Nationaal Lucht- en Ruimtevaartlaboratorium
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Pre Implementation Collision Risk Assessment for RVSM in the Africa Indian Ocean Region

G. Moek and J.W. Smeltink

Executive summary

Pre Implementation Collision Risk Assessment for RVSM in the Africa Indian Ocean Region

Following the implementation of a Reduced Vertical Separation Minimum (RVSM) in other ICAO Regions, the implementation of RVSM in the AFI Region is currently planned for September 2006. An important element in the implementation process is the AFI RVSM Safety Policy. Based on ICAO regulations, the AFI RVSM Safety Policy lists two specific safety objectives for collision risk assessment, namely an assessment of the technical vertical risk against a Target Level of Safety (TLS) of 2.5×10^{-9} fatal accidents per flight hour, and an assessment of the total vertical risk against a TLS of 5×10^{-9} fatal accidents per flight hour. This report presents the pertinent pre implementation collision risk assessments based on the best possible data and information available prior to the actual implementation.

In line with RVSM guidance material and with previous RVSM collision risk assessments, appropriate vertical collision risk models for the AFI Region have been specified. The models have been used to estimate the vertical collision risk under AFI RVSM. The estimate of the technical vertical collision risk meets the technical vertical TLS of 2.5×10^{-9} fatal accidents per flight hour but the estimate of the total vertical collision risk does not meet the total vertical TLS of 5×10^{-9} fatal accidents per flight hour. Significant risk mitigating measures have to be taken to reduce the number of vertical incidents and to bring the estimate of the total vertical collision risk below the total vertical TLS.

The estimate of the technical vertical collision risk is affected by a number of limitations in the traffic flow data used for estimating the passing frequency parameter of the collision risk model. Steps must be taken to make the passing frequency estimates more reliable. The estimate of the total vertical collision risk is most likely affected by under-reporting of operational vertical incidents. Measures are required to ensure proper incident reporting.

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Summary

This report presents a pre implementation collision risk assessment of the implementation of a Reduced Vertical Separation Minimum (RVSM) in the Africa - Indian Ocean (AFI) Region. It concerns two of the AFI RVSM Safety Policy objectives, namely an assessment of the technical vertical risk against a Target Level of Safety (TLS) of 2.5×10^{-9} fatal accidents per flight hour, and an assessment of the total vertical risk against a TLS of 5×10^{-9} fatal accidents per flight hour. The assessments are pre implementation assessments based on the best possible data and information available prior to the actual implementation.

In line with RVSM guidance material and with previous RVSM collision risk assessments, appropriate vertical collision risk models for the AFI Region have been specified. The models have been used to estimate the vertical collision risk under AFI RVSM. The estimate of the technical vertical collision risk meets the technical vertical TLS of 2.5×10^{-9} fatal accidents per flight hour but the estimate of the total vertical collision risk does not meet the total vertical TLS of 5×10^{-9} fatal accidents per flight hour. Significant risk mitigating measures have to be taken to reduce the number of vertical incidents and to bring the estimate of the total vertical collision risk below the total vertical TLS.

The estimate of the technical vertical collision risk is affected by a number of limitations in the traffic flow data used for estimating the passing frequency parameter of the collision risk model. Steps must be taken to make the passing frequency estimates more reliable. The estimate of the total vertical collision risk is most likely affected by under-reporting of operational vertical incidents. Measures are required to ensure proper incident reporting.

List of acronyms

AAD	Assigned Altitude Deviation
ACAS	Airborne Collision Avoidance System
ACC	Area Control Centre
AFI	Africa - Indian Ocean
AIAG	ATS Incident Analysis working Group
ARMA	African Regional Monitoring Agency
ASE	Altimetry System Error
ASECNA	L'Agence pour la Sécurité de la Navigation Aérienne en Afrique et à Madagascar
ATC	Air Traffic Control
ATM	Air Traffic Management
ATS	Air Traffic Services
CAA	Civil Aviation Authority
CNS	Communication Navigation and Surveillance
CO	Crossing Opposite
CRA	Collision Risk Assessment
CS	Crossing Same
CVSM	Conventional Vertical Separation Minimum
DDE	Double Double Exponential
DME	Distance Measuring Equipment
DRC	Democratic Republic of Congo
DS	Direct Speech
EUR	Europe(an)
FA	False Alert
FHA	Functional Hazard Assessment
FIR	Flight Information Region
FIS	Flight Information Service
FL	Flight Level
Ft	Foot
G	Gaussian
GDE	Gaussian Double Exponential
GNSS	Global Navigation Satellite System
H	Horizontal
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFBP	In Flight Broadcasting Procedure

IFR	Instrument Flight Rules
LoA	Letter of Agreement
MASPS	Minimum Aircraft System Performance Specification
MHz	Mega Hertz
NAT	North Atlantic
NDB	Non Directional Beacon
NLR	National Aerospace Laboratory NLR
NM	Nautical Mile
OAG	Official Airline Guide
OB	Outside flight level Band
PISC	Pre Implementation Safety Case
RA	Resolution Advisory
RCF	Radio Communication Failure
RNAV	Area Navigation
RVSM	Reduced Vertical Separation Minimum
SAT	South Atlantic
TBD	To Be Defined
TLS	Target Level of Safety
UIR	Upper (Flight) Information region
VHF	Very High Frequency
VOR	Very high frequency Omnidirectional Radio
WC	Wrong level Crossing
WO	Wrong level Opposite
WS	Wrong level Same

Change record

Version	Issue date	Change description
0.1	250705	First issue for internal review (with the exception of section 4).
0.2	150805	Processing of internal review comment. Inclusion of section 4. Update of section 5. Minor editorial corrections.
0.3	180805	Processing of internal review comment section 4. Minor editorial corrections. Final conclusions added.
1.0	190805	Released issue.

Contents

(129 pages in total)

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1 Introduction

This report presents the pre implementation Collision Risk Assessment of the implementation of a Reduced Vertical Separation Minimum, RVSM, in the Africa - Indian Ocean (AFI) Region. This implementation is scheduled for 28th September 2006 and is to be preceded by a stakeholder meeting in June 2006 to formally assess the region's readiness for implementation (Ref. 1). Major inputs to this meeting are the readiness of States, Air Traffic Service providers, aircraft operators and the Pre Implementation Safety Case (PISC). The PISC provides argument and evidence that all the safety objectives and requirements will be met when RVSM is implemented.

The safety objectives have been laid down in the AFI RVSM Safety Policy (Ref. 2). The policy prescribes among other things the conduct of a Collision Risk Assessment (CRA) and a Functional Hazard Assessment (FHA). Both assessments have been performed on behalf of the African Regional Monitoring Agency (ARMA) under a single project lead by the National Aerospace Laboratory NLR. NLR has performed the CRA part whereas the FHA part was performed by ALTRAN Technologies – CNS/ATM Division. The results of the FHA are available in reference 3.

Based on ICAO regulations (Refs. 4 and 5), the AFI RVSM Safety Policy lists two specific safety objectives for collision risk assessment, namely an assessment of the technical vertical risk against a Target Level of Safety, TLS, of 2.5×10^{-9} fatal accidents per flight hour, and an assessment of the total vertical risk against a TLS of 5×10^{-9} fatal accidents per flight hour. In line with the RVSM guidance material of reference 5 and with previous RVSM collision risk assessments, the two current assessments are based on appropriate vertical collision risk models for the AFI region. The assessments are pre implementation assessments based on the best possible data and information available prior to the actual implementation.

The safety assessments rely heavily on the characteristics of the airspace under consideration. Thus, section 2 of this report begins with an overview of the upper airspace in the AFI Region between FL290 and FL410 inclusive. Section 3 presents the assessment of the technical vertical collision risk and section 4 the assessment of the total vertical collision risk, i.e. the vertical collision risk due to all causes. Conclusions and recommendations are given in section 5. The information in this report will form one of the major inputs to the PISC (Ref. 6).

2 Airspace description

2.1 Introduction

This section provides a description of those elements of the African and Indian Ocean airspace that are related to the safety assessment of RVSM operations in the region. The 53 States that are participating in AFI RVSM (Ref. 7) and the FIR/UIRs involved (Ref. 8) are shown in table 2.1. Some FIR/UIRs comprise more than one State and some States' airspace is distributed over more than one FIR/UIR. Notice that the following FIR/UIRs are currently RVSM transition airspace for the European region: Algiers, Cairo, Casablanca, Tripoli and Tunis.

Transition tasks, if any, associated with the application of a 1000 ft vertical separation minimum within the AFI RVSM airspace shall be carried out in all or parts of the following FIR/UIRs: Abidjan, Addis Ababa, Algiers, Asmara, Cairo, Canarias, Casablanca, Dakar, Johannesburg, Khartoum, Luanda, Mauritius, Mogadishu, Roberts, Sal, Seychelles, Tripoli, Tunis.

State	**FIR/UIR**	**State**	**FIR/UIR**
Algeria	Algiers	Libya	Tripoli
Angola	Luanda	Madagascar	Antananarivo
Benin	Accra	Malawi	Lilongwe
Botswana	Gaborone	Mali	Dakar/Niamey
Burkina Faso	Niamey	Mauritius	Mauritius
Burundi	Bujumbara	Morocco	Casablanca
Cameroon	Brazzaville	Mozambique	Beira
Cape Verde	Sal Oceanic	Namibia	Windhoek
Central African Republic	Brazzaville/ N'Djamena	Niger	Niamey
Chad	N'Djamena	Nigeria	Kano
Comores	Antananarivo	Réunion	Réunion
Congo	Brazzaville	Rwanda	Kigali
Cote D'Ivoire	Dakar	Sao Tome and Principe	Brazzaville
DR Congo (Zaire)	Kinshasa	Senegal	Dakar Dakar Oceanic
Djibouti	Addis Ababa	Seychelles	Seychelles
Egypt	Cairo	Sierra Leone	Roberts
Equatorial Guinea	Brazzaville	Somalia	Mogadishu
Eritrea	Asmara	South Africa	Cape Town Johannesburg

			Johannesburg Oceanic
Ethiopia	Addis Ababa	Sudan	Khartoum
Gabon	Brazzaville	Swaziland	Matsapha
Gambia	Dakar	Tanzania	Dar Es Salaam
Ghana	Accra	Togo	Accra
Guinea	Roberts	Tunisia	Tunis
Guinea Bissau	Dakar	Uganda	Entebbe
Kenya	Nairobi	Zambia	Lusaka
Lesotho	Johannesburg	Zimbabwe	Harare

Table 2.1 States and FIR/UIRs participating in AFI RVSM[1, 2, 3, 4]

2.2 Route network and traffic flows

The route network and traffic flows have an impact on the frequency with which, on average, an aircraft passes another aircraft, i.e. on the amount of exposure to the risk due to the loss of vertical separation. Figure 2.1 shows the region's major route network. The main traffic flows are north-south, entering and exiting in the northern African states on the UA854, UM608, UM998, UM731, UB655, UB612 and the UR611. The east-west route UM999 connects the northern African States to Jeddah in Saudi Arabia (see also section 2.5). In addition, there is a triple of east-west routes in the middle part of Africa, namely the UM976-UG854-UA620-UB736, UA601-UB736 and UA601-UA609-UB532-UG450.

Without any direct information on the total number of flights in the AFI Region, a crude estimate has been obtained for the year 2003 as follows. For this year, the OAG database included approximately 606000 scheduled flights with both origin and destination within Africa and approximately 297000 scheduled flights with either the origin or destination in Africa (Ref. 9). Thus, approximately 67% of the total number of 903000 scheduled flights were made within Africa and 33% had an origin or destination outside of Africa. Reference 10 suggests a ratio of 81.5% / 18.5% between scheduled flights and non-scheduled flights. Application of this ratio gives a total of approximately 1,108,000 flights for Africa during the year 2003.

[1] Réunion is not in the list of provider states in the APIRG Procedural Handbook; Mauritania in the Handbook is not included in Table 2.1. Canaries is not included.
[2] Bujumbara, Dakar Oceanic, Johannesburg Oceanic and Kigali are not listed in the Doc 7030 Amendment proposal.
[3] Lesotho and Swaziland are covered by South Africa.
[4] The upper airspace of Djibouti is covered by Addis Ababa, the upper airspace of the Comores by Antananarivo, and the upper airspace of Sao Tome and Principe by Brazzaville.

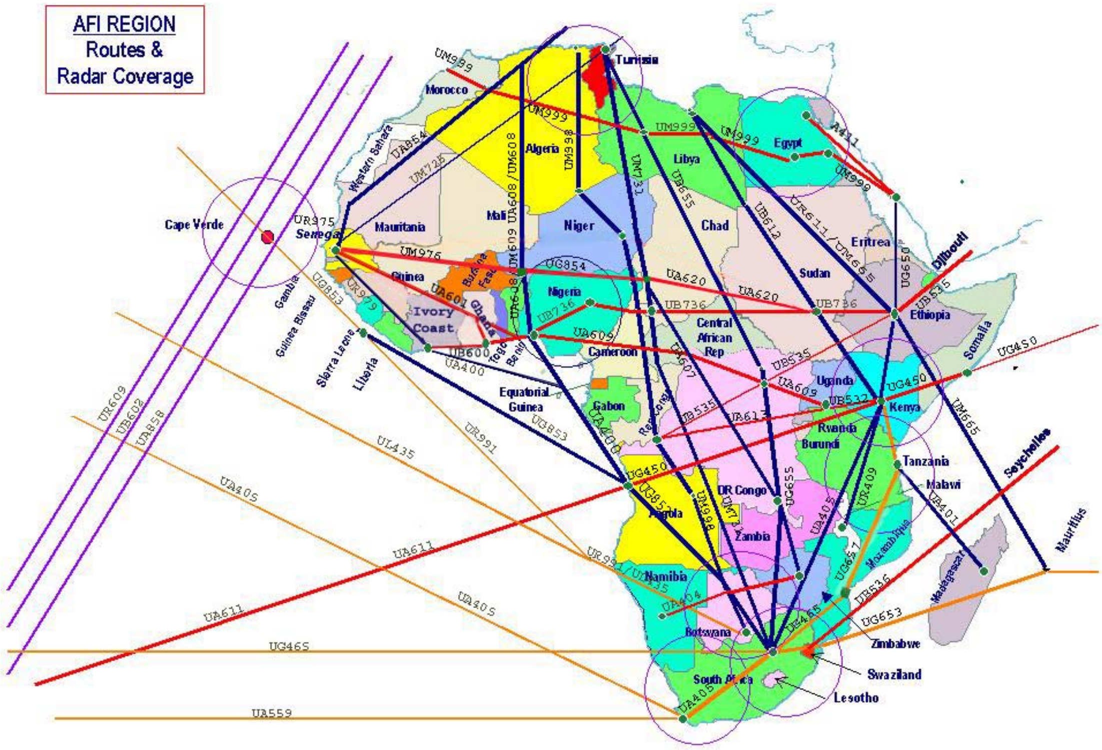


Figure 2.1 Major routes and radar coverage in AFI Region

The cruising levels (at or above FL290) currently in use in (most of) the FIR/UIRs are shown in table 2.2 and those to be used under RVSM are shown in table 2.3 (Ref. 11).

180° – 359° EVEN FL	360° – 179° ODD FL
310	290
350	330
390	370
Etc.	Etc.

Table 2.2 Cruising levels currently in use at or above FL290

180° – 359° RVSM	**360° – 179° RVSM**
FL300	FL290
FL320	FL310
FL340	FL330
FL360	FL350
FL380	FL370
FL400	FL390
	FL410

Table 2.3 Cruising levels to be used in AFI RVSM airspace

Based on information provided by States (Form 2, monthly movements, cf. section 2.6), figures 2.2 and 2.3 show the numbers of flights per month between FL290 and FL410 inclusive for the months November 2004 up to May 2005. Since some States also reported monthly movements for the period of time prior to November 2004, the diagram has been extended from January 2004 up to May 2005. It is remarked that the information in Form 2 is not necessarily consistent with that in Form 4 (traffic flow data).

Also based on the information in Form 2, it is estimated that approximately 80% of the flying time in the flight level band between FL290 and FL410 consists of level flight and 20% of climbing and descending.

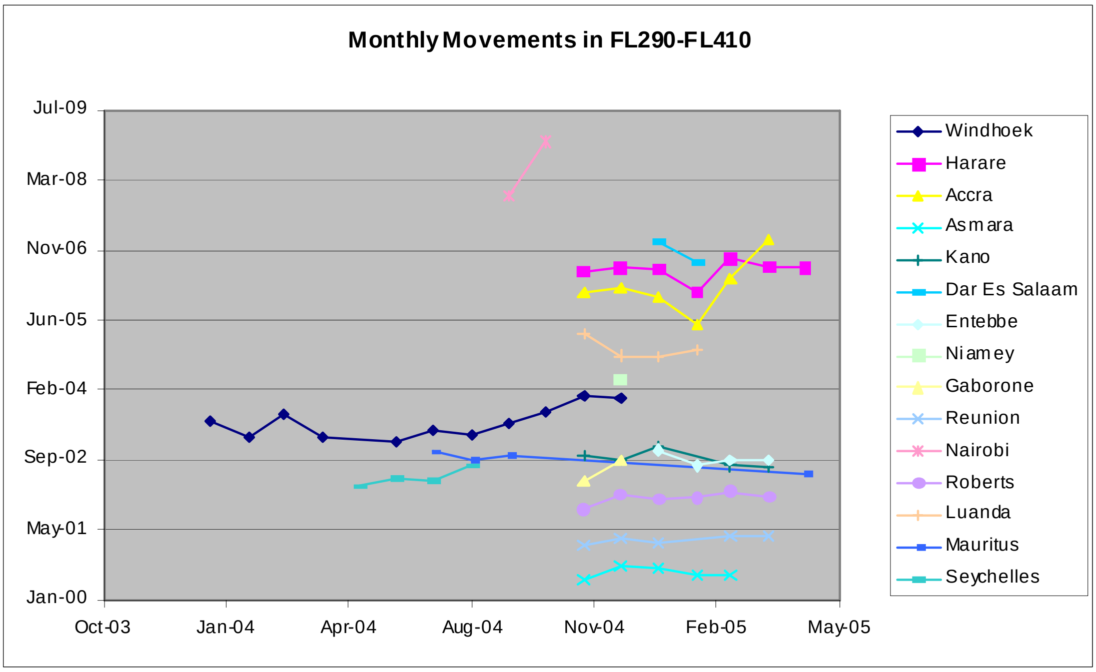


Figure 2.2 Number of flights per month between FL290 and F410 per FIR

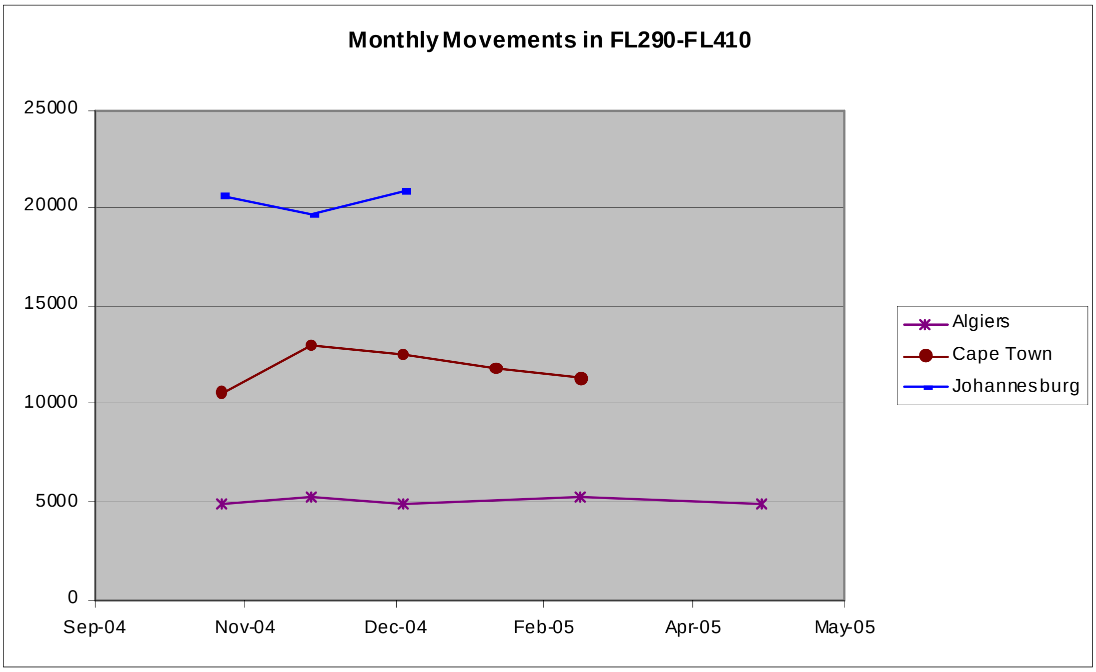


Figure 2.3 Number of flights per month between FL290 and F410 per FIR

2.3 Air traffic services and procedures

All flights in the AFI Region above FL150 shall be conducted IFR and flying outside of ATS routes is prohibited in many African countries (Refs. 11, 12). Table 2.4 shows the airspace classification for the FIR/UIRs involved in AFI RVSM (Ref. 11). The level of air traffic services may have an impact on collision risk.

FIR/UIR	**Airspace classification**	**Remarks**
Asmara	A	ATS Routes Class A
Accra FIR	G	CLASS (A): UA-560, UA-601 (TMA-TYE-POLTO), UA-608 (TYE-TMA), UA-609,UB-600, UB726, UR 983 (LM-TMA) CLASS (C): UG-865 CLASS (D): UA-601,UA603, UA-608, UB-600, UR-603, UR-981, UR-982, UR-983(LM-TMA) CLASS (F): UA-400, UR-979 CLASS (G): UG-853, UR-603, UR-981
Addis Ababa FIR	G	Airways within Addis Ababa FIR are class (A). All ATS routes prefixed W (white) within Addis Ababa FIR are for domestic use only.
Algiers FIR	G	ATS Routes Class A, D, F, G
Antananarivo UIR	G	ATS routes within Antananarivo UIR outside controlled airspace are classified (F) or (G)
Beira UIR	F	All ATS routes prefixed 'W' within Beira UIR are for use by domestic operators only.
Brazzaville UIR	G	ATS routes within Brazzaville UIR outside controlled airspace are classified (F) or (G). Advisory routes within Brazzaville UIR are classified F.
Bujumbura	G	Class A above FL245 controlled by Dar Es Salaam
Cairo FIR	A	ATS routes within Egypt are class (A). Victor ATS-routes within Cairo FIR are available for domestic national flights, other flights prior permission required.
Cape Town FIR	A	ATS Routes Class A
Casablanca FIR	G	Airways within Casablanca FIR are classified (A) Advisory routes (F).

		All airways within Casablanca FIR except UA-857, UA-873, UN-857, UN-858, UN-866 and UN-873 are conventional usable.
Dakar UIR	G	ATS routes within Dakar UIR outside controlled airspace are classified (F) or (G)
Dakar Oceanic UIR	D	ATS Routes Class A
Dar Es Salaam	A	ATS Routes Class A
Entebbe	G	Airways within Entebbe FIR are class (A)
Gaborone FIR	G	ATS Routes Class A, G
Harare UIR	UIR(G)/ UTA(C)	ATS Routes Class C
Johannesburg FIR	A	ATS Routes Class C
Johannesburg Oceanic FIR	A	ATS Routes Class A
Kano FIR	F/G	ATS routes within Kanao FIR outside controlled airspace are classified (F) or (G). Advisory routes within Kano FIR are classified (F).
Khartoum UIR	G	class (A): airways UA-727, UG-660 (Khartoum VORDME – port Sudan VORDME) & UB-526 class (C): airways A-727, G-660 class (F): advisory routes class (G): FIS routes
Kigala	A	Class A above FL245 controlled by Dar Es Salaam
Kinshasa UIR	G	Flight routes shown within DR of Congo are for information only. Permission to operate along these routes is subject to ATC discretion. All Hotel, Juliett, Victor & Whiskey ATS routes within DR of Congo are for use by domestic operators only.
Lilongwe FIR	G	ATS Routes Class A
Luanda UIR	G	ATS Routes Class G
Lusaka	G	ATS routes outside controlled airspace within Lusaka FIR are class (F).
Mauritius	A	ATS Routes Class A
Mogadishu	G	ATS Routes Class G
Nairobi FIR	G	AWYS(A)
N'Djamena UIR	G	ATS routes within N'Djamena UIR outside

		controlled airspace are classified (F) or (G).
Niamey UIR	G	ATS routes within Niamey FIR outside controlled airspace are classified (F) or (G)
Roberts FIR	G	Airways within Roberts FIR are classified (A)
SAL Oceanic UIR	A	ATS Routes Class A
Seychelles	A	ATS Routes Class A
Tripoli	G/A	Airways within Tripoli FIR are class (A), advisory routes are class (F).
Tunis UIR	G	Airways within Tunis UIR are class (A)
Windhoek	G	ATS Routes Class A

Table 2.4 Airspace classification for AFI region

It should be noted that some States provide air traffic services in the upper airspace for other States (e.g. Lesotho is covered by South Africa). Furthermore, some States collaborate to provide air traffic services; Roberts FIR, for example, is a collaboration of Sierra Leone, Liberia and Guinee. ASECNA (L'Agence pour la Sécurité de la Navigation Aérienne en Afrique et à Madagascar) is a collaboration of 16 French-speaking African states. In the upper airspace, ASECNA provides air traffic services for the following FIR/UIRs: Antananarivo, Brazzaville, Dakar, Dakar Oceanic, Niamey, and N'Djamena.

Two important elements of air traffic control services are radar surveillance and communication. Although radar surveillance coverage is very limited for the AFI region, nine areas have been marked in figure 2.1. More precise coverage areas may be found in reference 13. Most of area control in the AFI Region is procedural. As regards communication, each of the States in the AFI Region has several VHF stations, some ranging up to 200 NM. Some examples of VHF coverage in some States may again be found in reference 13. The VHF coverage contains some holes and communication problems are known to exist in the region (Ref. 14). Communication problems may have an impact on the safety of vertical separation (see Ref. 3).

The en route ground navigation infrastructure consists of NDBs and VOR/DMEs. Some of the routes in AFI RVSM airspace are RNAV routes. Aircraft navigation accuracy has an influence on the probability of two aircraft being in horizontal overlap and hence on the exposure to the risk due to the loss of vertical separation.

The minimum longitudinal separation in the AFI region is 10 minutes (Ref. 12). This quantity has an influence on the exposure to the vertical collision risk for aircraft on adjacent flight levels. Speed management is not utilised in en-route operations.

With effect from 1 January 2000, all aircraft operating as IFR flights in the AFI Region shall be equipped with a pressure-altitude reporting transponder (Ref. 12). With effect from 1 January 2005, all civil fixed-wing turbine-engined aircraft having a maximum take-off mass exceeding 5700 kg or a maximum approved passenger seating configuration of more than 19 shall carry and operate ACAS II (Ref. 12). ACAS can have a significant effect on air traffic control. Following an RA event, or other ACAS event, pilots and controllers should complete an ACAS RA report; aircraft operators and ATS authorities should forward the completed reports through established channels. This is one of the types of data collected from States by ARMA on a monthly basis for the benefit of the CRA.

