EUROPEAN ORGANISATION
FOR THE SAFETY OF AIR NAVIGATION

EUROCONTROL

EUROCONTROL EXPERIMENTAL CENTRE

STUDY OF THE ACQUISITION OF DATA FROM AIRCRAFT OPERATORS TO AID TRAJECTORY PREDICTION CALCULATION

EEC Note No. 18/98

EEC Task R23
EATCHIP Task ODP.ET5.ST03

Issued: September 1998

REPORT DOCUMENTATION PAGE

Reference: EEC Note No. 18/98	**Security Classification:** Unclassified
Originator: EEC - FDR (**F**light **D**ata **R**esearch)	**Originator (Corporate Author) Name/Location:** EUROCONTROL Experimental Centre B.P.15 F - 91222 Brétigny-sur-Orge CEDEX FRANCE Telephone : +33 (0)1 69 88 75 00
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TITLE:

STUDY OF THE ACQUISITION OF DATA FROM AIRCRAFT OPERATORS TO AID TRAJECTORY PREDICTION CALCULATION

Author	Date	Pages	Figures	Tables	Appendix	References
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EATCHIP Task Specification	EEC Task No.	Task No. Sponsor	Period
ODP.ET5.ST03	R23	ODP-5-E3	1997 to 1998

Distribution Statement:

(a) Controlled by: Head of FDR

(b) Special Limitations: None

(c) Copy to NTIS: YES / ~~NO~~

Descriptors (keywords):

trajectory prediction - aircraft operators - airlines - flight plans - data link - take-off weight - route - flight plan data processing

Abstract:

Several aircraft operators were consulted to determine if they could supply flight data to ATS which would make a significant difference to the trajectories calculated by flight data processing systems, particularly in the initial climb phase. In parallel, simulations were carried out using a typical trajectory prediction simulator to assess the benefits which might be obtained from this data. The study then went on to investigate when and how this data could be supplied.

Table of Contents

ACKNOWLEDGEMENTS ..... **VIII**

EXECUTIVE SUMMARY ..... **IX**

1. INTRODUCTION **1**

1.1 PURPOSE 1
1.2 REPORT STRUCTURE 1

2. REFERENCES **3**

3. DEFINITIONS AND ABBREVIATIONS **4**

4. FLIGHT PLAN DISTRIBUTION AND PROCESSING **7**

5. TRAJECTORY PREDICTION IN FDPS **9**

5.1 INTRODUCTION 9
5.2 DEFINITION OF TRAJECTORY PREDICTION 9
5.3 PURPOSE OF TRAJECTORY PREDICTION IN FDPS 9
5.3.1 Airspace Volumes Crossed by the Flight 10
5.3.2 Medium Term Conflict Detection and Conflict Probing 10
5.3.3 Flight Plan Event Management 10
5.3.4 Information About the Flight's Intentions 11
5.4 CONCLUSION 11

6. SHORTCOMINGS IN CURRENTLY AVAILABLE DATA **12**

6.1 INTRODUCTION 12
6.2 DATA USED FOR TRAJECTORY PREDICTION 12
6.2.1 Introduction 12
6.2.2 Flight plan route 13
6.2.3 Airspace description 13
6.2.4 Aircraft characteristics 13
6.2.5 Environmental Parameters 14
6.2.6 Operating Procedures 15
6.3 SHORTCOMINGS IN DATA AVAILABLE FOR TRAJECTORY PREDICTION 16
6.3.1 Introduction 16
6.3.2 Flight Plan Route 16
6.3.3 Airspace Description 17
6.3.4 Aircraft Characteristics 17
6.3.5 Environmental Parameters 21
6.3.6 Airline Operating Procedures 22
6.3.7 Differences in trajectories obtained using data currently available and data potentially supplied by Aircraft Operators 23
6.3.8 Conclusion 23

7. DATA AVAILABLE FROM AIRCRAFT OPERATORS ON GROUND **25**

7.1 INTRODUCTION 25
7.2 TRAJECTORY PROVISION 26
7.2.1 Introduction 26
7.2.2 OFPL Preparation and Use 26
7.2.3 OFPL Accuracy 27
7.3 AIRCRAFT CHARACTERISTICS 28

7.3.1 Full Aircraft Type ... *28*
7.3.2 Engine Type and Characteristics ... *28*
7.3.3 Take-Off Weight ... *29*
7.4 OPERATING PROCEDURES ... 30
7.5 CONCLUSION ... 31

8. DATA AVAILABLE FROM ON-BOARD AIRCRAFT ... 32

8.1 INTRODUCTION ... 32
8.2 TRAJECTORY ... 32
8.2.1 Introduction ... *32*
8.2.2 Future Flight Management Computer Systems (FMCS) ... *32*
8.2.3 FMS Trajectory Calculation Accuracy ... *33*
8.2.4 Conclusion ... *34*
8.3 AIRCRAFT CHARACTERISTICS ... 34
8.4 OPERATING PROCEDURES ... 35
8.5 CONCLUSION ... 35

9. INFRASTRUCTURE CONSIDERATION ... 36

9.1 INTRODUCTION ... 36
9.2 GROUND/GROUND COMMUNICATIONS NETWORKS ... 36
9.2.1 Introduction ... *36*
9.2.2 AFTN ... *36*
9.2.3 SITA ... *37*
9.2.4 ATN (Ground Part) ... *37*
9.3 AIR/GROUND COMMUNICATIONS ... 38
9.3.1 Introduction ... *38*
9.3.2 ACARS ... *38*
9.3.3 Planned Datalink Applications ... *39*
9.3.4 ATN (Airborne Part) ... *41*
9.4 CONCLUSION ... 41

10. POSSIBLE SOLUTIONS ... 43

10.1 INTRODUCTION ... 43
10.2 GROUND TO GROUND DATA EXCHANGE ... 44
10.2.1 Introduction ... *44*
10.2.2 Data for Distribution to ATS ... *44*
10.2.3 Ground-Ground Data Distribution ... *45*
10.2.4 Conclusion ... *45*
10.3 ON BOARD TO GROUND DATA EXCHANGE ... 45
10.3.1 Introduction ... *45*
10.3.2 Data for Distribution to ATS ... *46*
10.3.3 Air-Ground Data Distribution ... *46*
10.3.4 Conclusion ... *47*
10.4 ONBOARD AND GROUND TO GROUND DATA DISTRIBUTION ... 47

11. CONCLUSION ... 48

12. RECOMMENDATIONS ... 50

APPENDIX A - BADA PRESENTATION ... 51

APPENDIX A .1 GENERAL ... 51
APPENDIX A .2 THE AIRCRAFT MODEL BEHIND BADA ... 51
APPENDIX A .3 DESCRIPTION OF THE MODELS USED FOR THE SIMULATIONS IN THIS STUDY. 54

APPENDIX B - EFFECT OF TAKE-OFF WEIGHT ... 53

APPENDIX B .1 INTRODUCTION ... 53
APPENDIX B .2 ATR42 ... 53

Appendix B .2 .1 Difference between Typical and Maximum TOW 54
Appendix B .2 .2 Difference between Typical and Minimum TOW 55
Appendix B .2 .3 Difference between Max and Min TOWs 56
Appendix B .2 .4 Significant weight difference for a ATR42 57
APPENDIX B .3 EA32 58
Appendix B .3 .1 Difference between Typical TOW and Maximum TOW 58
Appendix B .3 .2 Difference between Typical TOW and Minimum TOW 59
Appendix B .3 .3 Difference between Maximum TOW and Minimum TOW 60
Appendix B .3 .4 Significant weight difference for a EA32 61
APPENDIX B .4 B747 62
Appendix B .4 .1 Difference between Typical TOW and Maximum TOW 63
Appendix B .4 .2 Difference between Typical TOW and Minimum TOW 65
Appendix B .4 .3 Difference between Max TOW and Min TOW 66
Appendix B .4 .4 Significant weight difference for a B747 67
APPENDIX B .5 B767 68
APPENDIX B .5 .1 DIFFERENCE BETWEEN TYPICAL AND MAXIMUM TOW 68
APPENDIX B .5 .2 DIFFERENCE BETWEEN TYPICAL AND MINIMUM TOW 71
APPENDIX B .5 .3 DIFFERENCE BETWEEN MAX AND MIN TOW 72
APPENDIX B .5 .4 SIGNIFICANT WEIGHT DIFFERENCE FOR A B767 73
APPENDIX B .6 IMPACT OF OFPL WEIGHT ERROR 74
APPENDIX B .7 CONCLUSION 74

APPENDIX C - ENGINE PERFORMANCE DEGRADATION 76

APPENDIX C .1 INTRODUCTION 76
APPENDIX C .2 DC10 77

APPENDIX D - OPERATING PROCEDURES 79

APPENDIX D .1 EFFECT OF COMPANY OPERATING PROCEDURES 79
APPENDIX D .2 CLIMB PROFILES WITH DIFFERENT SPEEDS 79
Appendix D .2 .1 ATR42 79
Appendix D .2 .2 EA32 81
Appendix D .2 .3 FK100 82
APPENDIX D .3 CONCLUSION 83

APPENDIX E - DIFFERENCES IN TRAJECTORIES OBTAINED USING DATA CURRENTLY AVAILABLE AND DATA POTENTIALLY SUPPLIED BY AO 84

APPENDIX F - WIND EFFECT 87

APPENDIX F .1 ATR42 87
APPENDIX F .2 EA32 89
APPENDIX F .3 B747 89
APPENDIX F .4 CONCLUSION 91

APPENDIX G - TEMPERATURE EFFECT 92

APPENDIX G .1 ATR42 92
APPENDIX G .2 EA32 94
APPENDIX G .3 CONCLUSION 96

Acknowledgements

The study authors would like to express their appreciation for the extensive support and assistance provided by representatives of the airline and service provider companies who assisted in the study:

Jean-Yves Jung, Gerard Cordier, Patrick Gastaud of Air France

Jean-Noel Garnier of AOM

Stephane Depeyre of Air Liberte

Wayne Beardsley of Air Foyle

John McMillan, Alison Hubbard of Britannia Airways

Colin Hume, Steve Stebbings, Dennis Dale-Green of British Airways

Andy Holmes of Easyjet

Wilfried Stuven, Gerd Beyer of Lufthansa

Richard Kneale, Mike Hyde of Magec Aviation

Norman Foster, Mark Deacon of Monarch

A Parmenion Charistos, Achileas Papagiorgiou of Olympic Airlines

Ron Rowlands of SITA

Steve Morris and Steve Parker of Virgin Atlantic

Executive Summary

Introduction

EUROCONTROL, in co-operation with Member States is in the process of developing the principles and requirements for the trajectory prediction function for European Air Traffic Control Harmonisation and Integration Programme (EATCHIP) Phase III Flight Data Processing Systems (FDPS).

Whilst statements have been made from many organisations and individuals in the past that the Air Traffic Control (ATC) service provider based prediction function could be radically improved by the receipt of data from aircraft operators and airborne platforms, such claims have yet to be validated and the benefits determined.

This document reports on a study carried out by the EUROCONTROL Experimental Centre on behalf of DED.2 to investigate this question.

Study Scope

The study investigated the following questions with regard to the trajectory prediction function and data available from aircraft operators:

- In addition to the data currently provided, what is the minimum data that can be supplied by an aircraft operator that would make a significant difference to the trajectory calculated by an ATC Flight Data Processing System (FDPS)?
- What data could be supplied by Airline Operations Centre (AOC) in addition to the minimum?
- When and how can this information be supplied to the trajectory prediction (TP) function?

More specifically, the study considered the data elements available to airline operators concerning a particular aircraft such as its load and performance and airline operating procedures, the availability of which in FDPS could significantly improve the calculated trajectory.

The issue of delivering an improved estimate of the departure (take-off) time was outside the scope of the study and was not considered.

Particular attention was paid to the accurate prediction of the climb phase as it is affected to a greater extent by aspects known to the aircraft operator.

Study Description

Initially the data that is currently supplied by the aircraft operator to ATC was investigated and its usefulness for trajectory prediction was considered.

Essentially this data is just that provided in the statutory flight plan sent to ATC to notify ATS of the planned flight.

Some initial simulations were carried out using one of the trajectory predictors, BADA, which is available at the EUROCONTROL Experimental Centre. These provided a baseline to assess the benefits of more accurate data.

A set of parametric studies was also carried out using BADA to determine the impact of varying certain parameters. The magnitudes of the changes in the trajectories caused by varying these parameters were compared against values which were considered to be significant in the context of ATC operations to allow the study team to assess what accuracy in trajectory prediction parameters was desirable. Particular runs demonstrated that, for example:

- a difference between the estimated and actual take-off weight of 1% would lead to a significant error of 5 nm in the along-track prediction accuracy of the top-of-climb (TOC) for a Boeing 747.
- a difference in the engine fit on the same airframe, a Boeing 767-200, would lead to a significant difference of 5 minutes and 11 nm in the along-track prediction accuracy of the TOC.

A survey form was then prepared identifying the information not currently available for use in ground-based trajectory prediction by ATS but thought to be available to aircraft operators. This included individual flight and aircraft characteristics and operating procedures.

A range of different types of airline operating companies was then contacted to discuss the information that could be made available. Contacts included major airlines, regional airlines, charter operators, business jet operators, cargo operators and flight plan preparation suppliers. The companies provided a great deal of useful and pertinent information including detailed operational flight plans and operating procedures. This information served to demonstrate the wide diversity of methods and facilities used in flight planning.

An analysis was carried out using the BADA results already described to determine what data could usefully be supplied by the AOCs to improve trajectory prediction. Factors considered in the analysis included the timescale of availability prior to taxi and the level of accuracy of the data. Additional simulations were carried out to further investigate the benefits of specific items of information.

A comparison was also made between filed flight plans, airline-supplied operational flight plans and actual flown trajectories.

An investigation was then carried out of the different potential means of distributing data to support improved trajectory prediction by ATS. This included an investigation of the down-linking of data from aircraft both after taxiing and when airborne, and distribution from aircraft operators by ground-based infrastructure.

Finally an analysis was performed to identify those data and distribution mechanisms that would provide the greatest benefit to ATC taking into consideration the benefits provided, implementation feasibility and cost.

Study Conclusions

Several shortcomings were identified in the data available for trajectory prediction by ATS:

- the ICAO aircraft type designator supplied in the flight plan does not provide sufficient information for accurate trajectory prediction by ATS. It lacks an indicator of the engine type and is not very precise as a means of identifying the particular aircraft type. Both of these parameters are significant in accurate trajectory prediction.

- ATS does not normally have available a good estimate of the take-off weight, but it was found that an error of a few percent has a significant effect on the calculation of the TOC. Hence non-availability of take-off weight by ATS is seen as a significant limitation.

- Airline operating procedures define how the aircraft should be flown for a given airline, airport and environmental conditions. Parameters include use of reduced thrust takeoff and climb speed. This information is not available to ATS.

It was therefore concluded that ATS trajectory prediction would be significantly improved by the provision of this information from aircraft operators.

Airline operating procedure information could be supplied to ATS off-line on a strategic timescale.

AOs could provide full aircraft type and engine fit, and an estimated take-off weight by ground-ground links four to five hours in advance of the flight. This would give a significant improvement in prediction accuracy at relatively low cost. A possible mechanism would be an extension of the existing FPL submitted to ATS.

The data may change closer to the time of flight. The specific airframe may be changed for operational reasons and the take-off weight will be more accurately determined. These data items could be sent by datalink-equipped aircraft to ATS closer to take-off. Possible solutions are being developed at present, such as the use of the Pre Departure Clearance (PDC) and Downlink of Aircraft Parameters (DAP) applications over ACARS.

Even with this data, the accuracy of the prediction could still be compromised for a number of reasons. In particular, pilot intervention during the flight may cause significant deviations from the anticipated trajectory.

A final, and important issue is the quality of the trajectory predictor available in the FDPS. At present few systems are capable of making use of improved input data. It will be necessary to progress with the development of improved systems compliant with EATCHIP III operational requirements for the benefits of improved data exchange with aircraft operators to be fully realised.

Recommendations

As a result of the study it is recommended that:

1. Arrangements for the provision of Operational Flight Plans (OFPLs), full aircraft type, engine fit and approximate take-off weights by AOs should be established on an experimental basis and trials carried out to evaluate the data provided.

2. An impact assessment of the provision of these data on the wide range of different trajectory predictors found in ATS systems should be made.

3. An impact assessment on AO-ATS communications of these changes should be assessed to determine the costs and feasibility of full scale implementation. Of particular concern to evaluate are additional costs to aircraft operators.

4. Further investigations should be made of the practicalities of delivering updates of airframe and take-off weight data via the PDC and DAP datalink applications should be investigated. This should involve experiments and trials.

5. Regard should be paid to ensuring that provision is made for downlink of the required data.

6. Trials should be carried out to obtain operating procedures from a variety of aircraft operators to evaluate their use in trajectory prediction.

7. Continuing research should be made into methods for dealing with trajectory prediction problems arising from pilot intervention in flight. This effect remains a very significant source of error for trajectory prediction.

1. INTRODUCTION

1.1 PURPOSE

The objectives of the study are the identification of aspects of the data available to Aircraft Operators (AOs) concerning a particular flight that are not generally available to Air Traffic Services (ATS) and which could significantly improve the Trajectory Prediction function in Flight Plan Processing System (FDPS).

The first task was to identify the shortcomings of data currently available for the determination of trajectories by ATM systems, and then to identify the data which could be available from a range of different aircraft operators to improve trajectory prediction.

The second task was to calculate the trajectories of flights from various operators by using a representative trajectory prediction algorithm but limited to the data currently supplied to ATS. This was then repeated using the improved data that could be supplied from AOs to assess the differences.

The third task was to analyse the future availability of trajectory data which could be down-linked from aircraft both while taxiing and when airborne and to indicate potential benefits to ATC.

The fourth task was to investigate and report on infrastructure considerations, in particular the potential means of transferring data for each of the AO types and identify costs and quality of service which could be provided.

The fifth and final task was to use the research and analysis performed to identify those data items available to AOs which would provide the greatest benefit to improving trajectory prediction by FDPS and to report on the feasibility of implementation and cost of solutions to distributing this data.

This document is the Final Report of the Study.

1.2 REPORT STRUCTURE

The structure of the report is as follows. Initially an overview of flight plan preparation and distribution is given, followed by a summary of the role of trajectory prediction in FDPS.

The current shortcomings in the data available to ATS for trajectory prediction was then determined. This was done by identifying the data currently available to ATS and comparing it with data which could be significant in improving trajectory prediction. This analysis is presented in chapter 6.

The next stage of the analysis was to interview a representative sample of AOs to determine if they could potentially act as a source of the data identified as significant in improvement of trajectory prediction estimates. The data which could be made available from Airline Operations Centres (AOCs) and the data which would have its origin on board aircraft are addressed separately in chapters 7 and 8.

A short investigation was also made of the infrastructure considerations which might affect the distribution and availability of this data to ATS, and this is described in chapter 9.

Some possible solutions were then identified and analysed qualitatively from the perspectives of feasibility, costs and potential benefits. The analysis took into consideration the infrastructure needed to distribute the information and the benefits that would result from availability of the information to ATS. This is described in chapter 10.

Chapter 11 and 12 present the Conclusions and Recommendations.

A number of Appendices contain results of simulations carried out in the course of the study and report on information gathered from AOs.

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3. DEFINITIONS AND ABBREVIATIONS

ACARS	Airborne Communications Addressing and Reporting System
ACC	Area Control Centre
ADEP	Aerodrome of Departure
ADES	Aerodrome of Destination
AES	Aircraft Earth Station (INMARSAT)
AFTN	Aeronautical Fixed Telecommunications Network
AGADE	Air Ground Automatic Data Exchanges
AIP	Air Information Publication
AO	Aircraft Operator
APC	Aeronautical Passenger Communications
ARINC	Aeronautical Radio, INCorporated
ATFM	Air Traffic Flow Management
ATN	Aeronautical Telecommunications Network
ATS	Air Traffic Services
ATSC	Air Traffic Services Communication
ATSU	Air Traffic Service Units
BPR	Bypass Ratio
CAS	Calibrated Air Speed
CFL	Cleared Flight Level
CFMU	Central Flow Management Unit
CMU	Communication Management Unit (INMARSAT)
CNS	Communications, Navigation, Surveillance
DSP	Data Link Service Provider

DME	Distance Measuring Equipment
EATCHIP	European Air Traffic Control Harmonisation and Integration Programme
ECAC	European Civil Aviation Conference
EFIS	Electronic Flight Instrument System
EFW	Empty Fuel Weight
EOBT	End of Block Time
ETA	Estimated Time of Arrival
ETE	End-to-End
ETOP	Extended Twin Engine Operations
FDPS	Flight Data Processing System
FDPS/T	Trajectory built by the Flight Data Processing System
FIRs	Flight Information Region
FIS	Flight Information Services
FMCS	Flight Management Computer System
FPL	ICAO Flight Plan message
GES	Ground Earth Station (INMARSAT)
GPS	Global Positioning System
IFPS	Integrated Initial Flight Plan Processing System
IFPS/FPL	Validated flight plan information produced by the IFPS
INMARSAT	International Maritime Satellite Organisation
MCDU	Multifunctional Control Display Unit
MTOW	Minimum Take-Off Weight
MU	ACARS Management Unit
NAVAID	Navigational Aid

OFPL	Operational Flight Plan
RNAV	Area Navigation
RPL	Repetitive Flight Plan
RTA	Required Time of Arrival
SATCOM	Satellite Communication System
SFPL	System Flight Plan
SID	Standard Instrument Departure
SITA	Socièté Internationale de Telecommunications Aeronautiques
STAR	Standard Terminal Arrival Route
TAS	True Airspeed
TOC	Top Of Climb
TOD	Top Of Descent
TOS	Traffic Orientation Scheme
TWDL	Two-Way data Link Communication
VOR	VHF Omnidirectional Radio Range
WAFS	World Area Forecast System
ZFW	Zero Fuel Weight

4. FLIGHT PLAN DISTRIBUTION AND PROCESSING

This chapter gives a background description of the flight plan information used by AOs and ATS and the various stages of flight plan preparation, processing and distribution from AO to ATS Units for flights within the ECAC region.

When an AO decides to establish a flight between two airports, appropriate airport slots will be negotiated as necessary and resources allocated by the AO. Internally to the AO, work will begin on preparation of an Operational Flight Plan (OFPL). Assuming a flight originating in the ECAC region, Planned Flight Data (PFD) identifying only the departure and destination airports will usually be prepared and sent to CFMU to help with longer-term planning. Alternatively a more detailed Repetitive Flight Plan (RPL) may be sent, the choice of which to use depending on the AO's preferred operating procedures. This task is carried out when the operator is preparing its schedule for the next season, several months in advance of the flight.

During the period up to the time of the flight the AOs develop the OFPLs according to their specific operating policies such as cost and delay estimations, and changes in the operating environment, such as the opening of new routes. For example, at this stage they will identify the type of aircraft to use and the possible routes between departure and destination airports.

A few hours before the planned departure time, the AO will generate the detailed OFPL. They may do this internally using an in-house computerised flight planning system or the task may be subcontracted to a service provider such as SITA or Jeppessen.

The OFPL is then supplied to the aircrew so that they can prepare for the flight. They can use the data in the OFPL to supply the FMS with the necessary operating parameters.

The AOs (or trajectory provider if the task is subcontracted) uses the OFPL to generate an ICAO-compliant flight plan for distribution to ATS. The flight plan is sent to the Initial Flight Plan Processing System (IFPS). This validates the flight plan that has been supplied and distributes the flight plan information to ATS, identified as IFPS/FPL in this document. If, however, the AO filed an RPL for the flight, the IFPS will itself generate an individual flight plan for each occurrence of the flight. In both cases, the IFPS distributes the FPL to the concerned ATS units.

The different ATS Units to which the IFPS/FPLs have been distributed then process them using their Flight Data Processing Systems (FDPS). Internally within a given FDPS, a System Flight Plan (SFPL) is maintained. Thus normally ATS units will base trajectory prediction on the data contained in the IFPS/FPL.

These processes are summarised in Figure 1.

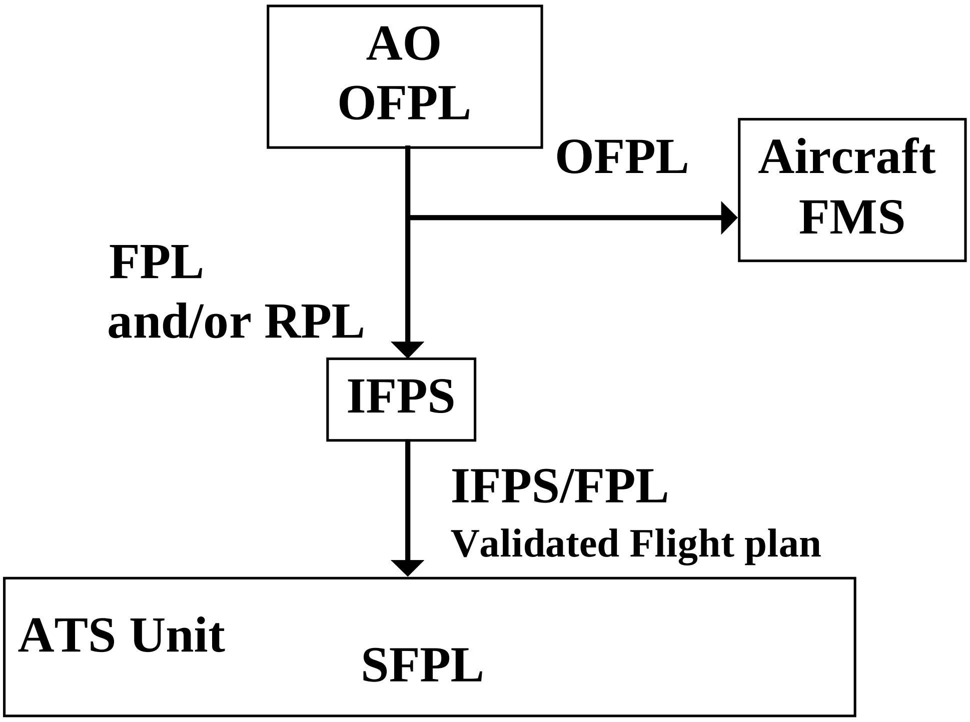

Figure 1: The Distribution of Flight Plan Information from AO to ATS in the ECAC Area.

5. TRAJECTORY PREDICTION IN FDPS

5.1 INTRODUCTION

This chapter gives a short description of trajectory prediction and its purposes. The objective of this section is not to specify trajectory prediction: for more information on the subject the reader should refer to [EURO TP].

5.2 DEFINITION OF TRAJECTORY PREDICTION

"A trajectory is a representation of the path of an aircraft, describing the horizontal and vertical profile over time". (ref. [EURO TP])

Within the FDPS, a flight plan trajectory is computed containing the path followed by the aircraft (in 3 dimensions - latitude, longitude and level) and a time estimation for each significant point. The term 4-dimensional trajectory is derived from consideration of these four dimensions of Longitude, Latitude, Level and Time.

Note that the trajectory produced by the process of trajectory prediction in the FDPS is identified by the abbreviation FDPS/T for the purposes of this document. The term 4-dimensional trajectory is derived from consideration of these four dimensions of Longitude, Latitude, Level and Time.

"Trajectory prediction is the process by which the predicted trajectory is determined." (ref. [EURO TP])

It should be noted that the trajectory prediction function described here is relevant to a General Air Traffic (GAT) flight operating in accordance with Instrument Flight Rules from take-off until landing for the purpose of support of Air Traffic Management (ATM) services.

5.3 PURPOSE OF TRAJECTORY PREDICTION IN FDPS

The SFPL and more specifically the trajectory (FDPS/T) is used by FDPS functions such as:

- determining the entry and exit points of airspace volumes such as sectors or areas of responsibility of other units,
- providing Medium term Conflict Detection (MTCD) and Conflict Probing,

– triggering various events during the life of a flight plan life, and
– informing the relevant controllers of the flight's intentions.

Trajectory prediction is, therefore, one of the main processes performed by Flight Data Processing Systems.

5.3.1 Airspace Volumes Crossed by the Flight

The different controlled areas crossed by the flight are determined by the analysis of the flight plan trajectory. This information is to send flight information to the relevant controllers and to trigger events such as the sending of co-ordination messages between ATSUs.

5.3.2 Medium Term Conflict Detection and Conflict Probing

Medium Term Conflict Detection and Conflict Probe processing are used in advanced systems to determine potential conflicts. The controller is warned of potential conflicts and can modify the flight trajectory in advance to reduce the risk of conflict.

5.3.3 Flight Plan Event Management

Flight plan status management consists of allocating a status to a flight according to its progress. Two different points of view can be taken: that of the overall flight or just the FDPS.

From the global point of view the flight plan life starts when the flight plan is created by the company a long time before the departure date or time. Its life finishes when the flight has been completed, the flight plan has been updated after the flight and details have been archived. This point of view is used for the flow control.

From the FDPS point of view the life of a flight plan life starts when the flight is about to enter the area of interest and more particularly in the first sector having the control of the flight. It finishes when the flight leaves the area of interest.

For both points of view, the flight plan trajectory is used to trigger the distribution of flight information and the provision of it to other functions such as correlation.

5.3.4 Information About the Flight's Intentions

Flight intentions can be shown to the controller using various graphical techniques. For example, warnings can be provided to allow him to check that the flight follows its correct path.

5.4 CONCLUSION

Trajectory prediction and hence the trajectory (FDPS/T**)** is central to the correct operation of ATC systems. It impacts on all the major aspects of the FDPS and, therefore, it is very important to have the trajectory calculated as accurately as possible.

Poor accuracy of the trajectory leads to greater uncertainty in the position of aircraft, which in turn wastes capacity by demanding larger aircraft separation and increased operator work load. [DERA TP errors]

6. SHORTCOMINGS IN CURRENTLY AVAILABLE DATA

6.1 INTRODUCTION

The objective of this section is to identify the shortcomings in the data currently available for trajectory prediction within FDPS.

Initially an assessment of the data required for good trajectory prediction was made by means of trajectory prediction simulations. Then a comparison was made with the data generally available to ATS for trajectory prediction. This allowed identification of the data which would be required to improve trajectory prediction in the FDPS.

This chapter is, therefore, structured as follows:

- With the support of simulations using the BADA trajectory predictor tool, the data needed for trajectory prediction are identified (section 6.2).
- The shortcomings in the different data items identified in section 6.2 for trajectory prediction are then assessed by considering the contribution that each makes to trajectory prediction This allows identification of the current shortcomings in the data available for trajectory prediction in section 6.3.

6.2 DATA USED FOR TRAJECTORY PREDICTION

6.2.1 Introduction

Many different trajectory prediction algorithms exist in the different FDPS used in ECAC states. They vary in complexity, but a number of different inputs can be identified as potential inputs to trajectory prediction. It should be noted that many current trajectory predictors are rudimentary and use only a bare minimum of the following parameters.

