	75.8	380	856	1
380	186840	186400	440	39.1	380	440	0
			Total:	1570.8			27

For better understanding of the values in Table 2, take the case of the 100ft step climb from FL363 to FL364, 903kg of fuel were used for that distance, 74.7NM. By flying the same distance, starting at the same weight, but at FL360, over the same distance, 904kg of fuel were used, resulting therefore in savings of 1kg of fuel over a segment of 74.7 NM. By doing the same exercise for all other FL's and summing up all the savings, we obtain the 27kg of fuel savings for the the flight segment of 1570.8NM mentioned in Table 2.

4. Conclusions

The application of fuel conservation strategies on the vertical profile of a cruise flight is translated into more efficient operations, which yields economic benefits for the airspace users as well as a reduction in the emission of greenhouse gases.

Even though the lack of real cruise climb procedures nowadays is considered an inefficiency in Air Traffic Management (ATM) for high density areas, there are confirmed opportunities for the use of this technique in low density areas, such as oceanic airspace. The fact that the current generation of avionics doesn't support the manoeuvre automatically is the biggest issue for implementation.

The results for the manual cruise climb were not the expected, as they did not yield the biggest savings. This might be due to the fact that those trials were performed manually and even the slightest deviation may yield negative results. However it was proved that through a better step design, savings can be obtained.

The best savings results were obtained in Case 2, twenty 100ft step climbs from FL360 to FL380, we believe that higher savings weren't attained because of the maximum climb rate used. Knowing that the limited cruise climb is easily done by the FMS, an interesting approximation to the real cruise climb, would be to perform the 100ft step climbs in a limited cruise climb rate of climb. But this could be the subject for a future research.

It is then necessary to develop the tools needed for the automatic execution of an actual cruise climb. As well as the tools needed for a better support of Air Traffic Control, specially in the trajectory prediction, and conflict detection tools.

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