The following procedures that may be relevant to the CRA of AFI RVSM have been taken from reference 8:

- All IFR flights shall comply with the procedures for air traffic advisory service when operating in advisory airspace.
- Controlled flights and certain IFR flights outside controlled airspace are required to maintain a continuous listening watch on the appropriate radio frequency and to report positions in specified circumstances (Annex 2 and PANS-ATM 4.11 (Refs. 15, 16)). More specifically, all aircraft on IFR flights outside controlled airspace shall maintain a watch on a radio station furnishing communications for the unit providing flight information service in the flight information region and file with that station information as to their position unless otherwise authorised by the State overflown. Position reports additional to those required by the general position-reporting procedures shall be made when entering or leaving controlled or advisory airspace.
- The pilot shall inform air traffic control as soon as possible of any circumstances where the vertical navigation performance requirements for the AFI Region cannot be maintained. When informed by the pilot of an RVSM approved aircraft operating in the AFI RVSM airspace that the aircraft's equipment no longer meets the RVSM MASPS, air traffic control shall consider the aircraft as non-RVSM approved. Air traffic control shall take action immediately to provide a minimum vertical separation of 600 m (2000 ft) or an appropriate horizontal separation from all other aircraft concerned operating in the AFI RVSM airspace. When an aircraft operating in the AFI RVSM airspace encounters severe turbulence (not forecast) due to weather or wake vortex that the pilot believes will impact the aircraft's capability to maintain its cleared flight level, the pilot shall inform ATC. Air traffic control shall establish either an appropriate horizontal separation or an increased minimum vertical

separation. Air traffic control shall, to the extent possible, accommodate pilot requests for flight level and/or route changes, and pass traffic information, as required. Where a meteorological forecast is predicting severe turbulence within the AFI RVSM airspace, air traffic control shall determine whether RVSM should be suspended and, if so, the period of time, and specific flight level(s) and/or area.

- ATC shall provide a minimum vertical separation of 2000 ft between an aircraft experiencing a communications failure in flight and any other aircraft, where both aircraft are operating within AFI RVSM airspace.

Aircraft wanting to climb or descend through the level of another aircraft are to be provided with longitudinal separation where the longitudinal separation minima to be applied are given in sections 5.4.2.2.2, 5.4.2.3.2.3 and 5.4.2.3.2.4 of the PANS-ATM (Ref. 16).

2.4 Aircraft population

For the CRA, the aircraft population plays a part with respect to the overall Altimetry System Error (ASE) distribution and the definition of average aircraft dimensions. Several sources of information have (had) to be used to infer the candidate AFI RVSM aircraft population. In this context, it is useful to make a distinction between African resident and registered aircraft and non-African resident and registered aircraft. Of the latter, the majority (82 %) has been found to be flying from Europe into and out of Africa (Ref. 9). The pertinent aircraft/operators, therefore, can be assumed to be RVSM approved.

African resident and registered aircraft types operating FL290 - FL410 in the AFI Region under the conventional vertical separation minimum (CVSM) of 2000 ft in the year 2004 have been inventoried in reference 17. This reference showed for each aircraft type the number of airframes operating in the region in the flight level band, subdivided into modern generation airlines, older generation airlines, corporate jets and turbo props. It is recognised that this population is not representative for AFI RVSM operations as it will not be economically viable to upgrade and obtain RVSM approval for all of these aircraft. To be able to make the most realistic projection of the AFI RVSM aircraft population, the African Regional Monitoring Agency (ARMA) is continually updating and maintaining a database of RVSM approvals.

Based on this, ARMA has compiled a list of African registered aircraft/operators capable of RVSM operations in the flight level band FL290 – FL410 inclusive as per 31st March 2005. A summary of the list per “aircraft monitoring group” is shown in table 2.5 below. A monitoring group consists of those aircraft that are of nominally identical design and build with respect to all details that could influence the accuracy of height keeping performance. Many monitoring groups are listed in references 18 and 19. A monitoring group can consist of several aircraft types with different ICAO codes, but an aircraft type characterised by a single ICAO code can also be in more than one monitoring group as can be seen in table 2.5.

The total number of monitoring groups is 98. The table shows for each monitoring group the number of African registered airframes together with the numbers of RVSM approved and non-RVSM approved airframes. It also shows that for 41 out of the total number of 98 monitoring groups none of the pertinent aircraft/operators have been RVSM approved. On the assumption that this situation will not change until the start of the RVSM operations in the AFI Region, the pertinent groups will be excluded from the candidate AFI RVSM aircraft population as far as African registered airframes are concerned.

Monitoring group	ICAO codes	Number of airframes	Number of approved airframes	Number of unapproved airframes
A124	A124	2	0	2
A300	A306,A30B	19	15	4
A310-GE	A310	7	7	0
A310-PW	A310	1	1	0
A320	A319, A320, A210	61	60	1
A330	A332,A333	1	1	0
A340	A342, A343	17	14	3
A346	A346	7	7	0
AN12[5]	AN12	1	0	1
AN2[5]	AN2	17	0	17
AN26[5]	AN26	9	0	9
AN32[5]	AN32	1	0	1
AN72	AN72, AN74	3	0	3
ATR	AT43,AT44,AT45	36	15	21
B190[5]	B190	74	20	54
B461[5]	B461	1	1	0
B701	B701	1	1	0
B703	B703	30	21	9
B727	B721,B722	90	31	59
B732	B732	97	64	33
B737CL	B733,B734,B735	42	34	8

[5] AN12, AN2, AN26, AN32, B190, B461, C130, D228, D328, DHC6, E120, F27, F28, IL18, IL62, LJ24, LJ25, PC12, S601, SW4, YK40 are not listed as monitoring groups in references 18 and 19.

B737NX	B736,B737,B738,B739	67	64	3
B744[6]	B744	10	10	0
B747CL	B741, B742, B743	26	14	12
B752	B752	9	8	1
B767	B762, B763	29	25	4
B772	B772	7	7	0
BA11	BA11	5	4	1
BE20	BE20, BE30, B350	18	0	18
BE40	BE40	4	1	3
C130[5]	C130	137	4	133
C500	C500 (all except serial nr 193)	11	3	8
C501-1	C501	3	1	2
C525	C525	1	0	1
C550-B	C550 (Citation Bravo)	3	1	2
C550-II	C550, C551 (Citation II)	10	1	9
C550-SII	C550 (Citation Super II)	2	0	2
C560	C560	13	0	13
C56X	C56X	1	0	1
C750	C750	1	0	1
CARJ	CRJ1, CRJ2	6	6	0
CL600	CL60 (CL-600)	1	0	1
CL604	CL60 (CL-604)	2	0	2
D228[5]	D228	24	3	21
D328[5]	D328	2	0	2
DC10	DC10	8	8	0
DC8[7]	DC86, DC87	1	0	1
DC85	DC85	4	2	2
DC86[7]	DC86	13	9	4
DC87[7]	DC87	1	0	1
DC93	DC93	16	9	7
DC95	DC95	2	2	0
DHC6[5]	DHC6	5	0	5
E120[5]	E120	1	0	1
E135-145	E135,E145	5	5	0
F100	F100	1	1	0

[6] B744 is split into two monitoring groups: B744-10 and B744-5 depending on the serial numbers.

[7] DC8 is not a monitoring group, but is split into DC86-7, DC86-7-1, DC86-7NG depending on the series.

F27[5]	F27	1	0	1
F28[5]	F28	30	19	11
F2TH	F2TH	1	1	0
F900	F900	9	5	4
FA10	FA10	4	4	0
FA20	FA20	8	4	4
FA50	FA50	8	7	1
G159[5]	G159	11	1	10
GLEX	GLEX	3	0	3
GLF2	GLF2	4	0	4
GLF3	GLF3	8	4	4
GLF4	GLF4	15	10	5
GLF5	GLF5	3	1	2
H25A	?	1	0	1
H25A-100	H25A (100 series)	3	0	3
H25A-400	H25A (400 series)	9	0	9
H25A-600	H25A (600 series)	4	0	4
H25B-700	H25B (700 series)	5	1	4
H25B-800	H25B (800 series)	5	1	4
H25CNG	H25C	1	0	1
IL18[5]	IL18	1	0	1
IL62	IL62	3	0	3
IL76	IL76	48	2	46
J328	J328	3	0	3
L101	L101	6	5	1
L29A-6	L29A (jetstar 6)	2	0	2
L29B-2	L29B (jetstar 2)	2	1	1
LJ24[5]	LJ24	6	0	6
LJ25[5]	LJ25	5	0	5
LJ31	LJ31	5	0	5
LJ35/6	LJ35, LJ36	3	0	3
LJ45	LJ45	8	1	7
MD80	MD81MD82,MD83,MD87,MD88	11	9	2
PC12[5]	PC12	1	1	0
PRM1	PRM1	5	0	5
S601[5]	S601	4	0	4
SW4[5]	SW4	1	0	1

T134	T134	4	0	4
T154	T154	1	0	1
T204	T204,T224,T234	5	2	3
YK40[5]	YK40	22	1	21
YK42	YK42	2	0	2

Table 2.5 African registered aircraft/operators

The candidate non-African resident and registered AFI RVSM population has been established as follows. Using the OAG database for 2003 (Ref. 9), the aircraft type/operator combinations involved with flights into or out of Africa have been filtered out first. The African registered aircraft type/operator combinations were then removed to produce a list of 51 monitoring groups, 19 of which are not covered by the groups in table 2.5. The 51 monitoring groups/aircraft types are shown in table 2.6. It should be recalled that the OAG database includes data on scheduled flights only. It is assumed, therefore, that non-scheduled flights will not involve any other aircraft types. Given the wide selection of candidate AFI RVSM aircraft types in the tables 2.5 and 2.6, this assumption is judged to be not unreasonable. A complete list of aircraft types that are (partially) RVSM approved is given in table 2.7. This list will be used in the remainder of the assessment.

As mentioned at the beginning of this subsection, the proportions of flying time by monitoring group/aircraft type are needed for the estimation of some of the parameters of the vertical collision risk model. Details of the pertinent modelling and calculations will be given in sections 3.3.2 and 3.6.

Monitoring group	ICAO code	OAG description	Number of scheduled flights
A300	A306,A30B		2197
A310-GE,A310-PW[8]	A310		2188
A320	A319,A320,A210		17028
A330	A332,A333		10105
A340,A345,A346[9]	A342,A343,A345,A346	Airbus Industry A340 (all series)	6016

[8] The ICAO code covers more than one monitoring group. Therefore, all groups are given.

[9] The aircraft type as given in the OAG database (based on the IATA codes) covers more than one ICAO code and / or Monitoring Groups. All codes and groups, therefore, are given.

A340	A343		3879
[10]	AN24	Antonov An-24	5153
ATR	AT43,AT44,AT45		6519
AVRO	RJ1H,RJ70,RJ85		309
BA11	BA11		52
B190	B190		6871
BE20	BE20, BE30, B350		548
B712	B712		203
B727	B727		2969
B737C,B737CL,B732, B737NX[9]	B732B733,B734,B735, B736,B737,B738,B739	Boeing 737 all series	48076
B732	B732		936
B737CL	B733,B734,B734		4954
B737NX	B736,B737,B738,B739		4425
B747CL,B744-10,B744-5 [9]	B741,B742,B743,B744	Boeing 747 (all series) Mixed configuration	165
B747CL,B744-10,B744-5 [9]	B741,B742,B743,B744	Boeing 747 all series	4723
B747CL,B744-10,B744-5 [9]	B741,B742,B743,B744	Boeing 747 Freighter	453
B747CL	B741,B742,B743		1358
B744-10,B744-5 [8]	B744		7952
B752	B752		1634
B767,B764 [9]	B762, B763, B764	Boeing 767 (all series)	4589
B767	B762, B763		1589
B772,B773 [9]	B722,B773	Boeing 777	8628
[10]	BN2P, BN2T	Britten Norman Islander	64
CARJ,CRJ-700,CRJ-900 [9]	CR1,CR2,CR7	Canadair Regional Jet	1347
[10]	C212	Casa/IPTN NC-212	833
[10]	DH8A,DH8B,DH8C,DH8D	De Havilland Canada DHC-8 (all series)	246
[10]	E120	Embraer EMB-120 Brasilia	116
[10]	SW4	Fairchild Metro	949

[10] The monitoring group is unknown from references 18 and 19.

F50	F50		124
F70	F70		227
F28	F28		2765
[10]	G159	Gulfstream 1/1-C	1608
[10]	IL18		70
IL62	IL62		10
[10]	L410	Let 410 Turbolet	1222
L101	L101		277
DC10	DC10		589
DC85,DC86-7 [9]	DC85,DC86,DC87	McDonnell Douglas DC-8 Freighter	261
DC93,DC94,DC95 [9]	DC93,DC94,DC95	McDonnell Douglas DC-9	1888
MD11	MD11		4897
MD80	MD80		3958
MD90	MD90		924
[10]	SF34	Saab 340	7870
T134	T134		179
T154	T154		300
YK42	YK42		17

Table 2.6 Non-African registered aircraft/operators

Monitoring group	**ICAO code**	**African registered operators**	**Non-African registered operators**
A300	A306,A30B	✓	✓
A310-GE	A310	✓	✓
A310-PW	A310	✓	✓
A320	A319,A320,A321	✓	✓
A330	A332,A333	✓	✓
A340	A342,A343	✓	✓
A345 (*)	A345		✓
A346	A346	✓	✓
ATR	AT43,AT44,AT45	✓	✓
AVRO	RJ1H,RJ70,RJ85		✓
B190	B190	✓	✓

(B461)[11]	B461	✓	
B701	B701	✓	
B703	B703	✓	
B712	B712		✓
B727	B721,B722	✓	✓
B732	B732	✓	✓
B737CL	B733,B734,B735	✓	✓
B737NX	B736,B737,B738,B739	✓	✓
B744-10	B744	✓	✓
B744-5	B744	✓	✓
B747CL	B741,B742,B743	✓	✓
B752	B752	✓	✓
B767	B762,B763	✓	✓
B764 (*)	B764		✓
B772	B772	✓	✓
B773	B773		✓
BA11	BA11	✓	✓
BE20	BE20,BE30,B350		✓
BE40	BE40	✓	
(C130)[11]	C130	✓	
C500	C500	✓	
C501-1	C501	✓	
C550-B	C550	✓	
C550-II	C550	✓	
CARJ	CRJ1,CRJ2	✓	✓
CRJ-700 (*)	CRJ7		✓
CRJ-900 (*)	CRJ9		✓
(D228)[11]	D228	✓	
DC10	DC10	✓	✓
DC85	DC85	✓	✓
DC86-7	DC86,DC87	✓	✓
DC93	DC93	✓	✓
DC94	DC94		✓
DC95	DC95	✓	✓
E135-145	E135,E145	✓	
F50	F50		✓
F100	F100	✓	✓

F28	F28	✓	✓
F2TH	F2TH	✓	
F900	F900	✓	
FA10	FA10	✓	
FA20	FA20	✓	
FA50	FA50	✓	
(G159)[11]	G159	✓	✓
GLF3	GLF3	✓	
GLF4	GLF4	✓	
GLF5	GLF5	✓	
H25B-700	H25B	✓	
H25B-800	H25B	✓	
IL62	IL62		✓
IL76	IL76	✓	
L101	L101	✓	✓
L29B-2	L29B	✓	
LJ45	LJ45	✓	
MD80	MD81,MD82,MD83, MD87,MD88	✓	✓
MD11	MD11		✓
(PC12)[11]	PC12	✓	
T204	T204,T224,T234	✓	
T134	T134		✓
T154	T154		✓
(YK40)[11]	YK40	✓	
YK42	YK42		✓
(BN2)[11]	BN2		✓
(C212)[11]	C212		✓
(DH8)[11]	DH8		✓
(E120)[11]	E120		✓
(SW4)[11]	SW4		✓
(SF34)[11]	SF34		✓

Table 2.7 Population of (partially) RVSM approved aircraft[11, 12]

[11] Monitoring groups in brackets are unknown from references 18 and 19.
[12] Some monitoring groups have been added due to the fact that some OAG aircraft types (based on the IATA codes) cover more than one ICAO code. Groups added solely for this reason are marked with an asterisk (*)

2.5 Airspace peculiarities

This subsection describes a few peculiarities that are specific to the AFI Region and which may have an impact on safety.

The Hadj is the annual pilgrimage of Muslim to Mecca. It begins during the 12th month of the Muslim calendar. (The Muslim calendar started on 16th July of the year 622.) A Muslim year counts 11 days less than a western calendar year with each month starting at new moon (in 2004, the Hadj ended on February 2nd, in 2005 on January 21st, and in 2006 on January 10th). The Hadj leads to a significant stream of west-east flights in northern and central Africa to and from Jeddah in Saudi Arabia over a 20-day period. It thus leads to a seasonal increase in traffic crossing the main north-south traffic stream. It will be examined in section 3.4 to what extent this affects the passing frequency parameters of the vertical collision risk model.

Based on the recognition that both fixed and mobile communications in many FIRs in the AFI Region have either not been implemented or operate well below the required reliability, the AFI Regional Technical Conference at its meeting in Nairobi, April 2002, decided that the IATA In-Flight Broadcast Procedure (IFBP) should be used within designated FIRs in the Region pending improvement of the communication facilities (Ref. 20). The procedure involves maintaining a listening watch on a frequency of 126.9 MHz, 10 minutes before entering the designated airspace until leaving this airspace. The area of applicability has been reproduced in figure 2.4. The operating procedures cover changes of cruising level, collision avoidance, normal position reporting procedures and operation of transponders. Specifically, the operating procedure states that cruising level changes should not be made within the designated airspace unless considered necessary by pilots to avoid traffic conflicts, for weather avoidance, or for other valid operational reasons.

Section 3.6.5 of ICAO Annex 2 deals with “communications” (Ref. 15). In case of communication failure, the “20 minutes rule” states that the last assigned speed and level should be maintained for a period of 20 minutes following the aircraft’s failure to report its position over a compulsory reporting point. A Modified Radio Communication Failure (RCF) procedure became effective in the entire EUR Region from 24th January 2002 coincident with the implementation of RVSM in the EUR Region. In summary, the 20 minutes rule changed into a 7 minutes rule with the requirement for pilots to always set the transponder to Code 7600. A similar modification has been agreed for AFI RVSM.

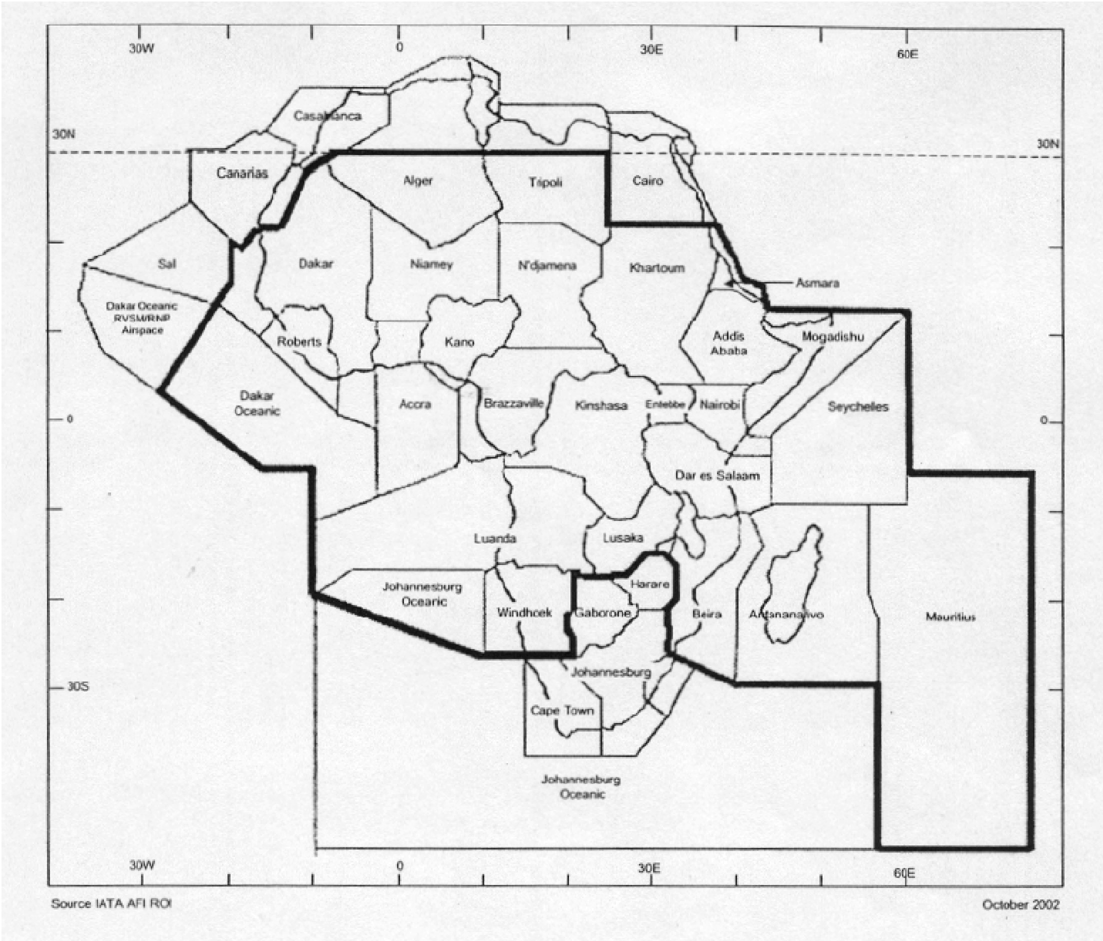


Figure 2.4 Area of applicability of IATA IFBP in the AFI Region

A specific operational scenario that may occur under AFI RVSM is that non-RVSM approved aircraft are allowed to transition through AFI RVSM airspace from below FL290 to above FL410 or vice versa (Ref. 3).

Another operational situation worth mentioning is that, dependent on the track headings and the pertinent cruising levels, aircraft may be required to change flight level at certain crossings within the AFI Region.

2.6 Data sources

Various types of data are needed for the collision risk models in sections 3 and 4. Two major providers of data have been ARMA and the African States. Height monitoring data and statistical information on height-keeping distributions has been made available by ARMA. ARMA has also collected information from States by means of the following data collection forms (Refs. 21 and 22):

- Form 1: Height deviations (State of registry, flight identification, operator, State of operator, aircraft type and series, registration, serial number, mode S address, total height deviation, total time of deviation, cause of deviation, date and time of measurement, assigned flight level, observed flight level, air route, geographical location, description of incident);
- Form 2: Monthly movements (total IFR movements for the month, total monthly IFR movements in the band FL290 – FL410, average time per movement in level band FL290 – FL410: level flight, climbing and descending);
- Form 3: Other operational considerations (co-ordination failures, communication failures, turbulence, ACAS incidents);
- Form 4: Traffic flow data (date, route, callsign, aircraft type, operator, departure aerodrome, destination aerodrome, nav equipment, waypoint, time at waypoint passing, FL).

The information collected in Form 4 is used to estimate the passing frequency parameters of the vertical collision risk model. The information collected in Forms 1, 2 and 3 is especially relevant to the estimation of the total vertical collision risk (section 5).

Some air proximity reports, air miss reports and incident data have been provided by IATA, CAA South Africa and ICAO.

The OAG database (Ref. 9) and some statistics from ICAO's online "icaodata" database (http://icaodata.com) have also been used.

3 Assessment of technical vertical risk

3.1 Introduction

This section deals with the assessment of the technical vertical risk under RVSM in the AFI Region. Technical vertical risk represents the risk of a collision between aircraft on adjacent flight levels due to normal or typical height deviations of RVSM approved aircraft. In line with the AFI RVSM Safety Policy (Ref. 2), the technical vertical collision risk will be assessed against a technical Target Level of Safety (TLS) of 2.5×10^{-9} fatal accidents per flight hour using a suitable collision risk model. It should be remarked that a collision between two aircraft is counted as two accidents. Vertical collision risk due to other than technical causes will be examined in section 4.

Vertical collision risk accounts for two basic factors, namely the likelihood of the loss of vertical separation and the exposure to the loss of vertical separation. This exposure is dependent on the traffic geometry, i.e. the angle of intersection between the routes carrying the aircraft at adjacent flight levels. Traffic geometry may be broadly subdivided into same direction traffic (zero intersection angle), opposite direction traffic (180º intersection angle) and crossing traffic (remaining intersection angles). Slightly different models exist for the different traffic geometries. Traffic flow data are the essential data source in estimating the exposure to the risk due to the loss of vertical separation. The likelihood of the loss of vertical separation due to typical aircraft height deviations depends on the probability distributions of Altimetry System Error (ASE) and Flight Technical Error (FTE). Height monitoring data are used to estimate these distributions and subsequently the probability of vertical overlap.

Section 3.2 presents the type of vertical collision risk model and its parameters. Details of the estimation of the various model parameters are given in sections 3.3 – 3.6. Estimates of the technical vertical risk are presented and compared with the pertinent TLS in section 3.7.

3.2 Collision risk model

The current vertical collision risk model is based on the two basic vertical collision risk models developed by the ICAO RGCSP for assessing technical vertical risk (Ref. 23). The first basic model pertains to aircraft flying on adjacent flight levels of the same route in either the same or opposite direction and the other basic model pertains to crossing routes. These models, based on knowledge of the traffic flows along a given route structure, have e.g. been used for the RVSM safety assessments in the NAT, Australia, EUR/SAM Corridor and Northern Canada (Refs. 24-27). Some additional applications are described in references 28 and 29. A more advanced form of these models has been used for the safety assessment of European RVSM to account for the highly complex and very variable traffic patterns resulting from direct routings that are frequently allowed under radar control (Refs. 19, 30, 31). As there is very little radar cover in the AFI Region, it is assumed that flights basically adhere to the regional route network and that, consequently, the original RGCSP collision risk models can be used as a starting point for the AFI RVSM collision risk assessment.

Collision risk models may be expressed in slightly different but numerically equivalent forms dependent on the way the model parameters can best be estimated. Thus, the vertical collision risk model for aircraft on adjacent flight levels of the same route, flying in either the same or the opposite direction can be given by

$$N_{az} = 2P_z(S_z)P_y(0)\left[n_z(same)\left\{ 1 + \frac{2\lambda_x}{2\lambda_y}\frac{|\dot{y}|}{|\Delta V|} + \frac{2\lambda_x}{2\lambda_z}\frac{|\dot{z}|}{|\Delta V|} \right\} + n_z(opp)\left\{ 1 + \frac{2\lambda_x}{2\lambda_y}\frac{|\dot{y}|}{2\bar{V}} + \frac{2\lambda_x}{2\lambda_z}\frac{|\dot{z}|}{2\bar{V}} \right\} \right] \tag{3.1}$$

The left-hand side variable N_{az} represents the expected number of aircraft accidents due to normal technical height deviations of RVSM approved aircraft for the given traffic geometry. All parameters in the model of eq. (3.1) are defined in table 3.1. The most important parameter is the probability of vertical overlap $P_z(S_z)$ with the vertical separation minimum S_z here being 1000 ft. The longitudinal overlap frequency parameters $n_z(same)$ and $n_z(opp)$ together with the kinematic factors in brackets (as functions of the relative speeds and aircraft dimensions) represent a major part of the different levels of exposure to the risk of the loss of vertical separation for the two traffic geometries covered by the collision risk model of eq. (3.1). (The subscript z in $n_z(same)$ and $n_z(opp)$ refers to aircraft on adjacent flight levels.)

Obviously, a collision between two aircraft can only occur when their bodies overlap in all three dimensions. For modelling purposes, the complex real aircraft bodies are represented by simpler bodies such as rectangular blocks or standing cylinders (hockey pucks) enveloping the real bodies. Although the model of eq. (3.1) is based on rectangular boxes with dimensions equal to the length, width and height of a typical real aircraft, cylinders will be used in this report by taking the radius of the cylinders equal to the larger of the length and the width of a typical aircraft. This is to be consistent with the crossing track case that is much more easily dealt with for cylindrically shaped aircraft.

Each of the terms within the accolades represents one of the three ways in which a collision can originate, i.e. head/tail, sideways, or top/bottom for same direction traffic and similarly for opposite direction traffic. (Each term in fact equals the inverse of the ratio of the duration of an overlap in the pertinent dimension to the duration of a longitudinal overlap.)