The parameters that can be identified are as follows:

- flight plan route
- airspace description
- aircraft characteristics
- environmental parameters (wind, temperature...)
- operating procedures

This section describes these parameters in more detail.

6.2.2 Flight plan route

The flight plan route segment within the Area of Responsibility of the FDPS is required. Only the major waypoints and the RFL are provided in the ICAO flight plan message.

An example of an ICAO Flight Plan message is supplied in Appendix I.

6.2.3 Airspace description

An airspace description is required to carry out trajectory prediction, including details of waypoints, airways, NAVAIDS, SIDs, STARs and ATC constraints.

6.2.4 Aircraft characteristics

The specific airframe and flight's characteristics are required in order to make an accurate trajectory prediction. The key characteristics are the aircraft type, its engine type, engine degradation and weight. Aircraft performance can be derived from manufacturers programs using these characteristics.

6.2.4.1 Aircraft type

Climb performance varies widely for the range of aircraft an ATC system can expect to handle. In general terms the time and distance from runway to FL300 ranges from 10-25 minutes and from 60-140 nautical miles, respectively.

The aircraft type is filed in the flight plan. It consists (currently) of a 4 character text field containing a recognised set of identifiers (ref. [ICAO A/C TYPE]).

6.2.4.2 Engine type

Manufacturers can supply more than one engine type for an aircraft and several versions for each engine type, each with different power ratings. Thus even if the aircraft type is known exactly the power rating of the individual aircraft may still vary.

6.2.4.3 Engine Performance Degradation

Engine performance degrades with time, resulting in a requirement for the pilot to use more fuel to achieve a given level of thrust. This degradation depends on each individual airframe.

6.2.4.4 Weight

Performance models are of limited use in the determination of the climb trajectory unless the take-off weight is available. This is essentially the sum of the weights of the airframe, fuel, passengers and freight.

The fuel loaded is at the discretion of the pilot and is a function of the route, altitude, temperature and many other factors. In some cases additional fuel is be uplifted at cheaper locations for economic advantage. Hence the actual take-off weight is difficult to predict accurately.

Fuel will be burnt during the phase from engine start-up to take-off. However, this is a relatively small amount and will be ignored for the purposes of this study.

6.2.5 Environmental Parameters

Several environmental parameters will affect the calculated trajectory and hence should be inputs to flight plan trajectory prediction. These are described below:

6.2.5.1 Temperature Profile

The thrust from gas turbine engines varies with the air temperature. Most modern jet engines have a “flat” region where performance does not change greatly with temperature; outside this region thrust decreases with increasing temperature. This characteristic leads to a distinct non-linear behaviour of the climb performance as a function of ambient temperature.

The temperature profile should therefore be taken into account in determining the trajectory.

6.2.5.2 Wind Profile

The wind profile is the direction and speed of the wind at a given level range for a given point or area. It is common for the volumes of airspace used for temperature profiles to be the same as those used for wind profiles. Winds have a large effect on the trajectories flown by aircraft and are therefore important when making trajectory prediction.

6.2.5.3 Atmospheric Pressure

The atmospheric pressure converted to mean sea level (QNH) affects the geometric altitudes of flight levels, the spread of pressures between 947Mb and 1047Mb representing 3000 ft.

For an accurate calculation of top of climb, trajectory prediction must take into account the QNH.

6.2.6 Operating Procedures

Each company has a set of operating procedures for each aircraft type it operates and which should be followed by the pilot. Typically these are based on the manufacturer’s procedures but with local variations. A knowledge of them is necessary for making good trajectory predictions.

6.2.6.1 Speed law

The most economic profile requires optimised climb at a specific speed to the optimum initial cruise altitude, followed by an optimum speed-altitude schedule to the proper descent point and then an optimum descent path at the appropriate speeds.

6.2.6.2 Timing of manoeuvres

The timing of manoeuvres, that is to say the time at which a climb is initiated can have an impact on the flight trajectory. For example, the pilot can decide to climb as soon as possible to reduce the fuel consumption or at a later stage according to other constraints.

6.2.6.3 Acceleration with a remaining rate of climb

The most economic procedure for the acceleration phase from initial climb speed to en-route climb speed is to accelerate horizontally. However, pilots accelerate whilst in climb, and this practice must be considered when making trajectory predictions.

6.2.6.4 Reduced thrust take-off

Most airlines now operate reduced thrust take-off when conditions allow in order to reduce wear on the engines by burning slightly more fuel. Reduced wear reduces service costs on the engines and thus saves the airline money.

The degree of reduction also varies according to the topographical environment at an airport.

6.2.6.5 Cruising speed

Operators define different operating policies for aircraft cruising speeds.

6.2.6.6 Other parameters

The airbleed for air-conditioning has an influence on the thrust and hence on the fuel consumption, as noted in [A/C PERF].

6.3 SHORTCOMINGS IN DATA AVAILABLE FOR TRAJECTORY PREDICTION

6.3.1 Introduction

Not all the data listed in the section 6.2 are significant for a high quality trajectory computation. It is necessary to identify which data it is most important to obtain.

In order to achieve this, the data identified in section 6.2 has been analysed by carrying out simulations using the EEC BADA trajectory prediction model.

This analysis has enabled identification of the data that could be obtained from AO or other sources in order to produce more accurate predictions. This section describes the results of this analysis.

The objective of the study is focused primarily on 3D trajectory prediction (i.e., position and height) and it does not address the precision of the take-off time. However, it should be noted that the high level of uncertainty in the estimated time of take-off available to ATC pre-flight makes it difficult to use trajectory predictors for tools such as Medium Term Conflict Detection.

6.3.2 Flight Plan Route

The planned route of flight is contained in the ICAO flight plan (ref. Appendix I) which, inter alia, provides the airport of departure (ADEP), route of flight, airport of destination (ADES), the true airspeed and RFL (and any planned changes of cruising level).

Also, individual ATC centres often make local adjustments to flight (e.g. by issuing an instruction for a flight to route direct to another point) which may invalidate some or the waypoints on the flight plan route. Such local adjustments are made at the ATC centre level and so it should be the responsibility of the controller to update the flight plan information accordingly in their own FDPS (although this facility is not always available).

It has been shown that often pilots do not respect the waypoints declared in the flight plan [SOFT].

However, for the purposes of this analysis it will be assumed that the appropriate updates are made locally to the flight plan by each FDPS, and the limited number of points and flight levels provided in the ICAO plan will not be considered as a shortcoming.

6.3.3 Airspace Description

This information is based on the Aeronautical Information Publication (AIP) of the country concerned. These publications do not currently have a standard layout and are not provided on a magnetic media.

Apart from the potential for introducing errors, the need for IFPS, ATS and AOs to maintain their own separate databases can lead to discrepancies in items such as sector boundaries and the identifiers of waypoints.

Inconsistencies between databases and erroneous manual inputs may lead to incorrect trajectories being determined from flight plans.

The existence of incompatible environmental data may lead to problems of consistency. However, work is in currently progress in EUROCONTROL to develop the European AIS Database (EAD) which will ensure the consistency of data. Hence this will not be considered as a shortcoming in the data available for trajectory prediction.

6.3.4 Aircraft Characteristics

This section reviews the aircraft characteristics required to make an accurate flight plan trajectory prediction.

6.3.4.1 Aircraft Type

The ICAO aircraft type is provided in the ICAO flight plan. However, the level of definition is coarse since often there is no distinction between the aircraft sub-model (ref. [ICAO A/C TYPE]). The following table gives examples of different aircraft having same type designation.

Aircraft Type Designation	Comment
ATR	No distinction between ATR42 and ATR72
B73B	No distinction between B737-300, 400 and 500
DHC8	No distinction between Dash 8 and Dash 8 - 300

Table 1: Examples of low resolution aircraft type designators

Difficulties arise because the aircraft performances used for trajectory prediction in a FDPS are usually based on tabular information relevant to an aircraft type. Due to a lack of precise data, sub-types of aircraft will be assumed to have the same performance characteristics such as minimum and maximum speed, maximum level speed, climb rate, descent rate, climb speed, and descent speed.

These considerations lead to the conclusion that the existing coarse definition of the aircraft type is a shortcoming in the data required for trajectory prediction.

6.3.4.2 Weight

6.3.4.2.1 Introduction

In this paragraph, the effect of the weight on the trajectory prediction is analysed.

Often FDPS trajectory predictors assume typical take-off weights for the aircraft class and the actual airframe, passenger, freight and fuel weights of each flight are not taken into account.

To analyse the impact of this, two different approaches have been followed:

- What difference in weight can be considered as significant, and hence is it important if standard weight is used?
- What is the error introduced in the climbing profile when a standard weight is taken instead of the real take-off weight?

In both cases, simulations were carried out using the BADA database.

6.3.4.2.2 Difference in weight considered as significant

In this case, the longitudinal distance along the track between TOC has been employed as a criterion. Two thresholds have been considered, 5 NM and 10

NM. That is to say, a difference in weight of otherwise identical flights that leads to a longitudinal separation at the Tops Of Climb which is greater than these thresholds will be considered as significant. The TOC used was the estimated commercial cruise level, that is to say FL390 for an EA32 (Airbus A320) and a B767, FL 250 for an ATR42 and FL380 for a B747.

Tables 2 and 3 were produced using the BADA model (ref. Appendix B) . The significant weight values at which the longitudinal distance thresholds are exceeded are indicated in tonnes and as a percentage of the weight.

Table 2: Difference in aircraft weight significant with a threshold of 5 NM

Aircraft	Aircraft Weight in tonnes	FL	Weight Increment Producing 5nm Difference in TOC (in tonnes)	Weight Increment Producing 5nm Difference in TOC (As a Percentage of Aircraft Weight)
ATR42	15	250	0.45	3.0%
EA32	62	390	0.84	1.35%
B767	150	390	2.1	1.4%
B747	280	380	2.8	1.0%

Table 3: Difference in aircraft weight significant with a threshold of 10 NM

Aircraft	Aircraft Weight in tonnes	FL	Weight Increment Producing 10nm Difference in TOC (in tonnes)	Weight Increment Producing 10nm Difference in TOC (As a Percentage of Aircraft Weight)
ATR42	15	250	0.83	5.5%
EA32	62	390	1.55	2.5%
B767	150	390	3.6	2.4%
B747	280	380	4.9	1.75%

These tables indicate that relatively small percentages in error in the aircraft weight will lead to significant differences in the longitudinal distance along track which a trajectory predictor will determine.

Hence, these simulations show that the aircraft weight (i.e. take-off weight) is required for an accurate trajectory prediction.

6.3.4.2.3 Error in the climbing profile when the standard weight is taken instead of the real take-off weight

This second analysis sought to determine the impact of errors in the take-off weight on the time and distance required to reach TOC. Again this analysis was carried out using BADA. A number of runs were made for different types in which the profiles calculated with a standard take-off weight was compared with those calculated using the maximum and minimum take-off-weight.(ref. Appendix B).

The simulation results in Table 4 show that there are very large differences in the time and distance required to reach TOC for all aircraft types. Hence a standardised take-off weight cannot be taken as a good reference for the trajectory prediction.

Table 4: Difference in climbing profiles with a standardised, maximum and minimum take-off weight

Aircraft	TOC FL	Max. TOW	Min TOW	Standard TOW	Difference	Difference	Difference
					Max - Std	Std - Min	Max - Min
ATR42	250	16.7 t	10.29 t	15 t	23 NM 6 min.	37 NM 11 min	60 NM 17 min
EA32	300	73.5 t	41.8 t	62 t	30 NM 4 min	36 NM 5.5 min	66 NM 9.5 min
B747	300	380 t	173 t	280 t	110 NM 16.5 min	46 NM 6.5 min	156 NM* 23 min*
B767	350	181.4 t	90 t	150 t	52 NM 7.5 min	52 NM 8 min	104 NM 15.5 min

*Note that the equivalent figure for the B747 in Appendix B.4 was determined using a maximum weight of 360t, not 380t, hence the discrepancy with the column ’Max-Min’.

6.3.4.3 Conclusion

The analysis above demonstrates the importance of having an accurate estimation of the take-off weight. However, information such as the weight of freight, passengers and fuel are only known accurately by the AO at the later stages of flight planning. A final take-off weight is known from the load and balance stage just prior to take-off.

Currently, none of this information is available to ATC.

Therefore the lack of an accurate take-off weight is a shortcoming for accurate trajectory prediction by FDPS.

6.3.4.4 Engine Type

Different engine types may be fitted to the same aircraft type, resulting in different thrusts for different airframes. For example, a comparison of trajectory predictions using data supplied by an AO for a B767/200 with GE CF6-80A2 engines and the same type with GE CF6-80C2B4F indicates that they expect a difference at TOC of about 5 minutes and 23 nautical miles for the same take-off weights (TOW) of 158.1 Tonnes [B767 PROF].

Hence for accurate trajectory prediction the engine type needs to be known by the FDPS.

6.3.4.5 Engine performance degradation

Engine performance degradation impacts on the fuel consumption and reduces thrust.

The typical value for engine performance degradation reported by a range of airlines is between 2% and 6% measured in terms of increased fuel. However, the DC10 was identified by an AO as an exception to this rule. For DC10 engine performance degradation can reach 15%.

Higher fuel consumption results in the aircraft weight falling more quickly than might otherwise be expected during the flight. To assess the impact of this, predictions have been made of climb and descent profiles late in a flight. It should be noted, however, that a significant climb late in a flight is unlikely.

The results of the simulations carried out are included in Appendix C. They demonstrate that engine performance degradation does not significantly impact climb or descent profiles.

6.3.5 Environmental Parameters

Environmental parameters are required to make an accurate flight plan trajectory prediction and hence are significant for accurate trajectory prediction.

6.3.5.1 Temperature Profile

Simulations performed with BADA show that the temperature variation significantly affects the climb phase, as shown in Appendix G. While temperature forecasts are potentially available for trajectory prediction by FDPS, they are not generally used at present, so this is identified as a shortcoming.

6.3.5.2 Wind Profile

The wind profile affects the aircraft ground speed and hence the time needed to reach a waypoint. Simulations demonstrating this are contained in Appendix F. Modern systems already use forecast wind data.

6.3.5.3 Atmospheric Pressure

The atmospheric pressure is already available at each airport and hence unavailability of this data is not identified as a shortcoming.

6.3.5.4 Aerodrome Elevation

The aerodrome elevation impacts on the time to reach a given altitude or flight level, and is used on-board to adjust the take-off thrust. The elevation of the departure aerodrome is known accurately and thus can be included in the trajectory prediction mechanism. The information is readily available so it is not identified as a shortcoming.

6.3.6 Airline Operating Procedures

Different company operating procedures may result in the actual trajectory flown being different from the standard manufacturers procedures. In addition, it seems that pilots do not always follow the company procedures [CENA TP EVA].

To demonstrate the impact of operating procedures on the aircraft trajectory simulations have been performed to show the effect of differences in climb speed (ref. Appendix D). These show that the climb speed is an important parameter for the trajectory prediction.

Examples of the impact of company operating procedures and deviations from them by pilots are:

- Speed law: on occasions company operating procedures can lead to the 250 knots speed limit imposed by many states below 10000 ft being exceeded, as has been demonstrated in research [CENA TP EVA].

- Timing of manoeuvres: the timing of manoeuvres can lead to differences in the time at which the cleared flight level is reached and differences in along-track distance if appropriate compensation is not made by the pilot. This was addressed in [RSRE TP]. It assesses that there will be a small difference in along-track distance of 2.45nm for two identical aircraft executing identical climbs (from 1000ft at 344 kts to 26000ft at 491kts) starting one minute apart.
- Reduced Thrust Take-Off: A typical reduction of thrust on take-off is 20% and will typically increase the climb to TOC by 0.15 min and 0.5nm. The BADA model has been improved to take into account reduction of take-off thrust according to the difference between the TOW and the maximum TOW, and this improvement was validated by a group of French controllers during a simulation at the EUROCONTROL Experimental Centre (Paris-TMA Real Time Simulation).
- Transition Altitude to Climb Thrust. The trajectory would be affected by a late transition from take off to climb thrust. Normally this takes place at about 1500 ft. Simulations using BADA show that the effect of the selection of climb thrust at 2500 ft compared with 1500 ft for a B737 (with JT8D-9 engines) is to increase the time to reach FL240 by 4.2 seconds and to increase the along-track distance by 0.89nm.

This analysis demonstrates that allowance for company operating procedures and deviations from them made by pilots has a minor impact on trajectory prediction.

6.3.7 Differences in trajectories obtained using data currently available and data potentially supplied by Aircraft Operators

Research comparing radar tracks, FPLs and OFPLs has been made [EEC SOFT]. Using this research a set of climb profiles was compared with the BADA predictions. It was observed that BADA climb profiles sometimes make the aircraft appear to climb steeper than it does in reality.

It was concluded that the operating procedures and individual pilot actions have a real impact on the climbing profile and they need to be known in order to improve trajectory predictions.

6.3.8 Conclusion

This chapter has reviewed the data required for trajectory prediction and the data currently available to FDPS for this function. Using simulations, a lack of information concerning the following parameters has been identified as a shortcoming for trajectory prediction:

- full aircraft type specification, including engine type
- take-off weight,
- company operating procedures, and deviations made by pilots

7. DATA AVAILABLE FROM AIRCRAFT OPERATORS ON GROUND

7.1 INTRODUCTION

In order to find what data could be available from aircraft operators (AOs) and flight plan providers to help improve trajectory prediction, a sample of AOs was interviewed.

This chapter describes the data that was found potentially to be available from AOs to meet the shortcomings identified earlier for trajectory prediction:

- trajectory information
- aircraft characteristics, including full aircraft type specification with engine type and take-off weight
- company operating procedures, and deviations made by pilots

The following AOs and flight plan providers were interviewed:

- Air Liberté,
- Air France,
- Air Foyle,
- AOM,
- Britannia Airways,
- British Airways,
- Easyjet,
- Lufthansa,
- Magec,
- Monarch Airways,
- Olympic Airways,
- SITA,
- Virgin Atlantic

7.2 TRAJECTORY PROVISION

7.2.1 Introduction

AOs establish their flight trajectories based on their desired operating schedule and taking into account factors such as cost and anticipated congestion. In order to support this task, many AOs use flight planning tools to prepare the flight's trajectory. The output from this flight planning process is normally used as the briefing package for the pilot.

For the purposes of this document, the output of the AO's flight planning process will be called the Operational Flight Plan (OFPL).

7.2.2 OFPL Preparation and Use

7.2.2.1 Introduction

The OFPL is used by the AO before the take-off and by the pilot when preparing for and during the flight. Some companies also compare it and actual flight data after the flight for analysis purposes.

It is normally prepared several hours before the flight. Limitations on this concern the availability of meteorological forecasts (temperature and wind) used in the planning and up-to-date information concerning the actual airframe used for the flight.

7.2.2.2 OFPL Preparation

Many airlines use sophisticated tools to prepare their OFPLs. Some AOs have their own flight planning system. Others use an existing product such as AirData while others outsource the flight planning to a provider such as SITA or Jeppesen. Lastly, some smaller AOs operating business jets prefer to manually prepare their flight plans.

Typically the following information is provided to computerised flight planning systems by AOs to generate OFPLs:

- Full aircraft type with engine characteristics
- Operating procedures, such as climb speed, cruise speed and descent speed
- Constraints. For example, the AO may place a priority on minimising fuel consumption or the duration of the flight

- Flight and airframe details, such as the Empty Fuel Weight (EFW) and engine performance degradation
- Number of passengers or estimated passenger weight, and estimated freight weight
- Airport of Departure (ADEP) and destination airport (ADES), and Alternate
- Estimated time of departure (ETD), to allow the meteorological forecast to be applied

The OFPL may be revised in the period leading up to the departure of the aircraft in order to allow for factors such as passenger connection, aircraft rotation and other operational considerations, and to secure an improved flow management slot.

7.2.2.3 Use of the OFPL

The OFPL is used by to produce the FPL submitted to ATS. It is normally sent to the IFPS 3-4 hours before the flight is due to depart.

Pilots use the OFPL before take-off in order to prepare for the flight. They may modify the information in the plan by, for example, modifying the amount of fuel to be loaded.

During the flight the pilot uses the OFPL to set the parameters of the on-board equipment, particularly the FMS. Frequently-used routes are often already entered in the FMS route database, allowing the pilot to select the required route.

The crew will manually update the OFPL on board to record flight progress and use it as a basis for their flight report. This includes information such as flight levels, estimates and the remaining fuel.

7.2.3 OFPL Accuracy

In general, the OFPL does not provide a highly accurate trajectory prediction. The factors affecting the accuracy of the OFPL are described in this section.

7.2.3.1 SID/STAR

At the time of OFPL preparation the AO cannot be certain which runway will be used for take-off or for landing. Hence the specific SID or the STAR to be used cannot be identified during flight planning by the AO.

For the AO’s purposes, a rough idea of the SID length from the airfield to the exit point is sufficient to make a reasonable assumption of the required fuel and the flight duration.

Typical approaches that are followed are either to assume the lengths of the most commonly-used SID and STAR or to use the longest of the published SIDs and STARs for the airports concerned.

The accuracy of the first and last segments of the trajectory described in the OFPL are therefore not adequate for FDPS trajectory prediction requirements.

7.2.3.2 TOC/TOD

Due to the approach described above for including the SID and STAR, the Top Of Climb and Top Of Descent cannot be accurately determined in the OFPL. Also, some tools used to build the OFPL only allow one TOC and/or one TOD. In such cases the TOC found for a step climb or the TOD found for a step descent may be incorrect.

7.2.3.3 Changing Flight Level

The OFPL does not normally indicate when the climb or descent will occur but only the flight level at the next waypoint.

7.2.3.4 Flight Path

The ground speed used to calculate waypoint timings given in the OFPL will be calculated from company operating procedures and some allowance may be made for forecast meteorological conditions. This will give a result which is more detailed than is provided in the FPL but it will still contain errors due to, for example, the choice of SID and STAR and ATC constraints.

7.3 AIRCRAFT CHARACTERISTICS

7.3.1 Full Aircraft Type

The full aircraft type is one of the key input parameters to the OFPL.

7.3.2 Engine Type and Characteristics

The engine type is available to the AOs but it is not explicitly contained in the OFPL.

7.3.3 Take-Off Weight

7.3.3.1 Introduction

The weight of an aircraft can be considered in terms of the following:

- Empty operating weight,
- Zero fuel weight,
- Fuel weight.

The weight and balance service assesses the actual weight just before departure.

7.3.3.2 Empty operating weight

An aircraft is weighed periodically (every 2 or 3 years) as it can change with time due, for example, to fitting of new equipment. Some AOs also track the weight of their aircraft while others increase the empty weight of aircraft by a specific percentage per year.

7.3.3.3 Zero fuel weight

The passenger and the freight weight are usually known to within a few percent the day before the departure, although the error is higher for scheduled than for charter services since there is less predictability over the seat occupancy.

The zero-fuel weight assessment is based on the number of passengers that have booked and the freight that is expected to be carried. Generally a simple estimate is made and systems do not attempt to predict the likely range of error in the value.

The pilot will adjust the zero fuel weight before the take-off according to the latest information collected from the weight and balance service.

7.3.3.4 Fuel weight

The weight of fuel planned to be loaded into the aircraft is made up of several components:

- Estimated fuel which will be burnt during the flight, the amount being evaluated by the flight planning system (if available).
- Fuel reserves,
- Taxi fuel requirements.

Uncertainty always arises in the pre-flight estimate made by the AO from the pilot's freedom to take on such extra fuel as he sees necessary in the light of the expected flight conditions.

7.3.3.5 Weight and balance

The weight and balance calculation is performed just before the departure in order to deliver to the pilot an accurate aircraft weight for the trim to be used. Some AOs use a specific tool to perform their weight and balance (e.g., Gaetan for Air France or DCS (Departure Control System) for British Airways and Olympic Airways).

The rule normally applied by the AOs is that the OFPL should be re-computed if the weight difference is greater than 5 tonnes, but whether this can be done depends on the availability of automated links to the AO flight planning systems. Otherwise a correction is manually analysed by the pilot before the departure to adjust the amount of fuel to be loaded and to insert the correct figures in the aircraft equipment (e.g., FMS).

Since only a few AOs currently receive the weight and balance reports near take-off, they cannot currently be considered as a good source of accurate take-off weights for use in trajectory prediction. However, this situation is likely to improve in the future as better communications facilities are introduced.

7.3.3.6 Conclusion

The OFPL is established about 4 or 5 hours before the estimated time of departure with an accurate airframe weight and an estimation of the weight of passengers and freight. The exact weight is only known after completion of the load sheet by the weight and balance service. Significant differences can exist between the weight assessed 5 hours before departure and the weight given by the weight and balance service.

7.4 OPERATING PROCEDURES

The AOs interviewed stated that that they are generally willing to make company operating procedures available to ATS for the purposes of improved trajectory prediction. However, availability of such data would not overcome errors caused by pilots deviating from procedures as may well happen under the pressure of operations.

Reduced thrust setting for take-off is practised by all AOs when possible and is based on pilot experience of the specific airfield and on information provided on tables published in the operating manual. However, the manuals do not give the corresponding thrust settings. A typical value of 20% of reduction of the thrust has been given by many AOs but it cannot be a generalised to all take-offs. The information is, therefore, considered to not be generally available.

7.5 CONCLUSION

The OFPL is produced by AO before the flight and can be considered to be available from AO.

The data used by the AO when preparing the OFPL includes most of the important aircraft characteristics needed for an improved trajectory prediction by the FDPS.

The principal exception is the take-off weight. The weight known at the time of flight plan preparation is based on assumptions made by the company and does not generally take into account updates shortly before the take-off, although this may improve in the future. An accurate assessment of the weight is performed by the weight and balance service but the information cannot be considered to be available at present from AOs since it is only infrequently fed back into flight planning systems.

Some operating procedures could be supplied for FDPS trajectory predictors by AOs. However, certain others depend on flight-specific circumstances and cannot be considered as available from AOs. Also, since operating procedures are not generally followed exactly by the pilot, some errors will remain.

In conclusion, the data available on ground from AOs could at least partially overcome the shortcomings identified in section 6 and help to support improved trajectory prediction. However, there remain several inaccuracies inherent in the data which could be supplied and which would affect the quality of such predictions.

8. DATA AVAILABLE FROM ON-BOARD AIRCRAFT

8.1 INTRODUCTION

This chapter describes the future availability of trajectory prediction data which could be down-linked from aircraft to ATS both while taxiing and when airborne.

The current shortcomings identified in section 6 are used to identify the data items that should be sought. That is, the chapter addresses separately the trajectory, aircraft characteristics and operating procedures.

8.2 TRAJECTORY

8.2.1 Introduction

The ICAO Future Air Navigation System (FANS) Standards And Recommended Practices (SARPS) for Communications, Navigation, Surveillance, and Air Traffic Management (CNS/ATM) are currently evolving and will continue to evolve over the coming years. Hence what is presented here is an assessment of CNS/ATM-related function development based on current projections.

This section initially describes the type of Flight Management Computer System (FMCS) which is expected to be available in the future and contrasts it with what is available now or in the immediate future. It then goes on to consider some of the accuracy issues concerning down-link of trajectory data for trajectory prediction purposes.

8.2.2 Future Flight Management Computer Systems (FMCS)

8.2.2.1 Future FMCS Capability

For the purposes of this document it will be assumed that a majority of aircraft will in the future be equipped with a FMCS along the lines described in [ARINC FMCS]. Current Flight Management Systems (FMS) are less capable. In particular they are not normally linked into datalink systems. Also, there is a wide variation in levels of capability of different FMS, reflecting the length of equipment lifecycles.

Following [ARINC FMCS], it can be anticipated that in the future FMCS will provide the following functions:

- navigation, providing continuous updates
- flight planning, including the sequence of waypoints, airways, flight levels, departure procedures, and arrival procedures to fly from the origin to the destination, and/or alternates. Manual input and up-link via air-ground data-link are foreseen
- lateral and vertical guidance, including speed control during all phases of flight
- trajectory prediction, predicting distance, time, speed, altitude, and gross weight at each future waypoint in the flight plan, including computed waypoints such as TOC and TOD
- performance calculation, to optimise vertical and speed profiles to minimise the cost of the flight or meet some other operating criterion, subject to a variety of constraints
- air-ground data link interfaces, with two-way data communication provided to the airline operations facility and to ATS
- pilot interfaces.

For further details, refer to [ARINC FMCS].

8.2.2.2 FMCS Trajectory Computation

The future FMCS on-board systems will compute the complete aircraft trajectory along the specified lateral routing.

The trajectory will be continuous from the origin airport (or current position if en-route) to the destination airport. It will be updated on a periodic basis, or whenever a flight plan or performance change is made.

The calculation will attempt to comply with the altitude constraints, speed restrictions and specified gradient constraints input to the system. If this is not possible due to aircraft performance or conflicting constraints, appropriate advisories will be provided to inform the crew of the specific problem.

All trajectories will take into account factors such as the aircraft performance, selected speed schedules and speed transitions, environmental considerations, intended control mode and other selections by the crew such as reduced thrust operation.

8.2.3 FMS Trajectory Calculation Accuracy

Trajectory planning is normally described in terms of meeting constraints at waypoints, rather than following particular intra-waypoint trajectories. Hence the behaviour between waypoints is unpredictable. Also, in typical current systems the number of waypoints the system calculates forward is limited to just eight.

When new instructions are given at short notice, crews usually implement them as manual corrections and hence they may not be fed across into the system. In these circumstances, the FMC is not coupled and the predicted trajectory will be inaccurate.

Other errors arise from navigational positioning errors, barometric and altitude control error.

The accuracy of navigation of the trajectory computed on-board is currently being assessed by work such as the Height Monitoring Units. These use differential GPS information to track the aircraft altitude and compare it to the on-board computed altitude.

8.2.4 Conclusion

The trajectory available on-board takes into account the specific aircraft characteristics and the OFPL developed by the AO. The model used is detailed and can be considered to be very accurate. However, some limitations are identifiable, particularly in circumstances when the FMS is de-coupled.

The trajectory available on board details how the pilot intends to fly, including pilot-selected options. However, down-link of the predicted trajectory by the aircraft to FDPS is currently not feasible given datalink capabilities, but this may be possible in the longer term.

8.3 AIRCRAFT CHARACTERISTICS

The detailed aircraft characteristics are available on board since they are included in the performance database used by the FMS. The exact weight of the aircraft is entered by the pilot just before take-off with the latest information following load and balance calculations.

In the future datalink applications such as the Downlink of Aircraft Parameters (DAP) will make available information such as the weight, full aircraft and engine type from the FMS.