Parameter	Definition
N_{az}	The expected number of fatal aircraft accidents per flight hour due to the loss of vertical separation
S_z	The vertical separation minimum
$P_z(S_z)$	The probability of vertical overlap for aircraft nominally flying on adjacent flight levels
$P_y(0)$	The probability of lateral overlap for aircraft nominally flying at the same route
$n_z(same)$	The frequency with which same direction aircraft on adjacent flight levels of the same route are in longitudinal overlap
$n_z(opp)$	The frequency with which opposite direction aircraft on adjacent flight levels of the same route are in longitudinal overlap
$\overline{\lvert\Delta V\rvert}$	The average of the absolute value of the relative along-track speed between two same direction aircraft flying at adjacent flight levels of the same route
$\overline{V}$	The average ground speed of a typical aircraft
$\overline{\lvert\dot{y}\rvert}$	The average of the absolute value of the relative cross-track speed between two typical aircraft flying at adjacent flight levels of the same route
$\overline{\lvert\dot{z}\rvert}$	The average of the absolute value of the relative vertical speed between two typical aircraft which have lost S_z feet of vertical separation
λ_x	The average length of a typical aircraft
λ_y	The average width of a typical aircraft
λ_z	The average height of a typical aircraft

Table 3.1 Definition of parameters of the vertical collision risk model of eq. (3.1)

An implicit assumption underlying the form of the vertical collision risk model of eq. (3.1) is that the probability of three-dimensional overlap factors into the product of the probabilities of overlap in each of the individual dimensions. This assumption is no longer valid for the case of aircraft flying on crossing routes. In this case, the probability of three-dimensional overlap factors into the probability of vertical overlap and the probability of horizontal overlap (the latter being a generalisation of the product of the probabilities of longitudinal and lateral overlap).

RGCSP's vertical collision risk model for aircraft on adjacent flight levels of two routes crossing at an angle θ and cylindrical aircraft models can be expressed as

$$N_{az} = 2P_z(S_z)n_z(\theta)\left\{ 1+\frac{\frac{\pi}{2}\lambda_{xy}}{2\lambda_z}\frac{\overline{|\dot{z}|}}{V_{rel}(\theta)}\right\} \qquad (3.2)$$

where the relative speed $V_{rel}(\theta)$ is defined by

$$V_{rel}(\theta) = \overline{V}\sqrt{2(1-\cos\theta)} \qquad (3.3)$$

The new parameters are defined in table 3.2. Notice that the lateral overlap probability $P_y(0)$ no longer appears explicitly in the model as it is effectively included within the crossing route frequency of horizontal overlap $n_z(\theta)$. The quantity $\frac{\pi}{2}\lambda_{xy}$ in eq. (3.2) represents the average length of a horizontal overlap between two typical aircraft on crossing routes as represented by cylinders with diameter λ_{xy}.

Parameter	**Definition**
θ	The angle of intersection between two routes
λ_{xy}	The average diameter of a standing cylinder representing a typical aircraft
$n_z(\theta)$	The frequency with which aircraft on adjacent flight levels of two routes intersecting at an angle of θ are in horizontal overlap
$V_{rel}(\theta)$	The average relative horizontal speed between aircraft flying at adjacent flight levels of two routes intersecting at an angle of θ

Table 3.2 Definition of additional parameters for vertical collision risk model of eq. (3.2)

For the case of n pairs of routes crossing at different angles $\theta_i, i = 1,...,n$, the collision risk model of eq. (3.2) is easily extended to

$$N_{az} = 2P_z(S_z)\sum_{i=1}^{n} n_z(\theta_i)\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{2\lambda_z}\frac{\overline{|\dot{z}|}}{V_{rel}(\theta_i)}\right\} \qquad (3.4)$$

Combining the models in eqs. (3.1) and (3.4) gives the total technical vertical collision risk model for AFI RVSM in the following form:

$$N_{az} = 2P_z(S_z)P_y(0)\left[n_z(same)\left\{1+\frac{2\lambda_{xy}}{2\lambda_{xy}}\frac{\overline{|\dot{y}|}}{|\overline{\Delta V}|}+\frac{2\lambda_{xy}}{2\lambda_z}\frac{\overline{|\dot{z}|}}{|\overline{\Delta V}|}\right\}+n_z(opp)\left\{1+\frac{2\lambda_{xy}}{2\lambda_{xy}}\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{2\lambda_{xy}}{2\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}\right]+$$

$$+2P_z(S_z)\sum_{i=1}^{n} n_z(\theta_i)\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)}\frac{\overline{|\dot{z}|}}{2\lambda_z}\right\} \qquad (3.5)$$

Notice that the original rectangular box dimensions λ_x and λ_y for the same and opposite direction components have been replaced by the cylinder diameter λ_{xy}. The lateral overlap probability parameter $P_y(0)$ may be combined with the same direction and opposite direction longitudinal overlap frequencies $n_z(same)$ and $n_z(opp)$ respectively to give frequencies of horizontal overlap for these two traffic types (comparable to the horizontal overlap frequency $n_z(\theta_i)$ for crossing traffic).

With the form of the vertical collision risk model specified by eq. (3.5), it remains to estimate the various parameters in the model. This will be described in the subsequent subsections, starting with the probability of vertical overlap $P_z(S_z)$ in section 3.3. As will be argued in section 3.4, longitudinal overlaps for same direction traffic and horizontal overlaps for crossing traffic are rather rare events. As this hinders the accurate estimation of their frequencies, these frequencies will be estimated from the frequencies of related but less rare events, so called proximity events, and suitable correction factors. The remaining parameters, i.e. the probability of lateral overlap for aircraft on the same route, and average aircraft dimensions and relative speeds will be dealt with in sections 3.5 and 3.6.

3.3 Probability of vertical overlap

3.3.1 Introduction

The probability of vertical overlap for aircraft flying at adjacent flight levels of the same route or intersecting routes is calculated from the probability distribution of normal height-keeping deviations of RVSM approved aircraft. Aircraft height-keeping deviations are usually defined in terms of Total Vertical Error (TVE) where:

$$TVE = actual\ pressure\ altitude\ flown\ by\ an\ aircraft - assigned\ altitude \qquad (3.6)$$

(in geometric feet). A representative TVE probability distribution is to be obtained from height monitoring of the aircraft population.

The approach that has been followed in e.g. the NAT, Europe and the EUR/SAM Corridor consists of separately modelling the two components of TVE, Altimetry System Error (ASE) and Flight Technical Error (FTE), i.e.

$$TVE = ASE + FTE \tag{3.7}$$

where

$$ASE = actual\ pressure\ altitude\ flown\ by\ an\ aircraft - displayed\ altitude \tag{3.8}$$

and

$$FTE = displayed\ altitude - assigned\ altitude \tag{3.9}$$

and where it is assumed that the two components are statistically independent.

The same approach will be followed for the AFI RVSM vertical collision risk assessment. Sections 3.3.2-3.3.4 describe the modelling of the probability distributions (densities) of ASE, FTE and TVE respectively and are followed by the estimation of the probability of vertical overlap in section 3.3.5.

3.3.2 Modelling the ASE distribution

Assume that n_{MG} aircraft monitoring groups (see e.g. Ref. 18) will be operating in AFI RVSM airspace. Each monitoring group's ASE probability density $f_i^{ASE}(a)$, $i = 1,\ldots,n_{MG}$, say, is the result of both within and between airframe ASE variability of all the airframes making up the group. See reference 31 for details of within and between airframe variability and their combined effect. An overall ASE probability density $f^{ASE}(a)$, say, for the full RVSM aircraft population is then found as a weighted mixture of the ASE densities by monitoring group, i.e.

$$f^{ASE}(a) = \sum_{i=1}^{n_{MG}} \beta_i f_i^{ASE}(a) \tag{3.10}$$

where the weighting factors β_i, $i = 1,...,n_{MG}$, are the proportions of flight time contributed by monitoring group i. Both the weighting factors and the monitoring group's ASE probability densities need to be inferred from monitoring data pertaining to the AFI RVSM airspace.

The monitoring groups' probability densities $f_i^{ASE}(a)$, $i = 1,...,n_{MG}$ are to be estimated on the basis of height monitoring data of RVSM approved aircraft. Height monitoring data can be collected by ground-based Height Monitoring Units (HMUs) or by air portable GPS Monitoring Units (GMUs). Ground-based HMUs are not available in the AFI region. However, as the normal height-keeping performance of RVSM approved aircraft is not dependent on the region of operation, HMU data collected in other ICAO Regions may be used for the modelling of a monitoring group's ASE probability density $f_i^{ASE}(a)$. Notice that the overall ASE probability density defined by eq. (3.10) will vary from region to region due to differences in the weighting factors β_i resulting from the particular composition of each region's aircraft population.

Table 3.3 shows the types of ASE probability densities for the various monitoring groups expected to be operating in AFI RVSM airspace (cf. section 2.4) as well as the parameter values characterising the densities. Three different types of probability densities are distinguished, namely gaussian (G), double exponential (DE) and gaussian double exponential (GDE). A GDE probability density for the i-th monitoring group is given by the following expression

$$f_i^{ASE}(a)_{GDE} = (1-\alpha_i)\frac{1}{\sigma_{1_i}\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{a-\mu_i}{\sigma_{1_i}}\right)^2} + \alpha_i\frac{1}{\sigma_{2_i}\sqrt{2}}e^{-\frac{|a-\mu_i|\sqrt{2}}{\sigma_{2_i}}} \qquad (3.11)$$

A gaussian density is obtained by putting $\alpha_i = 0$ and a double exponential density by putting $\alpha_i = 1$.

It is remarked that height monitoring data was available from the European height monitoring programme for all but the following monitoring groups (Ref. 19): F28, BA11, B190, F50, (PC12)[11], (C130), ATR, (YK40), (DH8), (G159). RVSM approved airframes for the F28, BA11, B190, (PC12), (C130), (YK40), (G159) and ATR are present in table 2.5 for the African registered aircraft/operators. For these monitoring groups, a default gaussian ASE density has been assumed with mean zero and a standard deviation of 81.7 ft based on the MASPS (Ref. 18). The F50 and (DH8) have come in from the OAG database and pertain to non-African registered aircraft/operators. Their RVSM approval status is unclear but because they contribute only a very small proportion of flying time, they have been treated as approved aircraft with the same default gaussian ASE density.

The (sorted) proportions of flight time β_i, $i = 1,...,n_{MG}$, are also included in table 3.3. See appendix A for details of the determination of the flight time proportions. The first ten Airbus and Boeing monitoring groups make up 76.8% of the total flying time. Together with the next nine monitoring groups (with more than 1% of the flying time each) they make up 94.3% of the total flying time.

Monitoring Group	**Flight time proportion**	**Type of ASE probability density**	**ASE probability density parameters**			
			μ (ft)	**α**	**σ_1 (ft)**	**σ_2 (ft)**
A340	0.117290	GDE	-5.3	0.5893	40.68946	58.84049
B737NX	0.113703	GDE	11.5	0.3149	41.20204	62.28882
A330	0.083266	GDE	47.1	0.1707	38.78191	43.28563
B744-10	0.077486	GDE	-55.5	0.5394	37.84900	47.14231
B744-5	0.077486	GDE	-60.9	0.2289	51.85683	53.68979
A320	0.069970	GDE	37.5	0.1998	43.57041	48.19218
B732	0.069351	GDE	-2.7	0.1637	35.45663	55.07860
B772	0.058257	GDE	28	0.4343	32.60254	50.83903
B767	0.055226	GDE	-60.9	0.6194	44.10159	50.95368
B737CL	0.046097	GDE	-40.1	0.2458	45.42245	50.45453
MD80	0.033815	GDE	1.4	0.2020	38.21512	43.49921
B747CL	0.029254	GDE	-39	0.2883	59.98429	64.39440
A346	0.020252	G	21.9		32.52050	
DC93	0.019861	GDE	22.4	0.5166	39.49744	42.97418
MD11	0.018071	GDE	-10.1	0.4577	52.98762	57.65188
B752	0.016233	GDE	-7	0.3643	39.89582	45.98975
B727	0.015626	GDE	55.7	0.5707	56.43107	67.52966
DC10	0.011561	G	-10.8		61.07926	
A300	0.010620	GDE	8.8	0.2000	51.78794	58.03694
E135-145	0.008254	GDE	-5.7	0.5092	61.56397	72.14784
CARJ	0.006924	GDE	-23.1	0.2290	48.42564	52.76377
IL76	0.005197	GDE	55	0.3219	61.55723	64.87729
F900	0.005094	GDE	21.8	0.3533	61.35922	80.09939
L101	0.003934	GDE	5.4	0.3386	73.02204	76.13709
FA50	0.003715	GDE	50.5	0.2280	64.34658	69.04695
GLF4	0.002729	GDE	-25.6	0.4583	52.16530	55.20544
A310-GE	0.002664	GDE	-58	0.2664	47.40961	51.17690
A310-PW	0.002664	GDE	14.5	0.2283	46.86872	48.57089

DC95	0.002430	G	-37.1		27.29642	
B773	0.001858	GDE	12.3	0.2000	18.07178	21.47749
DC86-7	0.001567	GDE	-39	0.3240	57.84132	54.92651
B703	0.001556	G	22.7		63.62519	
IL62	0.001258	GDE	55.9	0.9999	46.01140	50.06894
GLF5	0.000909	GDE	-2.9	0.4200	57.34001	62.46855
GLF3	0.000836	GDE	40.6	0.0312	56.85026	78.93982
T154	0.000496	GDE	-0.9	0.1518	48.72344	64.11073
FA10	0.000474	GDE	15.3	0.2348	54.30628	55.86480
FA20	0.000427	GDE	-14.5	0.2140	47.80010	59.28035
H25B-700	0.000403	GDE	3	0.0645	66.38120	112.2142
H25B-800	0.000403	GDE	23.2	0.2000	64.44523	68.34800
BE20	0.000391	G	27.7		38.05987	
F28	0.000380	G*	0		81.7	
B701	0.000378	GDE	53	0.2890	60.67652	50.79266
BA11	0.000274	G*	0		81.7	
LJ45	0.000252	DE	39.6		38.51837	
BE40	0.000162	GDE	-5.7	0.3817	54.79675	50.28776
T204	0.000141	GDE	-42.5	0.1416	86.39436	87.68536
F100	0.000129	GDE	-5.6	0.4618	47.47980	50.60727
C500	0.000114	G	-9.9		53.80877	
C550-II	0.000095	G	-0.7		44.82029	
B190	0.000078	G*	0		81.7	
A345	0.000069	G	-13.8		27.29563	
F50	0.000065	G*	0		81.7	
C550-B	0.000065	GDE	43.7	0.3733	39.70765	59.55795
F2TH	0.000053	GDE	-59.1	0.2960	57.78679	76.49081
T134	0.000033	GDE	12.4	0.7835	36.24600	68.02501
(PC12)[11]	0.000025	G*	0		81.7	
AVRO	0.000020	GDE	29.7	0.2516	49.78819	53.11856
(C130)[11]	0.000018	G*	0		81.7	
ATR	0.000011	G*	0		81.7	
YK42	0.000009	DE	48		55.99323	
DC85	0.000008	GDE	-3.5	0.34202	58.39929	87.52154
(YK40)[11]	0.000004	G*	0		81.7	
(DH8)[11]	0.000003	G*	0		81.7	

L29B-2	0.000001	G	11.6		103.6756	
(G159)[11]	0.000001	G*	0		81.7	

Table 3.3 Flight time proportions and ASE characteristics per monitoring group expected to be operating in AFI RVSM airspace
Note *: default gaussian density based on the MASPS

Figures 3.1 and 3.2 show the resulting ASE probability density $f^{ASE}(a)$ for AFI RVSM plotted against a linear and logarithmic scale respectively. The latter diagram gives a better indication of the tail of the overall ASE distribution. The core part of the density looks somewhat like a gaussian density but is actually slightly asymmetric. The far tails look like double exponential densities, i.e. approximately straight lines in figure 3.2. The mean value of the overall ASE density is 2.7 ft.

Figure 3.1 Overall ASE probability density defined by eq. (3.10)

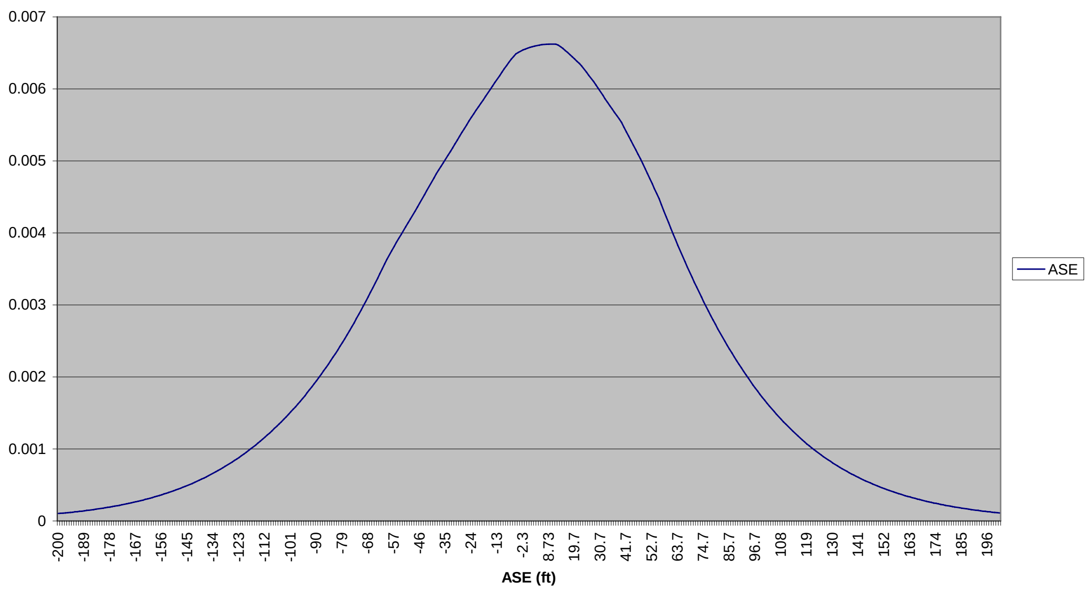
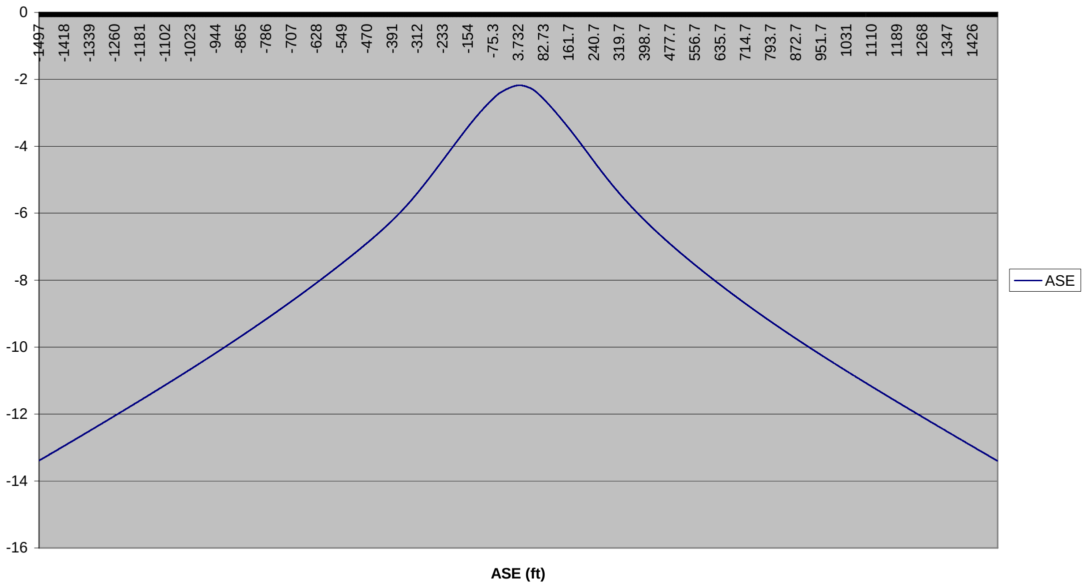


Figure 3.2 Logarithm (base 10) of overall ASE probability density defined by eq. (3.10)



3.3.3 Modelling the FTE distribution

Flight Technical Error was defined in section 3.3.1 as

$$FTE = displayed\ altitude - assigned\ altitude \qquad (3.9)$$

In practice, information on the displayed altitude and hence on FTE is difficult to obtain. Therefore, FTE is usually approximated by Assigned Altitude Deviation (AAD) defined by

$$AAD = transponded\ altitude - assigned\ altitude \qquad (3.12)$$

The difference between FTE and AAD is referred to as correspondence error. Data on AAD can be obtained by evaluating archived mode C or mode S data. AAD performance may be subdivided into typical and a-typical height deviations with each category having its own probability distribution. AAD data less than 350 ft in magnitude is assumed to pertain to the typical AAD performance probability distribution and this distribution is included in the technical vertical collision risk assessment. AAD data equal to or greater than 350 ft in magnitude are assumed to pertain to the a-typical AAD performance probability distribution and this distribution is taken into account within the total vertical collision risk assessment in section 4 of this report.

Although with effect from 1st January 2000 all aircraft operating as IFR flights in the AFI Region are required to carry a mode C transponder (Ref. 12), no data on typical AAD are available from within the AFI Region. However, like the ASE of RVSM approved aircraft, typical AAD is not dependent on the region of operation. Based on European height monitoring data (Ref. 19), the following double exponential AAD probability density is used for the AFI RVSM collision risk assessment:

$$f^{AAD}(a) = \frac{1}{\sigma_{AAD}\sqrt{2}} e^{-\frac{|a|\sqrt{2}}{\sigma_{AAD}}} \tag{3.13}$$

The standard deviation of this typical AAD probability density is taken as $\sigma_{AAD} = 39.8$ ft.

Figures 3.3 and 3.4 show the resulting AAD probability density, $f^{AAD}(a)$ plotted against a linear and logarithmic scale respectively. The latter diagram emphasises again the tail of the AAD probability density.

Figure 3.3 AAD probability density defined by eq. (3.13)

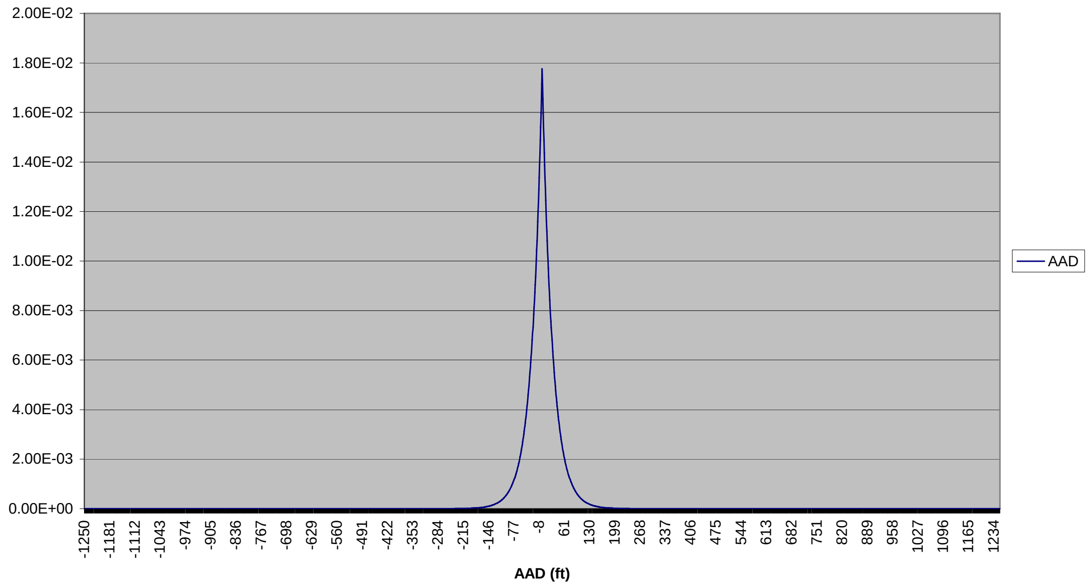
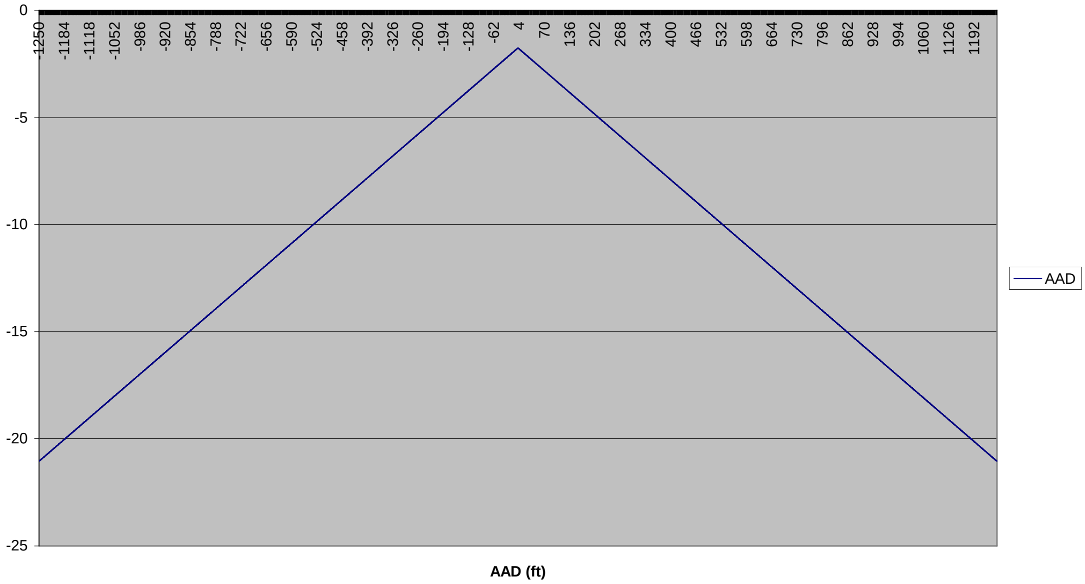


Figure 3.4 Logarithm (base 10) of AAD probability density defined by eq. (3.13)



3.3.4 Modelling the TVE distribution

Total Vertical Error (TVE) was defined in terms of ASE and FTE in section 3.3.1 as

$$TVE = ASE + FTE \tag{3.7}$$

Using AAD as a substitute for FTE, eq. (3.7) can be approximated by

$$TVE = ASE + AAD \tag{3.14}$$

Using eq. (3.14) and the assumption that the two components making up TVE are statistically independent, the TVE probability density function is given by

$$f^{TVE}(z) = \int_{-\infty}^{\infty} f^{ASE}(a) f^{AAD}(z-a)da \tag{3.15}$$

with the probability densities $f^{ASE}(a)$ and $f^{AAD}(a)$ given by eqs. (3.10) and (3.13) respectively.

Figures 3.5 and 3.6 show the resulting TVE probability density $f^{TVE}(z)$, again plotted against a linear and logarithmic scale respectively. The TVE probability density in figure 3.5 looks similar to the ASE probability density in figure 3.1. However, since TVE is the sum of ASE and AAD it has a wider spread. Hence, the peak in figure 3.5 is somewhat wider and lower than that in figure 3.1 for ASE.