8.4 OPERATING PROCEDURES

Company operating procedures are effectively available on-board an aircraft since they are input into the FMC by the crew. For example, the selection of performance mode permits the CAS and the thrust reduction to be set.

As a result, while they may not be available explicitly as parameters to down-link for input into the FDPS, the operating procedures are integrated into the trajectory of the aircraft calculated and flown by the FMS. Thus when down-link of trajectories becomes feasible, operating procedures will effectively be taken into account.

8.5 CONCLUSION

The information required for accurate trajectory prediction will be available on-board when the aircraft is equipped with a FMCS such as that described in [ARINC FMCS]. If augmented by the capability to down-link trajectories, this would permit integration of on-board trajectories with FDPS. However, the current situation is far from this and it will be 2015+ before all aircraft are comprehensively equipped to this level of technology.

However, the current and near-term FMS and datalink equipment could potentially provide useful data to ground-based FDPS trajectory predictors. In particular, short-term technical developments ought to make it possible to down-link key aircraft parameters (such as the weight) and even the next few way points to the ground. As discussed in section 6, such information could significantly improve the quality of current day ground-based trajectory prediction.

9. INFRASTRUCTURE CONSIDERATION

9.1 INTRODUCTION

The previous chapters have presented the current shortcomings in the data available to ATS to carry out trajectory prediction, and the data which could be available from AOs on ground and from on-board to improve trajectory prediction.

The objective of this chapter is to review the infrastructure which might be available to distribute the available information to ATS, either from AOs or aircraft.

Thus the infrastructure requirements are assessed on two axes:

- Ground/ground communication, principally for AO to ATS data exchange
- Air/ground communication, for aircraft to ATS data exchange

9.2 GROUND/GROUND COMMUNICATIONS NETWORKS

9.2.1 Introduction

For ground to ground data exchange, the networks identifiable for aeronautical telecommunications are:

- AFTN
- SITA
- ATN (in the future)

9.2.2 AFTN

The AFTN provides a world-wide capability to exchange ICAO-format flight plan data.

The network is long-established and was developed in the early days of the aviation industry on the basis of using teletype terminals. As a result, it is widely available, even at the smallest airports and aviation facilities.

However, the data communication rate is relatively slow and is based on a limited character set. In particular [FEATS] noted that the existing low speed

AFTN system in some parts of the ECAC region is not capable of supporting the efficient exchange of data required in the present ATS system. In Europe the AFTN is being upgraded by the implementation of CIDIN procedures, but as an alternative means of overcoming these problems, for inter-centre communication some states have found it necessary to use WANs.

Considering the requirements of this study, AFTN provides good connectivity between ACCs and other ATSU, but not between AOs and ACCs.

9.2.3 SITA

SITA provides a global network for data communications with many different levels of access which can be tailored to the specific nature of the data communications that the user requires. For example, direct access to Frame Relay services are available for large volume data exchange while cheaper indirect access to the SITA network via a third party public data network is more appropriate for a low volume user.

All the AOs interviewed in the study use the SITA network to exchange information with the CFMU and with other AOs. However, few ACCs are connected to SITA (Maastricht is an exception). Hence direct connectivity between ACCs and AOs is not generally feasible.

The cost of usage depends very much on the options chosen with fixed rate and load-sensitive rates being available. As an example, for a direct X.25 connection using leased lines and a speed up to 19.2 Kbp/s, SITA quotes a fixed monthly fee of between $900 and $1600 depending on the connection details.

9.2.4 ATN (Ground Part)

The ATN is planned for future development and will comprise applications and communication services which allow ground, air-ground and avionics sub-networks to inter-operate by adopting common interface services and protocols based on the ISO OSI reference model.

The ground parts of the ATN are a potential medium for exchange of data between AO and ATS for improvement of FDPS trajectory prediction, although at this stage it is difficult to identify what proportion of the organisations will actually be connected.

The ground part of the ATN will consist of:

- host computers e.g. ATC systems
- ground sub-networks e.g. LANs and WANs
- ATN routers

- mobile sub-networks
- ATN management systems

The ground sub-network technology is currently evolving. The ATN architecture will allow the integration of different types of (ground) sub-networks, so it is not necessary to make assumptions concerning the type of ground sub-networks that will be used.

Existing national WANs, once interconnected, will probably provide a backbone for the ground part of the European ATN.

9.3 AIR/GROUND COMMUNICATIONS

9.3.1 Introduction

This section describes options for air/ground data exchange in support of distributing on-board data for improved trajectory prediction.

At present, the only widespread air-ground datalink available operationally is ACARS.

A number of experiments are going on to investigate the use of mobile data communications, especially using satellite and VHF datalinks. These are being conducted in a realistic trials ATN environment, and can be expected to pave the way for a deployment of a wide range of packages of applications for data exchange in the longer term.

9.3.2 ACARS

ACARS is a general-purpose air/ground network used by airlines for a wide range of operational purposes including:

- out-off-on-in times which are transmitted automatically when the aircraft goes off-block, at take-off, landing and back in-block
- fuel status
- dispatch updates and flight status
- engineering and maintenance items

Message exchanges for ATC purposes are currently being evaluated using the ACARS network including Pre-Departure Clearances and Automatic Terminal Information Service.

The communications media used for the air-ground segment are satcom or VHF, and these feed into the relevant ground-ground network (SITA for Europe, ARINC for USA) for transmission to or from the airline operations centre or ATC as appropriate.

ACARS is being progressively fitted to the fleets of all larger aircraft operators, but as yet few smaller operators are connected.

Typical communications fees for aircraft-AOC data exchange are $2.6 per kilobit of data with a sliding scale dependent on volume usage. Individual messages are limited in length to 220 text characters, although multi-block messages can be build by sending several smaller messages which are recompiled at the destination. The data rate employed is 2.4 kb/s. Measured transit delay is minimum 3 seconds and average 5 seconds [EURO A/G], but total transfer time under SITA responsibility is evaluated at 12 seconds for 94% of the messages [EURO ACARS].

9.3.3 Planned Datalink Applications

A wide range of air-ground datalink applications have been proposed to support ATS and work is going on to agree international standards for these applications. In due course, these applications will be included in the framework of ATN applications packages (see section 9.3.4).

An inventory of these proposed applications is contained in [EURO A/G], but some examples of these which potentially relate to the current study are:

- Pre Departure Clearance (PDC),
- Automatic Dependent Surveillance (ADS),
- Air Ground Automatic Data Exchanges (AGADE), formerly Downlink of Aircraft Parameters (DAP)
- 4D Trajectory Negotiation (4DTN),
- Flight Plan Conformance (PLN).

9.3.3.1 Pre Departure Clearance (PDC)

When local procedures or the flight category require so, aircraft intending to depart from an airport must first obtain departure clearance from the responsible ATS Unit. The process can only be accomplished if the flight operator has filed a flight plan with the appropriate ATM authority.

The departure clearance will contain information relative to the take-off phase of flight (e.g. take-off runway and Standard Instrument Departure (SID), SSR Code, departure slot, next contact frequency).

In addition, the departure clearance request could be extended to include information on the departing aircraft which would support trajectory prediction by FDPS, such as precise details of the aircraft type and the final take-off weight as supplied by the weight and balance service.

9.3.3.2 Automatic Dependent Surveillance (ADS)

ADS provides for the transmission of flight data from the aircraft FMS to the ground surveillance unit, either periodically or on demand. The information passed is the aircraft state vector.

The data received on the ground are intended as an input for the surveillance data processing system, and could be used to enhance trajectory prediction.

9.3.3.3 Downlink of Aircraft Parameters (DAP)

The DAP or AGADE application provides a mechanism for the aircraft to supply on-board information from its navigation and flight management systems to the ground. It will also allow the ground system to up-link information for the airborne system.

The DAP application could be used to supply information such as aircraft weight and could therefore assist trajectory prediction by FDPS.

9.3.3.4 4D Trajectory Negotiation (4DTN)

4D trajectory negotiation is designed to support the full-scale dialogue between the pilot and the controller to negotiate an optimised trajectory. The dialogue would be initiated with a trajectory proposal coming from the aircraft or from the control centre. The trajectory negotiation would take place periodically as required by changing constraints imposed on the flight (weather, medium term traffic pattern, airspace congestion, etc.).

This application will require a very high datalink performance in terms of data integrity and availability. If it were available on all aircraft, it could be seen as a way to replace trajectory prediction by FDPS. However, it is not likely to be available until late in the EATMS timetable.

9.3.3.5 Flight Plan Conformance (PLN)

This application is proposed to support an air/ground dialogue to :

- compare the flight plan registered in the FMS on one side and in the ground FDPS on the other side.
- inform the controller (pilot) of airborne (ground) recorded flight plan data

– deal with inconsistencies according to the controller decisions
– update the flight plans in order to ensure conformance.

The dialogue could take place during different phases of the flight, for example, pre-flight complementing the departure clearance application. This application would help to ensure the accuracy of FDPS trajectory prediction.

9.3.4 ATN (Airborne Part)

Operational use of the first air/ground ATN application, DAP, is foreseen in early 2000.

The airborne part of the ATN will consist of:

– mobile ATN routers
– mobile ATN end systems
– mobile sub-networks

The degree of implementation of airborne ATN systems will determine the extent to which use can be made of the ATN and the corresponding ATC system implementation made by the different administrations in each country. In general, ATN-capable aircraft will support different applications packages, which will themselves be designed to allow an evolutionary implementation.

Examples of the applications that will make up the packages have been described above in 9.3.3.

The choice of mobile sub-network to use will in most cases be predefined and area related, and determined by airline policy and states regulations. Examples of mobile sub-networks that will be available are Satcom, Mode-S and VHF.

Performance of air/ground datalink applications operating under the ATN should be at least as good as the current day performance of ACARS with increasing demand being matched by corresponding improvements in infrastructure. Hence the majority of messages should be delivered within 20 seconds [EURO APPRQTS] .

9.4 CONCLUSION

AFTN and SITA networks provide existing ground-to-ground communications facilities. The former provides more complete connectivity between AO and ATS, but is generally already overloaded and less capable of supporting the requirements.

The ATN will provide further ground-to-ground inter-connectivity with access to integrated ATC-specific applications.

For on-board to ground links many aircraft are already ACARS-equipped (VHF and Satcom), and experiments are going on to use ACARS as a means of implementing ATC applications. These applications, particularly PDC could provide a short-term solution to passing on-board data to ATC for use in trajectory prediction.

In the longer term, further development of air-ground datalink application for ATC will enable exchange of a wider range of data, leading eventually to trajectories being down-linked. The ATN will integrate all these applications in a clear framework of sub-networks.

Thus there already exist some means of delivering both AO and on-board data to ATS for the purposes of improving trajectory prediction, and this capability can be expected to improve in the future [EURO APPRQTS].

10. POSSIBLE SOLUTIONS

10.1 INTRODUCTION

The objective of this study is to determine whether it is possible to obtain better information for trajectory prediction in FDPS from AOs and aircraft, with a particular focus on improving prediction in the early stages of flight. This places a premium on having the required information distributed in a timely way.

The study has demonstrated that such information is available from both AOs and the aircraft. The possible improvements in accuracy have been shown by the simulations performed during the study (see chapter 6 and Appendices B, C, D, E, F, G and H). Furthermore, investigations of the infrastructure requirements have shown that for air-ground datalink, delay times on the order of 10-20 seconds are feasible. Ground-ground links will provide equivalent or better service.

The data which it would be useful to have from AO are principally the OFPL, detailed aircraft type and engine fit, and an estimate of the take-off weight. Datalink may in the future make take-off weights determined by the weight and balance service available to AOs shortly before takeoff and these could be forwarded to ATS. In addition, it may also be useful to have information on company operating procedures although this is more difficult to incorporate into FDPS trajectory predictors.

Detailed trajectory information and parameter settings could be available from on-board if the aircraft were equipped with FMCS such as are described in [ARINC FMCS] and with widescale implementation of datalink. The current situation is far from this well developed since, for example, current FMS do not output the complete trajectories. However, the aircraft could provide data such as accurate take-off weight to help FDPS trajectory prediction through, for example, the PDC or DAP applications.

Essentially then, useful data is available a few hours before the take-off information from AOs. For more accurate information it is then necessary to wait until shortly before the take-off or early in the flight to obtain this information from on-board.

Clearly, however, availability of all these data will not overcome the effect of pilot action intervening during the flight, particularly as this such interventions may not even be entered in the FMS. This remains a large area of uncertainty in obtaining improved trajectory predictions.

Three possible approaches to obtaining the information are now discussed, as follows:

- solutions based on using only the information available from AOs on ground.
- solutions based on using only the available information from on-board the aircraft.
- solutions based on a mixed solution, collecting information both from ground and on-board.

10.2 GROUND TO GROUND DATA EXCHANGE

10.2.1 Introduction

In this approach, improvement to FDPS trajectory prediction is based on the distribution of information by ground-based flight planning systems of AOs to ATS.

10.2.2 Data for Distribution to ATS

The following parameters have been identified as shortcomings for trajectory prediction in chapter 6:

- Full Aircraft type,
- Engine type,
- Weight,
- Airline Operating Procedures.

The full aircraft type and the engine type are airframe specific and are considered to be available to an AO as soon as the OFPL is developed. However, there will always be the risk that for operational reasons (e.g. maintenance, delays) the airframe allocated to a flight may be changed just before departure.

An estimated take-off weight will also be available at the time of OFPL preparation. However, this is subject to significant errors which mean that it is not necessarily much more useful than using a standard weight for the type.

The full aircraft and engine types could be collected by ATS when the OFPL is available at the AO (usually between 4 and 5 hours before the take-off time) and then updated just before the take-off if needed to reflect a change of airframe.

Similarly, the estimated take-off weight could be distributed with the OFPL and updated if more up-to-date information became available prior to take-off from the aircraft handler.

Operating procedures are standardised long in advance of a flight and change infrequently. Hence these could be collected off-line through a process administered by an organisation such as EUROCONTROL. However, there will always remain an element of uncertainty because the procedures are not always fully complied with by pilots.

10.2.3 Ground-Ground Data Distribution

Regarding distribution of this data, several options exist, including:

- the ICAO FPL could be extended with the required data being added in specific new fields and the data forwarded to ATS by IFPS
- a specific new message containing the required data could be distributed directly to ATS by AOs.

The advantage of the first solution is that the infrastructure for distributing FPLs by AOs already exists. The main problem concerns the timeliness of updates, since FPLs are normally filed several hours before the time of flight so it would be difficult to take account of updates.

The second solution would offer a means of avoiding the problems of timeliness, but would introduce requirements to prepare and distribute new messages. Of particular importance, it would be necessary to improve existing links between AOs and ATS to ensure direct communication (e.g. to ensure full connectivity of AOs and ATSUs via SITA).

10.2.4 Conclusion

Ground-ground distribution of the data required for improved trajectory prediction from AO would be a feasible solution subject to enhancement of connectivity between AO and ATS. However, the data may not be up to date and this could lead to errors.

10.3 ON BOARD TO GROUND DATA EXCHANGE

10.3.1 Introduction

This solution is based on collecting information from on-board aircraft and sending it to the ATSU concerned for improved trajectory prediction.

10.3.2 Data for Distribution to ATS

In the future it may be feasible to downlink full trajectory information, reducing the requirement for trajectory prediction by the FDPS. This will require the aircraft are equipped with FMCS such as those described in [ARINC FMCS]. However, the current situation is far from this, and hence it is necessary to consider if a reduced information set could be provided.

It was identified in chapter 6 that the availability of the following data would help to improve FDPS trajectory prediction:

- Full Aircraft type and Engine type,
- Weight,
- Airline Operating Procedures.

The full aircraft and engine type, and the exact take-off weight could be available from on-board once the aircraft datalink equipment is switched on and the FMS settings input. Therefore this information is considered to be available on-board shortly before take-off and could be sent to ATSU for ground-based trajectory prediction by the PDC or DAP datalink applications.

Operating procedures are essentially incorporated into the intended trajectory and would only be available through downlink of the trajectory itself.

It may also be useful to collect information on the intended trajectory during the flight to help take into consideration changes in the crew's intentions compared with the trajectory planned by the trajectory predictor in the FDPS. Datalink applications such as PLN or 4DTN would make this possible, although these are clearly long term solutions.

10.3.3 Air-Ground Data Distribution

Air-ground datalink is currently in the process of early implementation, leading eventually to the development of the ATN. At present ACARS exists as a working example, and trials are in progress using it to implement some ATC applications such as PDC. These basic datalink applications provide a feasible short-term solution for passing the data identified as needed in this study.

Based on experience of ACARS communications delays do not appear to be a significant problem in making such data available to ATSU.

The costs for the solutions will not principally be the data communications costs for the transfer, but will more be the new infrastructure.

Security of the data links is also an important consideration since AOs may regard down-linked data to be commercially sensitive. ACARS, for example, is not secure and it is possible potentially for transmissions to be monitored (although they can do this at the present time).

10.3.4 Conclusion

The benefit of using downlink to obtain data for trajectory prediction is principally that a more accurate estimate of take-off weight would be available directly from the aircraft compared to using the OFPL estimate made by the AO. Information on company operating procedures would not be available.

The collection of the intentions of the aircraft during the flight would be an additional benefit, though coming at an increased cost in communications and infrastructure.

This approach would not provide a means of delivering the necessary information to FDPS for those aircraft that are not datalink equipped.

10.4 ONBOARD AND GROUND TO GROUND DATA DISTRIBUTION

Both solutions of supplying data needed for improved trajectory prediction purely from AO or from the aircraft are imperfect. Instead, a better solution could be developed by combining both sources. Thus there could be a distribution of preliminary information from AO ground-based flight planning systems a few hours before the flight supplemented by distribution from on-board systems of datalink-equipped aircraft shortly before take-off.

AOs could supply basic data with aircraft type and engine fit, and estimated take-off weight a few hours before the take-off time. This could probably most conveniently be done via an enhanced ICAO FPL. IFPS would distribute the FPLs to the concerned FDPS. The FDPS would now have basic data for improved trajectory prediction, but would have to act in the knowledge that this might be incorrect due to operational changes by the AO.

Near the take-off time the aircraft would downlink updated data to ATS with the full aircraft type, the engine fit and the exact take-off weight. This could be a part of the PDC for the first FDPS concerned, and the DAP application for later FDPS.

Details of operating procedures would have to be supplied off-line by the AO to ATS through an administrative process.

11. CONCLUSION

EUROCONTROL, in co-operation with Member States is in the process of developing the principles and requirements for the trajectory prediction function for European Air Traffic Control Harmonisation and Integration Programme (EATCHIP) Phase III Flight Data Processing Systems (FDPS).

The data currently available for trajectory prediction by FDPS is not sufficient to produce good results, particularly in the climb and descent phases. This study has used simulation to identify a number of data items which are of key importance for improvement of trajectory prediction by FDPS:

- full aircraft type and engine type
- take-off weight

In addition, details of company operating procedures would help to improve trajectory prediction.

However, the study has also noted that one of the key areas of uncertainty in trajectory prediction is the effect of pilot intervention during the flight, particularly where this is not input into the FMS. This factor will continue to be a significant problem even if better data is available for input to trajectory prediction.

The study has involved consultation with aircraft operators and trajectory planning service providers in order to determine the data which could be available from them to improve the performance of trajectory prediction by future FDPS.

A considerable amount of data is potentially available from the AOs operations centres four to five hours before the flight departs. This data is used in the preparation of the flight briefing packages for the pilots. Its accuracy increases as the take-off time approaches. Key parameters, particularly the take-off weight, are not known until the pilot signs off the load sheet at the very last stages before take-off and normally these are not available to the AO until several tens of minutes after the flight departs.

Much improved data is available from the flight plan produced by the FMS, but this is only available on-board and shortly before take-off. At present, except for a few isolated and limited cases, there is little or no feedback from this aircraft data to the AO.

The conclusion from this analysis is that AO data detailing aircraft type, engine fit and estimated take-off weight sent to FDPS at the time of FPL filing would certainly help to improve trajectory prediction even if, as is the case of take-off weight, the figure available is only an approximate one. These data could be provided to ATC at a relatively low cost through existing communications infrastructure.

Currently the feasibility of downloading the better data available in the FMS for all aircraft appears to be lower. The small proportion of aircraft equipped with data link militates against this approach. However, in the longer term this type of full exchange will be achievable with corresponding improvement in FDPS trajectory prediction capability.

In the shorter term the work on the integration of Pre Departure Clearance (PDC) application with ACARS would be a satisfactory solution for development of a basic infrastructure to deliver accurate last minute data to ATS from the aircraft with updates to take-off weight and any changes in the airframe being used for a flight.

Thus, the recommended shorter-term solution is to use the existing ground based flight plan submission mechanisms combined with an ACARS-based solution. The required airframe details would first be supplied to FDPS in FPLs from AOs, and later supplemented close to the take-off time with downlinked updated data.

12. RECOMMENDATIONS

The following recommendations are made as a result of this study:

1. Arrangements for the provision of OFPLs, full aircraft type, engine fit and approximate take-off weights by AOs should be established on an experimental basis and trials carried out to evaluate the data provided

2. An impact assessment of the provision of these data on the wide range of different trajectory predictors found in ATS systems should be made

3. An impact assessment on AO-ATS communications of these changes should be assessed to determine the costs and feasibility of full scale implementation. Of particular concern to evaluate are additional costs to aircraft operators.

4. Further investigations should be made of the practicalities of delivering updates of airframe and take-off weight data via the PDC and DAP datalink applications. This should involve experiments and trials.

5. Close attention should be paid to developments in air-ground datalink applications, particularly the on-going implementation of ATN. Regard should be paid to ensuring that provision is made for downlink of the required data.

6. Trials should be carried out to obtain operating procedures from a variety of aircraft operators to evaluate their use in trajectory prediction.

7. Continuing research should be made into methods for dealing with trajectory prediction problems arising from pilot intervention in flight. This effect remains a very significant source of error for trajectory prediction.

APPENDIX A - BADA PRESENTATION

APPENDIX A .1 GENERAL

BADA (Base of Aircraft Data) is an aircraft performance database. It provides a set of ASCII files containing performance and operating procedure data for 69 different aircraft types developed using reference sources such as Flight Manuals, Operating Manuals etc. These are the so-called directly supported aircraft. For 96 other types, the data is specified to be the same as one of the 69 directly supported aircraft.

The main application for BADA is trajectory simulation and prediction within the domain of ATM (Air Traffic Management). BADA is being maintained and developed by the EUROCONTROL Experimental Centre (EEC) in Brétigny, France.

Three different files are available for each directly supported aircraft in BADA:

- OPF file: This file holds all the thrust, drag and fuel coefficients to be used in the Total Energy Model (TEM) together with information on weights, speeds, maximum altitude etc.
- APF file: This file holds the operational climb, cruise and descent speeds used by the aircraft according to its Flight Manual.
- PTF file: This file presents the nominal performance of the aircraft model in the form of a look-up table. It gives the user direct access to average performance data without the necessity to implement the complete TEM.

APPENDIX A .2 THE AIRCRAFT MODEL BEHIND BADA

The model that is used is a so-called Total Energy Model or TEM. It can be considered as being a reduced point-mass model. TEM equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy. The Operations Performance Model of BADA defines, besides TEM: the aircraft type, mass, flight envelope, aerodynamics, engine thrust and fuel consumption. The Airline Procedure Model defines the speeds that are to be used during the climb, cruise and descent flight phases.

For the models that are available in BADA, the current release of BADA (revision 2.6) covers the aircraft types used for nearly 90 % of European air traffic.

APPENDIX A .3 DESCRIPTION OF THE MODELS USED FOR THE SIMULATIONS IN THIS STUDY.

The models used for the simulation performed in this study are detailed in the following table.

Each code used the table gives:

- type,
- engine,
- company.

The different models are based upon references given by a specific company, by example the EA32 is based on the A320-111 of Air France.

Code	Type	Engine	Company
AT42	ATR42-200	PW120	TAT
EA32	A320-111	CFM56-5-A1	Air France
B737	B737-228	JT8D-15A	Air France
B747	B747-228	CF6-50E2	Air France
B757	B757-200	RB211-535C	(Boeing)
B767	B767-300ER	PW4060	Aeromaritime
B73S	B737-300	CFM56-3-B1	SEA
B73V	B737-500	CFM56-3-C1	EAS
MD80	MD83	JT8-219	(McDonnell Douglas)
FK100	FK100	Tay-650	TAT
FK70	FK70	Tay-620	(Fokker)
DC10	DC10-30	CF6-50C2	Atlas

Figure 1 : Description of the models used in the simulations

APPENDIX B - EFFECT OF TAKE-OFF WEIGHT

APPENDIX B .1 INTRODUCTION

This appendix examines the effect of inaccuracies in the weight assumed for the aircraft on trajectory prediction. Two approaches are followed.

The first approach is to compare the BADA profiles with profiles calculated using a typical TOW and maximum and minimum TOWs for a given aircraft. The profiles are compared in distance and in time.

The second approach is to identify the difference in weight considered to be significant using the longitudinal distance along-track between TOCs for different take-off weights as a criterion. Two different thresholds are considered 5NM and 10 NM.

The simulations were carried out using BADA data. BADA uses the manufacturers' programs as references to evaluate flight profile, and in the graphs the curve tagged "reference" is extracted from manufacturers' program while the other curve is the extrapolation carried out by BADA.

The following set of aircraft is used for the analysis:

- ATR42,
- EA32,
- B747,
- B767.

APPENDIX B .2 ATR42

This section contains results of simulations of the ATR42, based on the following data:

Maximum Take-off weight = 16.7 t

Minimum Take-off weight = 10.29 t

Typical Take-off Weight = 15 t

Speed 160 knots, 0.45 Mach

Appendix B .2 .1 Difference between Typical and Maximum TOW

Figure 2 shows that the difference in along-track distance for an ATR42 is about 24nm at FL250 for profiles with a typical and a maximum TOW, while Figure 3 shows that the difference in time to reach this point is about 6 min.

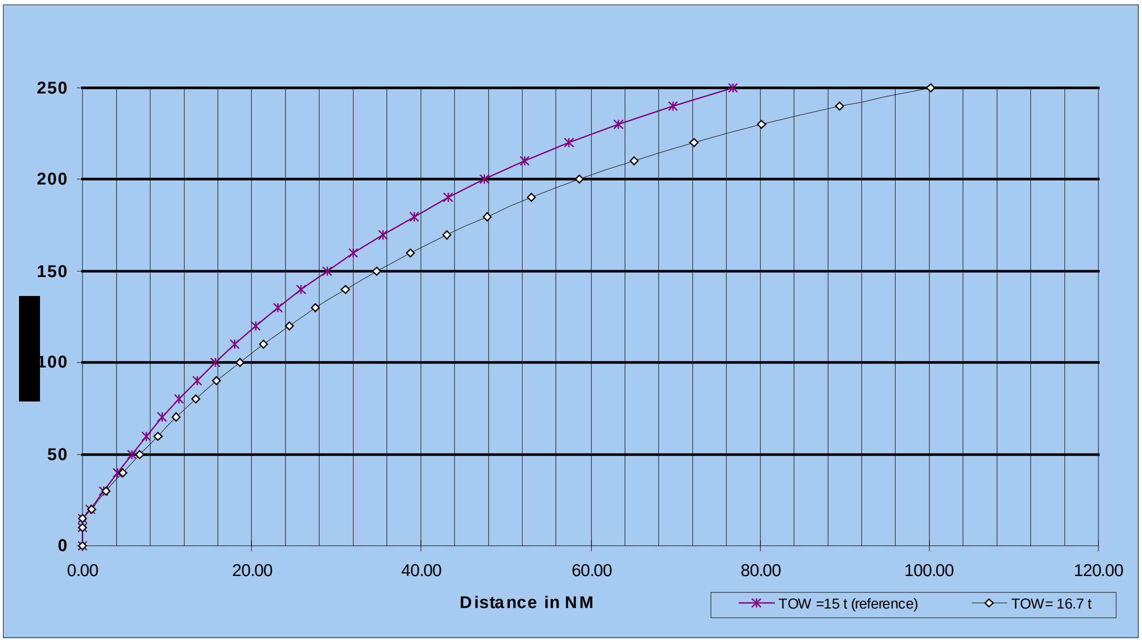

Figure 2: Difference in distance for a climb profile between typical TOW of an ATR42 (15 t) and the maximum TOW (16.7 t)

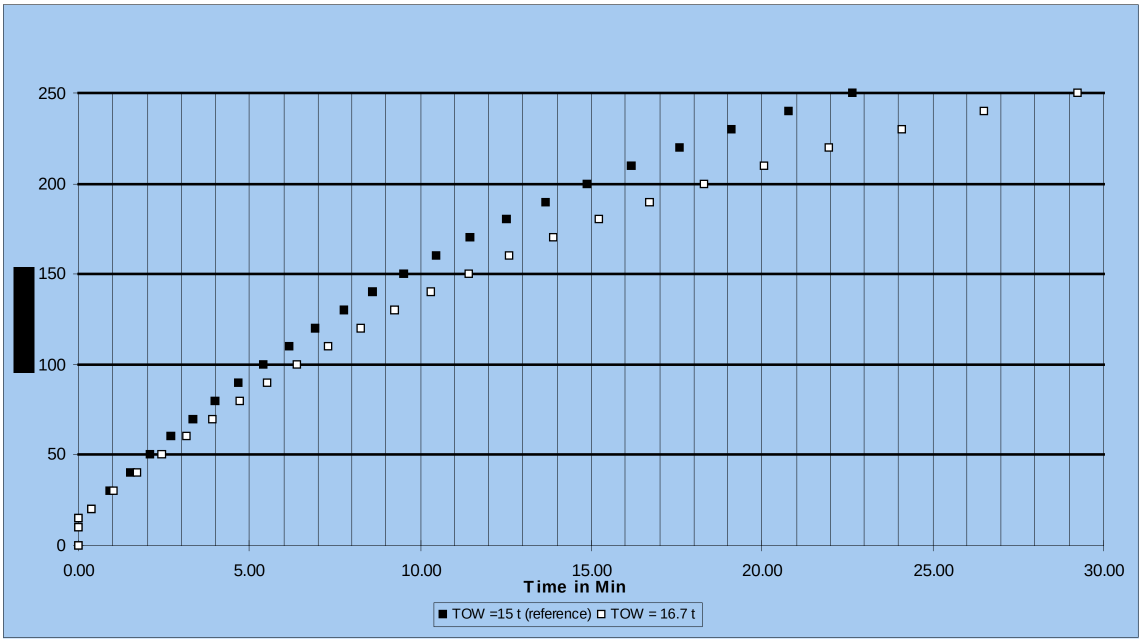

Figure 3: Difference in time for a climb profile between typical TOW of an ATR42 (15 t) and the maximum TOW (16.7 t)

Appendix B .2 .2 Difference between Typical and Minimum TOW

Figure 4 shows that the difference in along-track distance for an ATR42 is about 36nm at FL250 for profiles with a typical and a minimum TOW, while Figure 5 shows that the difference in time to reach this point is about 10 min.

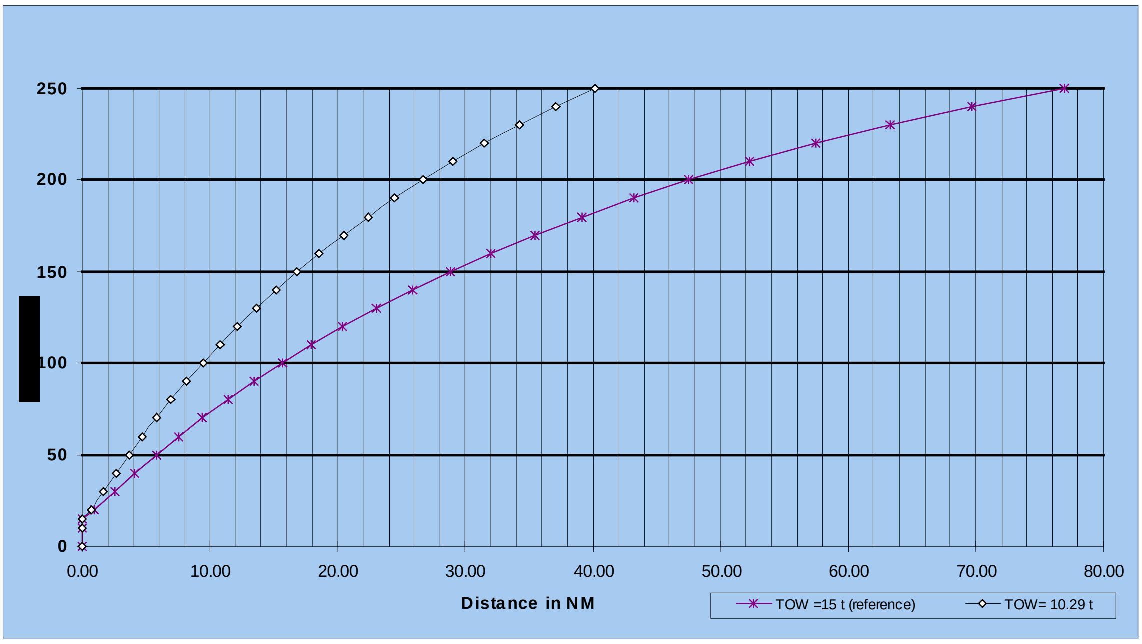

Figure 4: Difference in distance for a climb profile between typical TOW of an ATR42 (15 t) and the minimum TOW (10.29 t)

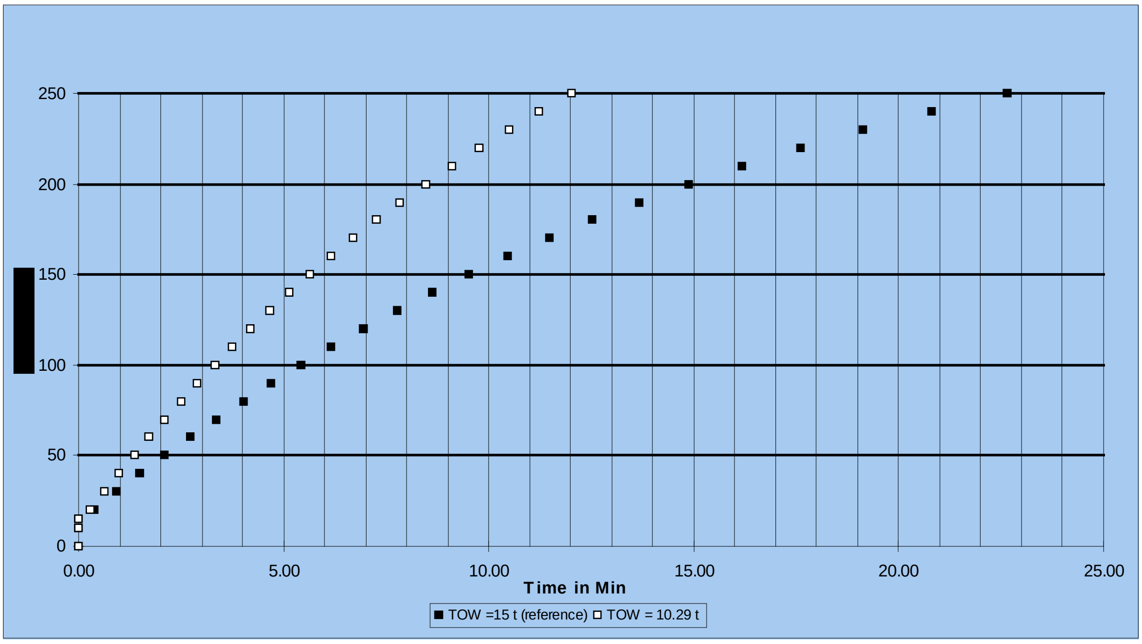

Figure 5: Difference in time for a climb profile between typical TOW of an ATR42 (15 t) and the minimum TOW (10.29 t)

Appendix B .2 .3 Difference between Max and Min TOWs

Figure 6 shows a difference in along-track distance for an ATR42 of about 60nm at FL250 for profiles with minimum and maximum TOWs, while Figure 7 shows that the differences in time to reach this point is about 17 min.

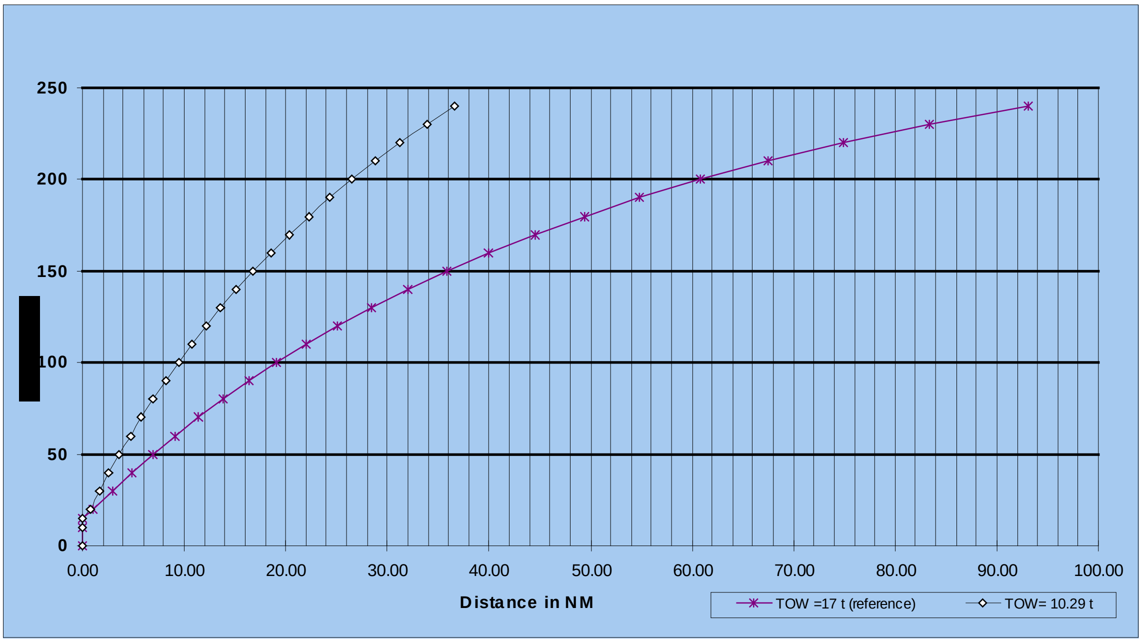

Figure 6: Difference in distance for a climb profile between maximum TOW of an ATR42 (17 t) and the minimum TOW (10.29 t)

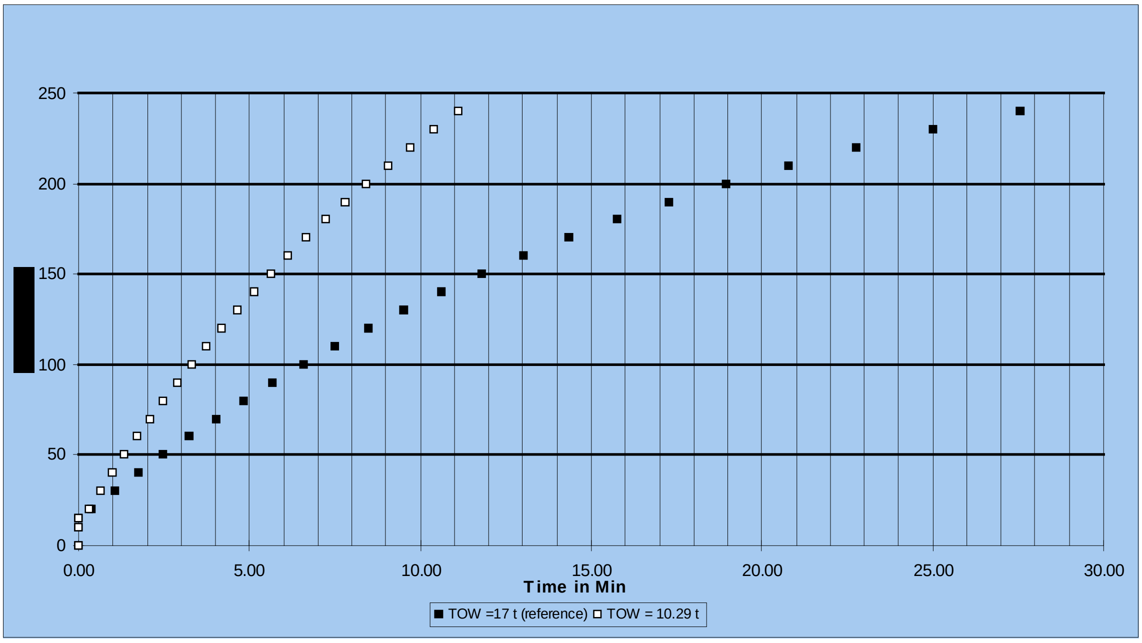

Figure 7: Difference in time for a climb profile between maximum TOW of an ATR42 (17 t) and the minimum TOW (10.29 t)

Appendix B .2 .4 Significant weight difference for a ATR42

Figures 9 and 10 show that an error in TOW of about 5% is significant

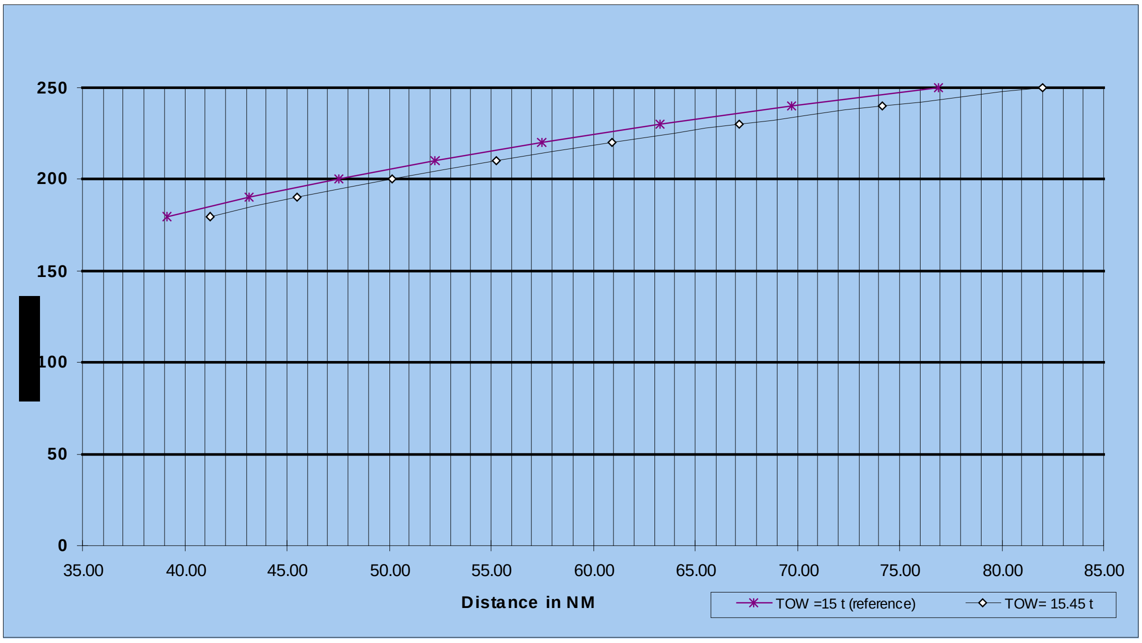

Figure 8: Significant Weight difference for a threshold of 5 NM - profile from FL 180 to FL 250.

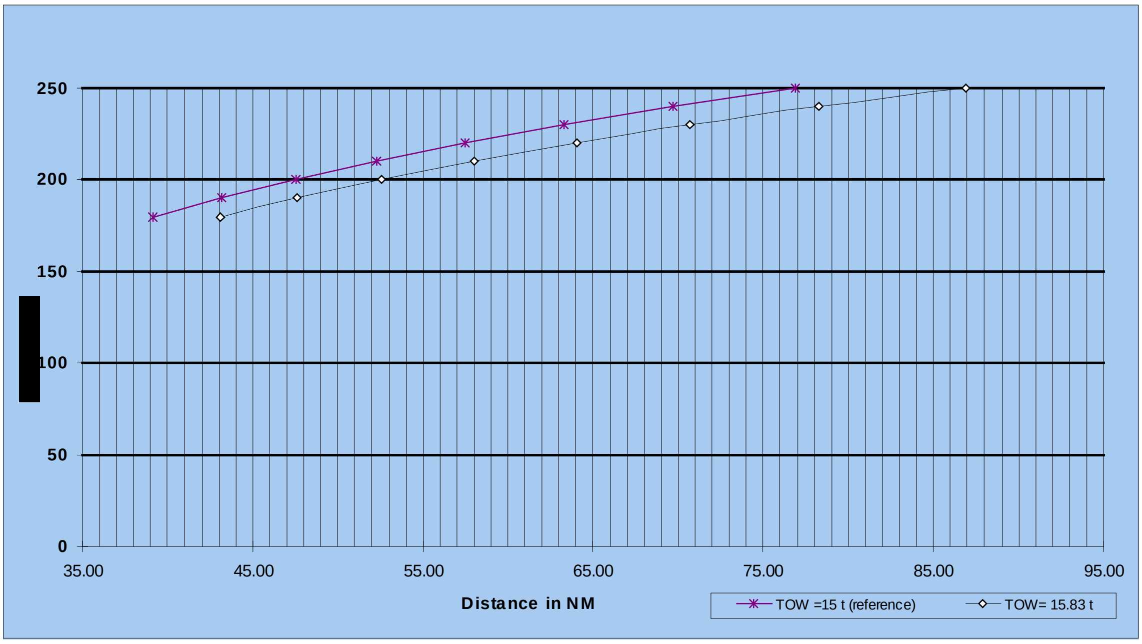

Figure 9: Significant Weight difference for a threshold of 10 NM - profile from FL 180 to FL 250.

APPENDIX B .3 EA32

Maximum weight = 73.5 t

Minimum weight = 41.8 t

Typical Take-off Weight = 62 t

Speed 300 knots, 0.78 Mach

Appendix B .3 .1 Difference between Typical TOW and Maximum TOW

Figure 10 shows that for an A320 a difference between typical and maximum TOW introduces a difference of 30nm in reaching at FL300, while Figure 11 shows that this corresponds to 4 minutes.

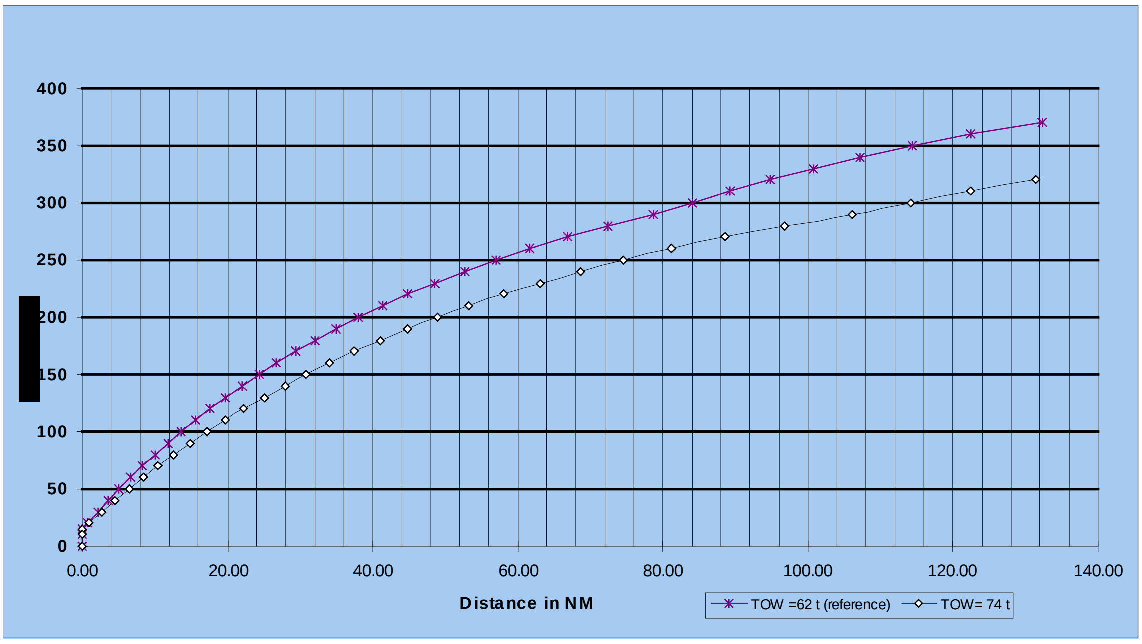

Figure 10: Difference in distance for a climb profile between typical TOW of an EA32 (62 t) and the maximum TOW (74 t)

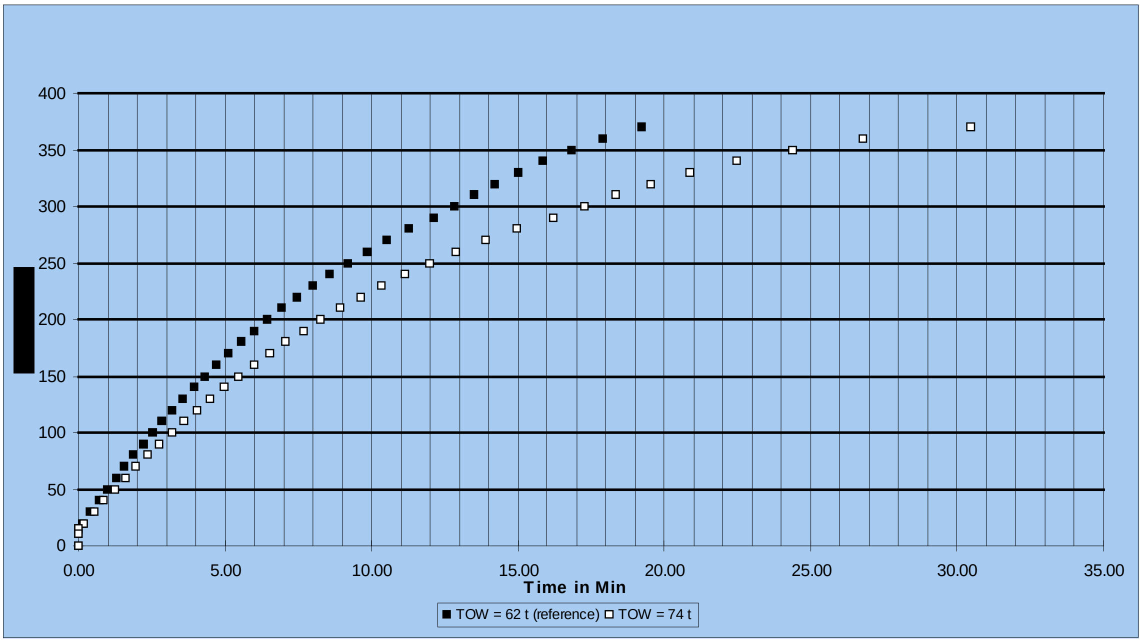

Figure 11: Difference in time for a climb profile between typical TOW of an EA32 (62 t) and the maximum TOW (74 t)

Appendix B .3 .2 Difference between Typical TOW and Minimum TOW

Figure 12 shows that for an A320 a difference between typical and minimum TOW introduces a difference of 36nm in reaching at FL300, while Figure 13 shows that this corresponds to 5.5 minutes.

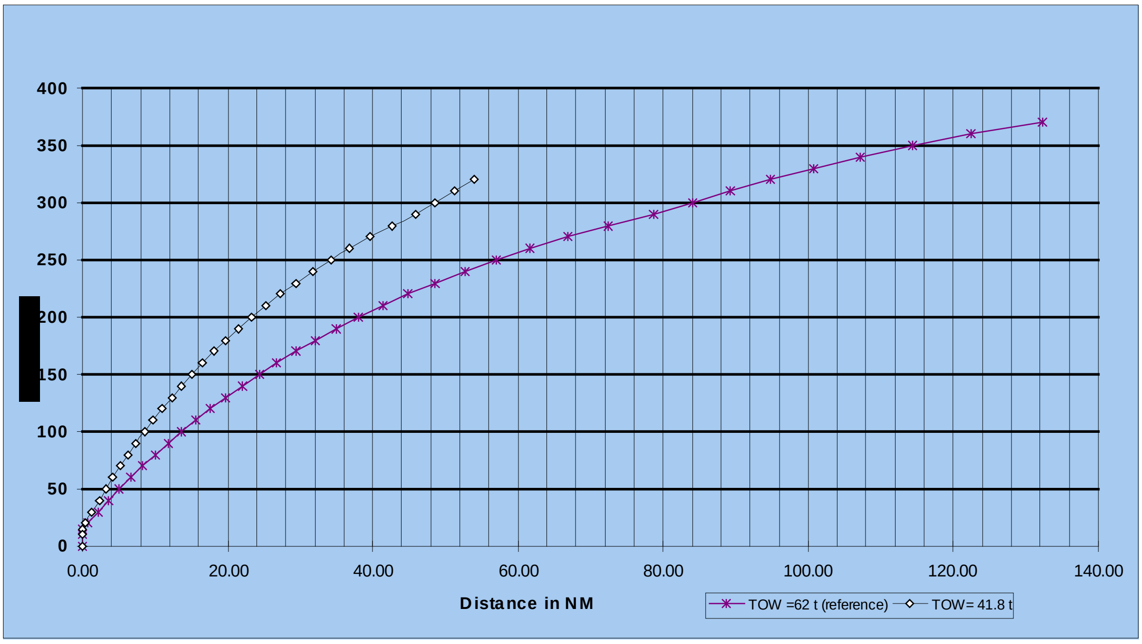

Figure 12: Difference in distance for a climb profile between typical TOW of an EA32 (62 t) and the minimum TOW (41.8 t)

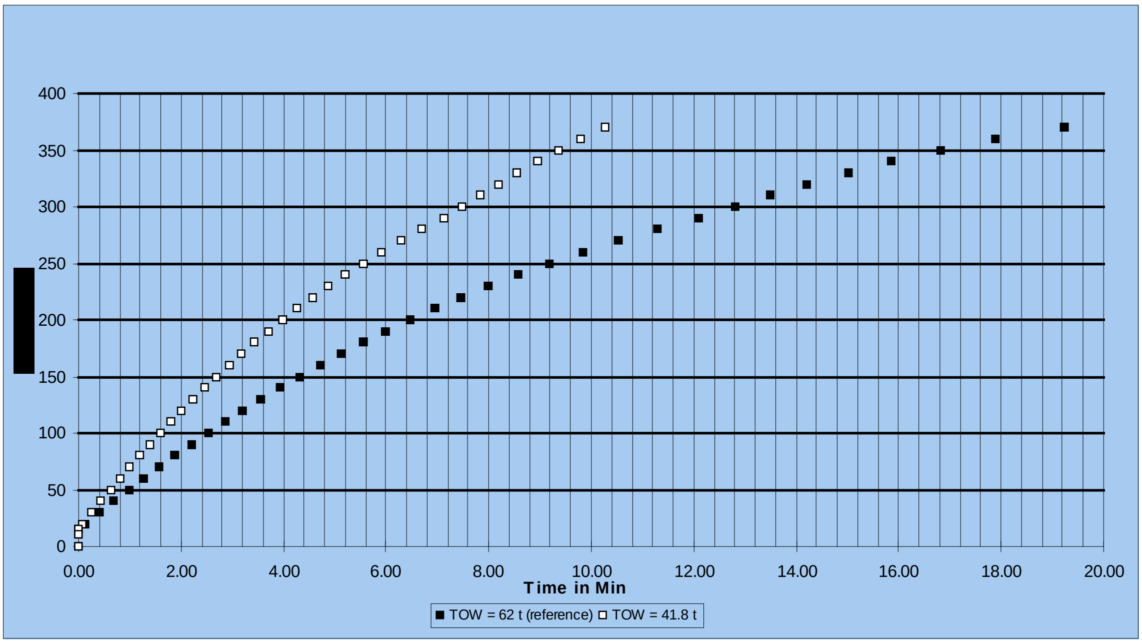

Figure 13: Difference in time for a climb profile between typical TOW of an EA32 (62 t) and the minimum TOW (41.8 t)

Appendix B .3 .3 Difference between Maximum TOW and Minimum TOW

Figure 14 shows that for an A320 the difference between max and min TOW introduces a difference of 66nm in reaching at FL300, while Figure 15 shows that this corresponds to 9.5 minutes.

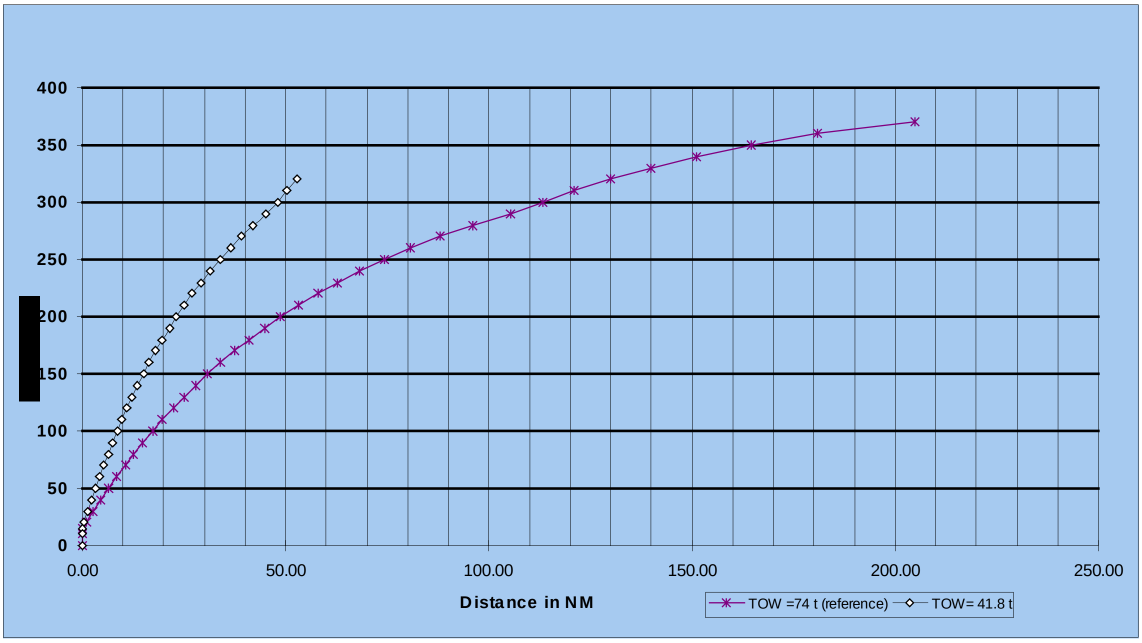

Figure 14: Difference in distance for a climb profile between maximum TOW of an EA32 (74 t) and the minimum TOW (41.8 t)

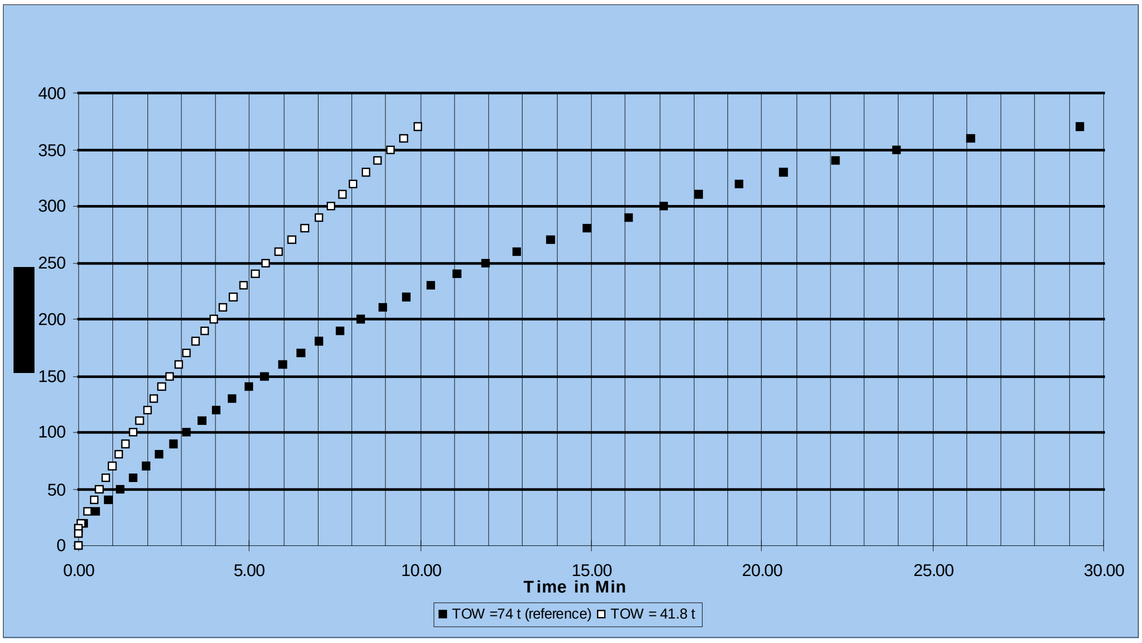

Figure 15: Difference in time for a climb profile between maximum TOW of an EA32 (74 t) and the minimum TOW (41.8 t)

Appendix B .3 .4 Significant weight difference for a EA32

Figure 16 and 17 show that errors of 1.3-2.5% introduce differences of 5-10nm in along-track prediction.