Figure 3.5 TVE probability density defined by eq. (3.15)

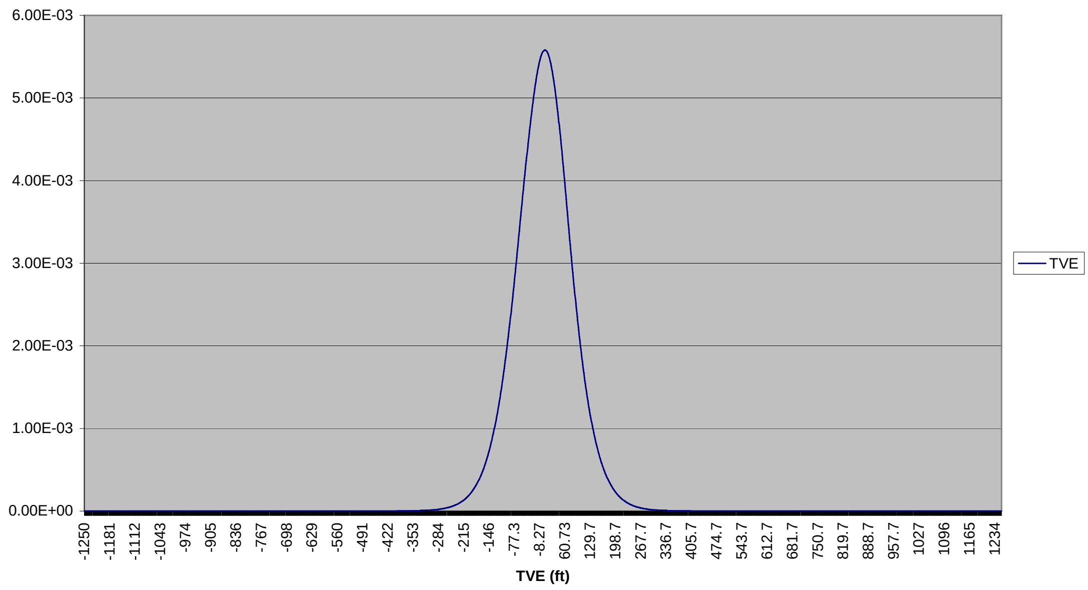
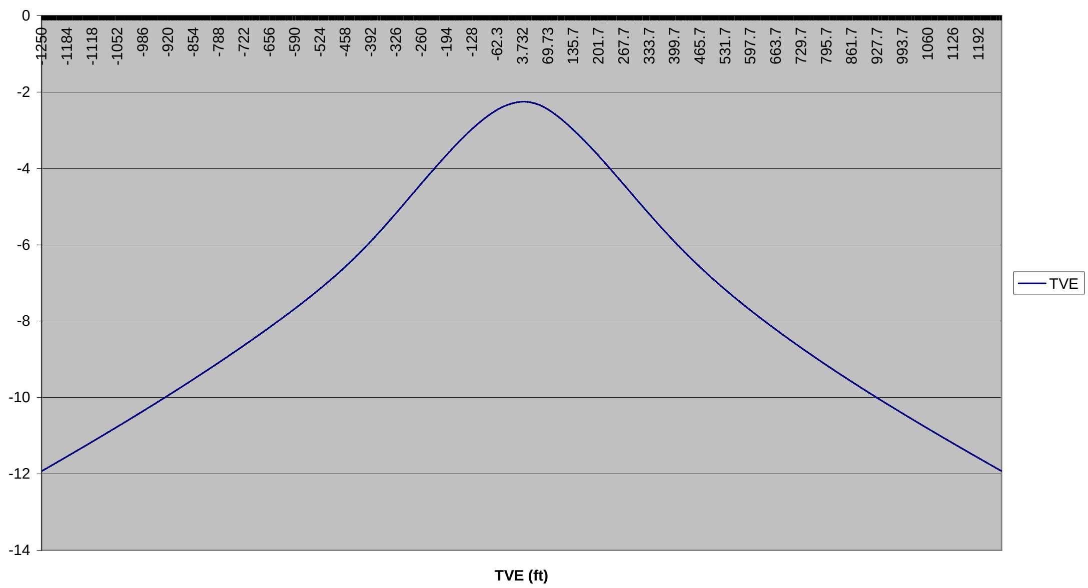


Figure 3.6 Logarithm (base 10) of TVE probability density defined by eq. (3.15)



As described in reference 5, there are some constraints on the TVE probability distribution to ensure that the probability of vertical overlap based on this distribution will, with a high level of confidence, meet a value of 1.7×10^{-8} as specified in the global system performance specification. The specific requirements on the TVE distribution are for the proportions of height-keeping deviations that are larger in magnitude than 300 ft, 500 ft or 650 ft, and between 950 ft and 1050 ft, and are as follows:

a) The proportion of height-keeping deviations beyond 90 m (300 ft) in magnitude is less than 2.0×10^{-3};
b) The proportion of height-keeping deviations beyond 150 m (500 ft) in magnitude is less than 3.5×10^{-6};
c) The proportion of height-keeping deviations beyond 200 m (650 ft) in magnitude is less than 1.6×10^{-7};
d) The proportion of height-keeping deviations between 290 m (950 ft) and 320 m (1050 ft) in magnitude is less than 1.7×10^{-8}.

The above mentioned proportions of height-keeping deviations have been calculated for the TVE density specified by eq. (3.15) and are shown in table 3.4.

Proportion	**Estimate**
$\Pr ob\{\mid TVE \mid \geq 300\}$	1.14×10^{-3}
$\Pr ob\{\mid TVE \mid \geq 500\}$	12.8×10^{-6}
$\Pr ob\{\mid TVE \mid \geq 650\}$	9.38×10^{-7}
$\Pr ob\{950 \leq \mid TVE \mid \leq 1050\}$	0.83×10^{-8}

Table 3.4 Estimated proportions of height-keeping deviations

It can be seen that the requirements on the proportions of TVE beyond 500 ft and 650 ft are not met. On the other hand, the most important requirement on the proportion of TVE between 950 ft and 1050 ft is met by a factor of 2 and also the requirement on the proportion of TVE beyond 300 ft is met by a factor of approximately 1.8. In this context, it should be noted that these proportions of TVE are only fairly crude indicators for the value of the probability of vertical overlap $P_z(1000)$ for aircraft on adjacent flight levels. The least crude indicator is the proportion of TVE between 950 ft and 1050 ft and this proportion is well within its bound. Thus, it may yet be expected with some confidence that the best estimate of $P_z(1000)$ to be presented in the next subsection will be meeting the requirement of the global system performance specification for RVSM in reference 5. Problems with the requirements for the proportions of TVE beyond 500 ft and 650 ft have also been experienced for European RVSM (Ref. 19). The background of the discrepancy is that the global height-keeping performance requirements were derived on the basis of a specific family of probability distributions consistent with a probability of vertical overlap of 1.7×10^{-8} (Ref. 5). However, other families of probability distributions may exist that are also consistent with this value but which nonetheless produce different proportions of TVE beyond 300 ft, 500 ft or 650 ft. The fact that some of the requirements of the global height-keeping performance are being met whilst others are not may in fact be interpreted as indicating that the actual type of TVE probability is different from the type of distribution assumed in the derivation of the specification.

3.3.5 Probability of vertical overlap

Two aircraft nominally flying at adjacent flight levels separated by S_z are actually in vertical overlap when their vertical distance is less than or equal to the (average) height λ_z of the aircraft in magnitude. This vertical distance z_{12}, say, can be defined by the equation

$$z_{12} = S_z + z_1 - z_2 \tag{3.16}$$

where z_1 and z_2 denote the deviations of the two aircraft from their assigned flight levels, i.e. TVE_1 and TVE_2. Assuming that the height-keeping deviations of the aircraft are independent and denoting their respective densities by $f_1^{TVE}(z_1)$ and $f_2^{TVE}(z_2)$, the probability density function $f^{z_{12}}(z)$ of the vertical distance between the pair is given by

$$f^{z_{12}}(z) = \int_{-\infty}^{\infty} f_1^{TVE}(z_1) f_2^{TVE}(S_z + z_1 - z)dz_1 \tag{3.17}$$

The probability of vertical overlap for a pair of aircraft nominally flying at adjacent flight levels is denoted by $P_z(S_z)$ and is defined by

$$P_z(S_z) = \int_{-\lambda_z}^{\lambda_z} f^{z_{12}}(z)dz \tag{3.18}$$

Substitution of the probability density function $f^{z_{12}}(z)$ of eq. (3.17) into eq. (3.18) gives for the probability of vertical overlap

$$P_z(S_z) = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f_1^{TVE}(z_1) f_2^{TVE}(S_z + z_1 - z)dz_1 dz \tag{3.19}$$

In practice, $P_z(S_z)$ may be able to be approximated by

$$P_z(S_z) \approx 2\lambda_z \int_{-\infty}^{\infty} f_1^{TVE}(z_1) f_2^{TVE}(S_z + z_1 - z) dz_1 \tag{3.20}$$

or

$$P_z(S_z) \approx 2\lambda_z f^{z_{12}}(0) \tag{3.21}$$

The probability of vertical overlap $P_z(1000)$ has been calculated by means of the exact eqs. (3.19) and (3.17) with $f_1^{TVE}(z_1)$ and $f_2^{TVE}(z_2)$ as shown in figure 3.5 (based on eq. (3.15)) and was found to be

$$P_z(1000) = 1.61 \times 10^{-8} \tag{3.22}$$

In addition to the technical TLS of 2.5×10^{-9} fatal accidents per flight hour which the collision risk estimate based on $P_z(1000)$ has to meet, the global system performance specification (Ref. 5) puts a direct constraint of 1.7×10^{-8} on the value of $P_z(1000)$. It is seen from eq. (3.22) that the current estimate of $P_z(1000)$ for the AFI RVSM aircraft population meets this constraint.

3.4 Passing frequency

3.4.1 Background

The distribution of the aircraft across the available flight levels of the route network in the AFI region determines the exposure to the risk due to the loss of vertical separation between aircraft on adjacent flight levels. This exposure is reflected in the frequencies of longitudinal and horizontal overlap, or passing frequencies, $n_z(same)$, $n_z(opp)$ and $n_z(\theta_i)$ in the collision risk model of eq. (3.5). Average values representative of AFI RVSM airspace are needed for each of these collision risk model parameters. To account for the fact that the exposure to the vertical collision risk varies greatly in space and time, the “RVSM Manual” (Ref. 5) dictates how the averaging should be performed. Based on the global system performance specification for RVSM, paragraph 6.2.13 of section 6, System Performance Monitoring, of reference 5 requires an assessment of the annual average passing frequency over the whole airspace of three adjacent area control centres (ACCs) covering the region’s busiest traffic flows or highest passing frequency. The use of these adjacent ACCs covering the highest passing frequency is to address the problem of high traffic flows where higher-than-average collision risk may pertain.

Ideally, the three different types of passing frequencies should be determined for each ACC in the AFI Region over a one year period and be used as a basis to identify the three busiest adjacent ACCs. Thus, as a part of the AFI RVSM programme, States in the AFI Region have been requested by ICAO State letter to provide monthly traffic flow data to the African Regional Monitoring Agency ARMA (Refs. 21, 22). Many, but not all, States have provided this data in one form or another. Prior to all the data being available, some judgement was applied to identify the three busiest adjacent ACCs by specifying the following four sets of adjacent ACCs as candidates for the ultimate passing frequency calculations:

- Algeria, Libya, Egypt;
- Central African Republic, Nigeria, Egypt;
- Nigeria, Chad, Cameroon; and
- South Africa, Botswana, Democratic Republic of Congo (DRC)/Angola.

Each of the four sets provides a kind of east-west cross-section through the major north-south routes shown in figure 2.1. The associated FIR/UIRs are:

- Algiers, Tripoli, Cairo;
- Brazzaville/ N'Djamena, Kano, Cairo;
- Kano, N'Djamena, Brazzaville; and
- Johannesburg, Cape Town, Gaborone, Kinshasa/Luanda.

At the time of drafting of this report, no relevant traffic flow data had been received yet from Libya, Egypt and DRC. As a result, the intended averaging over the ACCs included in each group could only be applied for the third group made up of Nigeria, Chad and Cameroon. For the remaining groups, the averaging was performed over the ACCs for which data was available. For example, data from Algeria only was used for the first group. In principle, averaging over fewer ACCs in a group tends to be conservative (less smoothing) unless the ACCs excluded from the averaging have the larger passing frequencies.

One final but important aspect of the passing frequency estimation process remains to be mentioned before presenting some results. The traffic flow data has been collected in the AFI Region under the current conventional vertical separation minimum. Under RVSM, the traffic will be redistributed across the newly available flight levels and this leads, in principle, to fewer aircraft per flight level and, consequently, to lower passing frequency values. Since it is extremely difficult to forecast accurately how the traffic will reorganise, it will be assumed that the passing frequency values based on the current data are also applicable under AFI RVSM. This assumption, which is conservative, was also made in other RVSM safety assessments, see e.g. reference 31. To some extent, it may be taken as an (over) compensation for short term increases in traffic.

3.4.2 Intermediate results

3.4.2.1 Introduction

Tables 3.5 to 3.13 summarise the passing frequency calculations for the FIR/UIRs associated with the States listed in section 3.4.1. Details of the calculations may be found in appendix B. Tables 3.5 to 3.11 show considerable gaps in the data over the period of time from November 2004 to May 2005. For Johannesburg and Cape Town West and East, a restructuring of the route network became effective in February 2005 and only the data from after the restructuring have been included. Notice that the data collection period for N'Djamena and Brazzaville in tables 3.12 and 3.13 differs from that for the FIR/UIRs in the other tables.

For each of the FIR/UIRs the following monthly information is shown in tables 3.5 to 3.13:

- Number of flights;
- Flying time (hours);
- Number of opposite direction longitudinal overlaps;
- Number of opposite direction horizontal overlaps;
- Number of crossing traffic proximity events;
- Number of crossing traffic horizontal overlaps;
- Frequency (per flight hour) of opposite direction longitudinal overlaps;
- Frequency (per flight hour) of opposite direction horizontal overlaps;
- Frequency (per flight hour) of crossing traffic proximity; and
- Frequency (per flight hour) of crossing traffic horizontal overlap.

The primary quantities in the tables as derived from the traffic flow data (Form 4) are:

- Flying time (hours);
- Number of opposite direction longitudinal passings; and
- Number of crossing track proximities.

The frequencies of opposite direction longitudinal passings and crossing track proximities cannot directly be compared for two reasons. Firstly, the former frequency is a frequency of overlap in only a single dimension. It can be converted into a frequency of horizontal overlap for opposite direction traffic by multiplying by $P_y(0)$, the probability of lateral overlap for aircraft on the same route. Secondly, as explained in Appendix B, only a very small proportion of the crossing track proximities actually leads to a crossing track horizontal overlap. Thus, the frequency of crossing track proximity needs to be converted into a frequency of crossing track horizontal overlaps.

The opposite direction traffic and crossing traffic results are discussed in further detail in the subsequent subsections (3.4.2.2 and 3.4.2.3), including the pertinent conversions. Following that, the combined effect of both traffic geometries on the vertical collision risk is examined in section 3.4.2.4. Finally, section 3.4.2.5 looks at the effect, if any, of the Hadj on passing frequency.

Algiers							
	Nov 2004	**Dec 2004**	**Jan 2005**	**Feb 2005**	**Mar 2005**	**Apr 2005**	**May 2005**
Nr Flights			3724				3469
Flying time (hours)			6701.05				6532.58
Opposite longitudinal			931				764
Opposite horizontal			98.686				80.984
Crossing proximate			39				43
Crossing horizontal			0.2166				0.2389
Frequency Opposite longitudinal			0.1389				0.1170
Frequency of Opposite horizontal			0.01473				0.01240
Frequency of Crossing proximate			0.005820				0.006582
Frequency of Crossing horizontal			3.23E-05				3.66E-05

Table 3.5 Summary of passing frequency calculations for Algiers

Kano							
	Nov 2004	Dec 2004	Jan 2005	Feb 2005	Mar 2005	Apr 2005	May 2005
Nr Flights	499	998	1117		957		
Flying time (hours)	351.16	701.71	840.59		671.15		
Opposite longitudinal	48	105	101		123		
Opposite horizontal	5.088	11.13	10.706		13.038		
Crossing proximate	4	4	8		2		
Crossing horizontal	0.02222	0.02222	0.04444		0.01111		
Frequency of Opposite longitudinal	0.1367	0.1496	0.1202		0.1833		
Frequency of Opposite horizontal	0.01449	0.01586	0.01274		0.01943		
Frequency of Crossing proximate	0.01139	0.0057	0.009517		0.00298		
Frequency of Crossing horizontal	6.33E-05	3.17E-05	5.29^{E}-05		1.66E-05		

Table 3.6 Summary of passing frequency calculations for Kano

Johannesburg							
	Nov 2004	Dec 2004	Jan 2005	Feb 2005	Mar 2005	Apr 2005	May 2005
Nr Flights					3665	4148	3961
Flying time (hours)					4615.32	5133.01	4743.40
Opposite longitudinal					122	68	41
Opposite horizontal					12.932	7.208	4.346
Crossing proximate					1	0	0
Crossing horizontal					0.005555	0	0
Frequency of Opposite longitudinal					0.02643	0.01325	0.008644
Frequency of Opposite horizontal					0.002802	0.001404	0.000916
Frequency of Crossing proximate					0.0002167	0	0
Frequency of Crossing horizontal					1.20E-06	0	0

Table 3.7 Summary of passing frequency calculations for Johannesburg

Cape Town East							
	Nov 2004	**Dec 2004**	**Jan 2005**	**Feb 2005**	**Mar 2005**	**Apr 2005**	**May 2005**
Nr Flights					235		
Flying time (hours)					448.79		
Opposite longitudinal					5		
Opposite horizontal					0.53		
Crossing proximate					0		
Crossing horizontal					0		
Frequency of Opposite longitudinal					0.01114		
Frequency of Opposite horizontal					0.001181		
Frequency of Crossing proximate					0		
Frequency of Crossing horizontal					0		

Table 3.8 Summary of passing frequency calculations for Cape Town East

Cape Town West							
	Nov 2004	**Dec 2004**	**Jan 2005**	**Feb 2005**	**Mar 2005**	**Apr 2005**	**May 2005**
Nr Flights					5		
Flying time (hours)					2.08		
Opposite longitudinal					0		
Opposite horizontal					0		
Crossing proximate					0		
Crossing horizontal					0		
Frequency of Opposite longitudinal					0		
Frequency of Opposite horizontal					0		
Frequency of Crossing proximate					0		
Frequency of Crossing horizontal					0		

Table 3.9 Summary of passing frequency calculations for Cape Town West

Gaborone **							
	Nov 2004	Dec 2004	Jan 2005	Feb 2005	Mar 2005	Apr 2005	May 2005
Nr Flights			307	290			
Flying time (hours)			141.65	125.92			
Opposite longitudinal			28	25			
Opposite horizontal			2.968	2.65			
Crossing proximate			0	0			
Crossing horizontal			0	0			
Frequency of Opposite longitudinal			0.1977	0.1985			
Frequency of Opposite horizontal			0.02095	0.02105			
Frequency of Crossing proximate			0	0			
Frequency of Crossing horizontal			0	0			

Table 3.10 Summary of passing frequency calculations for Gaborone

<u>Note **:</u> Based on sampling of four days a month (4th, 12th, 20th, 28th)

Luanda							
	Nov 2004	Dec 2004	Jan 2005	Feb 2005	Mar 2005	Apr 2005	May 2005
Nr Flights	1022	1071			1108	944	
Flying time (hours)	1620.69	1636.67			1709.68	1474.85	
Opposite longitudinal	31	25			36	15	
Opposite horizontal	3.286	2.65			3.816	1.59	
Crossing proximate	4	5			2	4	
Crossing horizontal	0.02222	0.02777			0.01111	0.02222	
Frequency of Opposite longitudinal	0.01913	0.01528			0.02106	0.01017	
Frequency of Opposite horizontal	0.002028	0.001619			0.002232	0.001078	
Frequency of Crossing proximate	0.002468	0.003055			0.00117	0.002712	
Frequency of Crossing horizontal	1.37E-05	1.7E-05			6.5E-06	1.51E-05	

Table 3.11 Summary of passing frequency calculations for Luanda

N'Djamena									
	Apr	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Nr flights	1336	996	1390	1497	1496	1444	978	1600	1608
Flying time (hours)	1318.22	991.04	1408.10	1751.99	1619.08	1578.93	945.35	1616.54	1723.96
Opposite longitudinal	1045	687	1003	1116	1219	1205	498	989	937
Opposite horizontal	110.77	72.822	106.318	118.296	129.214	127.73	52.788	104.834	99.322
Crossing proximity	0	3	9	4	5	4	3	2	6
Crossing horizontal	0	0.016665	0.049994	0.022219	0.027774	0.022219	0.016665	0.01111	0.033329
Frequency of Opposite longitudinal	0.792736	0.693211	0.712307	0.63699	0.752897	0.763175	0.526789	0.611801	0.543516
Frequency of Opposite horizontal	0.08403	0.07348	0.075505	0.067521	0.079807	0.080897	0.05584	0.064851	0.057613
Frequency of Crossing proximate	0	0.003027	0.006392	0.002283	0.003088	0.002533	0.003173	0.001237	0.00348
Frequency of Crossing horizontal	0	1.68E-05	3.55E-05	1.27E-05	1.72E-05	1.41E-05	1.76E-05	6.87E-06	1.93E-05
Brazzaville									
Nr flights	1808	1871	2036	1983	1924	1806	1883	1915	2093
Flying time (hours)	950.09	923.17	1082.55	1131.53	636.78	1010.83	833.28	1002.71	1205.82
Opposite longitudinal	58	55	57	54	38	57	43	95	110
Opposite horizontal	6.148	5.83	6.042	5.724	4.028	6.042	4.558	10.07	11.66
Crossing proximity	0	0	0	1	0	1	3	0	0
Crossing horizontal	0	0	0	0.005555	0	0.005555	0.016665	0	0
Frequency of Opposite longitudinal	0.061047	0.059577	0.052653	0.047723	0.059675	0.056389	0.051603	0.094743	0.091224
Frequency of Opposite horizontal	0.006471	0.006315	0.005581	0.005059	0.006326	0.005977	0.00547	0.010043	0.00967
Frequency of Crossing proximate	0	0	0	0.000884	0	0.000989	0.0036	0	0
Frequency of Crossing horizontal	0	0	0	4.91E-06	0	5.5E-06	2E-05	0	0

Table 3.12 Summary of passing frequency calculations for N'Djamena and Brazzaville for April to December 2003

N'Djamena								
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**
Nr flights	1913	1814	1597	1437	1453	1458	1520	1508
Flying time (hours)	2313.55	2076.56	1839.47	1821.07	1806.21	2035.35	1992.58	2147.94
Opposite longitudinal	876	871	661	874	801	1102	846	1079
Opposite horizontal	92.856	92.326	70.066	92.644	84.906	116.812	89.676	114.374
Crossing proximity	11	11	9	7	4	11	6	12
Crossing horizontal	0.061103	0.061103	0.049994	0.038884	0.022219	0.061103	0.033329	0.066658
Frequency of Opposite longitudinal	0.378639	0.419444	0.359343	0.479938	0.44347	0.54143	0.424575	0.502342
Frequency of Opposite horizontal	0.040136	0.044461	0.03809	0.050873	0.047008	0.057392	0.045005	0.053248
Frequency of Crossing proximate	0.004755	0.005297	0.004893	0.003844	0.002215	0.005404	0.003011	0.005587
Frequency of Crossing horizontal	2.64E-05	2.94E-05	2.72E-05	2.14E-05	1.23E-05	3E-05	1.67E-05	3.1E-05
Brazzaville								
Nr flights	2060	1839	1859	1841	857	1920	2002	2156
Flying time (hours)	1226.11	1065.80	1046.07	1027.28	513.27	1158.32	1121.70	1247.69
Opposite longitudinal	116	78	60	59	11	77	80	102
Opposite horizontal	12.296	8.268	6.36	6.254	1.166	8.162	8.48	10.812
Crossing proximity	4	3	1	2	0	2	1	4
Crossing horizontal	0.022219	0.016665	0.005555	0.01111	0	0.01111	0.005555	0.022219
Frequency of Opposite longitudinal	0.094608	0.073184	0.057358	0.057433	0.021431	0.066476	0.07132	0.081751
Frequency of Opposite horizontal	0.010028	0.007758	0.00608	0.006088	0.002272	0.007046	0.00756	0.008666
Frequency of Crossing proximate	0.003262	0.002815	0.000956	0.001947	0	0.001727	0.000892	0.003206
Frequency of Crossing horizontal	1.81E-05	1.56E-05	5.31E-06	1.08E-05	0	9.59E-06	4.95E-06	1.78E-05

Table 3.13 Summary of passing frequency calculations for N'Djamena and Brazzaville for January to August 2004

3.4.2.2 Opposite direction traffic

Consider the opposite direction passing frequencies first. The opposite direction passing frequencies for Algiers and Kano are reasonably stable over the range of 0.12 – 0.18 opposite direction passings per flight hour. For Johannesburg, the opposite direction passing frequency varies between 0.0086 and 0.026 passings per flight hour. This variability appears to be caused mainly by the variability in the number of opposite direction longitudinal passings. There is too little data for Cape Town to be able to draw any conclusion. For Gaborone, the opposite direction passing frequency is approximately 0.20. The opposite direction passing frequency for Luanda is reasonably stable, perhaps with the exception of the month of April 2005. The values are a factor of approximately 10 smaller than the values for Algiers and Kano.

Figures 3.7 and 3.8 show some of the data from tables 3.12 and 3.13 for N'Djamena and Brazzaville respectively, namely the monthly number of flying hours and the monthly number of opposite direction passings for the period April 2003 – August 2004. For N'Djamena, flying hours shows a positive trend of approximately 54 hours/month and opposite direction passings show a small negative trend of approximately 5 passings/month. The resulting frequency of opposite direction passings per flight hour is shown in the upper curve in figure 3.9. Overall, it shows a negative trend of approximately 0.02 passings/flight hour per month, in line with the trends observed in figure 3.7. However, when only the period of time January 2005 to August 2005 is considered, the opposite direction passing frequency is approximately constant, with a very small positive trend. An average value over the 17 months period has been calculated as

$$n_z(opp)_{N'Djamena} = 0.5514 \qquad (3.23)$$

The trend in the flying hours for Brazzaville as shown in figure 3.8 is smaller than for N'Djamena, approximately 8.5 hours/month. The opposite direction passings also have a small positive trend of approximately 1.5 passings/month. Notice that the number of passings, on average, is approximately ten times smaller than for N'Djamena whereas the number of flying hours is about one third to one half of that for N'Djamena. Thus, the Brazzaville traffic appears to be much more spread in time. Consequently, the opposite direction passing frequency for Brazzaville is much smaller than for N'Djamena, see the lower curve in figure 3.9. An average value over the 17 months period has been calculated as

$$n_z(opp)_{Brazzaville} = 0.06832 \qquad (3.24)$$

The frequency of opposite direction longitudinal overlaps can be converted into a frequency of horizontal overlap for opposite direction aircraft by multiplying by $P_y(0)$, the probability of lateral overlap for aircraft on the same route. The value of this parameter of the vertical collision risk model depends on the type of navigation being used, e.g. VOR/DME or GNSS. For the benefit of tables 3.5 to 3.13, a value of $P_y(0) = 0.106$ was used, see section 3.5.