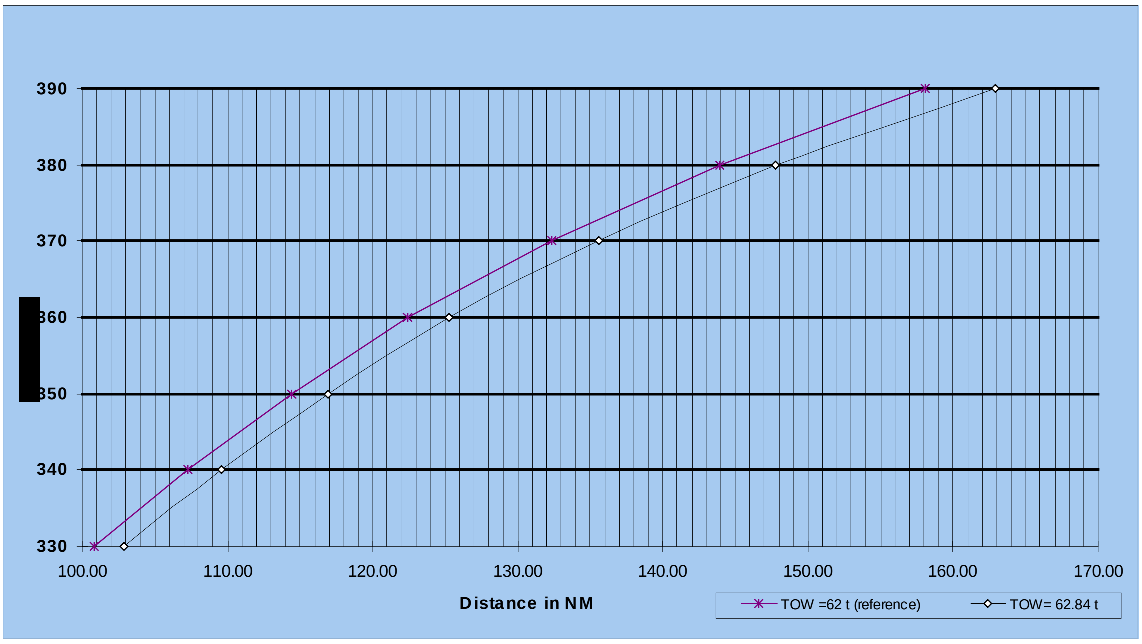

Figure 16: EA32 - Significant Weight difference for a threshold of 5 NM - profile from FL 330 to FL 390

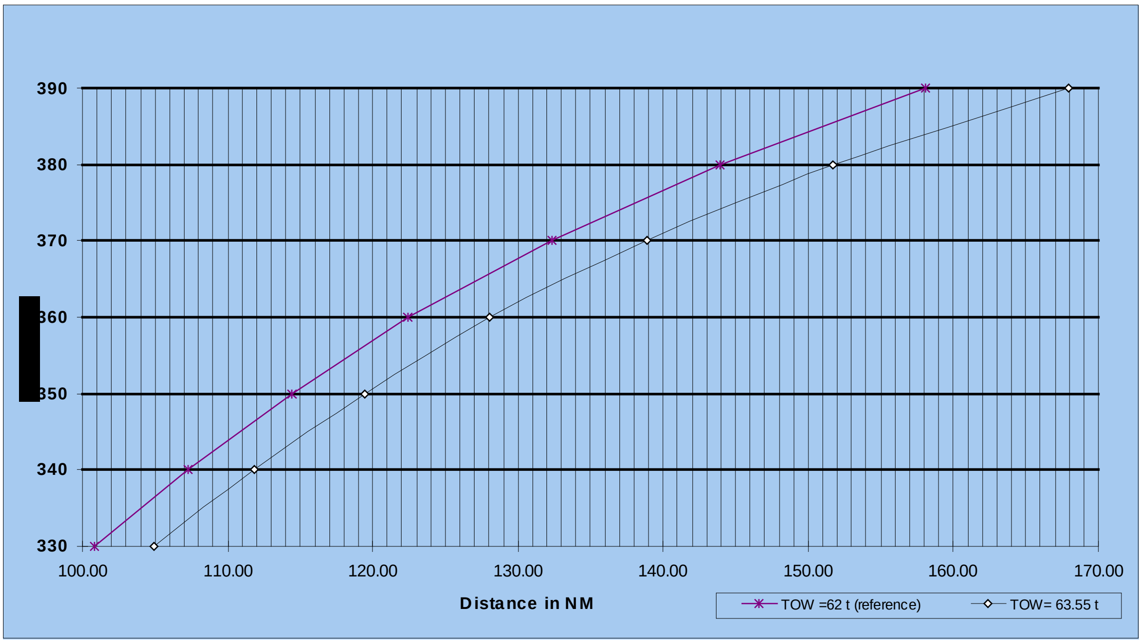

Figure 17: EA32 - Significant Weight difference for a threshold of 10 NM

APPENDIX B .4 B747

Maximum weight = 380 t

Minimum weight = 173 t

Typical Take-off Weight = 280 t

Speed 310 knots, 0.82 Mach

Appendix B .4 .1 Difference between Typical TOW and Maximum TOW

Figure 18 shows that for a B747 a difference between typical and maximum TOW introduces a difference of 110nm in reaching at FL300, while Figure 19 shows that this corresponds to 16.5 minutes.

The discontinuities observed at about FL100 are due to the way the aircraft is operated. Up to FL100 its speed is restricted to 250kts. At FL100 the aircraft reduces climb rate to make a near-level acceleration to pick up speed. Once the required speed has been reached, the aircraft climbs again up to TOC.

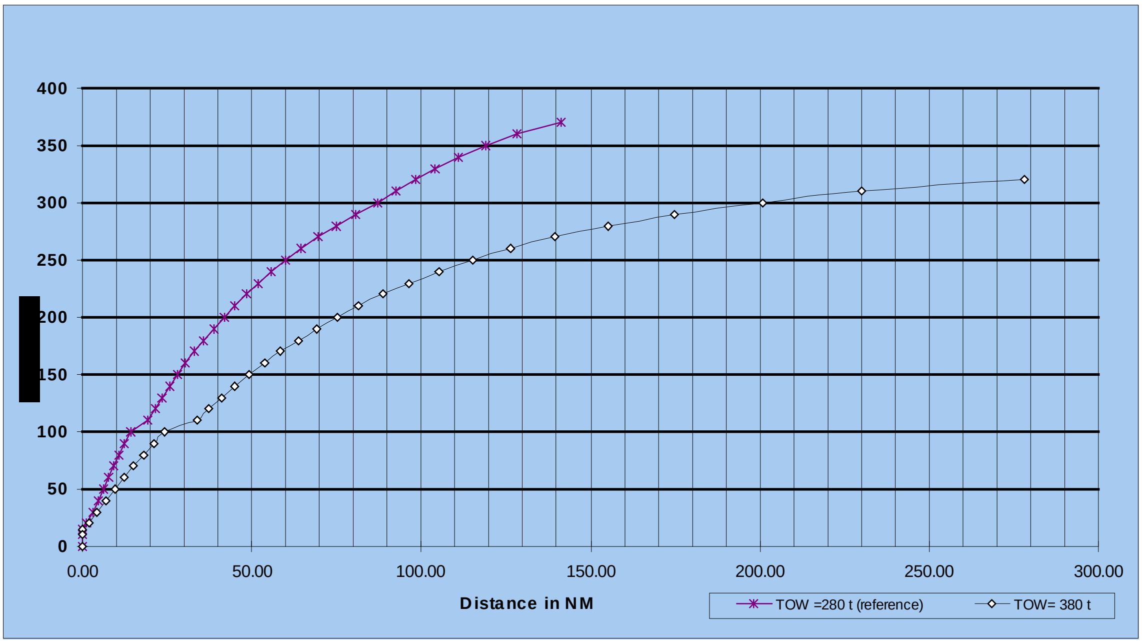

Figure 18: Difference in distance for a climb profile between typical TOW of an B747 (280 t) and the maximum TOW (380 t)

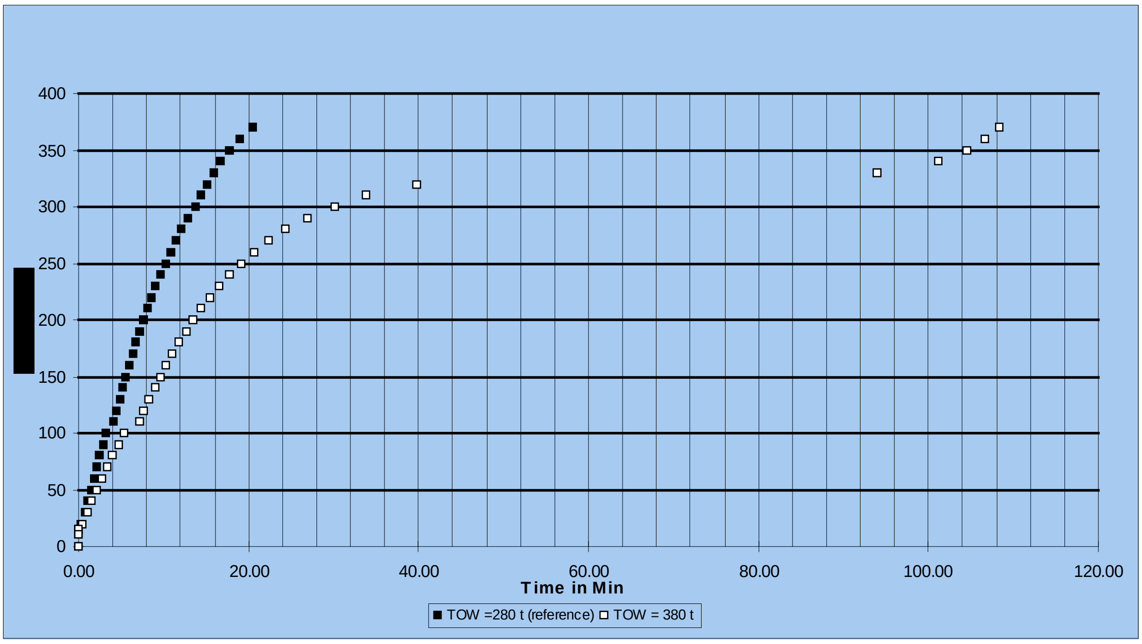

Figure 19: Difference in time for a climb profile between typical TOW of an B747 (280 t) taken as reference and the maximum TOW (380 t)

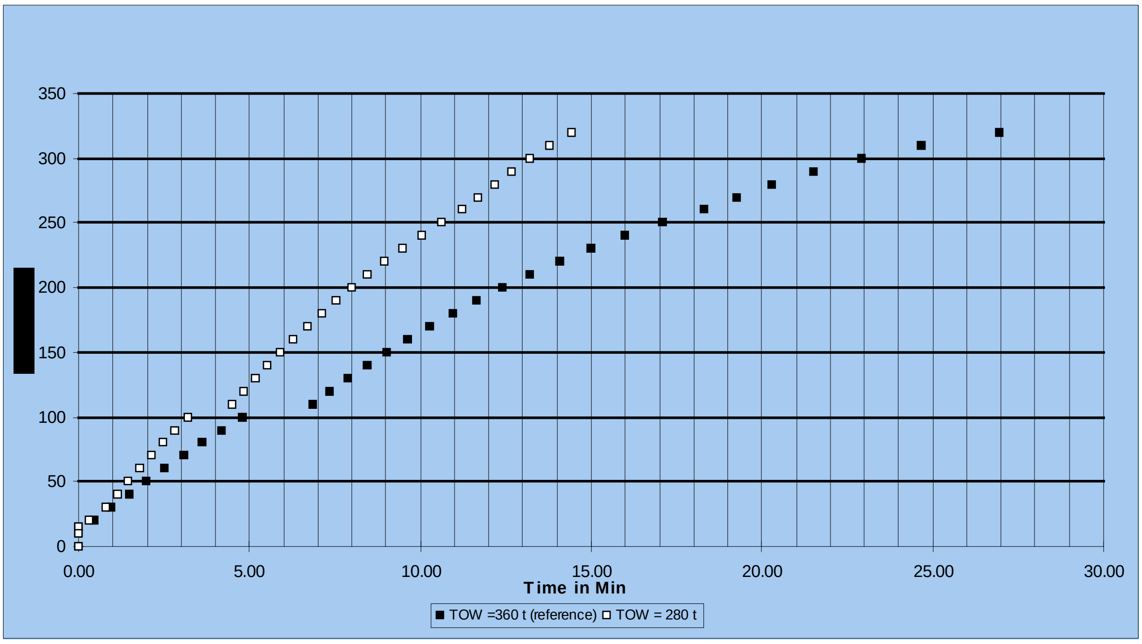

Figure 20: Difference in time for a climb profile between typical TOW of an B747 (280 t) and a weight near the maximum TOW taken as reference (360 t)

When examining Figure 20 it should be noted that a lower reference weight of 360t was used instead of 380t used in Figures 18 and 19.

Appendix B .4 .2 Difference between Typical TOW and Minimum TOW

Figure 21 shows that for a B747 a difference between typical and minimum TOW introduces a difference of 46nm in reaching at FL300, while Figure 22 shows that this corresponds to 6.5 minutes.

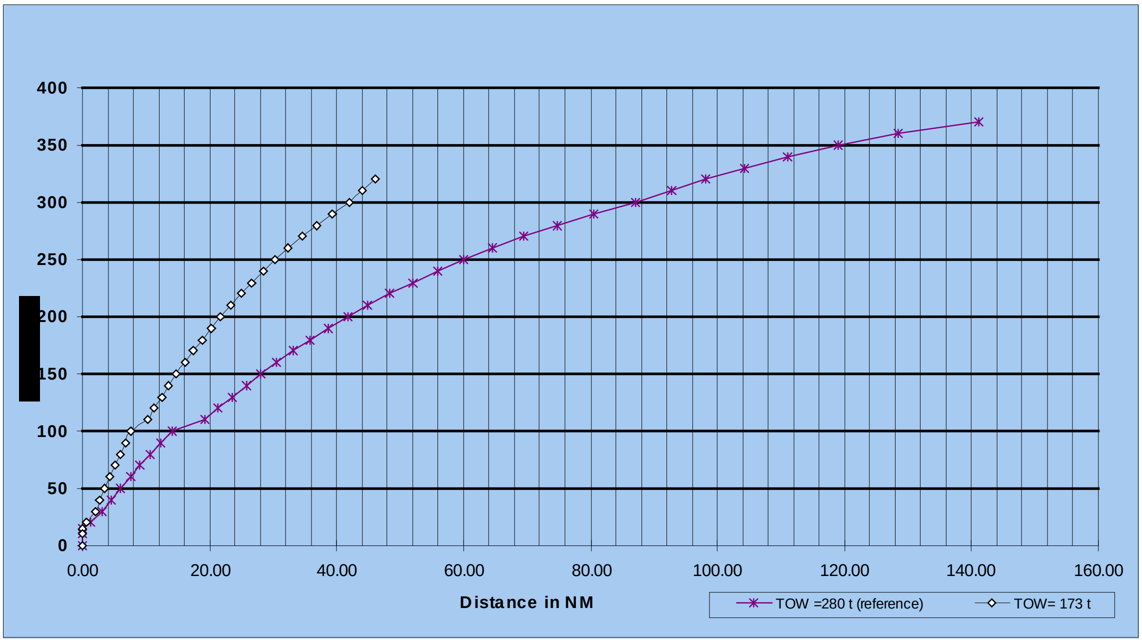

Figure 21: Difference in distance for a climb profile between typical TOW of an B747 (280 t) and the minimum TOW (173 t)

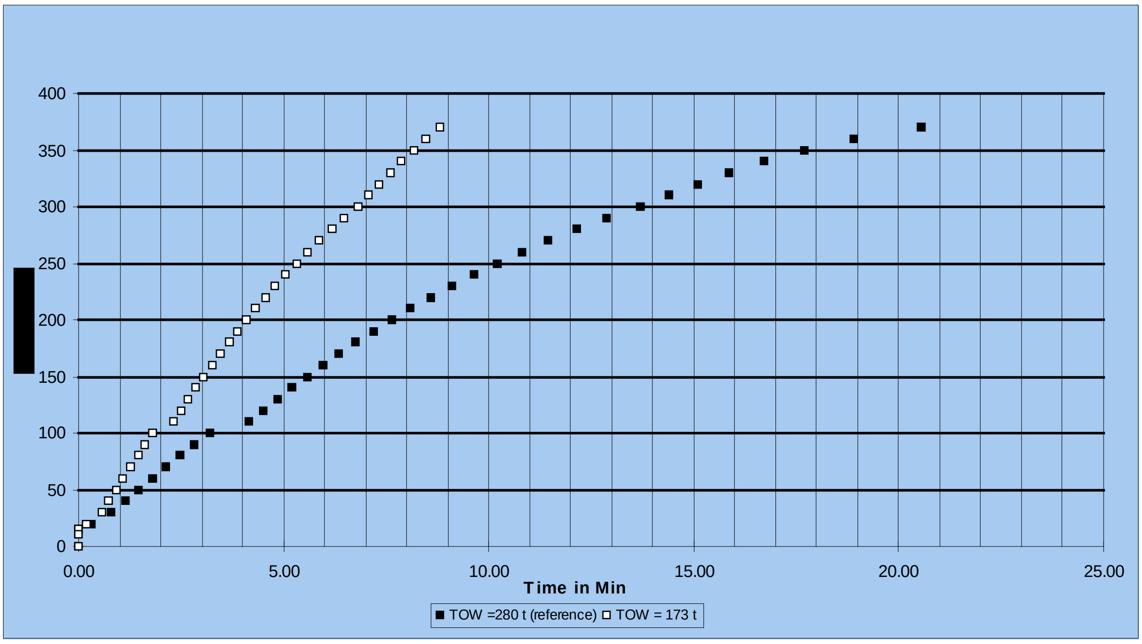

Figure 22: Difference in time for a climb profile between typical TOW of an B747 (280 t) and the minimum TOW (173 t)

Appendix B .4 .3 Difference between Max TOW and Min TOW

Figure 23 shows that for a B747 the difference between max and min TOW introduces a difference of 112nm in reaching at FL300, while Figure 24 shows that this corresponds to 20 minutes. Note that a maximum weight of 360t was used (compared with 380t in B.4.1 and B.4.2).

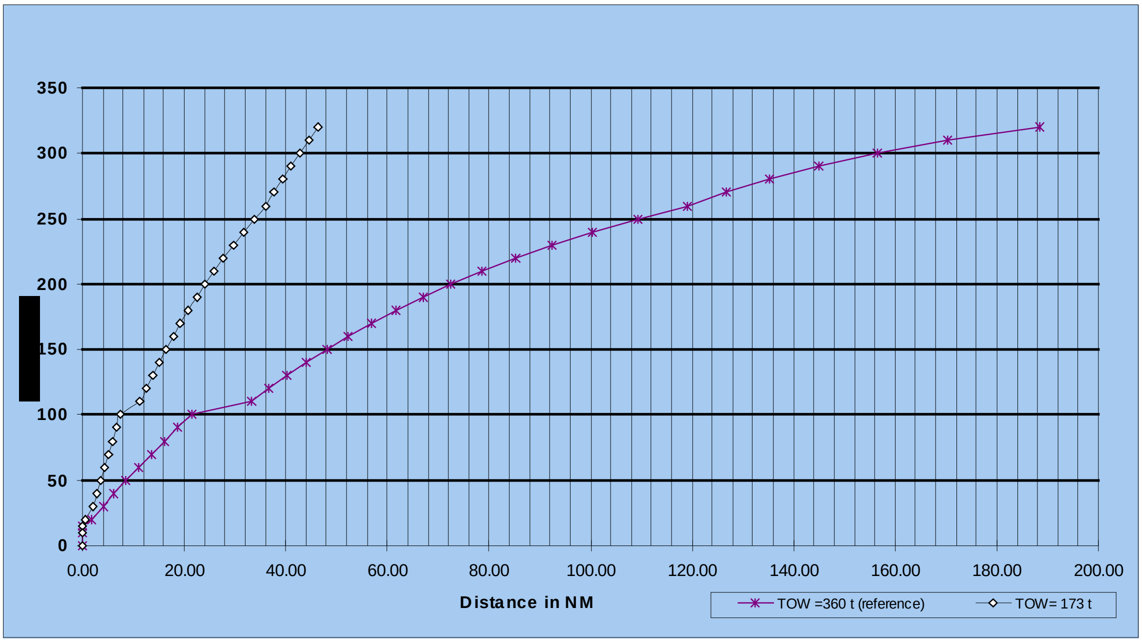

Figure 23: Difference in distance for a climb profile between a weight near the maximum TOW of an B747 (360 t) and the minimum TOW (173 t)

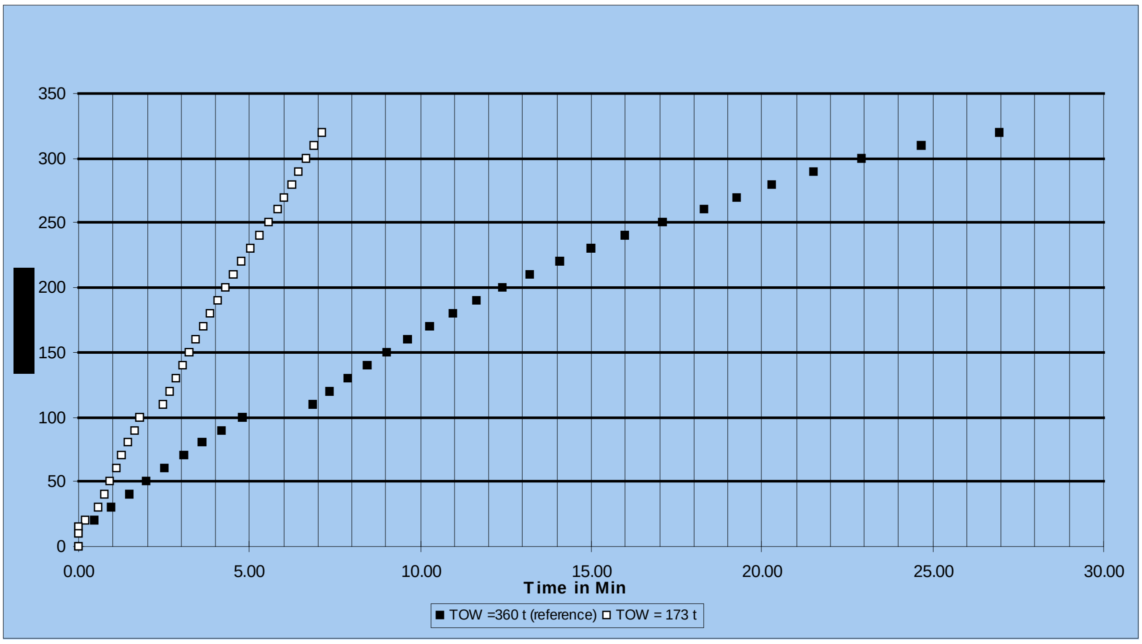

Figure 24: Difference in time for a climb profile between a weight near the maximum TOW of an B747 (360 t) and the minimum TOW (173 t)

Appendix B .4 .4 Significant weight difference for a B747

Figure 25, 26 and 27 show that errors of 1-2% introduce differences of 5-10nm in along-track prediction.

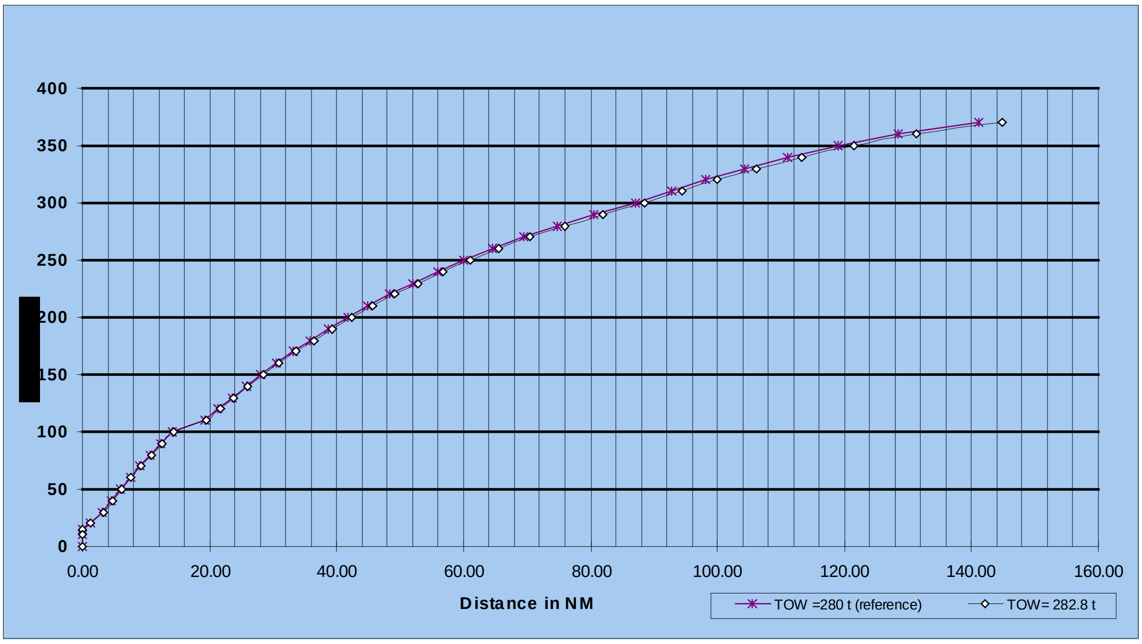

Figure 25: Significant Weight difference for a threshold of 5 NM - profile from 0 to FL 380

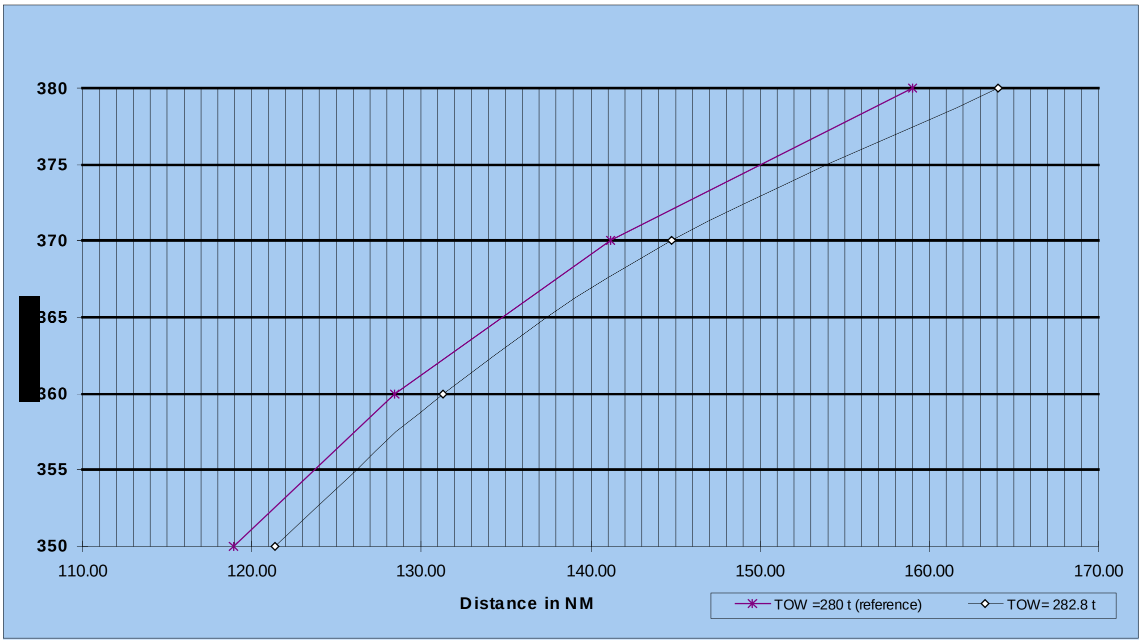

Figure 26: Significant Weight difference for a threshold of 5 NM - - profile from 360 to FL 380

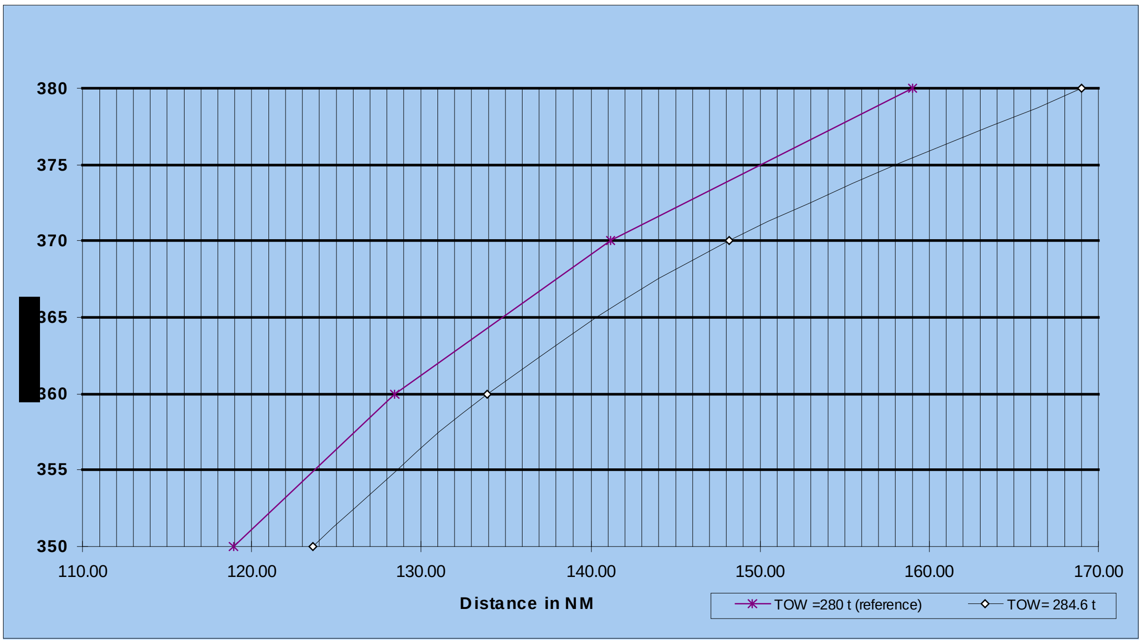

Figure 27: Significant Weight difference for a threshold of 10 NM

APPENDIX B .5 B767

Maximum weight = 181.4 t

Minimum weight = 90 t

Typical Take-off Weight = 150 t

Speed 290 knots, 0.78 Mach

Appendix B .5 .1 Difference between Typical and Maximum TOW

Figures 28 and 30 show that for a B767 a difference between typical and maximum TOW introduces a difference of about 52nm in reaching at FL350, while Figures 29 and 31 show that this corresponds to about 7.5 minutes.

The discontinuities observed at about FL100 are due to the operating procedures for transition to climb thrust.

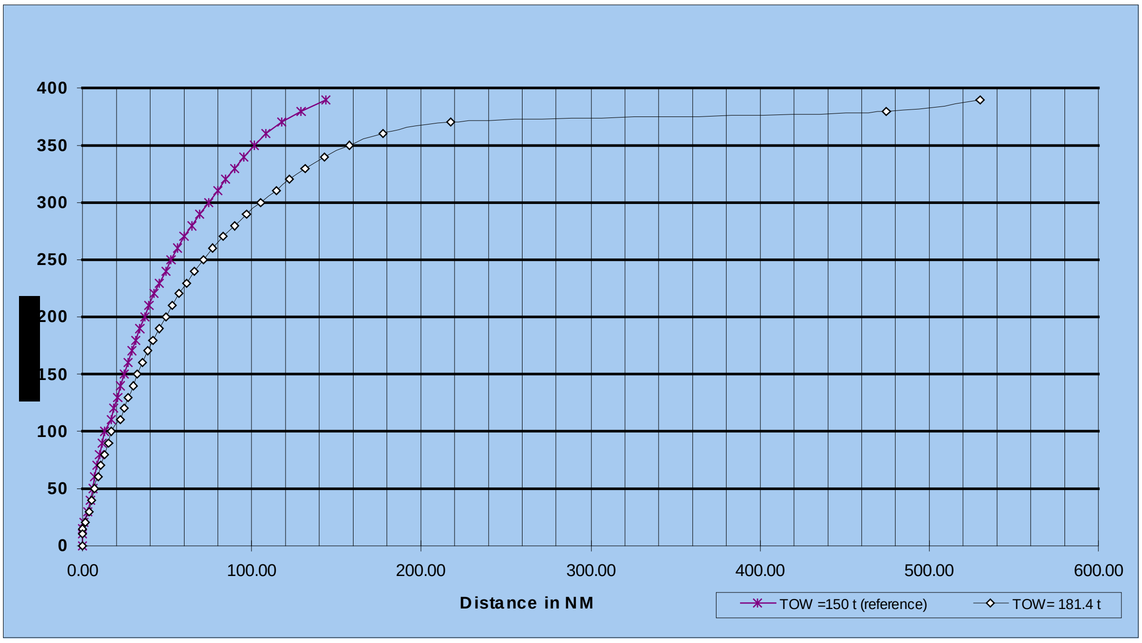

Figure 28: Difference in distance for a climb profile between typical TOW of an B767 (150 t) and the maximum TOW (181.4 t)

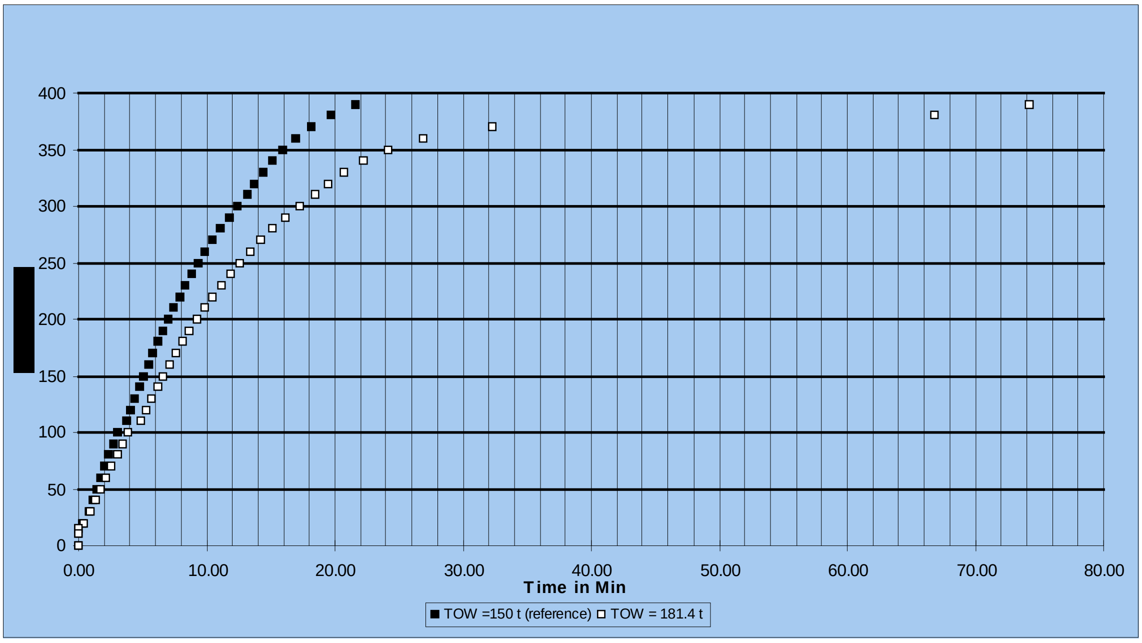

Figure 29: Difference in time for a climb profile between typical TOW of an B767 (150 t) taken as reference and the maximum TOW (181.4 t)

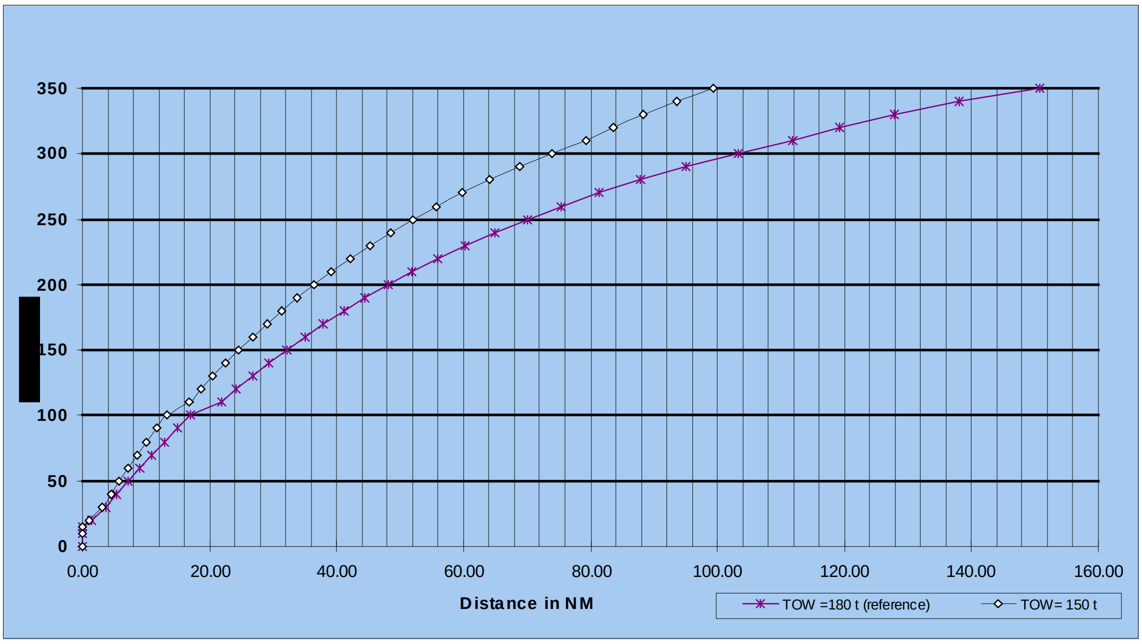

Figure 30: Difference in distance for a climb profile between typical TOW of an B767 (150 t) and a weight near the maximum TOW taken as reference (180 t)

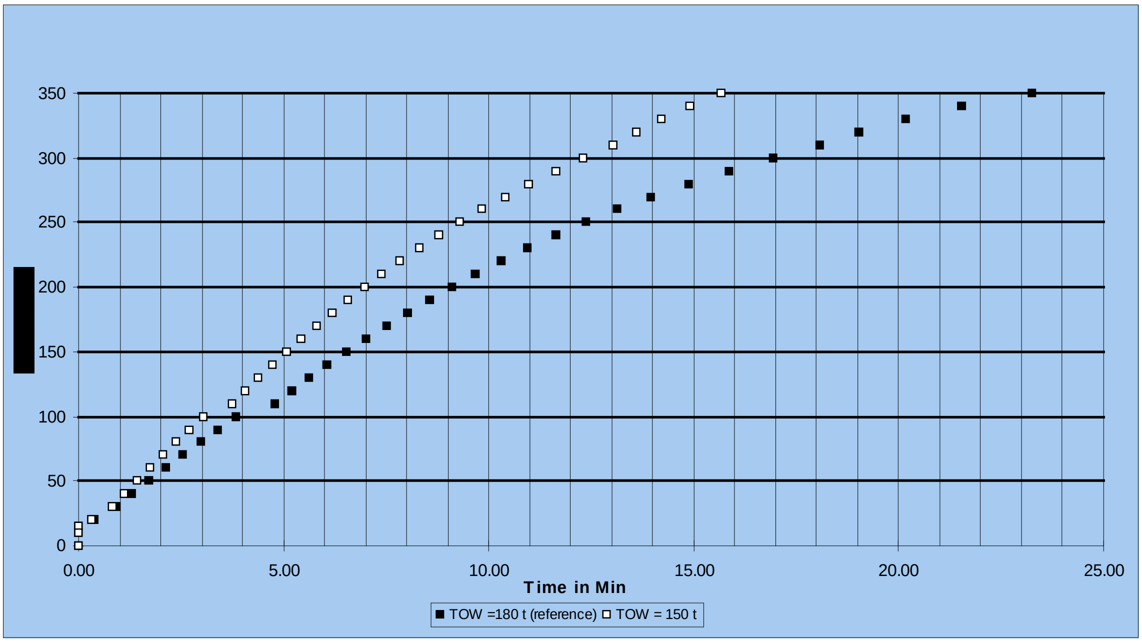

Figure 31: Difference in time for a climb profile between typical TOW of an B767 (150 t) and a weight near the maximum TOW taken as reference (180 t)

Appendix B .5 .2 Difference between Typical and Minimum TOW

Figures 32 and 33 show that for a B767 a difference between typical and minimum TOW introduces a difference of about 52nm and 8 min in reaching at FL350.

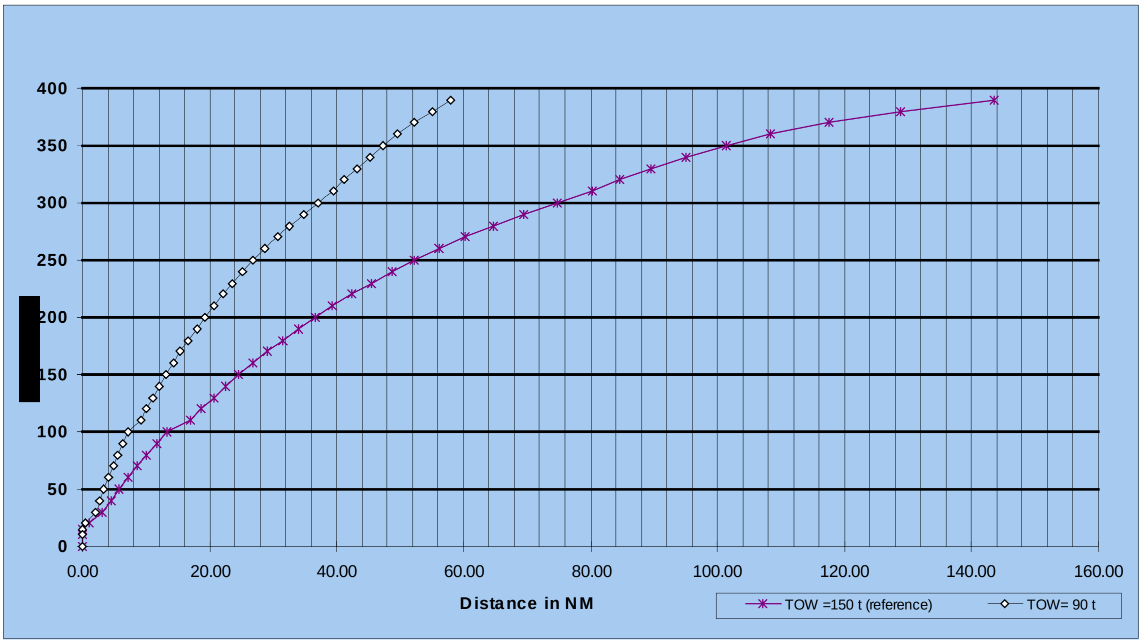

Figure 32: Difference in distance for a climb profile between typical TOW of an B767 (150 t) and the minimum TOW (90 t)

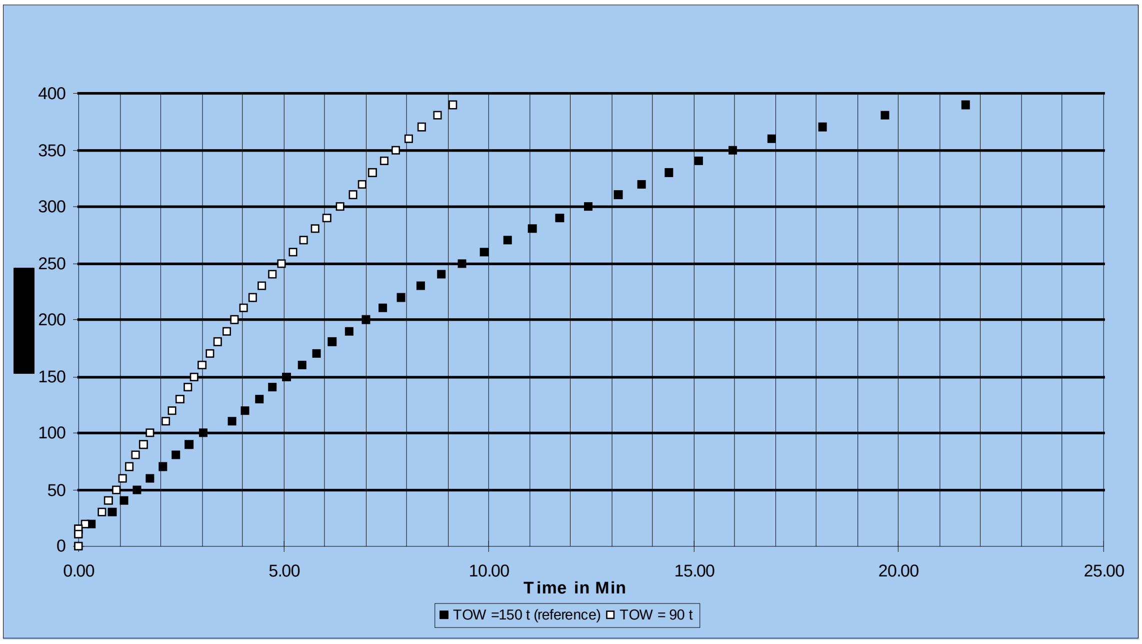

Figure 33: Difference in time for a climb profile between typical TOW of an B767 (150 t) and the minimum TOW (90 t)

Appendix B .5 .3 Difference between Max and Min TOW

Figures 34 and 35 show that for a B767 a difference between max and min TOW introduces a difference of about 104nm and 15.5min in reaching at FL350.

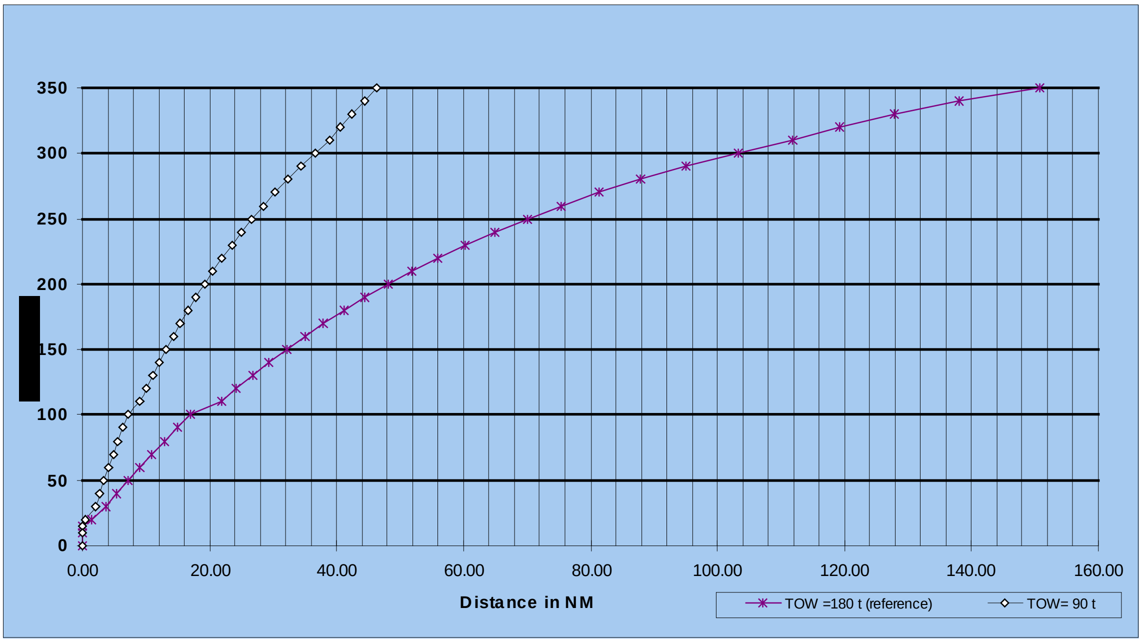

Figure 34: Difference in distance for a climb profile between a weight near the maximum TOW of an B767 (180 t) and the minimum TOW (90 t)

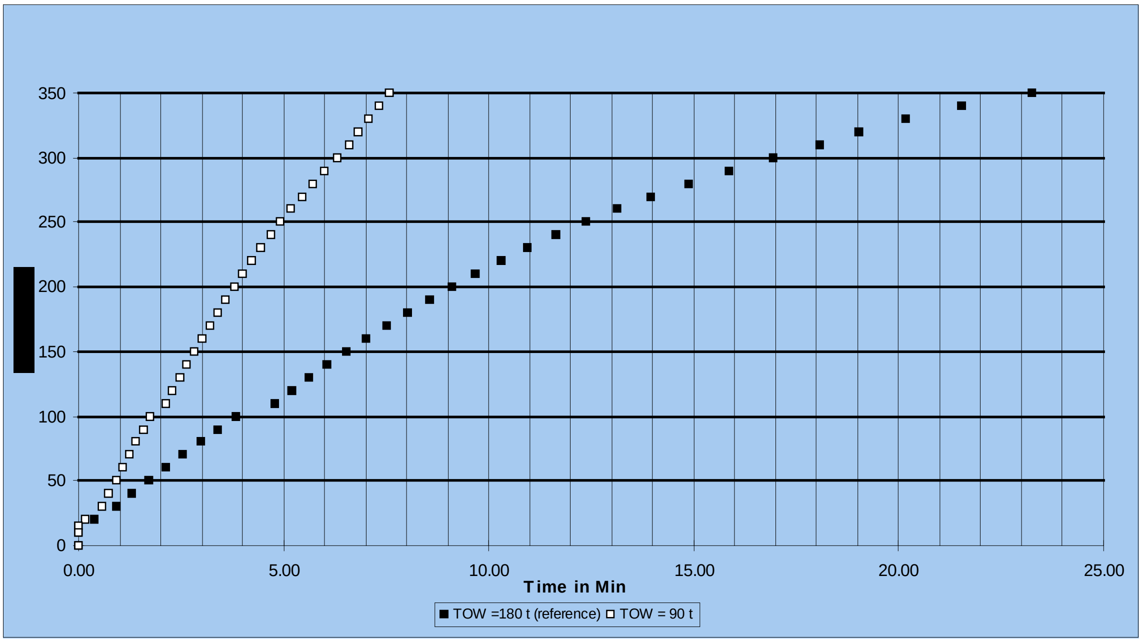

Figure 35: Difference in time for a climb profile between a weight near the maximum TOW of an B767 (180 t) and the minimum TOW (90 t)

Appendix B .5 .4 Significant weight difference for a B767

Figures 36 and 37 show that 1.4-2.8% error in weight causes 5-10nm error in the predicted TOC.

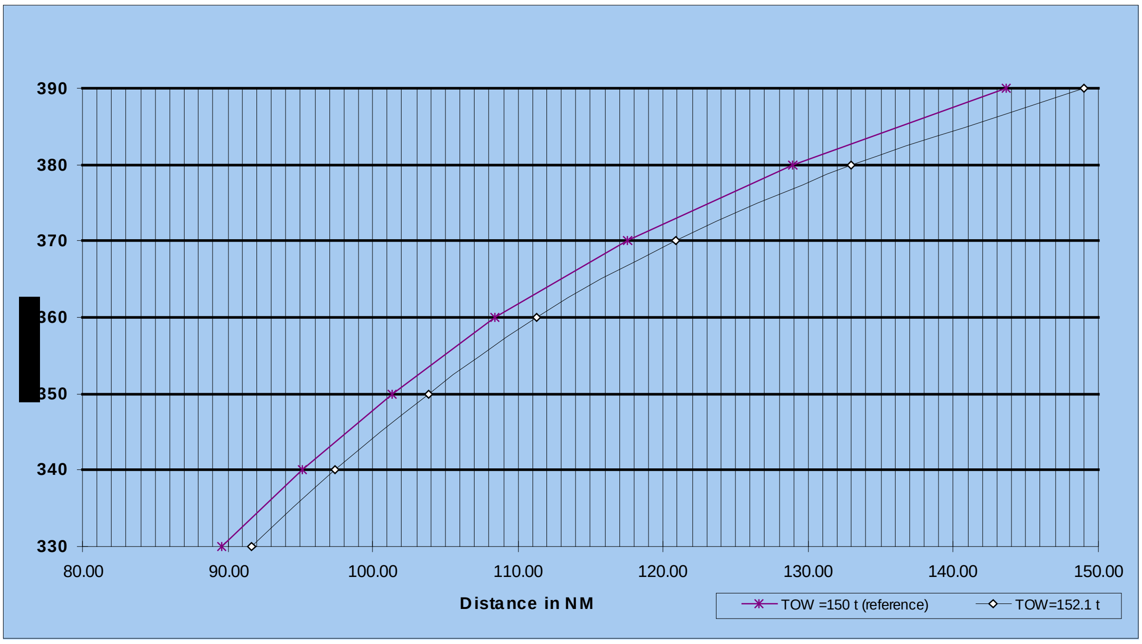

Figure 36: Significant Weight difference for a threshold of 5 NM - profile from FL 330 to FL 390

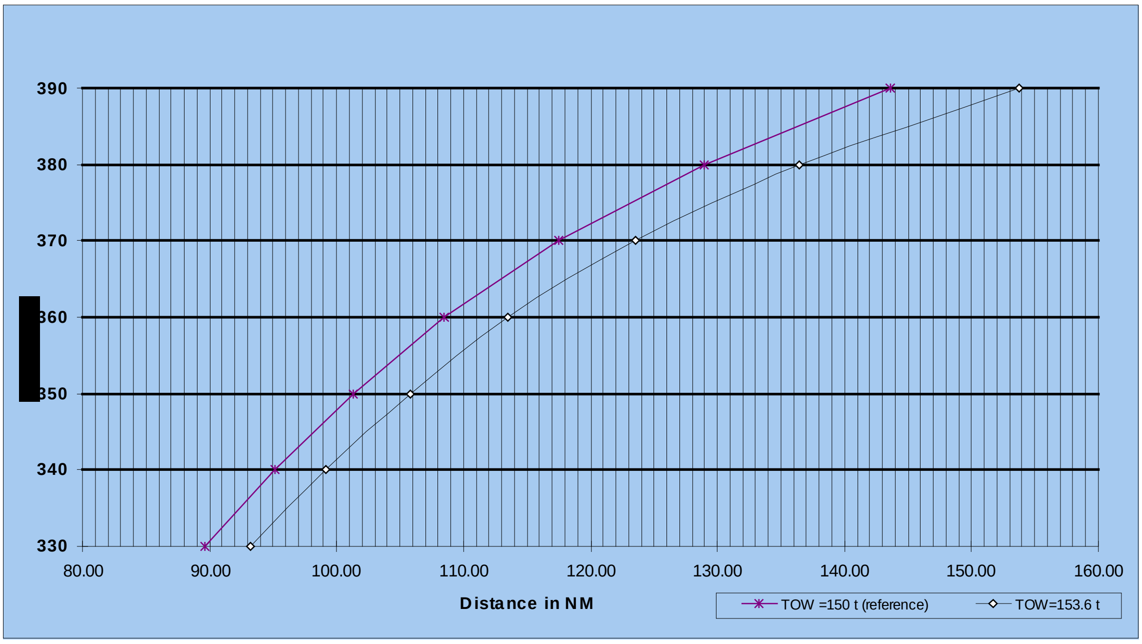

Figure 37: Significant Weight difference for a threshold of 10 NM - profile from FL 330 to FL 390

APPENDIX B .6 IMPACT OF OFPL WEIGHT ERROR

AOs estimate the take-off weight about four hours before the flight is due to leave. The actual TOW can differ from the assumed value by as much as 4 or 5 tonnes, depending on the type of aircraft.

As an example of the impact of such an error, Figure 38 shows two profiles for a B747 with take-off weights of 280t and 285t.

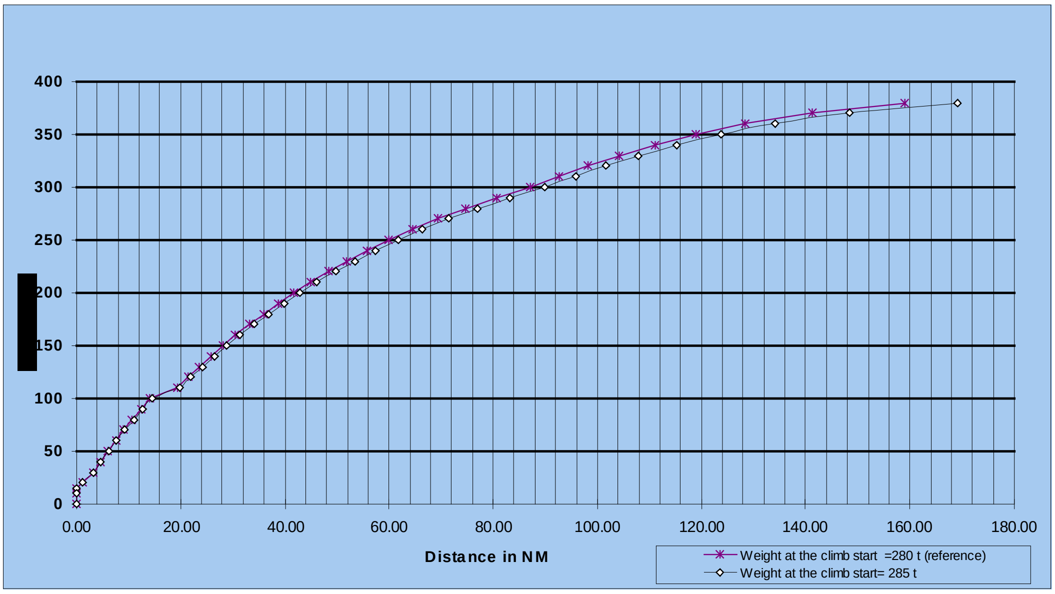

Figure 38: The climb of B747 with a difference in weight of 5 tonnes

This gives an approximate along-track variation in the predicted TOC of over 6 NM at FL 360 and about 10 NM at FL380.

APPENDIX B .7 CONCLUSION

In this appendix the effect of the aircraft take-off weight was analysed, enabling an assessment of the impact of errors on trajectory prediction quality.

The differences found by comparing profiles produced from a typical TOW with those using maximum and minimum TOWs show that there is a large variation in the predicted trajectories, and hence it is undesirable to use a typical TOW as an approximation to the actual TOW.

Considering the difference in TOWs which has a potentially significant impact of 5-10nm in along-track distance required to reach TOC yields the following results:

Table 1: Difference in aircraft weight significant with a threshold of 5 NM

Aircraft	Aircraft Weight in tonnes	FL	Weight Increment Producing 5nm Difference in TOC (in tonnes)	Weight Increment Producing 5nm Difference in TOC (As a Percentage of Aircraft Weight)
ATR42	15	250	0.45	3.0%
EA32	62	390	0.84	1.35%
B767	150	390	2.1	1.4%
B747	280	380	2.8	1.0%

Table 2: Difference in aircraft weight significant with a threshold of 10 NM

Aircraft	Aircraft Weight in tonnes	FL	Weight Increment Producing 10nm Difference in TOC (in tonnes)	Weight Increment Producing 10nm Difference in TOC (As a Percentage of Aircraft Weight)
ATR42	15	250	0.83	5.5%
EA32	62	390	1.55	2.5%
B767	150	390	3.6	2.4%
B747	280	380	4.9	1.75%

Thus the simulations show that the predicted trajectory is very sensitive to weight variations. A 5 tonne error in the TOW is significant using to the threshold of 5NM or 10NM in along-track distance between TOC.

It is concluded that trajectory prediction could be improved significantly by using an accurate TOW.

APPENDIX C - ENGINE PERFORMANCE DEGRADATION

APPENDIX C .1 INTRODUCTION

Engine performance degradation impacts on fuel consumption and reduces thrust. Pilots correct for this by increasing the thrust setting with the consequence that fuel consumption is increased.

The typical value for engine performance degradation reported by a range of airlines is a degradation of between 2 and 6% measured in terms of increased fuel consumption.

However, the DC10 has been identified by an AO as an exception to this rule. For the DC10 up to 15% more fuel can be expended.

Table 3 uses a typical engine performance degradation and, based on a typical take-off weight for a number of aircraft types, the difference in weight over a long flight is assessed.

The table demonstrates that in practice, engine performance degradation makes only a small impact on the weight, even after a long flight.

Appendix C.2 presents descent profiles at the latest stage of the flight for the most significantly affected aircraft, the DC10 in order to demonstrate the impact of this error in weight on the profile. The simulations were performed by using BADA. BADA use the manufacturers' programs as references to evaluate flight profile. In the graphs the curve tagged reference is extracted from manufacturers' program while the other curve is extrapolated via BADA.

The simulations demonstrate that even for the DC10, engine performance degradation does not significantly impact the descent profiles. Therefore it can be ignored as a cause of error in trajectory prediction.