Figure 3.7 Flying hours and number of opposite direction passings for N'Djamena during the period April 2003 - August 2004

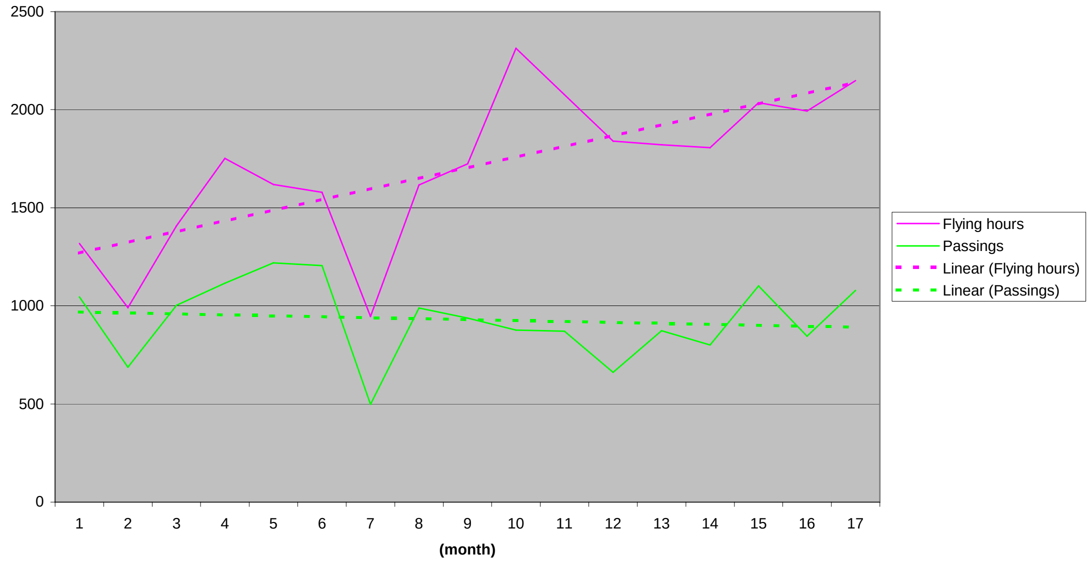


Figure 3.8 Flying hours and number of opposite direction passings for Brazzaville during the period April 2003 to August 2004

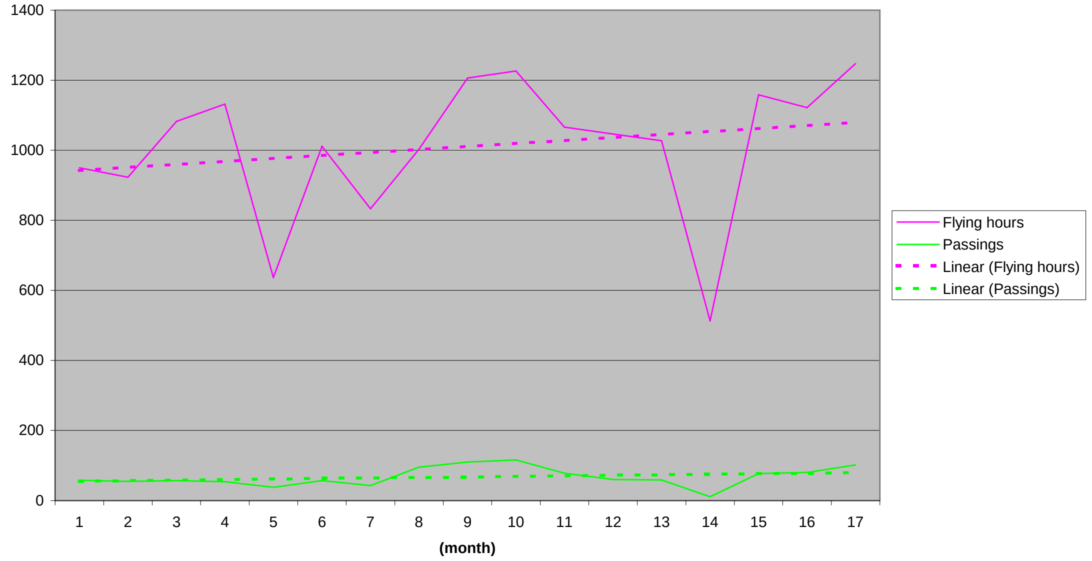
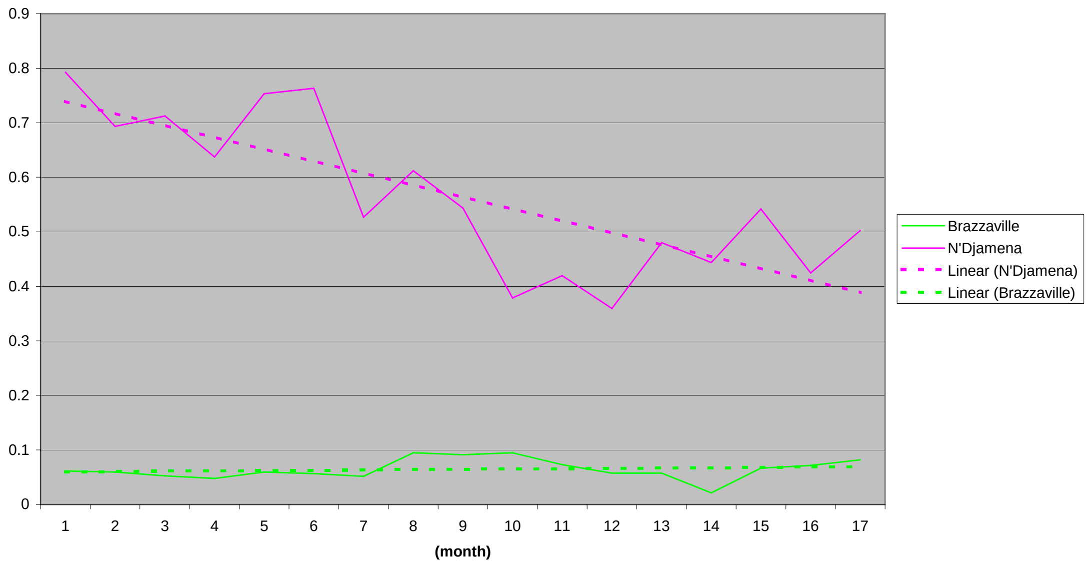


Figure 3.9 Opposite direction passing frequency for N'Djamena and Brazzaville over the period April 2003 August 2004



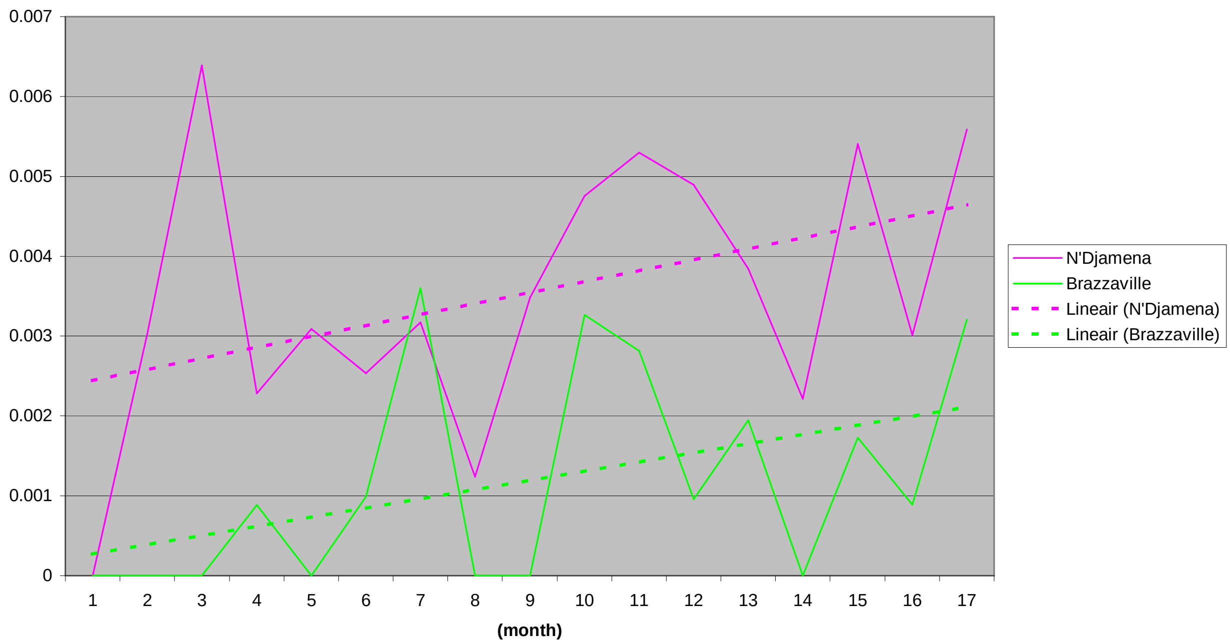
3.4.2.3 Crossing traffic

As explained in appendix B, a horizontal overlap for aircraft on adjacent flight levels on crossing routes is a rare event. As a result, a very large amount of data would be required to estimate its frequency with a reasonable level of precision. Alternatively, the frequency of passings at a crossing within a much larger so-called proximity distance $\tilde{S}_x$, say, is estimated and subsequently analytically corrected to obtain the frequency of horizontal overlap between aircraft at a crossing. (The same approach can be applied to aircraft flying in the same direction at adjacent flight levels of the same route, but this type of traffic does not actually exist in the AFI Region.)

Thus, a crossing track proximity is a passing between two aircraft at the crossing of two routes with a minimum distance less than $\tilde{S}_x$ NM. Tables 3.5 to 3.13 include the frequencies of crossing track proximities for each of the pertinent FIR/UIRs based on $\tilde{S}_x = 5$ NM. In the tables, no distinction is made between crossing track frequencies for different crossing angles. However, the collision risk estimates to be presented in section 3.7, based on eq. (3.5) from section 3.2, do take differences between crossing angles into account.

The crossing track proximities for Algiers and Kano vary between approximately 0.006 and 0.011 with an exception for Kano in March 2005 with a smaller value, viz. 0.002. The crossing track proximity for Johannesburg is very small and it is zero for Cape Town and Gaborone. For Luanda, it is of the order of 0.001 – 0.003 proximities per flight hour. Finally, figure 3.10 shows the frequencies of crossing track proximities for both N'Djamena and Brazzaville. N'Djamena shows a considerable peak over May and June 2003. Overall, it shows a small positive trend over time. A similar trend appears to be present for Brazzaville's frequency of crossing track proximity events.

Figure 3.10 Frequency of crossing traffic proximities for N'Djamena and Brazzaville over the period April 2003 to August 2004



The crossing track proximity frequencies can be converted into frequencies of horizontal overlap at crossings by multiplying the former by the conditional probability of horizontal overlap (relative distance between aircraft centres less than λ_{xy}) given proximity (relative distance between aircraft centres less than $\widetilde{S}_x$). As a first approximation, this conditional probability may be taken as the ratio $\lambda_{xy} / \widetilde{S}_x$. Some details may be found in Appendix B. For $\lambda_{xy} = 0.02777$ NM (cf. Table 3.17 in section 3.6) and $\widetilde{S}_x = 5$ NM, this gives a factor of approximately 0.0056. Multiplication of the crossing track proximity frequencies with this factor gives the crossing track horizontal overlap frequencies in the last row of tables 3.5 to 3.13.

3.4.2.4 Combining different passing frequency components

As was mentioned in section 1.4.1, an annual average passing frequency over the whole airspace of three adjacent area control centres (ACCs) covering the region's busiest traffic flows or highest passing frequency needs to be determined (Ref. 5). As there are different types of passing frequency, same direction, opposite direction and crossing, it is necessary to specify how to determine the highest passing frequency. In line with the global system performance specification for RVSM, the combined effect of the three types of passing frequency is expressed in terms of an "equivalent opposite direction" passing frequncy. This is done as follows.

Recall the technical vertical collision risk model eq. (3.5) from section 3.2. Neglecting same direction traffic and simplifying slightly one obtains

$$N_{az} = 2P_z(S_z)P_y(0)n_z(opp)\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}+2P_z(S_z)\sum_{i=1}^{n}n_z(\theta_i)\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)}\frac{\overline{|\dot{z}|}}{2\lambda_z}\right\}$$

(3.25)

Aside from , the impact of any opposite direction passing on the vertical collision risk is determined by the probability of lateral overlap and the kinematic factor $\left\{1+\overline{|\dot{y}|}/2\overline{V}+\lambda_{xy}/\lambda_z\times\overline{|\dot{z}|}/2\overline{V}\right\}$. Thus, any crossing traffic passing included in may be translated into an equivalent opposite direction passing by means of these two factors, i.e.

$$N_{az} = 2P_z(S_z)P_y(0)n_z(opp)\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}+$$

$$2P_z(S_z)P_y(0)\frac{1}{P_y(0)}\sum_{i=1}^{n}n_z(\theta_i)\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}\frac{\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)}\frac{\overline{|\dot{z}|}}{2\lambda_z}\right\}}{\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}}$$

(3.26)

or

$$N_{az} = 2P_z(S_z)P_y(0)\left[n_z(opp)+\frac{1}{P_y(0)}\sum_{i=1}^{n}n_z(\theta_i)\frac{\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)}\frac{\overline{|\dot{z}|}}{2\lambda_z}\right\}}{\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}}\right]\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}$$

(3.27)

Defining

$$n_z(equiv) = \left[n_z(opp) + \frac{1}{P_y(0)} \sum_{i=1}^{n} n_z(\theta_i) \frac{\left\{1 + \frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)} \frac{\overline{|\dot{z}|}}{2\lambda_z}\right\}}{\left\{1 + \frac{\overline{|\dot{y}|}}{2\overline{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}} \right] \tag{3.28}$$

eq. (3.27) can be written as

$$N_{az} = 2P_z(S_z)P_y(0)n_z(equiv)\left\{1 + \frac{\overline{|\dot{y}|}}{2\overline{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{\overline{|\dot{z}|}}{2\overline{V}}\right\} \tag{3.29}$$

The last expression is precisely of the opposite direction traffic form, whereas numerically it takes account of all the different types of traffic geometries.

In conclusion, eq. (3.28) defines the way the passing frequency is to be calculated for each FIR/UIR. Next, a weighted average of the passing frequencies for each subset of three adjacent ACCs needs to be calculated and the highest average value needs to be taken as the ultimate passing frequency parameter for the technical vertical collision risk model.

Table 3.14 shows for each of the selected FIR/UIRs its equivalent opposite direction passing frequency in the middle column. For reference, the original opposite direction passing frequencies are also included in the last column. (All values are averages over the periods of time for which data was available.) Crossing traffic is seen to have a significant effect for the FIR/UIRs of Algiers, Kano and Luanda, a moderate effect for N'Djamena and Brazzaville, and only little effect for Johannesburg, Cape Town and Gaborone.

FIR/UIR	n_z**(equiv)**	n_z**(opp)**
Algiers	0.1860	0.1280
Kano	0.2123	0.1470
Johannesburg	0.01664	0.01594
Cape Town East	0.01114	0.01114
Cape Town West	0.0	0.0
Gaborone	0.1981	0.1981
Luanda	0.03856	0.01661
N'Djamena	0.5802	0.5454
Brazzaville	0.07876	0.06693

Table 3.14 Summary of equivalent opposite direction passing frequency for the different FIR/UIRs

It follows from the equivalent opposite direction passing frequency values in table 3.14 that the three busiest adjacent ACCs are Kano, N'Djamena and Brazzaville. Thus, the overall value to be used for the vertical collision risk assessment for the AFI Region is a (weighted) average across these three ACCs, i.e.

$$n_z^{AFI}(equiv) = w_1 \times n_z(equiv)_{Kano} + w_2 \times n_z(equiv)_{N'Djamena} + w_3 \times n_z(equiv)_{Brazzaville} \qquad (3.30)$$

where the weighting factors w_1, w_2 and w_3 are the proportions of flying time ($\approx 0.05, 0.6 \text{ and } 0.35$) in the respective FIR/UIRs. Substitution of the various parameter values finally gives

$$n_z^{AFI}(equiv) = 0.3840 \qquad (3.31)$$

3.4.2.5 Hadj and passing frequency

During the Hadj, one would expect additional west-east traffic on the routes UM999 from Morocco to Jeddah, UM974-UG854-UA620-UB736 from Senegal to Ethiopia and further North, and on the UB736 from Nigeria to Ethiopia.

For the first of these routes, the UM999 from Morocco to Jeddah, traffic flow data from Algeria was available only. This covered the Month of January 2005 and the effect, if any, has therefore been included in table 3.5.

For the second route, the UG854 was covered by Kano and the UA620 by N'Djamena. The UB736 in the Khartoum UIR has not been analysed as no data from Sudan has been received. For the third route, the UB736 was covered by Kano and N'Djamena. Kano shows an increase in both the flying hours and the number of crossing proximities in January 2005. Nonetheless, the corresponding frequency of crossing horizontal overlaps is only a small proportion of the opposite direction horizontal overlaps.

For Algiers and Kano, the amount of data is too small to draw any firm conclusions about the possible effect of the Hadj on passing frequency. For N'Djamena, however, the situation is different. The number of crossing track proximities in January and February 2005 is approximately 50% higher than for December and there appears to be a clear peak in the crossing-traffic horizontal overlap frequency. Nonetheless, the contribution of crossing traffic passing frequency is small compared to that from opposite direction traffic.

3.4.3 Data limitations, corrections and results

It should be clear that in order to produce a representative prior estimate of the technical vertical collision risk in AFI RVSM airspace, it is necessary to collect data on all flights currently operating on all routes in the flight level band FL290 to FL410 inclusive. This data is needed to estimate the number of flying hours in the band FL290 - FL410 on the one hand and the number of horizontal passing events (of each of the different types) on the other. Thus, the data must cover overflights between FL290 - FL410 inclusive as well as those portions of inbound and outbound flights that take place in this flight level band. The four data collection forms described in section 2.6, particularly Form 2 (monthly movements) and Form 4 (traffic flow data), have been designed for this purpose, cf. reference 18.

Provided the information in Form 4 is complete, flying time can be derived from it and can be cross-checked against the flying time reported in Form 2.

A key element of the traffic flow data information in Form 4 is the actual flight progress information, i.e. waypoint identification, reporting time at waypoint, and FL at waypoint (Ref 34). It should be clear that even for a single route segment bounded by a waypoint at either side, the reporting times at both waypoints are needed to determine whether a (longitudinal) passing has occurred between two aircraft flying at adjacent flight levels, independent of their flying in the same or opposite direction. More generally, to be able to handle all possible route configurations, the flight progress information at all the waypoints along an aircraft's flight path through a FIR/UIR is required.

Table 3.15 summarises for each of the nine FIR/UIRs the limitations, if any, of the traffic flow data reported in Form 4. It is remarked that it has been assumed that there is no limitation with regard to the routes, i.e. that all the routes have been covered for each FIR/UIR.

It follows from table 3.15 that the information available from the States was not perfect. The problems caused by the flight progress information being available at a single waypoint only have been summarised in Appendix B3. See also reference 34. The inconsistencies between the amounts of flying time reported in the Forms 2 and those derived from the Forms 4 are rather worrying since they affect almost all the parameters of the vertical collision risk model: flight time proportions for the overall ASE probability distribution model and the average aircraft dimensions (see Appendix A) as well as the denominator for the passing frequency parameter.

Some deficiencies had been foreseen and it had been intended, therefore, to derive and apply some correction factors, particularly with regard to the effect of the flights and waypoint issues on passing frequency. However, it has been found to be very difficult to correct for the various factors. As a result, no correction factors have been calculated. Very crudely, one might guess that the passing frequency estimate should not be off by a factor of more than two. Hence, a margin of this order of magnitude should be maintained between the best estimate of the technical vertical collision risk and the technical TLS in section 3.7.

FIR/UIR	Flights			Waypoints	Form 4 / Form 2 Consistency	Other
	over flights	in-bound	Out-bound			
Algiers	✓			All	75%	
Kano	✓			1	95%	
Johannesburg		✓	✓	1	10%	Domestic only
Cape Town East		✓	✓	1	10%	Domestic only
Cape Town West		✓	✓	1	10%	Domestic only
Gaborone	✓	✓	✓	FIR entry	-	
Luanda	✓	✓	✓	1, mostly FIR entry	60%	
N'Djamena	✓	✓	✓	FIR entry & FIR exit	-	
Brazzaville	✓	✓	✓	FIR entry & FIR exit	-	

Table 3.15 Summary of data limitations

3.5 Probability of lateral overlap

The probability of lateral overlap for aircraft nominally flying on (adjacent flight levels of) the same route is denoted by $P_y(0)$ and is defined by

$$P_y(0) = \int_{-\lambda_y}^{\lambda_y} f_{y_{12}}(y)dy \tag{3.25}$$

where λ_y denotes the average width of the aircraft (cf. table 3.1). In eq. (3.25), the integrand $f_{y_{12}}(y)$ denotes the probability density of the lateral distance y_{12}, say, between two aircraft with lateral deviations y_1 and y_2 from the nominal route, i.e.

$$y_{12} = y_1 - y_2 \tag{3.26}$$

On the assumption that the lateral deviations y_1 and y_2 are independent identically distributed random variables with probability density $f_Y(y)$, say, the probability density $f_{y_{12}}(y)$ can be written as

$$f_{y_{12}}(y) = \int_{-\infty}^{\infty} f_Y(y_1) f_Y(y_1 - y) dy_1 \tag{3.27}$$

Substitution of eq. (3.27) into eq. (3.25) gives

$$P_y(0) = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f_Y(y_1) f_Y(y_1 - y) dy_1 dy \tag{3.28}$$

In practice, eq. (3.28) is often approximated by

$$P_y(0) \approx 2\lambda_y \int_{-\infty}^{\infty} f_Y(y_1) f_Y(y_1) dy_1 \tag{3.29}$$

or

$$P_y(0) \approx 2\lambda_y f_{y_{12}}(0) \tag{3.30}$$

with

$$f_{y_{12}}(0) = \int_{-\infty}^{\infty} f_Y(y_1) f_Y(y_1) dy_1 \tag{3.31}$$

If follows that the probability density $f_Y(y)$ is needed to calculate the probability of lateral overlap $P_y(0)$. This probability density is dependent on the type of navigation equipment being used in the airspace under consideration. It was mentioned in section 2.3 that the ground-based navigation infrastructure in the AFI Region consists of NDBs and VOR/DMEs. However, more and more aircraft have started to use satellite-based navigation (GNSS). $P_y(0)$, therefore, will be calculated on the assumption that a proportion α, $0 < \alpha < 1$, of the AFI RVSM airspace users is using GNSS navigation and that the remaining proportion $1-\alpha$ is using VOR/DME navigation. Denoting the respective probability densities of the lateral deviations under the two types of navigation systems by $f(y)_{GNSS}$ and $f(y)_{VOR/DME}$ respectively, it follows that

$$f_Y(y) = (1-\alpha)\times f(y)_{VOR/DME} + \alpha \times f(y)_{GNSS} \tag{3.32}$$

It remains to specify the type and parameter values characterizing the two constituent probability densities. Both probability densities will be taken as gaussian densities. As the calculation of $P_y(0)$ is dominated by the core of the densities, no heavy extrapolation for the densities is involved and the choice of the type of probability density is less critical than for e.g. the calculation of $P_z(1000)$. Following the RVSM global system performance specification, the standard deviation for VOR/DME navigation is taken as 0.3 NM. It is noted in passing that the more accurate the lateral path keeping is (the smaller the standard deviation of the lateral deviations), the larger the value of $P_y(0)$. It is recognised that GNSS navigation is highly accurate. Therefore, a standard deviation of 0.06123 NM will be used for the GNSS subpopulation operating in AFI RVSM airspace, cf. reference 32. Thus, $f_Y(y)$ may be expressed as

$$f_Y(y) = (1-\alpha)\frac{1}{\sigma_{VOR/DME}\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{y}{\sigma_{VOR/DME}}\right)^2} + \alpha\frac{1}{\sigma_{GNSS}\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{y}{\sigma_{GNSS}}\right)^2} \tag{3.33}$$

with

$$\sigma_{VOR/DME} = 0.3NM \tag{3.34}$$

$$\sigma_{GNSS} = 0.06123NM \tag{3.35}$$

The probability density $f_{y_{12}}(y)$ of the lateral distance between two aircraft on the same route then becomes

$$f_{y_{12}}(y) = (1-\alpha)^2\frac{1}{\sigma_{VOR/DME}\sqrt{2}\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{y}{\sigma_{VOR/DME}\sqrt{2}}\right)^2} +$$

$$2\alpha(1-\alpha)\frac{1}{\sqrt{\sigma_{VOR/DME}^2+\sigma_{GNSS}^2}\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{y}{\sqrt{\sigma_{VOR/DME}^2+\sigma_{GNSS}^2}}\right)^2} + \alpha^2\frac{1}{\sigma_{GNSS}\sqrt{2}\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{y}{\sigma_{GNSS}\sqrt{2}}\right)^2}$$

(3.36)

Based on eq. (3.25), table 3.16 shows values for the probability of lateral overlap $P_y(0)$ for aircraft on the same route as a function of the proportion. $P_y(0)$ is seen to vary by a factor of five when the proportion α of GNSS flying time increases from 0 to 1. Unfortunately, it is not easy to obtain an accurate estimate for α for the AFI Region. Although the forms used to collect traffic flow data included a column for the navigation equipment on board the aircraft, this information was generally not provided.

Proportion α of GNSS flying time	**$P_y(0)$**
0	0.0491
0.05	0.0513
0.1	0.0544
0.2	0.0627
0.25	0.0679
0.5	0.106
0.75	0.162
1	0.237

Table 3.16 $P_y(0)$ as a function of the proportion α of GNSS flying time

A rough estimate for the proportion of GNSS flying time has been made as follows. All scheduled flights with either an origin or a destination aerodrome outside the AFI Region are assumed to be made with GNSS navigation. Non-scheduled flights within, into or out of the AFI Region are assumed to be utilising VOR/DME navigation. Using the numbers of flights presented in section 2.2, it is estimated that 297,000 flights may be using GNSS navigation as opposed to 811,000 flights using conventional navigation. Taking the average flying time inside the AFI region for a GNSS aircraft entering/or leaving the Region as 4 hours and the average flying time for a conventional flight as 2 hours results in an estimate of 42% for the proportion of GNSS flying time. A slightly conservative reference estimate for the proportion α of GNSS flying time in the AFI Region then is $\alpha_0 = 0.5$. The corresponding value for the probability of lateral overlap to be used in the vertical collision risk model is $P_y(0) = 0.106$. This value is approximately twice the value of 0.0491 for all aircraft using conventional navigation.

A means to reduce the increase in the probability of lateral overlap $P_y(0)$ due to very accurate GNSS based navigation is the use of lateral offsets under certain conditions as set out in an

ICAO State letter (Ref. 33). The risk mitigating effect on $P_y(0)$ has not been taken into account in this report.

3.6 Aircraft dimensions and relative speeds

3.6.1 Aircraft dimensions

Weighted average aircraft dimensions have been calculated as described in Appendix A. The resulting dimensions for a typical aircraft in AFI RVSM airspace are shown in Table 3.17. A comparison with aircraft dimensions from some other airspaces is given in table 3.18 (Refs. 19, 24 - 26, 29). The values for the AFI region are seen to be larger than those for the EUR Region and smaller than those for the NAT Region.

Aircraft dimension	Parameter	Value (ft)	Value (NM)
Length	λ_x	168.72	0.02777
Width	λ_y	158.71	0.02612
Height	λ_z	49.25	0.008106
Diameter	λ_{xy}	168.72	0.02777

Table 3.17 Typical aircraft dimensions for AFI Region

Aircraft dimension (ft)	Airspace					
	EUR	**AFI**	**NAT**	**SAT**	**Japan**	**Australian FIRs**
Length λ_x	132.44	168.72	185.93	193.12	221.17	221.17
Width λ_y	-	158.71	165.27	174.45	195.04	195.04
Height λ_z	38.67	49.25	52.25	55.43	61.37	61.37
Diameter λ_{xy}	132.44	168.72	-	193.12	221.17	221.17

Table 3.18 Comparison of typical aircraft dimensions from different airspaces

3.6.2 Relative speeds

The vertical collision risk model of eq. (3.5) contains four relative speed parameters, $2|\overline{V}|$, $|\overline{\Delta V}|$, $|\overline{\dot{y}}|$ and $|\overline{\dot{z}}|$. The average aircraft speed has been estimated in Appendix A as $\overline{V} = 466$ kts. For $|\overline{\Delta V}|$, the same value has been taken as in reference 26, viz. $|\overline{\Delta V}| = 20$ kts.