A/C type	Min. TOW	Max. TOW	TOW	Extra Fuel consumption in tonnes per hour (at the given flight level)		Engine degradation	Assumed flight duration in hours	Fuel burned in tonnes	Extra fuel burned due to engine degradation in tonnes	A/C weight at the latest stage of the flight in tonnes	Difference in % between normal and degraded consumption
B747/400	173	380	280	11	FL350	6.00%	8	88	5.3	192	2.75%
B737	273	52.4	47	2.6	FL330	6.00%	4	10.4	0.6	37	1.70%
B757	116	60	95	3.57	FL340	6.00%	4	14.3	0.9	81	1.06%
EA32	41.8	73.5	62	2.4	FL350	6.00%	5	12	0.7	50	1.44%
DC10	121	250	194	8	FL350	15.00%	8	64	9.6	130	7.38%
MD80	72.6	36.5	61.2	2.94	FL320	6.00%	5.5	16.2	1.0	45	2.15%
FK70	40	22.8	34	1.8	FL320	6.00%	3.5	6.3	0.4	28	1.36%
ATR42	10.3	16.7	15	0.44	FL240	6.00%	3	1.3	0.1	14	0.58%

Table 3: Impact of Engine Performance Degradation

APPENDIX C .2 DC10

The descent is initiated 4 NM after the foreseen TOD, but this is not considered as a significant difference in distance.

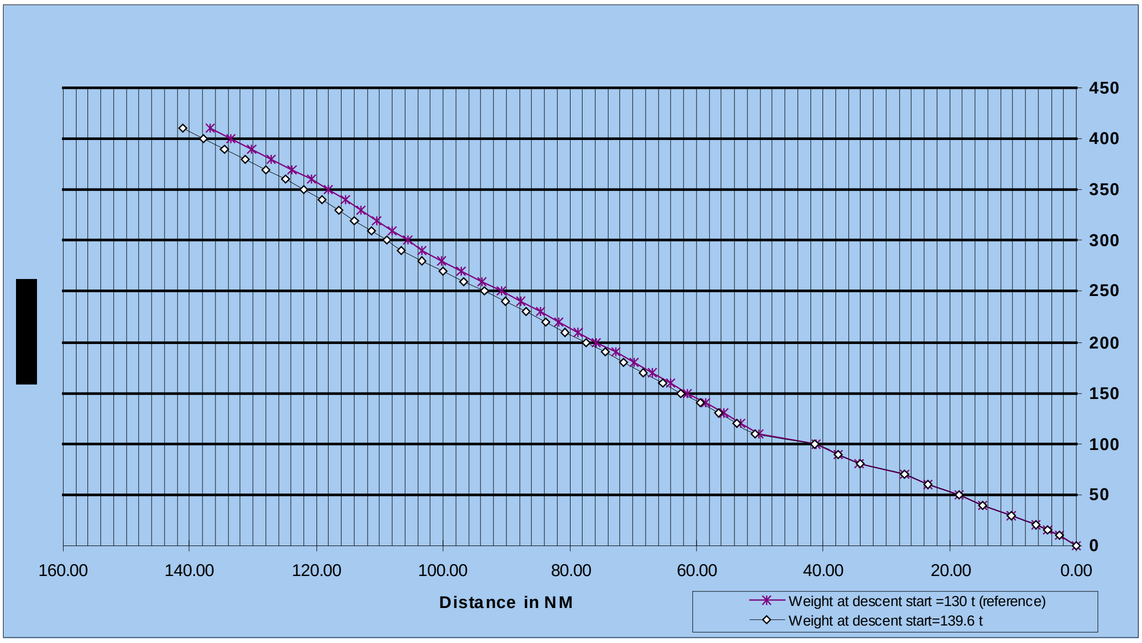

Figure 39: Influence of engine degradation after 8 hours flight on the descent (distance profile)

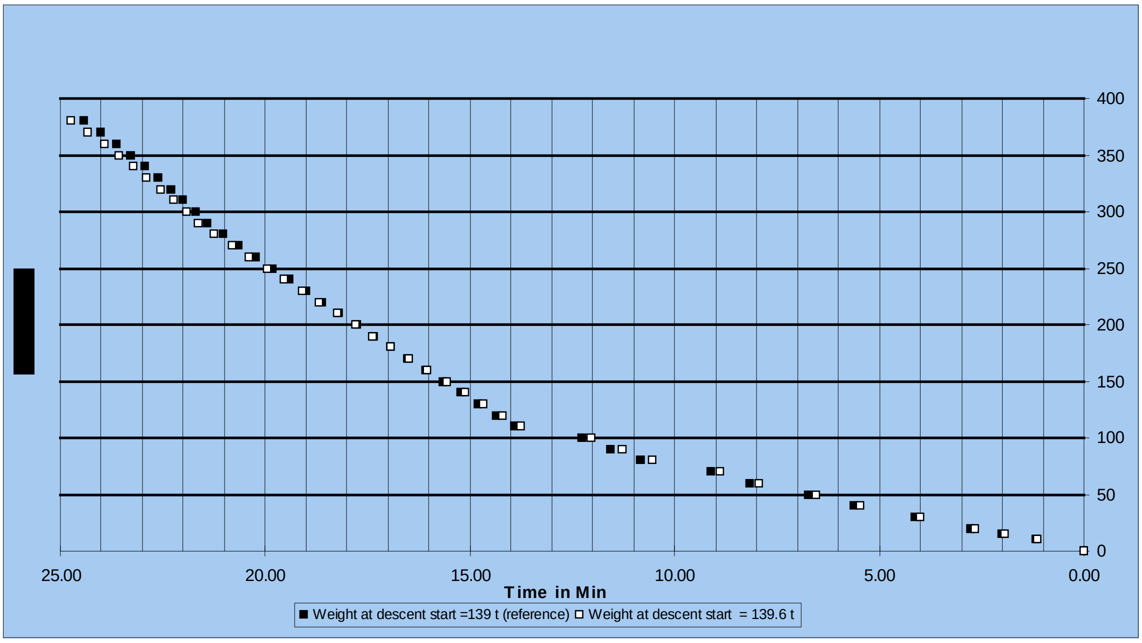

Figure 40: Influence of engine degradation after 8 hours flight on the descent (time profile)

APPENDIX D - OPERATING PROCEDURES

APPENDIX D .1 EFFECT OF COMPANY OPERATING PROCEDURES

Details of company operating procedures have been received from a number of companies for range of aircraft types.

By collecting information from three companies the following differences have been identified:

- For a B737-200 the climb speed and the cruise speed above FL100 varies from 300 kts to 320 kts depending on the company.
- For a B737-400 the climb speed and the cruise speed above FL100 varies from 290 kts to 300 kts depending on the company.
- For a B767-300 the climb speed varies from 290 kts to 320 kts and the cruise speed above FL100 varies from 300 kts to 320 kts depending on the company.

Note that these speeds are quoted as calibrated air speeds (CAS).

APPENDIX D .2 CLIMB PROFILES WITH DIFFERENT SPEEDS

To examine the effect of different company procedures, a number of simulations have been performed studying the effect of different climb speeds.

Appendix D .2 .1 ATR42

TOW: 15 t

Speed : 160 kts and 140 kts

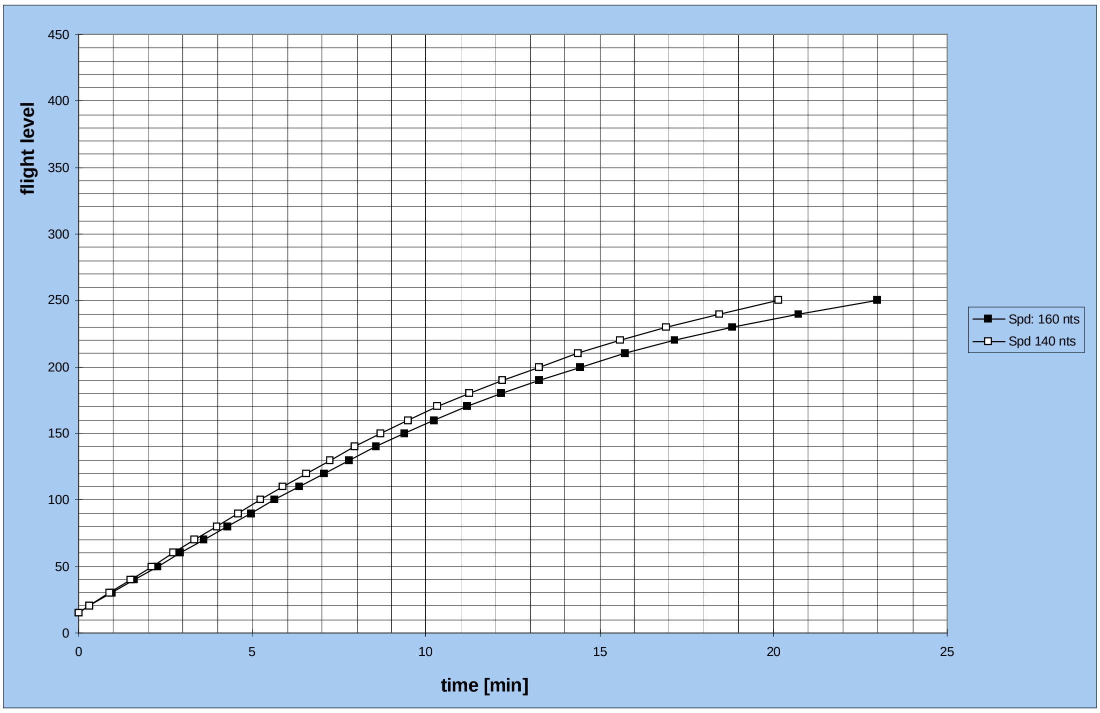

Figure 41: Different speed profiles for ATR42 (time)

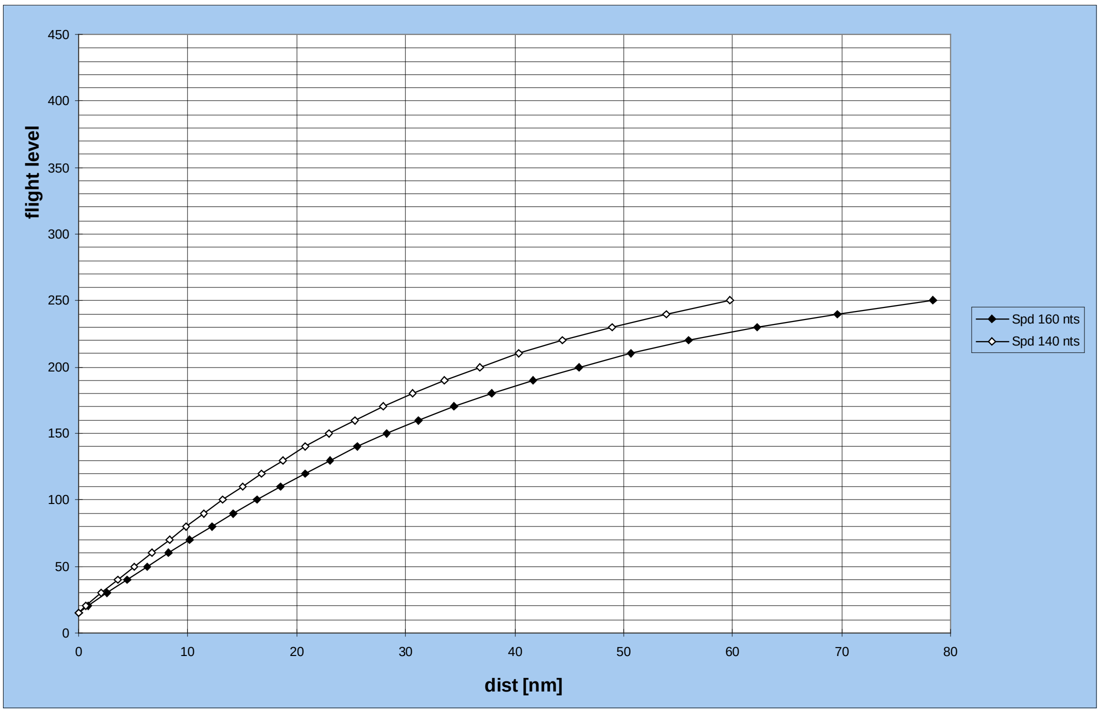

Figure 42: Different speed profiles for ATR42 (distance)

The speed affects the climb of the ATR42: with a speed of 160 kts instead of 140 kts the TOC is reached about 3 minutes and 18 NM later.

Appendix D .2 .2 EA32

TOW: 62 t. Speed : 300 kts and 280 kts. With a speed of 300 kts instead of 280 kts the TOC is reached about at the same time.

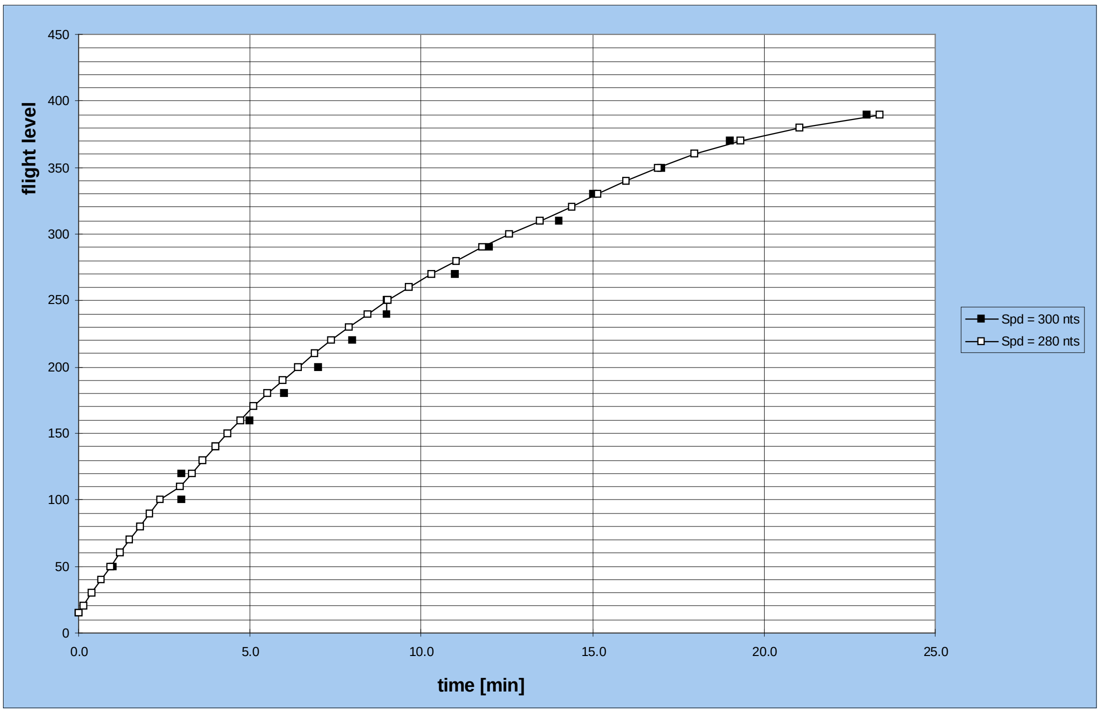

Figure 43: Different speed profiles for EA32 (time)

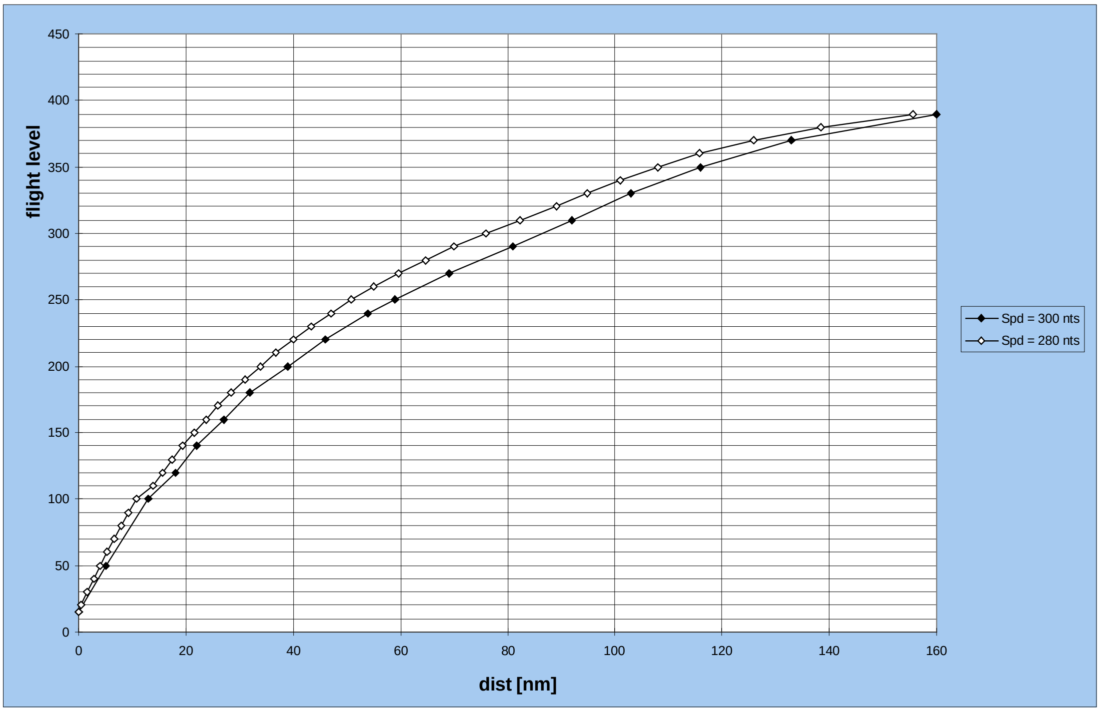

Figure 44: Different speed profiles for EA32 (distance)

The speed affects the climb of the EA32: with a speed of 300 kts instead of 280 kts there is a difference of 11 NM at FL 290, but it is of interest to notice that the difference is smaller at lower and at higher flight levels.

Appendix D .2 .3 FK100

TOW: 40t

Speed : 255 kts and 280 kts.

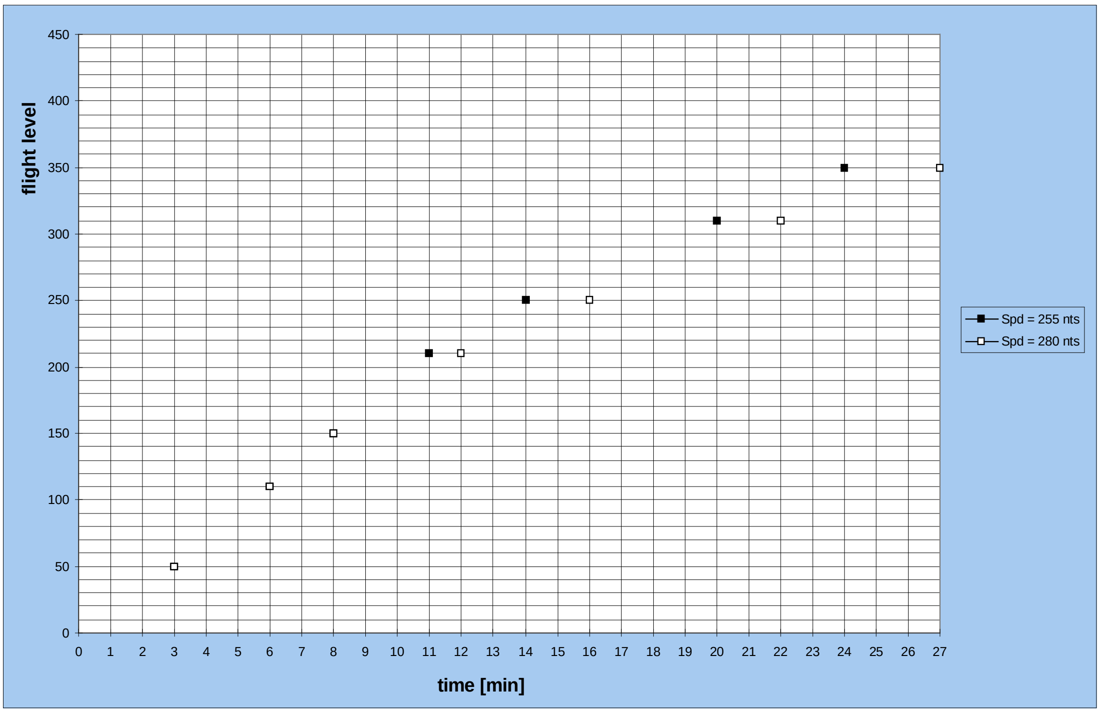

Figure 45: Different speed profiles for FK100 (time)

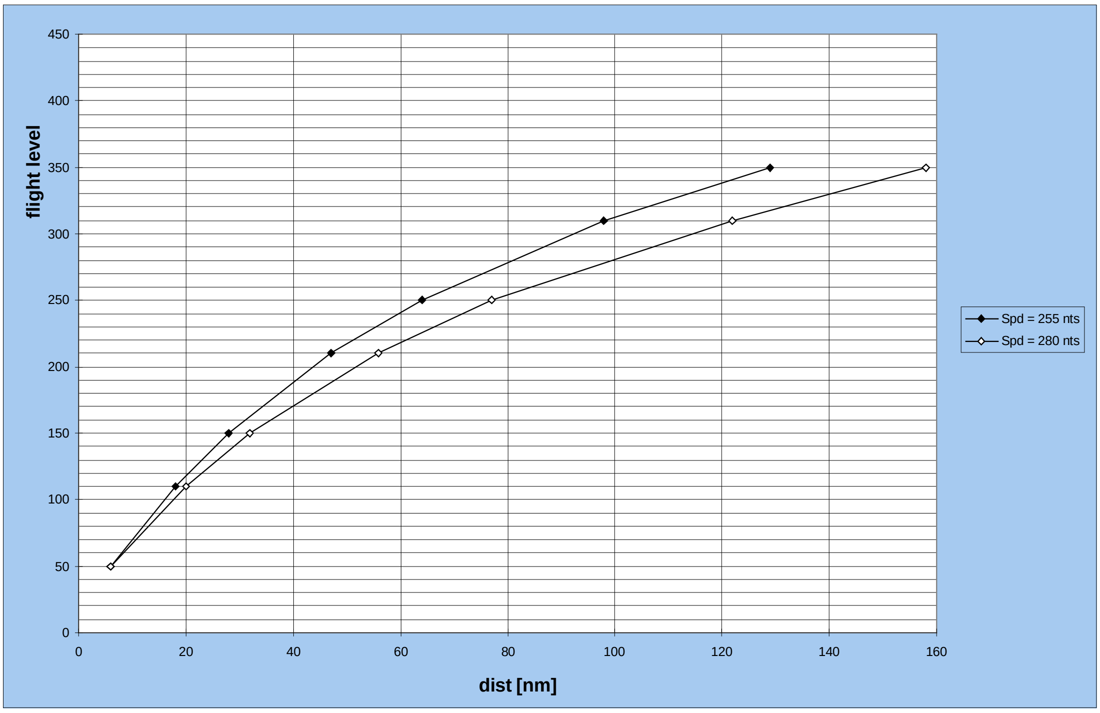

Figure 46: Different speed profiles for FK100 (distance)

The speed affects the climb of the FK100 : with a speed of 255 kts instead of 280 kts there is a difference of 19 NM and 3 min at FL 350.

APPENDIX D .3 CONCLUSION

The speed defined in the operating procedures affects the climb profile and hence the operating procedures should be known for trajectory prediction.

APPENDIX E - DIFFERENCES IN TRAJECTORIES OBTAINED USING DATA CURRENTLY AVAILABLE AND DATA POTENTIALLY SUPPLIED BY AO

This section compares some profiles calculated by extracting data from FPLs and the corresponding OFPLs.

Figures 47 and 48 show a B737 of a major airline. The weight is not given in the FPL so the typical take-off weight of 42t is taken as reference. In the OFPL the given TOW is 54t.

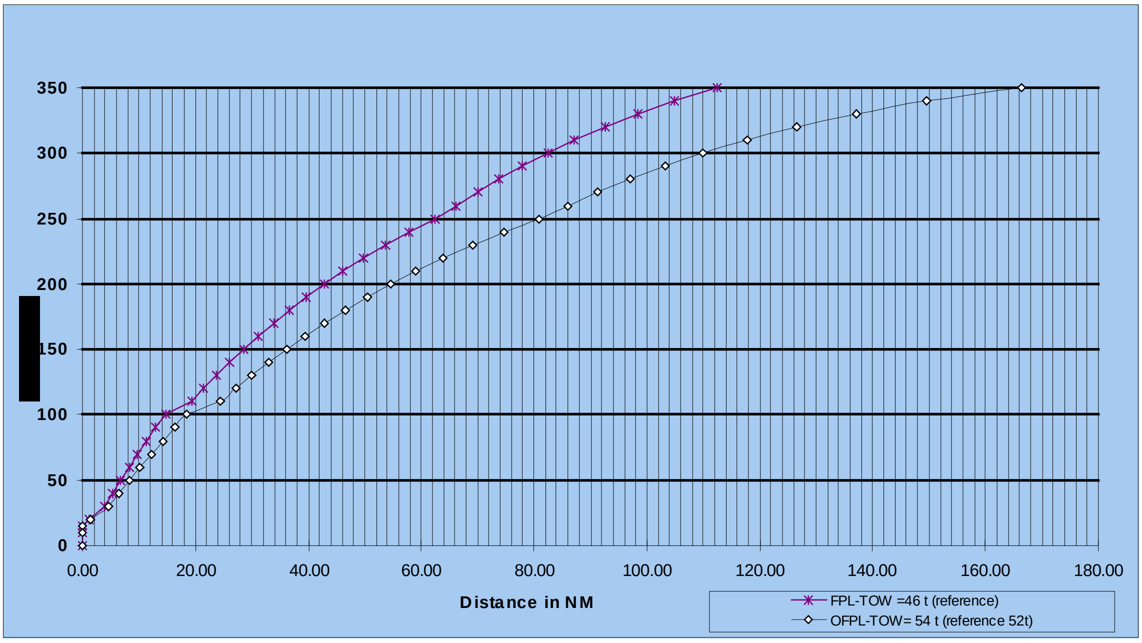

Figure 47: Difference in distance between a climb based on reference TOW (FPL) and on the TOW extracted form OFPL

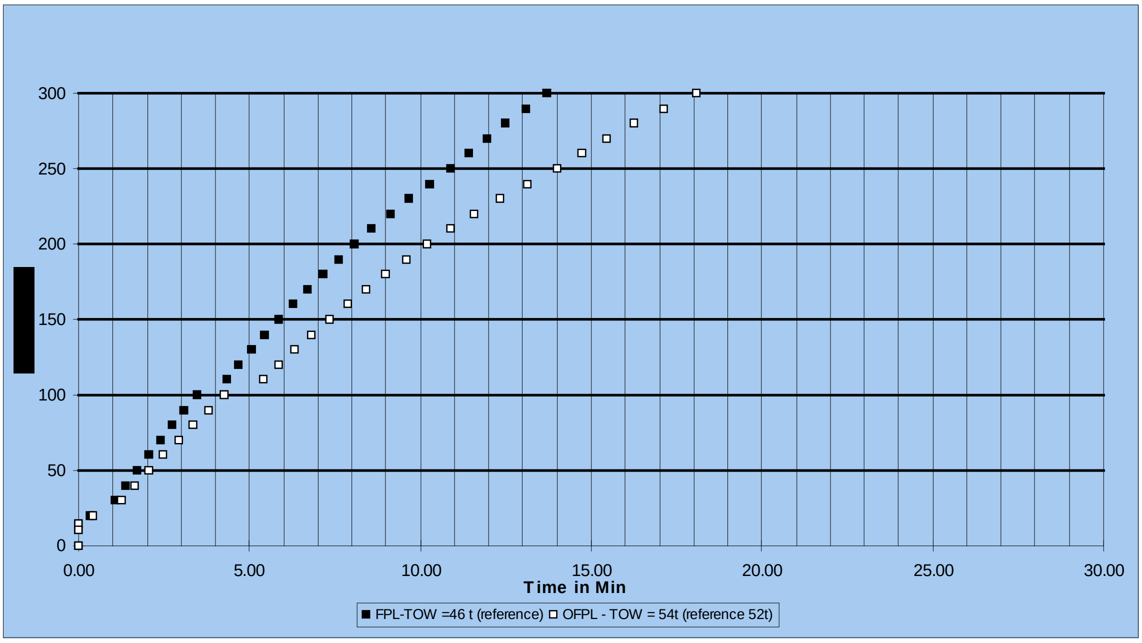

Figure 48: Difference in time between a climb based on reference TOW (FPL) and on the TOW extracted form OFPL

The Cleared Flight Level is 290. The difference in distance and time to reach FL290 is about 26 NM and 4mn.

Figures 49 and 50 show profiles of an A320 of a major airline. The weight is not given in the FPL so a typical take-off weight of 62t is taken as reference. In the OFPL the given TOW is of 73.5t.

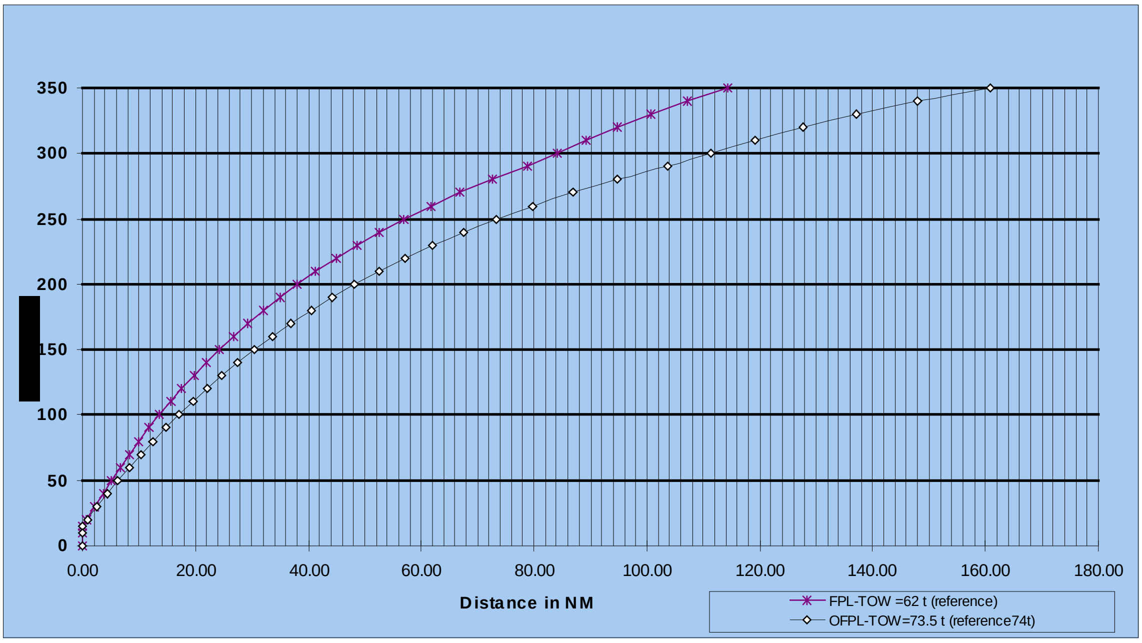

Figure 49: Difference in distance between a climb based on reference TOW (FPL) and on the TOW extracted form OFPL

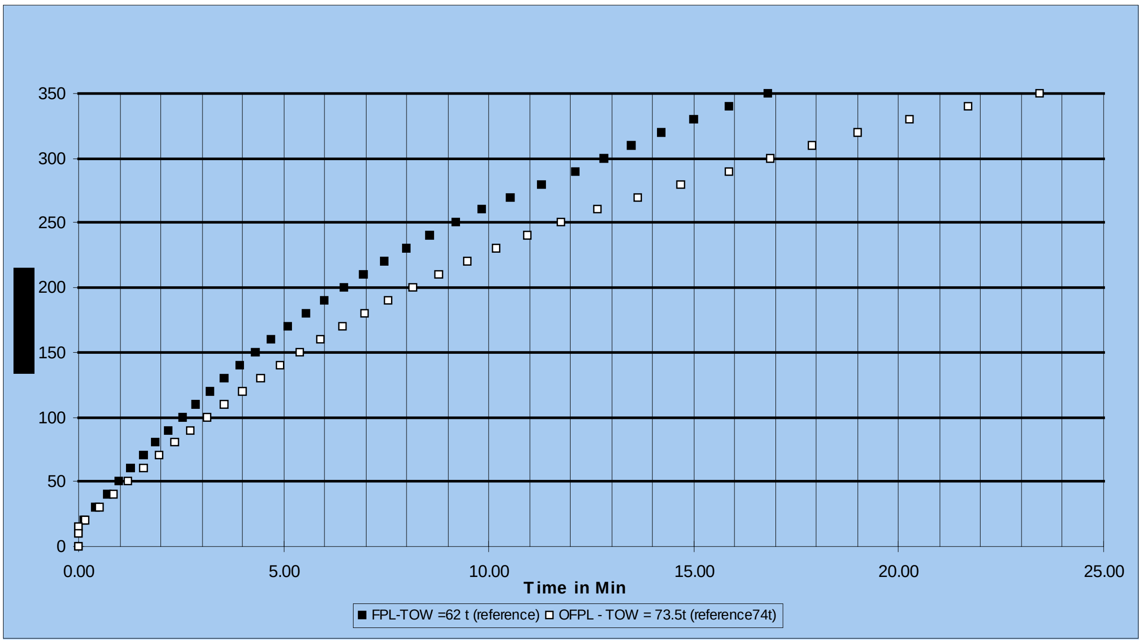

Figure 50: Difference in time between a climb based on reference TOW (FPL) and on the TOW extracted form OFPL

The Cleared Flight Level is 350. The difference in distance and time to FL350 is about 46 NM and 6mn.

APPENDIX F - WIND EFFECT

Errors between the forecasted and actual wind have an effect on the trajectory, as demonstrated in this section.

APPENDIX F .1 ATR42

TOW: 17 t

Speed : 160 kts

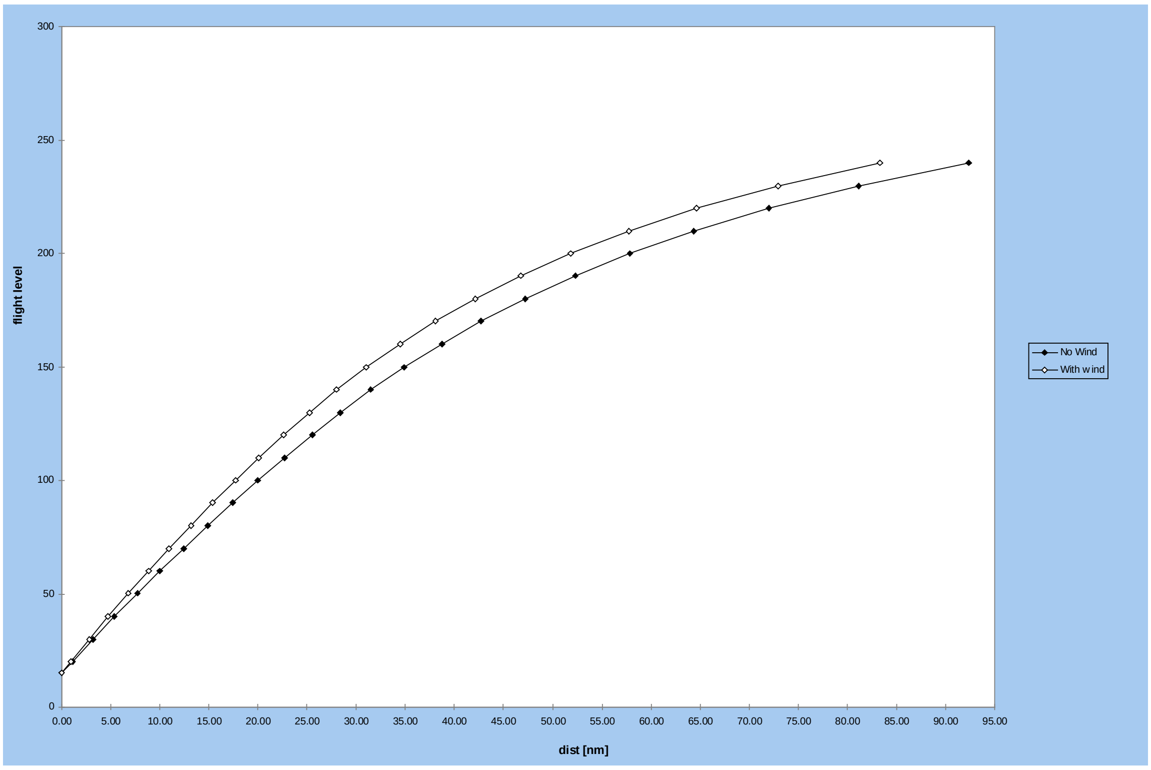

Figure 51: Effect of a 20 knots head wind on ATR42 climb

Figure 51 shows that the wind affects the climb of the ATR42: with a 20 knot headwind error the TOC is reached about 10 nm earlier.

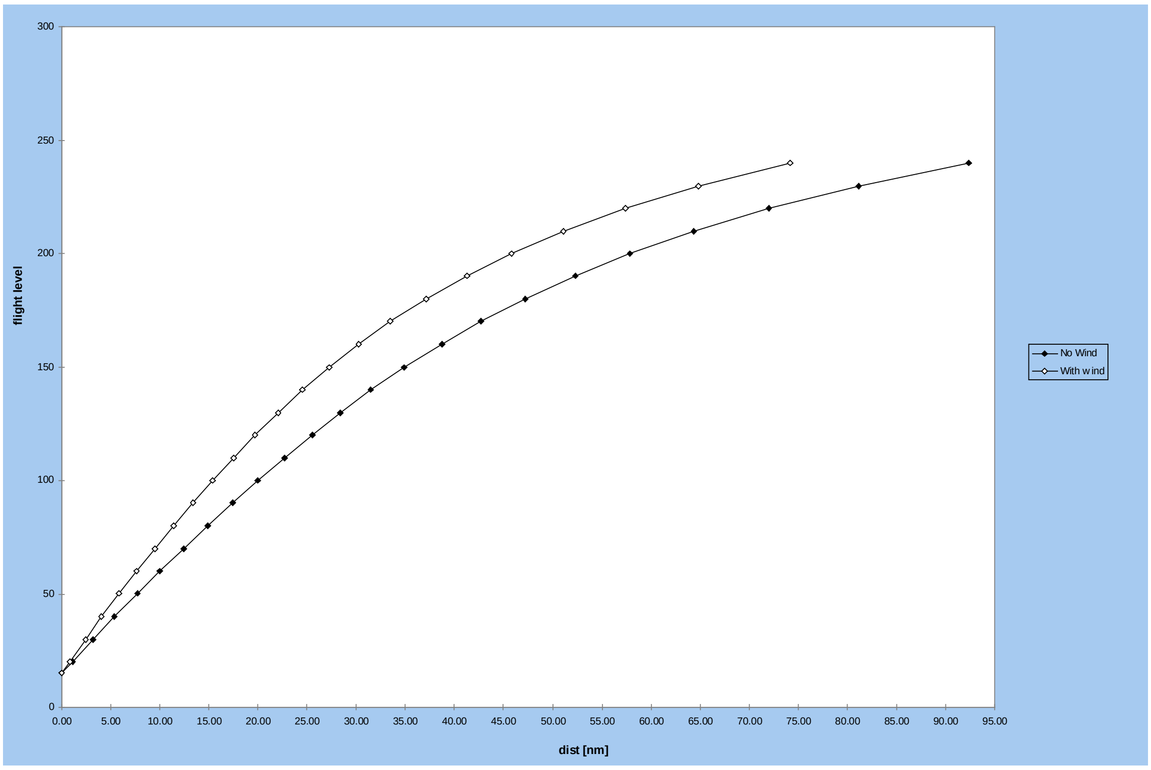

Figure 52: Effect of a 40 knots head wind on ATR42 climb

Figure 52 shows that the wind affects the climb of the ATR42: with a 40 knot headwind the TOC is reached about 20 nm earlier.

APPENDIX F .2 EA32

TOW: 74 t

Speed : 300 kts

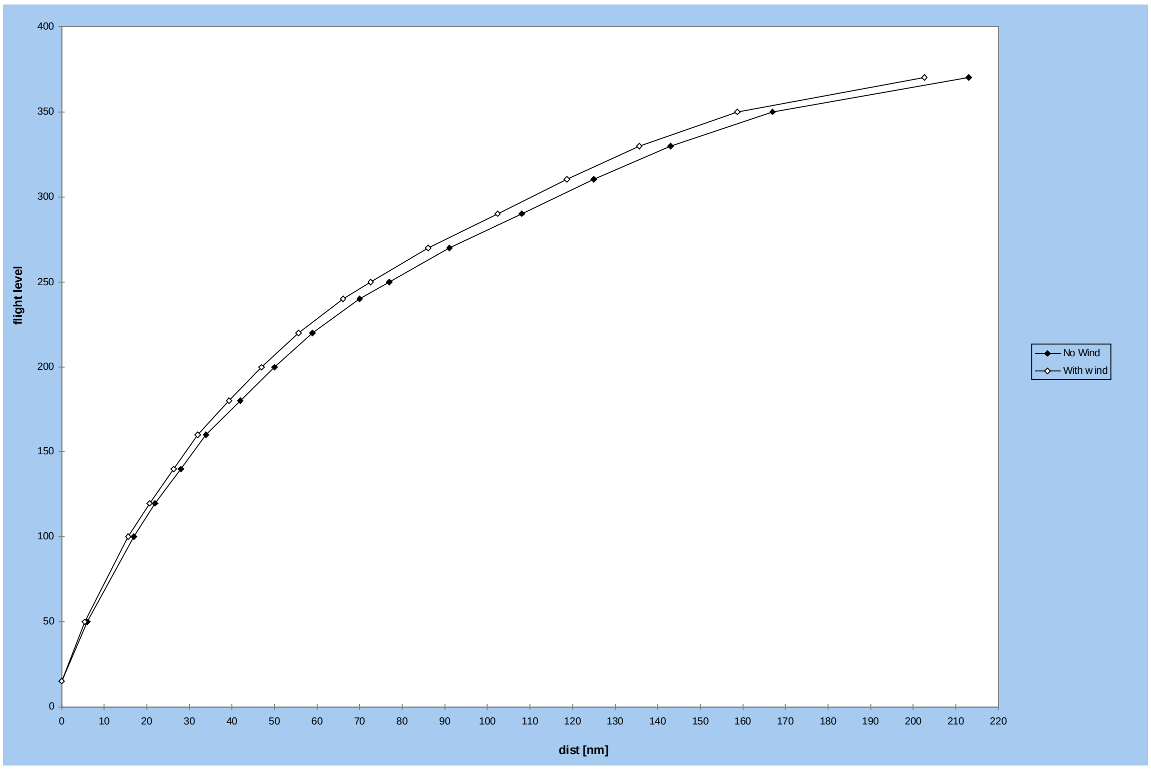

Figure 53: Effect of a 20 knot headwind on EA32 climb

Figure 53 shows that the wind affects the climb of the EA32: with a 20 knot headwind the TOC is reached about 10 nm earlier.

APPENDIX F .3 B747

TOW: 290 t

Speed : 360 kts

Figures 54 and 55 show that the wind affects the climb of the B747: with a 20 knot headwind the TOC is reached about 7 nm earlier and with a 60 knot headwind the TOC is reached about 25 nm earlier.

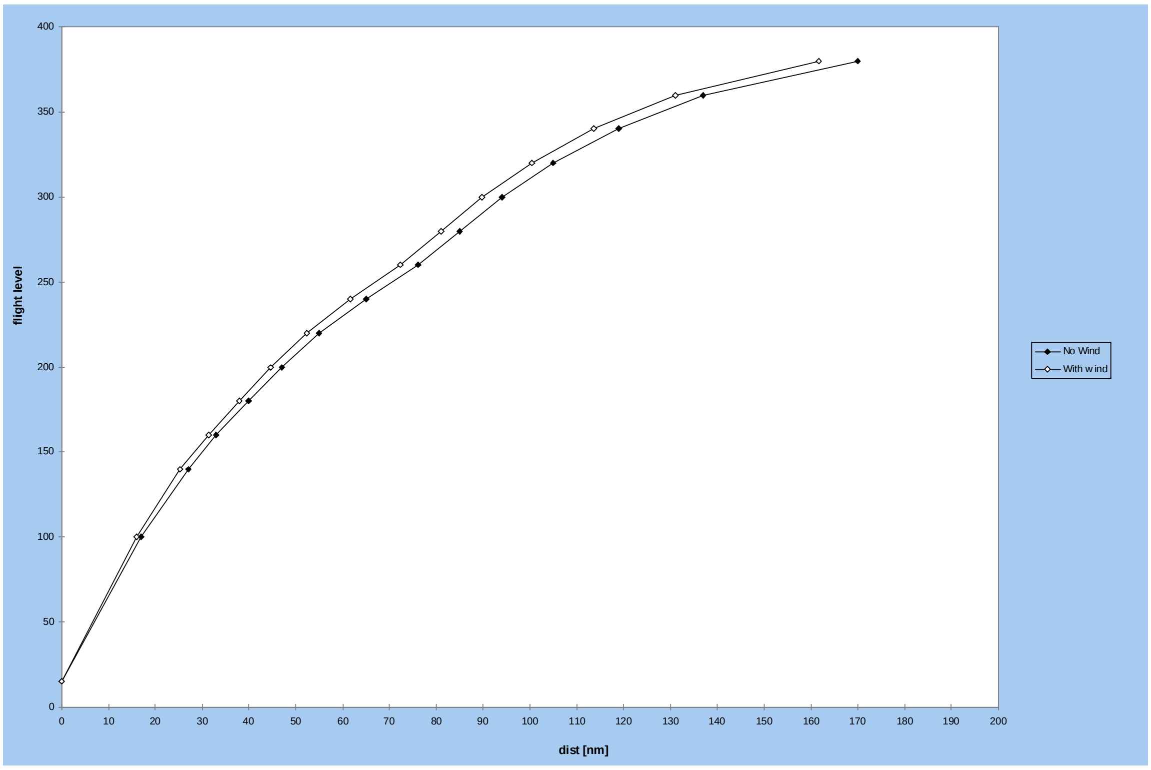

Figure 54: Effect of a 20 knot headwind on B747 climb

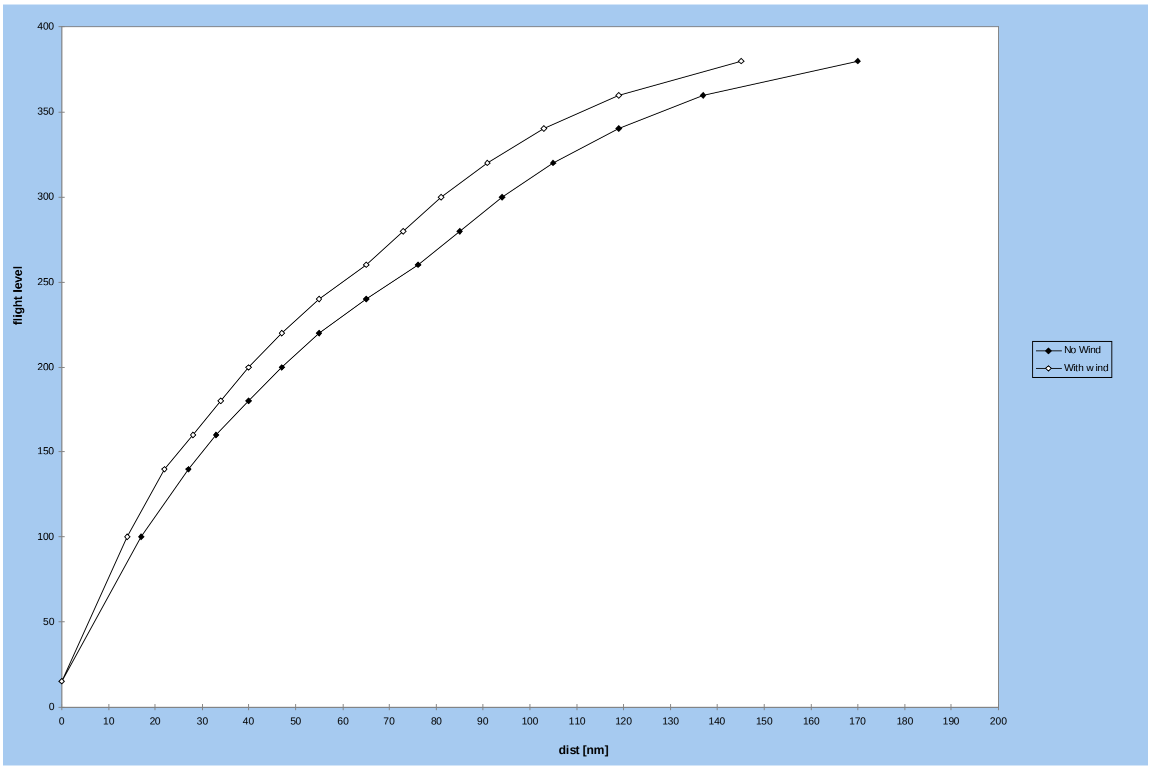

Figure 55: Effect of a 60 knots head wind on B747 climb

APPENDIX F .4 CONCLUSION

A/C type	TOC/CFL (FL)	Wind (knots)	Difference in NM
ATR42	240	20	10
ATR42	240	40	20
EA32	370	20	10
B747	380	20	7
B747	380	60	25

Differences between the wind used to calculate predictions and the true wind have an important impact on the climb phase and hence should be taken into account in trajectory prediction. Wind impacts the distance but not the time to reach a specific flight level.

APPENDIX G - TEMPERATURE EFFECT

This section concerns the impact of errors in the temperature used for trajectory prediction and the true temperature.

APPENDIX G .1 ATR42

TOW: 17 t, speed : 160 kts

Figures 56 and 57 show that a temperature error of 10C results in the TOC is reached about 10 nm and 4.5 min. later.

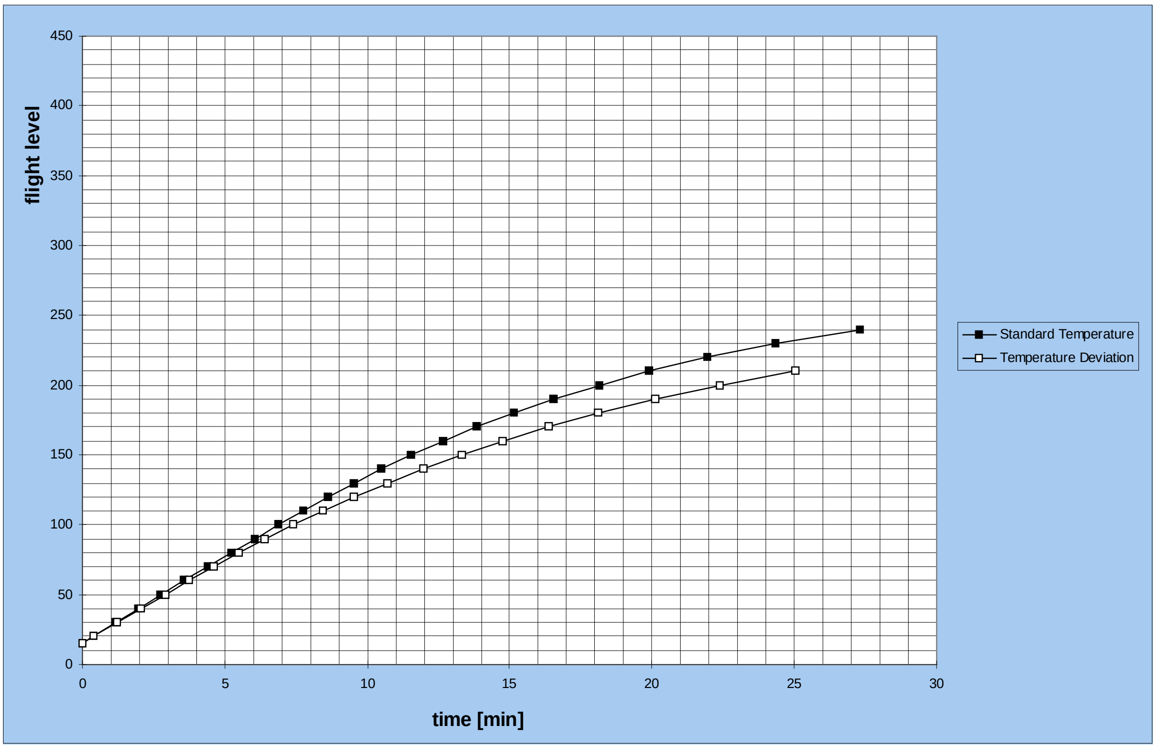

Figure 56: Effect of a 10C temperature deviation on ATR42 climb (time)

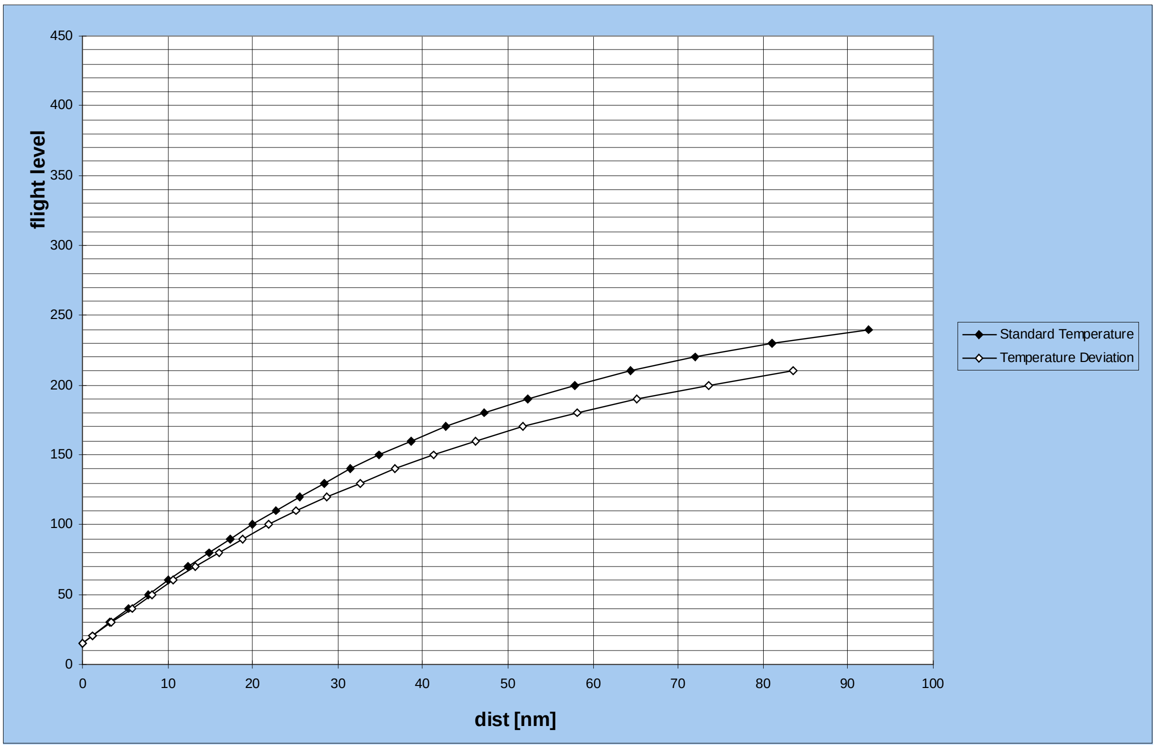

Figure 57: Effect of a 10C temperature deviation on ATR42 climb (distance)

APPENDIX G .2 EA32

TOW: 62 t, Speed : 300 kts

Figures 58 and 59 show that a 10C temperature error means the TOC is reached about 1 min. and 10nm later.

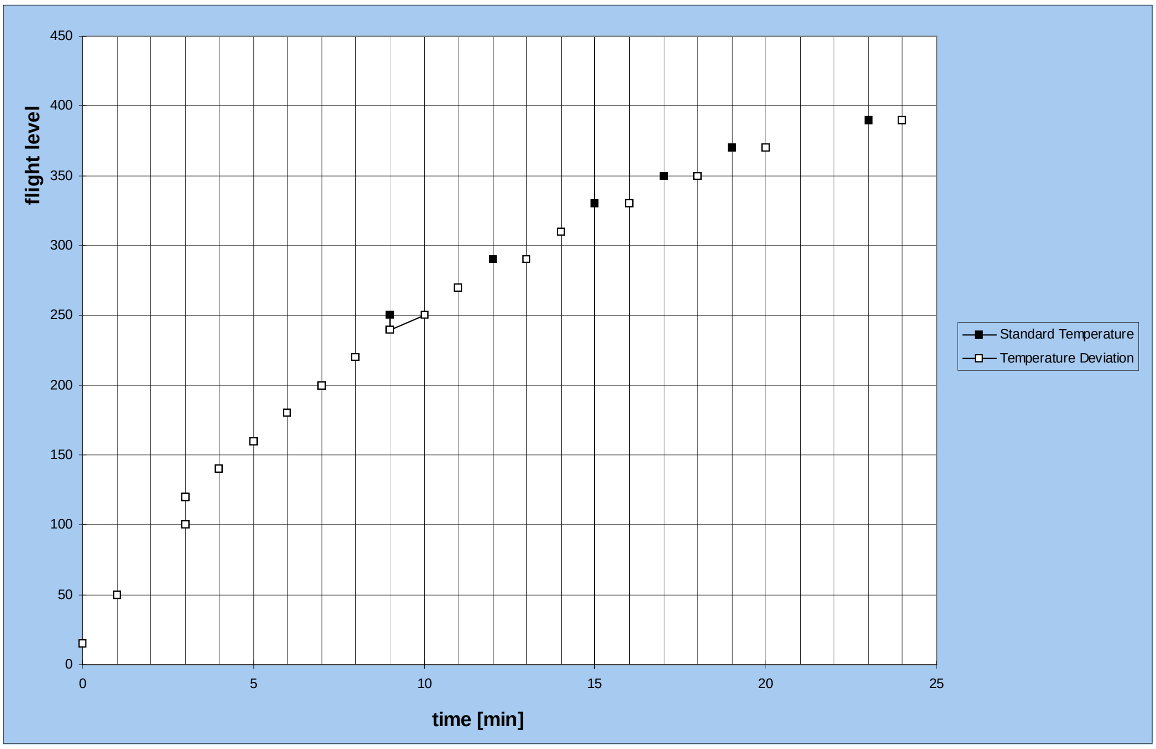

Figure 58: Effect of a 10C temperature deviation on EA32 climb (time)

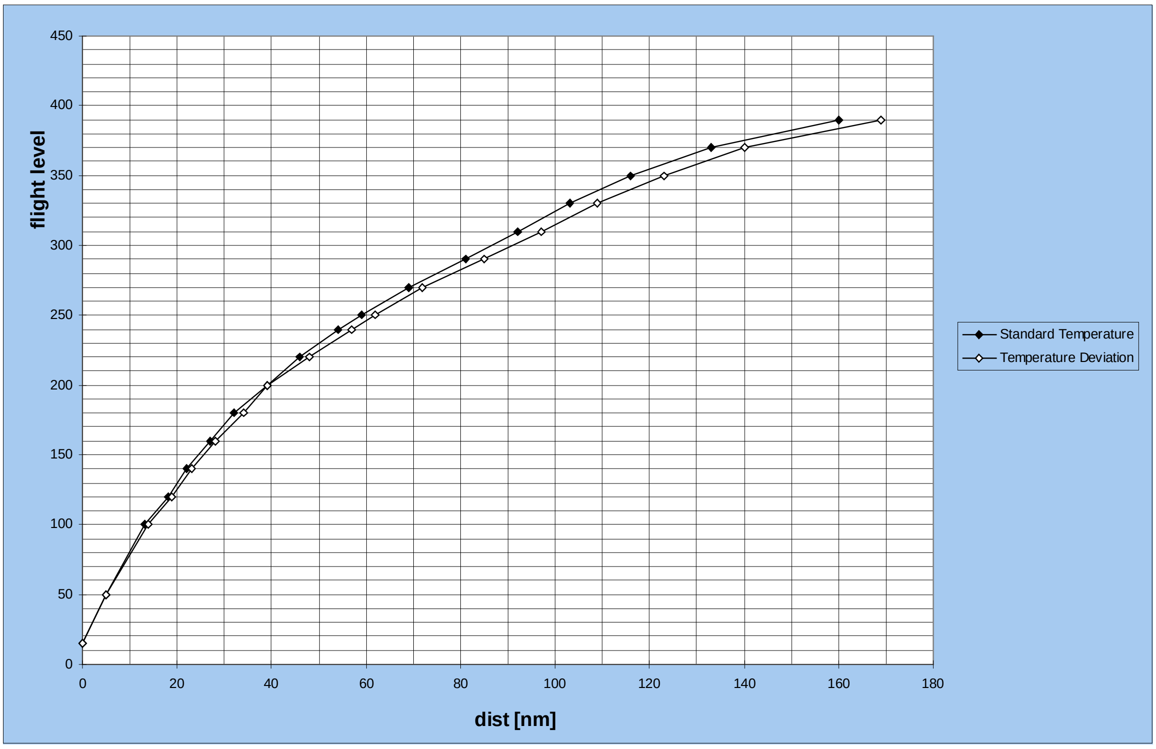

Figure 59: Effect of a 10C temperature deviation on EA32 climb (distance)

APPENDIX G .3 CONCLUSION

Table 4 below summarises the above results.

A/C type	CFL (FL)	Temperature deviation in degrees	Difference in time to CFL(min)	Difference to CFL (nm)
ATR42	200	10	4.5	15
EA32	390	10	1	10

Table 4: Synthesis of the temperature effect on a climb

The table shows that temperature errors have an impact on the climb phase and hence should be taken into account in trajectory prediction.