Consider finally the relative speeds $\overline{|\dot{y}|}$ and $\overline{|\dot{z}|}$. These vertical collision risk model parameters cannot be estimated from the traffic flow data provided by the States in the AFI Region. A potential issue with regard to these two relative speed components is to what extent they are related to the magnitude of the lateral and vertical separation between a pair of aircraft. For the vertical collision risk model, the relative speed component $\overline{|\dot{y}|}$ is the mean of the (absolute value of the) relative lateral speed between aircraft on the same route. Consequently, there is no operational reason why this parameter should have a particularly large value. Previous vertical collision risk assessments for procedural airspaces assumed values of 20 and 4 kts (Refs. 24-26). The more conservative value, albeit perhaps somewhat outdated, will be used here, i.e. $\overline{|\dot{y}|} = 20$ kts. The mean absolute value of the relative vertical speed $\overline{|\dot{z}|}$ of the vertical collision risk model applies to aircraft that have lost their assigned vertical separation minimum of S_z ft. Unfortunately, data on $\overline{|\dot{z}|}$ are rather scarce. Data from the European studies of vertical separation above FL290 showed an approximately constant relationship between $\overline{|\dot{z}|}$ and the vertical separation $|z|$ (Ref. 23, part II, Annex A, section 5.5.6). From this source, a value of $\overline{|\dot{z}|} = 1.5$ kts has been taken.

3.7 Technical vertical risk

The technical vertical collision risk model was specified in eq. (3.5) of section 3.2. It was transformed into the following equivalent form in section 3.4.2.4:

$$N_{az} = 2P_z(S_z)P_y(0)n_z(equiv)\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\} \quad (3.29)$$

Table 3.19 summarises the main parameter estimates for this model.

Parameter	Value
S_z	1000
$P_z(S_z)$	1.61×10^{-8}
$P_y(0)$	0.106
$n_z(equiv)$	0.3840
$\left\{1+\frac{\overline{\lvert\dot{y}\rvert}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{\lvert\dot{z}\rvert}}{2\overline{V}}\right\}$	1.02697

Table 3.19 Summary of parameter values for vertical collision risk model of eq. (3.29)

Substitution of these values into eq. (3.29) gives

$$N_{az} = 2 \times 1.61 \times 10^{-8} \times 0.106 \times 0.3840 \times 1.02697 = 1.35 \times 10^{-9} \quad (3.37)$$

This risk estimate is expressed in fatal accidents per flight hour and is to be compared with the technical vertical TLS of 2.5×10^{-9} fatal accidents per flight hour.

It can be concluded that the technical vertical TLS is being met. Moreover, it is being met by a reasonable margin, viz. a factor of approximately 1.9. This is deemed to be sufficient to cover the effect of the data limitations discussed in section 3.4.2.6.

4 Assessment of total vertical risk

4.1 Introduction

Section 3 dealt with the assessment of the technical vertical collision risk under RVSM in the AFI Region. There may, however, exist additional causes of vertical collision risk. The combined effect of all these potential causes and the normal technical causes is to be assessed against the total vertical TLS of 5×10^{-9} fatal accidents per flight hour. Thus, suitable collision risk models describing the risk due to the additional causes are needed, leading to the following issues:

- What additional causes of vertical risk are known to exist;
- What is the relationship between causes and resulting height deviations;
- What data on these causes and effects are available;
- How to model the relationship between causes, effects and vertical risk?

In addressing these issues, knowledge and experience from other Regions can and should be used but the specificities of the AFI Region will have to play a major role.

Section 4.2 provides some background discussion on the above issues followed by a detailed examination of the currently available data in section 4.3. Following that, sections 4.4 and 4.5 will present suitable models for the total vertical collision risk and estimates of this risk respectively.

4.2 Background on total vertical collision risk

Fortunately, a collision between two aircraft is an extremely rare event. On the other hand, the fact that no collision has been observed over even a long period of time does not imply that the true rate of collisions is zero. The observation period has most probably been too short in comparison to the true collision rate. Thus, to be able to estimate the collision risk, data on related but more frequently occurring events are needed. Incident data have been used in collision risk assessment for this purpose for a long time. Incidents could have led to collisions if circumstances had been (slightly) different. A collision may not have occurred in a given case simply due to chance or because of some form of effective intervention. Thus, the causes of incidents are essentially the same as those of collisions.

Consider now the four issues listed in the introductory section 4.1. Based on experience from other ICAO regions, e.g. Europe and the NAT, the following broad categories of potential causes of total vertical collision risk may be distinguished (Refs. 24, 26 and 30):

- ATC error;
- Pilot error;
- ACAS;

- Non-RVSM approved aircraft;
- Equipment failure;
- Turbulence/weather;
- Unknown civil aircraft;
- Unknown military aircraft operating outside designated military areas;
- Aircraft contingency events.

Each category may be subdivided further dependent on the specific nature of the error or problem. From a collision risk assessment point of view, the importance of these causes is that they may lead to large or atypical height deviations of more than 300 ft, say. It is the vertical risk due to this type of height deviations that is to be modelled for comparison with the total vertical TLS of 5×10^{-9} fatal accidents per flight hour.

The resulting height deviations have been classified into

- large height deviations involving whole numbers of flight levels; and
- large height deviations not involving whole numbers of flight levels.

For example, an ATC error in issuing a clearance may lead to an aircraft levelling off at a wrong flight level leading to two types of risk. Firstly, it may lead to a risk for any aircraft that may already correctly be flying at that level. Secondly, on its way towards the wrong flight level, the pertinent aircraft may have traversed through one or more intermediate flight levels. As another example, ATC misjudging the climb speed of an aircraft may lead to the aircraft passing through another aircraft's flight level too late. From a risk point of view, this is similar to passing through a level without a proper clearance.

A pilot error in following a correct ATC clearance may also lead to a large height deviation of the whole number of flight levels type. On the other hand, a level bust is an example of a pilot error not involving a whole number of flight levels. It involves an overshoot over a certain short period of time after which the aircraft levels off correctly at the intended flight level.

Height deviations due to ACAS do not normally involve whole numbers of flight levels but may be much larger than an aircraft's typical height deviations (see section 4.3.3). Height deviations of non-RVSM approved aircraft will generally not involve whole numbers of flight levels either but may be expected to have a larger probability of relatively large height deviations, larger than 300 ft say. Height deviations due to equipment failure, turbulence or other adverse weather conditions will also generally lead to large height deviations not involving whole numbers of flight levels.

Unknown civil or military aircraft operating at an AFI RVSM flight level involve by definition height deviations of the whole number of flight levels type as they should simply not be flying where they are. When such aircraft also happen to be non-RVSM approved, they may also cause the other type of large height deviation. Aircraft contingency procedures should be designed in such a way that they do not involve any significant risk when executed properly. Due to the nature of the situation, however, it may occasionally not be possible to fully comply with the procedure as a result of which one or more flight levels may be crossed without a proper clearance before levelling off at a new level.

Data on causes and effects of large atypical height deviations under the current 2000 ft vertical separation minimum above FL290 have been obtained via ARMA from three different sources, namely from several African States, IATA and from ICAO. An important issue with regard to this data is whether or not it is affected by under-reporting. The fact that a State may not be reporting any large height deviations or reports precisely zero deviations over a certain period of time does not necessarily mean that the true rate of occurrence of large height deviations is zero, cf. references 19 and 30. As regards the type of data, data on the occurrence frequency of each type of cause is needed first of all. Secondly, the data needed on the resulting effects is dependent on the type of large height deviation. For large height deviations involving whole numbers of flight levels, the numbers of flight levels crossed without proper clearance at what vertical speed are needed and also the time spent at a resulting incorrect flight level. For large height deviations not involving whole numbers of flight levels, the magnitude and duration of the deviation is needed.

The last issue to be discussed concerns the modelling of the relationship between the various causes, resulting large height deviations, and total vertical collision risk. Two elements that are of particular importance with regard to this modelling are:

- To what extent is the occurrence of any error (cause) with respect to an aircraft dependent on the location of that aircraft or related to any other aircraft; and
- To what extent is there a possibility for ATC and/or the pilot(s) to intervene and prevent a potential collision after the occurrence of an error?

The first element has led to two different approaches to the modelling of the total vertical collision risk that may be referred to as the <u>conventional</u> approach/model and the <u>conditional</u> approach/model.

The <u>conventional</u> approach to modelling the total vertical collision risk is essentially the same as that applied to technical vertical collision risk (Refs. 24, 26, 31). In this context, it is useful to note first that the technical vertical collision risk model assumes that the normal technical height deviations of an aircraft are independent of its horizontal navigation. In addition, the height deviations and horizontal navigation deviations of any aircraft in a pair are assumed to be independent of other aircraft. As a result, the technical vertical collision risk can essentially be modelled by the product of passing frequency and the probability of vertical overlap due to normal technical height deviations. With reference to the nine error categories listed above, it seems that pilot error, non-RVSM approved aircraft, equipment failure, turbulence and adverse weather conditions, unknown civil or military aircraft and aircraft contingency events are un-correlated with the presence of other aircraft. Thus, the risk due to these causes may again essentially be modelled as the product of passing frequency and a probability of vertical overlap, where the particular form of the latter is dependent on the type of cause. This approach is sometimes referred to as assuming the large height deviations to occur into a random stream of traffic.

The conditional approach to modelling of total vertical collision risk has been developed specifically with regard to ATC error (Refs. 35 - 39) since in many cases an ATC error is directly related to the presence of another aircraft, cf. section 4.3.4. For example, an ATC error in issuing a change of flight level instruction involves by definition another aircraft since otherwise the clearance would have been correct. ATC misjudgement of the climb rate of an aircraft might be a purely random event but it might also be the result of confusing the aircraft in question with a different aircraft somewhere else in the environment. The conditional approach is based on work performed on the development of a 3-D collision risk model for European airspace (Refs. 40 and 41). It takes the correlation between the vertical and horizontal dimensions into account through a conditional probability (based on 3-D geometrical considerations) which represents the likelihood of a pair of aircraft colliding given that they have lost separation.

Both the conventional model and the conditional model will be utilised in the sections 4.4 and 4.5. If a real correlation exists between the vertical and horizontal dimensions in case of an operational error, then, dependent on the strength of the correlation, the corresponding risk may be underestimated by the conventional model.

Both the conventional model and the conditional model may be supplemented with a model for intervention, but this has not been done in this report for the following reasons. Firstly, the intervention capability of ATC is dependent on the type of air traffic control service being provided. As mentioned in section 2.3, most of the AFI region is provided with procedural control. It is reasonable, therefore, to assume that there is essentially no intervention capability for ATC once an error resulting in a large height deviation has occurred. This is similar to the situation in e.g. the NAT Region and the vertical collision risk model for the NAT does not include an intervention factor either (Ref. 24).

Secondly, with regard to a pilot's intervention capability, it should be noted that based on current ICAO policy, ACAS is to be considered a safety net and that its potential risk mitigating effect is not allowed to be taken into account in any collision risk assessment (Ref. 42). A second intervention capability for a pilot in the AFI Region concerns the IFBP. However, like ACAS, its risk mitigating effect should not be accounted for in the total vertical collision risk assessment for AFI RVSM. Finally, visual avoidance of collisions by pilots may be feasible in CVSM airspace but is not considered an option in RVSM airspace. Hence, if visual avoidance has been able to play a part in preventing an incident in CVSM airspace to lead to a collision and if the same incident could happen in RVSM airspace, then this visual avoidance should not be accounted for in the RVSM collision risk assessment.

4.3 Data

4.3.1 Introduction

This subsection examines the data that was available for the assessment of the total vertical collision risk under AFI RVSM. Data collected by ARMA from States in the monthly forms will be presented first. This concerns Form 1, large height deviations, and Form 3, other operational considerations, respectively. Following that, some data from the AFI ATS Incident Analysis Working Group (AIAG) will be presented. Only the Form 1 data and the AIAG data will be used for the assessment of the total vertical collision risk under AFI RVSM. Obviously, all data has been collected prior to the implementation of RVSM in the AFI Region and the validity of the data for AFI RVSM will need to be established.

4.3.2 ARMA Form 1 – large height deviations

4.3.2.1 Data

Table 4.1 summarises the numbers of height deviations reported to ARMA by a number of African States in Form 1 over the period September 2004 – May 2005. Empty cells indicate that no information was received. As to the causes of the 31 reported non-zero height deviations, no cause was included in the report on 14 deviations, altimetry error/problem was stated as the cause for 15 deviations, an emergency descent for one deviation and company policy for one deviation.

The above data is understood to have been collected by radar in conformity with conclusion 3/13 of the RVSM/RNAV/RNP/TF/3 meeting (Ref. 43). However, conclusion 3/4 of the same meeting requires **all** States to institute procedures for reporting data, incidents and conditions necessary for the vertical collision risk assessment including data on height deviations of 300 ft or more. As e.g. no data on incidents caused by ATC error have been reported (cause of error number 6 on Form 1), there appears to be a problem of under-reporting by States. Notice also a number of gaps in table 4.1 for the period November 2004 to May 2005 (although some of the

May 2005 data may not yet have been included). Finally, not any pilot reported incidents seem to have been included in the Forms 1. Such reports, however, are available in the AIAG data set to be examined in section 4.3.4.

FIR/UIR	**Underlying Countries**	**Number of height deviations reported**								
		2004				**2005**				
		Sep	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**
Accra	Ghana / Togo / Benin					3	7			
Algiers	Algeria			0	0	0	4		3	
Asmara	Eritrea							0		0
Cairo	Egypt					0	0			
Cape Town East	Republic of South Africa			0	0	0	0	0		
Cape Town West	Republic of South Africa			0	0	0	0	0		
Dar Es Salaam	Tanzania / Rwanda / Burundi			0	0	0	0			
Harare	Zimbabwe						0	2	0	0
Johannesburg	Republic of South Africa			0?	2	0?				
Kano	Nigeria				0	0		0	0	
Mauritius	Mauritius	8				0?	0?	0?	0?	0?
Nairobi	Kenya	2								
Reunion	Reunion (France)			0	0	0		0	0	
Sal Oceanic	Cape Verde							0		
Windhoek	Namibia			0*	0*	0*	0*	0*		

Table 4.1 Summary of height deviations reported in ARMA Form 1
<u>Note 0?:</u> An empty Form 1 was submitted to ARMA.
<u>Note 0*:</u> No height deviations reported due to no availability of radar.

The ten height deviations reported by Accra over the months of January and February 2005 were all equal to 100 ft. Consequently, they are assumed to represent typical height-keeping performance rather than large height deviations.

All but one of the seven height deviations reported by Algiers was 100 ft with the last one being 200 ft. Again, these deviations are assumed to represent typical performance.

Harare reported 2 deviations for March 2005, one being 300 ft in magnitude, lasting for 10 minutes, the other being 700 ft and lasting for 50 minutes. Both deviations have been classified as large height deviations.

Mauritius reported a total of eight height deviations for September 2004, five and two of which equalled 100 ft and 200 ft respectively. These are assumed to represent typical performance. One deviation of 400 ft lasting for 9 minutes has been classified as a large height deviation.

Nairobi reported two deviations of 300 ft with a total duration of 40 minutes for September 2004. Both have been classified as large height deviations.

Johannesburg reported two large height deviations for December 2004, one of 1700 ft in magnitude that lasted for 20 minutes and one of 2000 ft lasting for 20 seconds. The cause of the former deviation was aircraft equipment error whereas the cause of the latter was an emergency descent. The time duration of 20 seconds refers to the time from the start of the descent until advising ATC. Both deviations have been classified as large height deviations.

Despite the potential lack of representation of the height deviation data in table 4.1, it may still be useful to evaluate the vertical risk due to those deviations that have been reported. To this end, all the height deviations in table 4.1 are assumed to be representative of AFI RVSM airspace and will as such be included in the risk assessment. Further, all the height deviations but the one caused by the emergency descent have been modelled as large height deviations not involving whole numbers of flight levels. The emergency decent related height deviation has been classified as involving a whole number of flight levels.

The total flying time during which the height deviations of table 4.1 occurred is also needed for the modelling of the vertical risk due to these deviations. This has been calculated from the information in ARMA Form 2, monthly movements. Table 4.2 shows for each FIR/UIR in table 4.1 the number of movements per month based on the information in Form 2. Notice that this information was not available in Form 2 for several FIR/UIRs, the pertinent cells in table 4.2 being marked “-“.

FIR/UIR	Number of movements								
	2004				2005				
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Accra					2170	1960			
Algiers			4902	5229	4916	-		-	
Asmara							184		-
Cairo					-	-			
Cape Town			-	12999	12552	11834	11334		
Dar Es Salaam			-	-	2560	2421			
Harare						2200	2444	2383	2366
Johannes-Burg			20593	19645	20835				
Kano				992	1096		953	944	
Mauritius	1034				-	-	-	-	901
Nairobi	2889	3273							
Reunion			387	433	407		454	451	
Sal Oceanic							-		
Windhoek			1457	1434	-	-	-	-	

Table 4.2 Summary of number of movements reported in ARMA Form 2

FIR/UIR	Average flying time per movement (hours)	FIR/UIR	Average flying time per movement (hours)
Accra	2.3	Johannesburg	1.17
Algiers	1.88*	Kano	0.70*
Asmara	-	Mauritius	2.25
Cairo	-	Nairobi	0.88
Cape Town	0.58	Reunion	0.5
Dar Es Salaam	2.13	Sal Oceanic	-
Harare	0.78	Windhoek	1.5

Table 4.3 Average flying time per movement reported in ARMA Form 2
Note *: Estimated using Form 4

Flying time can be calculated as the product of number of movements per month and average flying time per movement. Table 4.3 shows the latter for the FIR/UIRs from table 4.1. The average flying time per movement was not available in Form 2 for Algiers, Asmara, Cairo, Kano and Sal Oceanic. It has been estimated for Algiers and Kano using Form 4. As this was not possible for Asmara, Cairo, and Sal Oceanic, these FIR/UIRs have been excluded from the final calculations. Windhoek has also been excluded based on the note in table 4.1. On the other hand, the "0?" entries in table 4.1 have been treated as confirmed zero deviations. When for any of the remaining FIR/UIRs the number of movements was missing for a particular month for which the large height deviation form was available, an average of the available numbers of movements was taken.

The resulting number of flying hours is 204487.2 hours distributed over a total of 39 months and containing 7 large height deviations, only one of which involves a whole number of flight levels. Total flying time together with the number and duration of large height deviations allows calculating the probability of the occurrence of large height deviations as described in the next sub-section.

4.3.2.2 Data modelling

A probability distribution for assigned altitude deviation (AAD) needs to be constructed that represents both normal technical (typical) performance and the effect of the large height deviations in table 4.1. This probability distribution represents the proportions of time spent at each magnitude of AAD. Based on the double exponential (DE) probability density for typical AAD defined by eq. (3.13), the following double double exponential (DDE) mixture density has been adopted:

$$f^{AAD}(a) = (1-\alpha)\frac{1}{\sigma_1^{AAD}\sqrt{2}}e^{-\frac{|a|\sqrt{2}}{\sigma_1^{AAD}}} + \alpha\frac{1}{\sigma_2^{AAD}\sqrt{2}}e^{-\frac{|a|\sqrt{2}}{\sigma_2^{AAD}}} \tag{4.1}$$

The first or core density function in the right-hand side of eq. (4.1) represents typical AAD whereas the second or tail density represents atypical or large AAD. Double exponential tail densities are often used in risk assessment as a conservative approach to dealing with a lack of data on rare events such as (very) large height deviations. The parameter α in eq. (4.1) is a weighting factor, $0 \le \alpha \le 1$. Based on the interpretation of the two constituent probability densities it should hold that the standard deviation σ_2^{AAD} of the tail density is markedly larger than the standard deviation σ_1^{AAD} of the core density.

Before considering the model of eq. (4.1) in more detail, it is necessary to look at the impact of the six large height deviations (not involving a whole number of flight levels), also referred to as atypical deviations. Taking the quantised nature of AAD data into account, the proportions of typical AAD deviations and combined typical and atypical AAD deviations in the intervals (-50,50), (-150, -50), (50,150) ft etc. have been calculated and folded about zero. Table 4.4 shows these proportions in the second and third column. There is no difference between pure typical performance and combined typical and atypical performance on the first three intervals. In fact, 99.5% of the deviations is less than 150 ft in magnitude. There is a marginal difference on the third interval due to the 50 minutes of 300 ft large height deviations. Then, there is a difference of about 15% on the fifth interval due to the nine minutes of 400 ft deviations. However, there is a five orders of magnitude difference in the proportions on the eighth interval due to the 700ft deviation that lasted for 50 minutes. Finally, there are 20 orders of magnitude difference on the 18th interval as a result of the 1700 ft deviation with a duration of 20 minutes.

Interval	Proportion of typical deviations in interval	Proportion of typical and atypical deviations in interval	Proportion of typical deviations in interval or beyond	Proportion of typical and atypical deviations in interval or beyond
(-50,0) & (0,50)	0.8308	0.8308	1.00000	1.00000
(-150,-50) & (50,150)	0.16436	0.16436	0.16923	0.16921
(-250,-150) & (150,250)	0.00471	0.00471	0.00484	0.00485
(-350,-250) & (250,350)	0.00013	0.00014	0.00014	0.00015
(-450,-350) & (350,450)	3.9E-06	**4.6E-06**	4E-06	**1E-05**
(-550,-450) & (450,550)	1.1E-07	1.1E-07	1.1E-07	**5.8E-06**
(-650,-550) & (550,650)	3.2E-09	3.2E-09	3.3E-09	**5.7E-06**
(-750,-650) & (650,750)	9.1E-11	**4.1E-06**	9.3E-11	**5.7E-06**
(-850,-750) & (750,850)	2.6E-12	2.6E-12	2.7E-12	**1.6E-06**
(-950,-850) & (850,950)	7.4E-14	7.4E-14	7.6E-14	**1.6E-06**
(-1050,-950) & (950,1050)	2.1E-15	2.1E-15	2.2E-15	**1.6E-06**
(-1150,-1050) & (1050,1150)	6.1E-17	6.1E-17	6.3E-17	**1.6E-06**
(-1250,-1150) & (1150,1250)	1.7E-18	1.7E-18	1.8E-18	**1.6E-06**
(-1350,-1250) & (1250,1350)	5E-20	5E-20	5.1E-20	**1.6E-06**
(-1450,-1350) & (1350,1450)	1.4E-21	1.4E-21	1.5E-21	**1.6E-06**
(-1550,-1450) & (1450,1550)	4.1E-23	4.1E-23	4.2E-23	**1.6E-06**
(-1650,-1550) & (1550,1650)	1.2E-24	1.2E-24	1.2E-24	**1.6E-06**
(-1750,-1650) & (1650,1750)	3.3E-26	**1.6E-06**	3.4E-26	**1.6E-06**

Table 4.4 Some characteristics of the proportions of typical and atypical AAD

Figure 4.1 shows the above graphically. The diagram shows the proportions on a logarithmic scale. The peaks due to the 700 ft and 1700 ft deviations are clearly visible. In risk analysis, it is common practice to not just look at the proportions of deviations per interval, but also at the proportions of deviations larger than or equal to a certain interval. This is shown numerically in the two right-most columns of table 4.4 and graphically in figure 4.2. This type of diagram may be referred to as a one-minus-cumulative diagram. Figure 4.2 shows a very large discrepancy between typical height deviations on the one hand and the combination of typical and atypical height deviations on the other. The one-minus-cumulative curve for the latter shows a nearly flat tail. In terms of the probability distribution model of eq. (4.1), this implies, at least, a very large standard deviation σ_2^{AAD} for the tail distribution. Using the data from table 4.4, the parameters of the model of eq. (4.1) may be obtained by means of the method of maximum likelihood estimation as described in reference 44. However, because of the extremely flat tail of the one-minus-cumulative curve for combined typical and atypical performance, a more pragmatic approach has been followed by fixing σ_1^{AAD} at the value of 39.8 ft specified in section 3.3.3 and by varying the remaining parameters α and σ_2^{AAD} so as to obtain a reasonable fit to the lilac curve in figure 4.2.

Figure 4.1 Logarithm (base 10) of proportions of AAD per interval

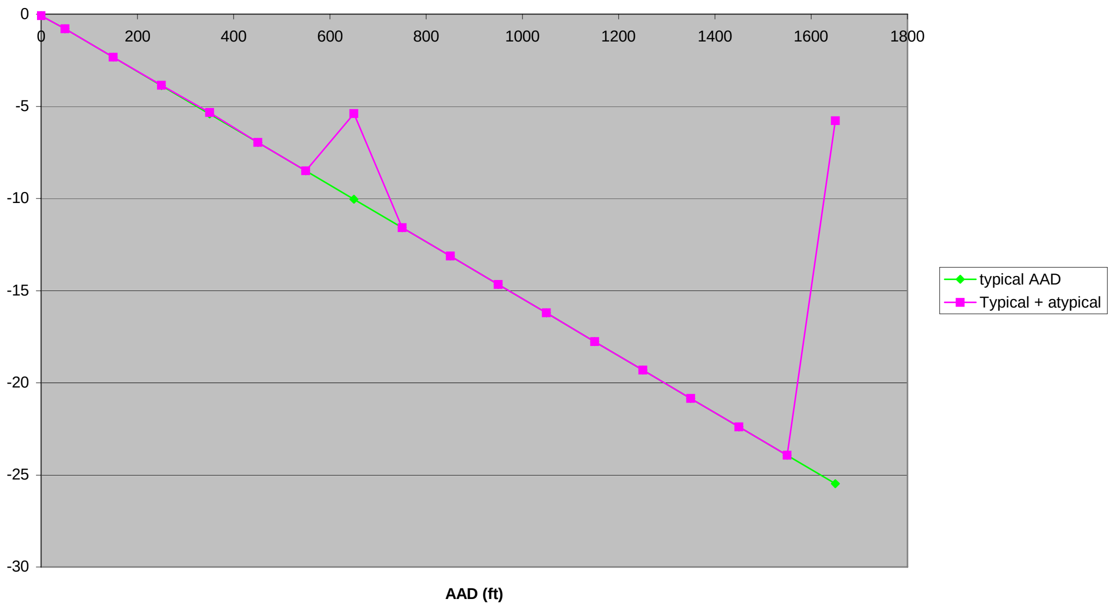


Figure 4.2 Logarithm (base 10) of proportion of deviations equal to or larger than a given value

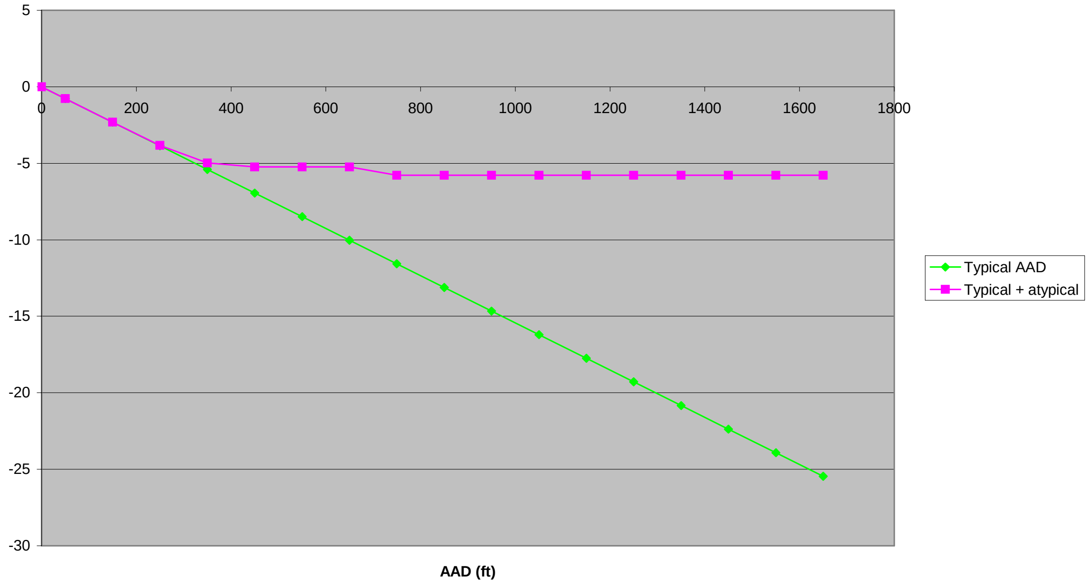


Figure 4.3 Logarithm (base 10) of proportion of deviations equal to or larger than a given value

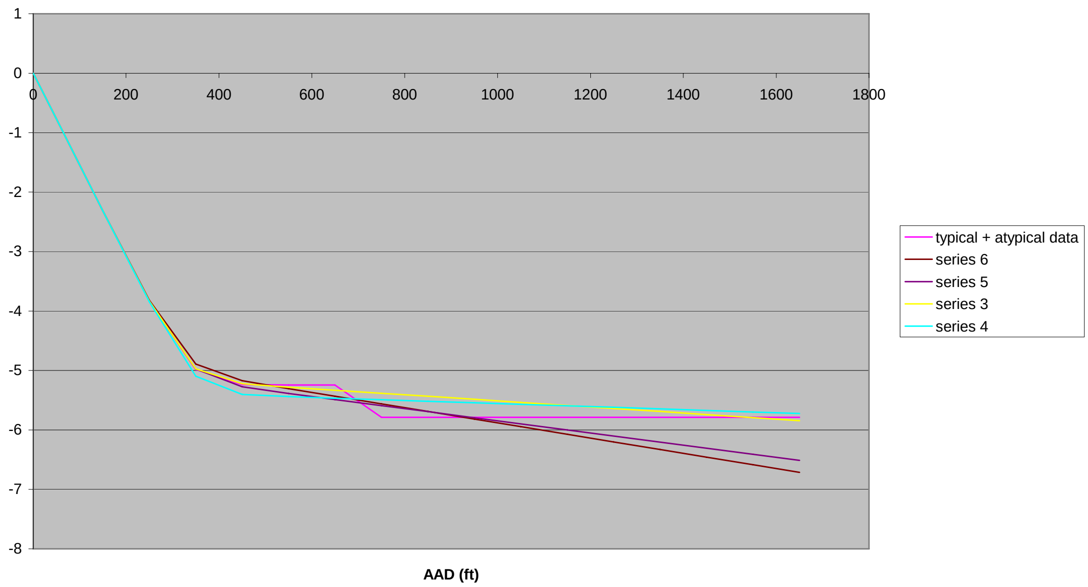


Figure 4.3 shows two pairs of two analytical curves based on eq. (4.1) that more or less represent the lilac curve based on the observed data. The parameters characterising the four curves are shown in table 4.5. The weighting factor α takes fairly small values, which indicates that the proportion of time during which large height deviations occur is fairly small. However, the corresponding standard deviation values for the tail distribution representing the large height deviations are very large. The lower values of 480 ft and 600ft provide a reasonably good fit of

the lilac curve up to about 900 ft but are underestimating the remaining tail area. This is, again, a direct consequence of the lilac curve for the large height deviations being nearly flat. Such a curve can only be captured by a very large value for the standard deviation σ_2^{AAD}.

Curve series	**Estimated parameter value**		
	σ_1^{AAD} (ft)	σ_2^{AAD} (ft)	α
3	39.8	1200	1.0×10^{-5}
4	39.8	2400	0.5×10^{-5}
5	39.8	600	1.5×10^{-5}
6	39.8	480	2.5×10^{-5}

Table 4.5 Four sets of parameter estimates for AAD probability density of eq. (4.1)

Once the parameters of the probability density $f^{AAD}(a)$ defined by eq. (4.1) have been estimated, $f^{AAD}(a)$ can be combined with the overall ASE probability density (eq. (3.10)) to obtain a TVE probability density (see eq. (3.15)) representing both typical and large, atypical height deviations (not involving whole numbers of flight levels). The calculation of the probability of vertical overlap proceeds in a similar manner as for normal technical height deviations described in section 3.3.5.

This process has been applied to each of the four probability densities $f^{AAD}(a)$ based on the parameter values in table 4.5. As might be expected, the resulting probabilities of vertical overlap, to be presented in section 4.5, will take fairly large values.

It should be clear that the observed large height deviations (not involving a whole number of flight levels) have a dramatic impact on the probability distributions of AAD and TVE and hence on the safety of RVSM operations. It is fundamental, therefore, to identify and eliminate the causes of these large height deviations.

4.3.3 ARMA Form 3 – other operational considerations

ARMA Form 3 was developed to collect information on a number of operational circumstances that may affect the safety of RVSM operations in the AFI Region, specifically co-ordination failures, communication failures, turbulence and ACAS incidents. Tables 4.6 – 4.9 summarise the information as received by ARMA for the period of time up to May 2005. An empty cell indicates that no Form 3 was received for the month in question and the symbol "-" indicates that although a copy of Form 3 was received, the form did not contain any information on the pertinent operational circumstance(s). It might be speculated (cf. section 4.3.2.1) that, for the latter cases, the actual number of events was zero but this speculation would need to be confirmed. Notice also that the tables contain information from only 15 out of the 37 FIR/UIRs listed in table 2.4 of section 2.3. Compared with table 4.1 for Form 1, information from two more FIR/UIRs is included namely from Entebbe and Roberts, but no Form 3 information was received from Sal Oceanic.

It is difficult to draw any firm conclusions from the data received. In fact, two factors play a part with respect to the observed occurrence rate for each type of events in the tables, namely the true occurrence rate of an event and the reporting rate. There may be several reasons why an event is not being reported, e.g. because it is not really considered a safety issue and hence not worth reporting. In this context, it would be useful, in a later stage, to compare the information in the Forms 3 and 1 over e.g. the year 2005 with the incident reports in the AFI AIAG database (see section 4.3.4).

As far as observed co-ordination failures are concerned, non-zero rates are found for only four out of the 15 FIR/UIRs included in table 4.6. The observed numbers of events appear to be more or less consistent for each of these FIR/UIRs with the numbers for Kano being significantly higher than for the others.

Very detailed information on communication failures was provided by Algiers, namely for various sectors and radio stations per sector. The numbers of stations included for the months March, April and May 2005 were 17, 18 and 19 respectively, leading to average durations of failure per station of 3705, 2791 and 1884 minutes. The average failure duration per event was 663, 316 and 267 minutes over the three successive months respectively. Information was also provided for November and December 2004 but this was not subdivided as for the three months in 2005 (**). Fairly detailed information was also provided for Nairobi, subdivided in two categories. The total durations of all the events in both categories in September, October and November 2004 were 31, 57 and 13 days (***).

Turbulence was reported by Accra, Harare and Johannesburg. Information on the duration was only provided by Accra, namely a total of 139 minutes for four events of light turbulence, 568 minutes for 14 events of moderate turbulence and 152 minutes for four events of heavy turbulence.

Consider finally the ACAS events in Table 4.9. ACAS events may be classified into three classes of events: nuisance events, false alerts or genuine events (Ref. 30). A nuisance advisory is one where there is or would have been no risk of collision between two aircraft. An ACAS false alert refers to an event where an aircraft receives and follows a resolution advisory without there actually being any other aircraft in the vicinity to trigger the advisory. A genuine ACAS event is one where actual collision avoidance takes place. In principle, the different classes of events need to be treated differently for the purpose of collision risk assessment (see e.g. reference 30). Table 4.9 shows only one false alert in February 2005. No information on the magnitude of the height deviation, if any, was available and the event will not be dealt with any further. The low rate of ACAS reports is remarkable in light of the need of ACAS performance monitoring as set out in reference 12 and also with respect to the significant risk mitigating role of ACAS in the incidents included in the AIAG database.

In conclusion, the information provided in data collection Form 3 is useful for a better understanding of the operational circumstances in AFI RVSM airspace but will not be incorporated directly in the assessment of the total vertical collision risk. Rather, the assessment of the total vertical collision risk will be based on the height deviations reported in Form 1 as described in section 4.3.2 and on the AFI AIAG incident data to be described below in section 4.3.4.

FIR/UIR	Number of co-ordination failures per month								
	2004				2005				
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Accra			2	3	4	-	1	0	
Algiers							12	2	7
Asmara							0		-
Cairo					-		-		
Cape Town				-	-	-	-		
Dar Es Salaam			6	3	5				
Entebbe			-	0		0	1		
Harare			0	0	0	0	0	0	0
Johannesburg			0	0	0				
Kano			25	28	20		25	32	
Mauritius		0	0	0	0	0	1	0	0
Nairobi	-	-	-						
Reunion					-				
Roberts			0	0	0	0	0	0	
Windhoek					0				

Table 4.6 Summary of co-ordination failures reported in ARMA Form 3

FIR/UIR	Number/duration (minutes) of communication failures per month								
	2004				2005				
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Accra			2/95	3/80	4/231	1/3	1/30	0	
Algiers			**	**			95/ 62989	168/ 53030	127/ 33918
Asmara							0		0
Cairo					4/878		5/773		
Cape Town				0	0	0	0		
Dar Es Salaam			6	3/648	2/446	2/1764			
Entebbe			0	0		0	1/26		
Harare			0	0	0	0	0	0	0
Johannesburg			1/5	1/5	0				
Kano			5/190	12/ 1287	7/953		35/ 7860	12/ 2765	
Mauritius		0	0	0	6/339	0	1/55	2/156	-
Nairobi	4/***	2/***	2/***						
Reunion					-				
Roberts			0	0	0	0	0	0	
Windhoek					0				

Table 4.7 Summary of communication failures reported in ARMA Form 3

Notes ** and *:** see text (page 85)

FIR/UIR	Number/duration (minutes) of turbulence reports per month								
	2004				2005				
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Accra			3/119	2/43	3/83	4/155	4/155	5/304	
Algiers									
Asmara							0		0
Cairo					0		0		
Cape Town				0	0	0	0		
Dar Es Salaam			0	0	0				
Entebbe			-	-		0	0		
Harare			2/	1/	0	0	4/	3/	2/
Johannesburg			5/	-	-				
Kano			-	-	-		-	-	
Mauritius		0	0	0	0	0	0	0	0
Nairobi	-	-	-						
Reunion					0				
Roberts			0	0	0	0	0	0	
Windhoek					0				

Table 4.8 Summary of turbulence events reported in ARMA Form 3

FIR/UIR	**Number of ACAS incidents per month**								
	2004				**2005**				
	Sep	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**
Accra			0	0	0	1/FA	1	0	
Algiers									
Asmara							0		0
Cairo					0		0		
Cape Town				0	0	0	0		
Dar Es Salaam			0	0	0				
Entebbe			-	-		-	-		
Harare			0	0	0	0	0	0	
Johannesburg			-	-	-				
Kano			-	-	-		-	-	
Mauritius		0	0	0	0	0	0	0	0
Nairobi	-	-	-						
Reunion					0				
Roberts			0	0	0	0	0	0	
Windhoek					0				

Table 4.9 Summary of ACAS incidents reported in ARMA Form 3

4.3.4 AFI ATS Incident Analysis Working Group (AIAG) data

4.3.4.1 The incident data

Airmiss reports for the years 2002 and 2003 have been made available by ARMA and IATA (Refs. 45, 46). To date, only the 2003 data has been analysed. Data on airproximity and ATC incident events in the AFI Region during the year 2003 made available by the South African CAA was also covered in the larger 2003 data set.

The 2003 airmiss data set included reports for various phases of flight and types of airspace. A total of 44 reports for the en route phase of flight were filtered out. One duplicated report (references 627 and 642) was deleted, leaving 43 reports to be analysed. The incident events described in the reports have been classified into eight categories as shown in table 4.10. It is important to remark that none of the incidents developed into a collision thanks to timely intervention. For the events involving “wrong FL”, the incorrectness of the flight level was inferred from the incident report and/or the applicable cruising levels. The “horizontal” events have been identified in the same manner. Six more events have been excluded from further analysis because they occurred below FL290. It follows that 21 out of the remaining 37 events were related to vertical separation and 16 to horizontal separation. Within the set of vertical events, a potential crossing through an opposite direction flight level occurred most frequently, viz. in approximately two thirds of the cases. Only a single flight level would have been crossed in each of these events. Notice also four cases where an opposite direction aircraft was identified at the same flight level.

Event type	Event Code	Number of events
Crossing through FL, opposite direction	CO	13
Crossing through FL, same direction	CS	2
Wrong FL, opposite direction	WO	4
Wrong FL, crossing traffic	WC	1
Joining wrong FL, same direction	WS	1
Horizontal	H	16
Outside of FL290 – FL410 band	OB	6

Table 4.10 Type and number of incident events in 2003 airmiss data set

Table 4.11 provides some additional information on each of the 21 vertical incident reports, particularly with respect to ACAS and IFBP. ACAS played a part in 90.5% of the events, but IFBP was in use in only 23.8% of the cases. Controller proficiency and lack of co-ordination appear to be the main causes underlying the incidents.

Each of the 21 vertical deviations will be treated as a large height deviation involving a whole number of flight levels for the collision risk modelling in section 4.4. Based on the nature of the events, it will be assumed that they could occur equally well in a 1000 ft environment as in a conventional 2000 ft environment. To relate the incidents to potential collisions (accidents), the effect of intervention by either ATC or the pilot will have to be taken into account. It will be assumed that ACAS played a part in preventing the incidents to develop into collisions (accidents) except for the events referenced 552 and 638. This is important with regard to the role of ACAS as a safety net. It may be inferred from the incident report that pilot visual intervention played a part for event number 552. For event number 638, pilot situational awareness in combination with IFBP use appears to have been effective.

Reference	Event code	Type of airspace	IFBP use	ACAS	Ro-I comments (quoted from reference 46)
552	CO	FIR	No	No	Controller proficiency
557	CO	FIR	No	Yes	Co-ordination
575	CO	FIR	Yes	Yes	Controller proficiency
577	CO	FIR	No	Yes	
578	CO	FIR	Yes	Yes	Controller proficiency
581	CS	FIR	No	Yes	Separation to clarify
584	CO	FIR	No	Yes	TBD
586	CO	FIR	Yes	Yes	Co-ordination? TBD
589	CO	FIR	No	Yes	Controller proficiency
592	CO	TMA	No	Yes	Controller proficiency
594	WO	FIR	No	Yes	Lack of co-ordination
595	WO	TMA	No	Yes	Controller proficiency
596	WO	FIR	No	Yes	ATC error
597	CO	FIR	No	Yes	Lack of co-ordination?
603	CO	TMA	No	Yes	TBD
607	CO	FIR	No	Yes	Controller proficiency
608	CO	FIR	No	Yes	Fixed communications (ATS/DS) LoA should have provisions for handling traffic when fixed coms not available
626	WO	FIR	Yes	Yes	TBD
627/642	CO	FIR	No	Yes	TBD
629	CS	FIR	No	Yes	TBD
638	WS	FIR	Yes	No	TBD

Table 4.11 Some details of the vertical incident events

4.3.4.2 Matching flight hours

Since the vertical collision risk is measured in fatal accidents per flight hour, an estimate of the total amount of flight hours during which the incident reports were generated is also needed (cf. section 4.3.2.1). In principle, this estimate can be obtained from the flight hours in the FIR/UIRs concerned. A complicating factor is that the incident data pertain to the year 2003 for which no accurate flight hour information is available. Thus, flight hour information as collected in Form 2 and Form 4 for the years 2004 and 2005 will have to be used. On the assumption that the incident data for 2003 would form a random sample of an approximately constant error rate, this should not affect the results by a large amount.

Table 4.12 lists the FIR/UIRs concerned together with some relevant data. It should be noted first that not any flight hours related information is available from Addis Ababa, Kinshasa and Tripoli. Form 2, monthly movements, information is not available from Beira and Dakar. However, traffic flow data is available in Form 4 for these two FIR/UIRs but has not yet been able to be processed. Maputo should be covered by Beira. Matsapha should be covered by South Africa. Notice that there is a considerable difference between the flight hour estimates for Algiers and Luanda, dependent on whether the Form 2 or Form 4 information is used (cf. section 3.4.2.6).

FIR/UIR	**Reports**	**Form 2**			**Form 4**
		Monthly movements	**Average time per movement (hours)**	**Monthly flight hours**	**Monthly flight hours**
Addis Ababa	2	-	-	-	-
Algiers	1	5026	1.88*	9448.88	6616.82
Beira	1				
Dakar	1				
Gaborone	1				1003.39
Harare	1	2354	0.78	1836.12	
Kano	2				641.15
Kinshasa	2	-	-	-	-
Luanda	1	1794	1.13	2027.22	1610.47
Maputo	1				
Matsapha	1				
Nairobi	2	3081	0.88	2711.28	
N'Djamena	3				1705.06
Niamey	1	3133	0.74	2310.30	
Tripoli	1	-	-	-	-

Table 4.12 Average number of flight hours per month for FIR/UIRs with vertical incident reports in the AIAG 2003 airmiss data set

Due to the limited flight hour information, it is very difficult to provide accurate estimates for the different vertical error rates. Two scenarios, therefore, will be evaluated in section 4.5 (total vertical collision risk) as follows:

Scenario 1

This scenario includes the FIR/UIRs for which both incident and flight hour information is (currently) available, i.e. Algiers, Gaborone, Harare, Kano, Luanda, Nairobi, N'Djamena and Niamey. Twelve incidents, out of twenty-one, and eight FIR/UIRs, out of fifteen, remain under scenario 1. The numbers of vertical incidents of each type for scenario 1 are shown in table 4.13. The total number of flight hours for a 12-month period would vary between 221215.1 hours and 260200.8 hours (dependent on the data used for Algiers and Luanda). An average value of 240708 flight hours will be used for the remainder of this report.

Event code	Number of events
CO	8
CS	1
WO	3
WS	0
WC	0

Table 4.13 Numbers of vertical incidents of each type under scenario 1

Scenario 2

This scenario includes all the FIR/UIRs with all the reported vertical incidents. Rather than treating the total flight time as an estimated parameter value, it will be treated as a free parameter. This means that a minimum value for the number of flight hours will be determined such that the vertical incident rate will be just consistent with the TLS. This can be done by specifying all of the parameters of the total vertical collision risk model other than the total number of flight hours, equating the resulting risk to the TLS and then solving for the free parameter.

If the vertical incidents would be distributed equally over the fifteen FIR/UIRs, then the error rate would be 21/15= 1.4 vertical incident per FIR/UIR. Thus, one would expect 11.2 incidents for the eight FIR/UIRs under scenario 1. This corresponds fairly well with the actual number of 12 incidents. In fact, scenario 1 may be considered to be slightly conservative for the whole set of FIR/UIRs for which vertical incidents were reported during the year 2003. On the other hand, the vertical incident rate (number of incidents per flight hour) is a more useful indicator of collision risk. It can be inferred from table 4.12 that the incident rates for the various FIR/UIRs vary from 8.8 x 10^{-6} to 2.6 x 10^{-4} incidents per flight hour. Scenario 1 can provide a conservative estimate of the total vertical collision risk only if the vertical incident rates for the FIR/UIRs not included are lower than those of the FIR/UIRs that are included under scenario 1, but this requirement cannot be verified due to the missing flight hour information.

More generally, the question should be asked as to whether there is any reason to suspect that certain FIR/UIRs are suffering from under-reporting of vertical incidents as under-reporting of incidents will clearly lead to under-estimation of the risk.

4.4 Total vertical collision risk models

4.4.1 Introduction

This sub-section presents the collision risk models for total vertical collision risk in addition to the technical vertical collision risk model of eqs. (3.5) and (3.29). Both the conventional and the conditional vertical collision risk models will be presented.

4.4.2 Conventional model

Three sub-models are needed for:

- Large height deviations not involving whole numbers of flight levels;
- Aircraft climbing or descending through a flight level; and
- Aircraft levelling off at a wrong level.

The last two cases concern large height deviations involving whole numbers of flight levels.

As argued in section 4.2, the vertical collision risk due to large height deviations not involving whole numbers of flight levels can be modelled in the same way as the technical vertical collision risk, i.e.

$$N_{az}^{*} = 2P_z(S_z)^{*} P_y(0) n_z(equiv) \left\{ 1 + \frac{\overline{|\dot{y}|}}{2\overline{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{\overline{|\dot{z}|}}{2\overline{V}} \right\} \qquad (4.2)$$

A superscript “*” is used to distinguish this type of vertical risk from the technical vertical collision risk. The probability of vertical overlap $P_z(S_z)^{*}$ can be calculated by means of eqs. (3.19) and (3.15) where the AAD probability density $f^{AAD}(a)$ is now to be taken from eq. (4.1) and the ASE probability density continues to be given by eq. (3.10).

The conventional vertical collision risk model for aircraft climbing or descending through a flight level is of the same form as eq. (4.2) (Ref. 26),

$$N_{az}^{cl/d} = 2P_z(S_z)^{cl/d}\,P_y(0)n_z(equiv)\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\} \tag{4.3}$$

where the superscript "cl/d" refers to an aircraft climbing or descending through a flight level without a proper clearance and $P_z(S_z)^{cl/d}$ is given by

$$P_z(S_z)^{cl/d} = \frac{n^{cl/d} \times 2\lambda_z / \overline{|\dot{z}_c|}}{T} \tag{4.4}$$

The new parameters are defined in table 4.14. Information on the number of incorrect flight level crossings and the pertinent vertical speeds is to be obtained from the incident reports. When no information on the vertical speed is included in a particular report, a default value will have to be used. Default values for a number of cases are given in references 24 and 31.

Parameter	Definition
$N_{az}^{cl/d}$	Expected number of fatal aircraft accidents per flight hour due to aircraft climbing or descending through a flight level without a proper clearance
$P_z(S_z)^{cl/d}$	Probability of vertical overlap due to aircraft climbing or descending through a flight level without a proper clearance
$n^{cl/d}$	Number of aircraft climbing or descending through a flight level without a proper clearance during a period of time with T flying hours
$\overline{\lvert\dot{z}_c\rvert}$	Average climb or descent rate for aircraft climbing or descending through a flight level without a proper clearance
T	Amount of flying time during the period of time the incident data were collected

Table 4.14 Definition of additional parameters of the vertical collision risk model of eq. (4.3)

Finally, the conventional vertical collision risk model for aircraft levelling off at a wrong flight level is given by

$$N_{az}^{wl} = 2P_z(S_z)^{wl}\,P_y(0)n_z(equiv)\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\} \tag{4.5}$$

where the superscript "wl" refers to levelling off at a wrong level and $P_z(S_z)^{wl}$ is given by

$$P_z(S_z)^{wl} = \frac{P_z(0) \times n^{wl} \times \bar{t}^{wl}}{T} \tag{4.6}$$

The additional new collision risk model parameters are defined in table 4.15. Not surprisingly, the number of times an aircraft levels off at a wrong level as well as the average duration of its stay at the wrong level are a part of the probability of vertical overlap for this particular type of event (Ref. 26). Information on these two parameters is to be obtained from the incident reports. The probability of vertical overlap $P_z(0)$ accounts for the normal technical height deviations of aircraft that, in this case, are flying at the same flight level after the incorrect levelling off. $P_z(0)$ can be calculated in a similar manner as the probabilities of vertical overlap $P_z(S_z)$ or $P_z(S_z)^*$ due to technical or large height deviations by putting $S_z = 0$ in the pertinent formulae.

Parameter	Definition
N_{az}^{wl}	Expected number of fatal aircraft accidents per flight hour due to aircraft levelling off at a wrong flight level
$P_z(S_z)^{wl}$	Probability of vertical overlap due to aircraft levelling off at a wrong flight level
$P_z(0)$	Probability of vertical overlap for aircraft nominally flying at the same flight level
n^{wl}	Number of aircraft levelling off at a wrong flight level during a period of time with T flying hours
$\bar{t}^{wl}$	Average sojourn time (hours) of an aircraft at a wrong flight level after incorrectly levelling off

Table 4.15 Definition of additional parameters of the vertical collision risk model of eq. (4.5)

Each of the three collision risk models of eqs. (4.2), (4.3) and (4.5) might, in principle, be extended with some intervention factor. This has not been done as AFI RVSM airspace is essentially procedurally controlled airspace and the risk mitigating effect of ACAS (and IFBP) as a safety is not allowed to be accounted for in collision risk assessment (Ref. 42).

4.4.3 Conditional model

The conditional model differs from the conventional model only for the two types of large height deviations involving whole numbers of flight levels, i.e.

- Aircraft climbing or descending through a flight level; and
- Aircraft levelling off at a wrong level.

The conditional model is based on all incident events where separation between two aircraft is lost or would have been lost without resolving action having been taken. Loss of separation is defined as any event where simultaneously vertical separation is less than H ft, say, and horizontal separation is less than R NM, say. In practice, there may be some underreporting of slight infringements of the horizontal separation minimum. As the conditional model assumes all events to be reported, it may be necessary to take the value of R somewhat smaller than the actual horizontal separation minimum.

The conditional vertical collision risk model for aircraft on the same track climbing or descending through a flight level is given by (Refs. 36, 40)

$$N_{az_{cond}}^{cl/d} = 2\frac{n_{cond}^{cl/d}}{T} \times P_{cond}^{cl/d} \times A \qquad (4.7)$$

with the conditional probability of a collision given a loss of separation defined by

$$P_{cond}^{cl/d} = \frac{1}{n_{cond}^{cl/d}} \sum_{i=1}^{n_{cond}^{cl/d}} \left[P_y(0) \frac{\lambda_z}{H} \frac{1+\frac{\pi}{4}\frac{\lambda_{xy}}{\lambda_z}\frac{v_z}{v_{xy}}}{1+\frac{R}{H}\frac{v_z}{v_{xy}}} \right]_i \qquad (4.8)$$

The notation $[\ ]_i$ in eq. (4.8) is used to indicate that the relative speed components v_{xy} and v_z may vary from incident to incident. The meaning of the subscript "cond" and the superscript "cl/d" should be clear. The new parameters in eqs. (4.7) and (4.8) are defined in table 4.16. Although an intervention factor A is formally included in the collision risk model of eq. (4.7) (and in that of eq. (4.9) below), it will not be utilised in the actual risk assessment of section 4.5. (This is equivalent to $A = 1$.)

The conditional vertical collision risk model for aircraft on the same track having levelled off at a wrong level is given by (Refs. 36, 39 and 40)

$$N_{az_{cond}}^{wl} = 2\frac{n_{cond}^{wl}}{T} \times P_{cond}^{wl} \times A \qquad (4.9)$$

with

$$P_{cond}^{wl} = \frac{1}{n_{cond}^{wl}} \sum_{i=1}^{n_{cond}^{wl}} P_y(0) P_z(0) \left[1 + \frac{\pi}{4} \frac{\lambda_{xy}}{\lambda_z} \frac{v_z}{v_{xy}} \right]_i \qquad (4.10)$$

The various new parameters are defined in table 4.17.

Parameter	Definition
$N_{az_{cond}}^{cl/d}$	Expected number of fatal aircraft accidents per flight hour due to aircraft climbing or descending through a flight level without a proper clearance as estimated by the conditional vertical collision risk model
$P_{cond}^{cl/d}$	Conditional probability of collision between a pair of aircraft with vertical separation less than H ft and horizontal separation less than R NM of which one aircraft would be climbing or descending through the other aircraft's flight level without a proper clearance
$n_{cond}^{cl/d}$	Number of aircraft with vertical separation less than H ft and horizontal separation less than R NM that would be climbing or descending through an other aircraft's flight level without a proper clearance during a period of time with T flying hours
H	Criterion for loss of vertical separation
R	Criterion for loss of horizontal separation
v_{xy}	Relative speed in the horizontal plane between the aircraft involved in the event
v_z	Relative vertical speed between the aircraft involved in the event
T	Amount of flying time during the period of time the incident data were collected
A	Probability that there is no effective intervention in a situation where two aircraft are on collision trajectories

Table 4.16 Definition of additional parameters of the vertical collision risk model of eq. (4.7)

Parameter	Definition
$N^{wl}_{az_{cond}}$	Expected number of fatal aircraft accidents per flight hour due to aircraft levelling off at a wrong flight level as estimated by the conditional vertical collision risk model
P^{wl}_{cond}	Conditional probability of collision between a pair of aircraft with vertical separation less than H ft and horizontal separation less than R NM of which one aircraft would be wrongly levelling off at the other aircraft's flight level
n^{wl}_{cond}	Number of aircraft with vertical separation less than H ft and horizontal separation less than R NM that would be levelling off at a wrong flight level during a period of time with T flying hours

Table 4.17 definition of additional parameters of the vertical collision risk model of eq. (4.9)

4.5 Total vertical collision risk

4.5.1 Introduction

In this sub-section, both the conventional and the conditional vertical collision risk models will be applied to obtain pre implementation estimates of the total vertical collision risk under AFI RVSM. The estimated total vertical collision risk is to be compared with the total vertical TLS of 5 x 10^{-9} fatal accidents per flight hour.

Three data sets will be used, namely:

- Data on large height deviations not involving whole numbers of flight levels, see table 4.1, eq. (4.1) and table (4.4);
- A single large height deviation involving a whole number of flight levels described in section 4.3.2.1; and
- Data on large height deviations involving whole numbers of flight levels, see tables 4.11 - 4.13.

4.5.2 Conventional model

4.5.2.1 Scenario 1

The three conventional vertical collision risk models of eqs. (4.2), (4.3) and (4.5) differ only with respect to their probability of vertical overlap parameters. Based on the analysis of the incidents reported in tables 4.11 and 4.13, table 4.18 gives estimates for the sub-parameters $n^{cl/d}$, n^{wl}, $|\dot{z}_c|$, $\bar{t}^{wl}$, $P_z(0)$ and T making up the probabilities of vertical overlap $P_z(S_z)^{cl/d}$ and $P_z(S_z)^{wl}$. Since the three collision risk models are given in terms of the equivalent passing frequency $n_z(equiv)$ and the vertical overlap probability $P_z(S_z)^{cl/d}$ of eq. (4.4) depends only on the relative vertical speed $\left|\dot{z}_c\right|$, $n^{cl/d}$ is the sum of the eight "CO" events and the single "CS" event from table 4.11 plus one (see the note on table 4.18) and similarly for n^{wl}. Information on the climb/descent speed or the aircraft type was not included in the pertinent incident reports. As the incidents all occurred with respect to "normal" flight level changes, a default relative vertical speed of 15 kts has been adopted (Ref. 31). The incident reports contained no information on how long aircraft might have been flying at an incorrect level either. Therefore, the following assumption has been made. It was assumed that the conflicting aircraft had been on the wrong flight level since their last-passed waypoint. This approach resulted in an average sojourn time at a wrong level of 0.25 hours for the specific incidents in the 2003 AIAG data set.

Parameter	Estimated value
$n^{cl/d}$	10 **
n^{wl}	3
λ_z (NM)	0.008106
$\left|\dot{z}_c\right|$ (kts)	15
$\bar{t}^{wl}$ (hrs)	0.25
$P_z(0)$	0.10
T (hrs)	240708

Table 4.18 Summary of sub-parameter estimates for conventional model under scenario 1
Note **: Including the large height deviation involving a whole number of flight levels from section 4.3.2.1

It should be remarked that a value of 0.10 for $P_z(0)$, the probability of vertical overlap for aircraft on the same flight level, is relatively small compared to the values cited in reference 26. This may be correlated with the relatively large value for $P_z(1000)$ obtained in section 3.3.5 for the technical vertical collision risk. In other words, within the bound set by the global system performance specification for RVSM, the probability distribution of TVE is spread relatively widely, resulting in a relatively low vertical overlap probability for aircraft on the same flight level and a relatively large vertical overlap probability for aircraft on adjacent flight levels.

Table 4.19 summarises the estimates for the various parameters of the three collision risk models of eqs. (4.2), (4.3) and (4.5) with the probability of vertical overlap $P_z(S_z)^*$ due to large height deviations not involving a whole number of flight levels being referenced to table 4.20.

Parameter	Value	Parameter	Value
S_z (ft)	1000	$n_z(equiv)$	0.3840
$P_z(S_z)^*$	**See table 4.20**	$P_y(0)$	0.106
$P_z(S_z)^{cl/d}$	4.49×10^{-8}	$\left\{1+\frac{\overline{\lvert\dot{y}\rvert}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{\lvert\dot{z}\rvert}}{2\overline{V}}\right\}$	1.02697
$P_z(S_z)^{wl}$	31.2×10^{-8}		

Table 4.19 Summary of parameter values for conventional vertical collision risk models of eqs. (4.2), (4.3) and (4.5)

Curve series	Parameter values			Probability of vertical overlap
	σ_1^{AAD} (ft)	σ_2^{AAD} (ft)	α	$P_z(S_z)^*$
3	39.8	1200	1.0×10^{-5}	38.1×10^{-8}
4	39.8	2400	0.5×10^{-5}	18.0×10^{-8}
5	39.8	600	1.5×10^{-5}	36.1×10^{-8}
6	39.8	480	2.5×10^{-5}	42.3×10^{-8}

Table 4.20 Probability of vertical overlap due to the large height deviations not involving a whole number of flight levels analysed in section 4.3.2.2

Recall from section 4.3.3.2 that the reported large height deviations had a dramatic impact upon the probability distributions of AAD and TVE and that it was anticipated that the resulting probability of vertical overlap would be fairly large. The numbers in table 4.20 confirm this anticipation. In this context, it is useful to recall that the upper limit for $P_z(1000)$ in the global system performance specification and the global height-keeping performance specification for RVSM (Ref. 5) is 1.7×10^{-8} (cf. section 3.3.4). The values for $P_z(S_z)^*$ in table 4.20 exceed this limit value by a factor of 11 to 25, dependent on the particular combination of parameter values for α and σ_2^{AAD}. The precise relationship between the values of $P_z(S_z)^*$ and the parameters α and σ_2^{AAD} of the AAD probability density of eq. (4.1) is rather complex. It appears that for the large values of σ_2^{AAD} in table 4.20, the value of $P_z(S_z)^*$ is particularly sensitive to the weighting factor α. Formally, the largest value of $P_z(S_z)^*$ for “curve series 6” might be taken as a conservative value, but it should be clear that each of the values in table 4.20 is too large and needs to be reduced before RVSM could be implemented.

Substitution of the table 4.19 values and $P_z(S_z)^* = 42.3 \times 10^{-8}$ into the collision risk model equations finally gives

$$N_{az}^{*} = 2 \times 42.3 \times 10^{-8} \times 0.106 \times 0.3840 \times 1.02697 = 35.4 \times 10^{-9} \tag{4.11}$$

$$N_{az}^{cl/d} = 2 \times 4.49 \times 10^{-8} \times 0.106 \times 0.3840 \times 1.02697 = 3.75 \times 10^{-9} \tag{4.12}$$

$$N_{az}^{wl} = 2 \times 3.12 \times 10^{-7} \times 0.106 \times 0.3840 \times 1.02697 = 26.05 \times 10^{-9} \tag{4.13}$$

It should be noted that the vertical collision risk N_{az}^{*} due to large height deviations not involving whole numbers of flight levels includes the normal technical vertical collision risk. Hence, the extra risk due to the large height deviations amounts 34.0 × 10^{-9} fatal accidents per flight hour, i.e. approximately 26 times as large as the technical vertical collision risk.

Finally, the total vertical collision risk due to all causes under AFI RVSM would be the sum of the risks given by eqs. (4.11) – (4.13), i.e.

$$N_{az}^{total} = 65.2 \times 10^{-9} \tag{4.14}$$

fatal accidents per flight hour. This estimate exceeds the total vertical TLS of 5 x 10^{-9} fatal accidents per flight hour by a factor of approximately thirteen! It should be emphasised that, intentionally, the risk estimate of eq. (4.14) does not include the risk mitigating effect of ACAS (and IFBP).

Based on the foregoing analysis, it must be concluded that there is not a single cause for the total vertical TLS not being met. Each of the components N_{az}^{*} and N_{az}^{wl} individually exceeds the total vertical TLS by a significant amount. The reason for this has already been amply described for the vertical collision risk N_{az}^{*} due to large height deviations not involving a whole number of flight levels. As N_{az}^{wl} represents the vertical collision risk due to aircraft having levelled off at an incorrect flight level, it is not surprising that the three events of this type carry a considerable vertical collision risk. Its estimated value of 26.1×10^{-9} fatal accidents per flight hour might be pessimistic if the estimate of 240708 hours for the total number of flight hours would be pessimistic. This element will to some extent be examined under scenario 2. On the other hand, the estimate of N_{az}^{wl} might be optimistic if underreporting of operational incidents would play a part for the FIR/UIRs in which the incidents occurred. Notice finally that the sum of the technical vertical collision risk of eq. (3.37) and the risk due to incorrectly traversing through a flight level given by eq. (4.12) would just exceed the total vertical TLS of 5×10^{-9} fatal accidents per flight hour.

4.5.2.2 Scenario 2

Under this scenario, all the 21 vertical incidents are included and the total flight time T is treated as a free parameter for which a minimum value is to be determined. The numbers of vertical incidents of each type under scenario 2 are shown in table 4.21. It follows that $n^{cl/d} = 17$ (16+1) and $n^{wl} = 5$. The corresponding probabilities of vertical overlap are shown in table 4.20.

Event code	Number of events
CO	14
CS	2
WO	4
WS	1
WC	0

Table 4.21 Numbers of vertical incidents of each type under scenario 2

Parameter	Estimated value
$n^{cl/d}$	17 **
n^{wl}	5
$P_z(S_z)^{cl/d}$	0.0183736 $/T$
$P_z(S_z)^{wl}$	0.1225$/T$

Table 4.22 Summary of parameter estimates for conventional model under scenario 2
<u>Note **:</u> Including the large height deviation involving a whole number of flight levels from section 4.3.2.1

The collision risk models for the two types of events involving whole numbers of flight levels can now be written as

$$N_{az}^{cl/d} = \frac{0.001536099}{T} \tag{4.15}$$

$$N_{az}^{wl} = \frac{0.010450447}{T} \tag{4.16}$$

Equating the sum of N_{az}^{*} (see eq. (4.11)), $N_{az}^{cl/d}$ and N_{az}^{wl} to the total vertical TLS of 5×10^{-9} fatal accidents per flight hour gives

$$\frac{0.011986545}{T} + N_{az}^{*} = 5\times10^{-9} \tag{4.17}$$

Before attempting to solve for T from eq. (4.17), it needs to be noticed that N_{az}^{*} alone as given by eq. (4.11) is already larger than 5×10^{-9}. Hence, eq. (4.17) would give a negative value for the total number of flight hours T. The only way to be able to proceed with the evaluation of scenario 2 is to <u>postulate</u> a more realistic value for N_{az}^{*}. As an example, a value of twice the estimate for the technical vertical risk has been taken for N_{az}^{*}, i.e. $N_{az}^{*} = 2.68\times10^{-9}$. Substitution of this value into eq. (4.17) and solving for T gives:

$$T = 5166615 \text{ (hrs)} \tag{4.18}$$

Thus, if the total number of flight hours for the FIR/UIRs with all the incidents reported in table 4.12 would have been larger than 5166615 hours for a 12-month period, than the total vertical TLS would just be met, provided that the risk due to large height deviations not involving whole numbers of flight hours would not be larger than twice the estimate of the technical vertical risk. This number of flight hours would have to be generated by the FIR/UIRs of Addis Ababa, Beira, Dakar, Kinshasa, Maputo, Matsapha and Tripoli, together with the estimated number of 240708 flight hours for Algiers, Gaborone, Harare, Kano, Luanda, Nairobi, N'Djamena and Niamey. It is hypothesised that the actual number of flight hours for the fifteen FIR/UIRs will be less than the value specified in eq. (4.18). This means that, like for scenario 1, the number of incidents needs to be reduced in order to meet the total vertical TLS.

4.5.3 Conditional model

4.5.3.1 Scenario 1

The numbers of vertical incidents of each type under scenario 1 were presented in table 4.13. The total number of 12 incidents included eight potential flight level crossings in the opposite direction (CO), one level crossing in the same direction (CS) and three opposite direction aircraft having levelled off at a wrong flight level (WO). Because the relative horizontal speeds v_{xy} for opposite direction and same direction traffic are quite different, the conditional collision probability of eq. (4.8) will be evaluated for the CO and CS events separately and the conditional vertical collision risk model of eq. (4.7) is replaced by

$$N_{az_{cond}}^{cl/d} = 2\frac{n_{cond}^{cl/d}(CO)}{T} \times P_{cond}^{cl/d}(CO) + 2\frac{n_{cond}^{cl/d}(CS)}{T} \times P_{cond}^{cl/d}(CS) \qquad (4.19)$$

Notice that the intervention factor A has been dropped simultaneously, in the same way as for the conventional model and essentially based on the role of ACAS (and IFBP) as a safety net.

Table 4.23 summarises the values of the various sub-parameters making up the two conditional collision risk probabilities $P_{cond}^{cl/d}$ and P_{cond}^{wl} defined by eqs (4.8) and (4.10) and table 4.24 summarises the estimates for the three conditional collision probabilities.

Parameter	Estimated value	Parameter	Estimated value
$n_{cond}^{cl/d}(CO)$	9**	$v_{xy}(CO)$	932
		$v_z(CO)$	15
$n_{cond}^{cl/d}(CS)$	1	$v_{xy}(CS)$	20
		$v_z(CS)$	15
$n_{cond}^{wl}(WO)$	3	$v_{xy}(WO)$	932
		$v_z(WO)$	1.5
λ_{xy}	0.02777	R	80
λ_z	0.008106	H	0.329158
T (hours)	240708		

Table 4.23 Summary of sub-parameter estimates (speeds in kts, dimensions in NM).
Note **: Including the large height deviation involving a whole number of flight levels from section 4.3.2.1

Parameter	Estimated value
$P_{cond}^{cl/d}(CO)$	5.54 x 10^{-4}
$P_{cond}^{cl/d}(CS)$	4.30 x 10^{-5}
$P_{cond}^{wl}(WO)$	1.06 x 10^{-2}

Table 4.24 Summary of conditional collision probabilities for scenario 1

Substitution of the conditional collision probabilities into the collision risk model equations together with the numbers of incidents of each type gives

$$N_{az_{cond}}^{cl/d} = 2 \times \frac{9}{240708} \times 5.54 \times 10^{-4} + 2 \times \frac{1}{240708} \times 4.30 \times 10^{-5} = 41.8 \times 10^{-9} \quad (4.20)$$

$$N_{az_{cond}}^{wl} = 2 \times \frac{3}{240708} \times 1.0646 \times 10^{-2} = 265.4 \times 10^{-9} \quad (4.21)$$

These two components of the total vertical collision risk due to large height deviations involving whole numbers of flight levels need to be supplemented with the estimate N_{az}^{*} of eq. (4.11) for the vertical collision risk due to large height deviations not involving whole numbers of flight levels. Thus, the combination of the three parts gives

$$N_{az_{cond}} = N_{az}^{*} + N_{az_{cond}}^{cl/d} + N_{az_{cond}}^{wl} = (35.4 + 41.8 + 265.37) \times 10^{-9} = 342.6 \times 10^{-9} \quad (4.22)$$

fatal accidents per flight hour. This estimate exceeds the total vertical TLS of 5×10^{-9} fatal accidents per flight hour by a factor of approximately 70! In the same manner as for the conventional model in section 4.5.2.1, it is emphasised that, intentionally, the risk estimate of eq. (4.24) does not include the risk mitigating effect of ACAS.

4.5.3.2 Scenario 2

Like for the conventional total vertical collision risk model, all the 21 vertical incidents are now included and the total flight time T is treated as a free parameter for which a minimum value is to be determined. The numbers of vertical incidents of each type under scenario 2 were shown in table 4.21. Notice that there is now also an incident of type WS, same direction aircraft levelling off at a wrong flight level. The relative speed components for this incident type are taken as $v_{xy}(WS) = 20$ kts and $v_z(WS) = 1.5$ kts. Table 5.25 summarises the four conditional collision risk probabilities. Notice that the first three values are exactly equal to their counterparts in table 4.22 under scenario 1. This is correct as within the class of each type of events CO, CS, WO and WS no distinction is made between the parameters of each individual event.

Parameter	Estimated value
$P_{cond}^{cl/d}(CO)$	5.54 x 10^{-4}
$P_{cond}^{cl/d}(CS)$	4.30 x 10^{-5}
$P_{cond}^{wl}(WO)$	1.06 x 10^{-2}
$P_{cond}^{wl}(WS)$	1.27 x 10^{-2}

Table 4.25 Summary of conditional collision probabilities for scenario 2

Substitution of the numbers of incidents of each type and the corresponding conditional collision probabilities into the two conditional vertical collision risk models gives

$$N_{az_{cond}}^{cl/d} = 2\times\frac{14}{T}\times 5.54\times 10^{-4} + 2\times\frac{2}{T}\times 4.30\times 10^{-9} = \frac{0.010067}{T} \tag{4.23}$$

$$N_{az_{cond}}^{wl} = 2\times\frac{4}{T}\times 0.010646 + 2\times\frac{1}{T}\times 0.012739 = \frac{0.063875}{T} \tag{4.24}$$

Equating again the sum of N_{az}^{*} (see eq. (4.11)), $N_{az_{cond}}^{cl/d}$ and $N_{az_{cond}}^{wl}$ to the total vertical TLS of 5×10^{-9} fatal accidents per flight hour gives

$$\frac{0.0733942}{T} + N_{az}^{*} = 5\times 10^{-9} \tag{4.25}$$

The free parameter T can, in principle, be solved for from eq. (5.25). However, as the value of N_{az}^{*} is larger than the right-hand side value of 5×10^{-9}, a meaningful solution will not be able to be obtained. The same problem existed for the conventional model and scenario 2 in section 4.5.2.2 where it was solved by making an additional assumption on a corrected value for N_{az}^{*}. The resulting minimum value for the total number of flight hours was found to be very large. Making the same assumption here would result in an even larger minimum values and has not been pursued.

5 Conclusions

5.1 General

Two collision risk assessments have been conducted to meet the AFI RVSM Safety Policy objectives concerning the technical vertical collision risk and the total vertical collision risk. The two risk estimates have been compared with the technical and total vertical TLSs of 2.5×10^{-9} and 5×10^{-9} fatal accidents per flight hour respectively. The technical vertical TLS was found to be met and the total vertical TLS was found not to be met. Additional RVSM safety objectives have been addressed by the AFI RVSM Programme and will be reported in the AFI RVSM Pre Implementation Safety Case.

5.2 Data

The main parameters of the technical and total vertical collision risk models are the probabilities of vertical overlap due to the different causes. Height monitoring data from the European height monitoring programme has been used to estimate the probability of vertical overlap due to normal technical height-keeping deviations. Such data was available for almost all the aircraft groups expected to be operating in AFI RVSM airspace. Default assumptions on RVSM approved aircraft have been made for a few remaining groups. Some monitoring data on those groups is expected to become available in the near future and may be used to confirm the assumptions made.

Various sources of data have been used to estimate the probability of vertical overlap due to all causes other than normal technical height-keeping deviations. Firstly, data on large height deviations and other operational issues have been reported to ARMA by many African States on a monthly basis. Secondly, some air proximity reports, air miss reports and incident data have been made available by IATA, CAA South Africa and ICAO. Nonetheless, there remains considerable concern as to whether a complete and fully representative sample of incident error data has been obtained. All the stakeholders involved with AFI RVSM must do the utmost to ensure that sufficient and reliable data on operational issues becomes available.

The next important parameter of the vertical collision risk model is passing frequency. This is estimated from traffic flow data collected by ARMA from the African States on a monthly basis. A considerable amount of data limitations has been identified. These limitations must be eliminated in order to make the passing frequency estimation process more precise and reliable.

5.3 Technical vertical collision risk

Based on current traffic levels, the technical vertical collision risk was estimated as 1.35×10^{-9} fatal accidents per flight hour, i.e. well below the technical TLS of 2.5×10^{-9} fatal accidents per flight hour. Opposite direction traffic is the main contributor to the risk. The precision of lateral navigation is an important factor with regard to the vertical collision risk. It has been assumed that 50% of the flying time in AFI RVSM airspace would be based on GNSS navigation and the remaining 50% on VOR/DME navigation. The risk mitigating effect of strategic lateral offsets has not been taken into account. The risk increasing effect of future traffic growth has not been incorporated either.

The estimate for the technical vertical collision risk is considered to be conservative since no credits have been taken for the redistribution of the traffic under RVSM. The risk estimate is considered to be not conservative with regard to the data limitations affecting the passing frequency estimation. Nonetheless, the margin between the technical TLS and the estimate of the technical vertical risk is believed to be sufficient to account for these limitations.

5.4 Total vertical collision risk

Total vertical collision risk is the risk due to all causes including normal technical height-keeping performance. Causes of vertical risk other than normal technical height-keeping performance generally lead to large, atypical height deviations. These large height deviations have been classified into large height deviations involving a whole number of flight levels and those not involving a whole numbers of flight levels. Different causes of vertical collision risk may need to be modelled differently. Two different modelling approaches have been used, the conventional approach and the conditional approach.

Based on a set of incident data for the year 2003 and data on large height deviations reported to ARMA over the period from September 2004 to May 2005 inclusive, the total vertical collision risk was estimated using the conventional modelling approach as 65.2×10^{-9} fatal accidents per flight hour. This is approximately thirteen times as large as the total vertical TLS of 5×10^{-9} fatal accidents per flight hour. Both the risk due to large height deviations not involving a whole number of flight levels and the risk due to large height deviations involving a whole number of flight levels individually exceed the total vertical TLS. The estimate of the total vertical collision risk using the conditional modelling approach was 342.6×10^{-9}. Significant risk mitigating measures have to be taken before the total vertical TLS will be met under RVSM in the AFI Region.

The estimates for the total vertical collision risk under AFI RVSM are considered to be non-conservative, as it is most likely that there is an issue of under-reporting of operational incidents. Hence, improvements in incident reporting are required. Although an improved incident reporting rate will initially lead to an even higher estimate for the total vertical collision risk, it is absolutely necessary that the total vertical collision risk be not under-estimated. On the other hand, since it may be expected that there are certain common patterns underlying the reported vertical incidents, it may also be expected that with an appropriate risk mitigation strategy in place the real number of vertical incidents will be effectively reduced.

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Appendix A Calculation of flight time proportions

A.1 Introduction

Flight time proportions are needed with respect to two parameters of the vertical collision risk model, namely the overall ASE probability distribution and the average aircraft dimensions.

The traffic flow data collection form (Form 4) includes for each flight the aircraft type by ICAO code. In principle, therefore, the flight time by ICAO code can be calculated for each FIR in the AFI Region for the flight level band FL290 – FL410 and be combined to give the precise flight time proportions by ICAO code for the AFI Region. (An implicit assumption is that all flights between FL290 and FL410 inclusive have been included in the Forms 4.) Due to missing data from some States, it has been decided to base the calculation of the flight time proportions on the data from the FIR/UIRs associated with the four groups of adjacent States (ACCs) specified in section 3.4 of the main text of this report. It is remarked that the overall ASE probability model is insensitive to the flight time proportions in the specific sense that each individual monitoring group must meet the MASPS.

Some monitoring groups/aircraft types from the candidate AFI RVSM aircraft population turned out not to be represented in the traffic flow data forms from the subset of adjacent States. These groups/types have been excluded from further processing. This concerned firstly the ICAO codes DC94, B712, B764, BN2, C212, CRJ7, CRJ9, E120, SW4 and SF34 that had been included in the candidate population on the basis of the OAG database. It also included the ICAO codes B461, C501-1, and D228 that were in the ARMA database.

A.2 Flight time proportions for the overall ASE distribution

The flight time proportions β_i, $i = 1,...,n_{MG}$, in the overall ASE probability density model of eq. (3.10) are needed by monitoring group.

The total flight time for all the aircraft types in the traffic flow data collection forms (Form 4) was 16914.94 hours. However, some of the aircraft types included in Form 4 were not valid ICAO codes. Some of these have been regarded as typing errors and have been corrected. The following corrections have been made: A130 → A310, A139 → A319, A230 → A320, A303 → A306, A307 → A306, A313 → A310, A316 → A319, A329 → A319, A341 → A340, A348 → A346, B723 → B732, B73G → B738, B745 → B744, B74F → B744, B74S → B744, BD70 → BE70, BE02 → BE20, BJ40 → BE40, D 10 → DC10, DA10 → FA10, DA20 → FA20, DA50 → FA50, DA90 → F900, EA30 → A300, EA31 → A310, EA32 → A320, EA33 → A330, EA34 → A340, F200 → FA20, FK10 → F100, FK28 → F28, GLAX → GALX, g732 → B732, G2 → GLF2, G3 → GLF3, G4 → GLF4, G5 → GLF5, LR24 → LJ24, LR25 → LJ25, LR31 →

LJ31, LR35 → LJ35, LR45 →LJ45, LR55 → LJ45, TU34 → T135, TU54 → T154, RA50 → FA50 and Q346 → A346.

The remaining aircraft types that had invalid ICAO codes have been removed. This concerned the following types: 23TF, 23UH, 24DL, 25EA, 296I, 29V1, AN4R, AS50, BE90, C12, C25A, CS12, CV44, DGAA, GV, KC35, L100, L329, N265, ND16, OMSJ, PA28, SRB1, ZZ04 and ZZ05. This reduced the initial total flight time estimate by 0.22% from 16914.94 hours to 16876.91 hours.

Next, the ICAO codes were mapped onto the monitoring groups. For some ICAO codes, no monitoring group was available. The pertinent codes were removed, reducing the initial total flying time by another 117.72 hrs (0.70%). For some others, monitoring groups were available but not represented in table 2.7 of the main text. The pertinent groups were also removed, reducing the initial total flying time by an extra 112.53 hrs (0.67%). The latter removal concerned the following monitoring groups: A124, ASTR, B753, C525, C560, C56X, C650, C750, CL600, GALX, GLEX, GLF2, GLF2B, H25A-100, H25A-400, H25A-600, IL86, IL96, LJ31, LJ35/6, LJ55, LJ60, MD90, and PRM1. Thus, 98.41% of the initial total flying time was used to determine the flight time proportions. For aircraft types with an ICAO code that covered more than one monitoring group, flight time was distributed equally over the groups. The ultimate monitoring groups with the associated flight time proportions based on a resulting overall flying time of 16646.66 hours are listed in table A.1.

Monitoring Group	**Proportion of flight time**	**Monitoring Group**	**Proportion of flight time**
A340	0.117290	T154	0.000496
B737NX	0.113703	FA10	0.000474
A330	0.083266	FA20	0.000427
B744-10	0.077486	H25B-700	0.000403
B744-5	0.077486	H25B-800	0.000403
A320	0.069970	BE20	0.000391
B732	0.069351	F28	0.000380
B772	0.058257	B701	0.000378
B767	0.055226	BA11	0.000274
B737CL	0.046097	LJ45	0.000252
MD80	0.033815	BE40	0.000162
B747CL	0.029254	T204	0.000141

A346	0.020252	F100	0.000129
DC93	0.019861	C500	0.000114
MD11	0.018071	C550-II	0.000095
B752	0.016233	B190	0.000078
B727	0.015626	A345	0.000069
DC10	0.011561	F50	0.000065
A300	0.010620	C550-B	0.000065
E135-145	0.008254	F2TH	0.000053
CARJ	0.006924	T134	0.000033
IL76	0.005197	(PC12)	0.000025
F900	0.005094	AVRO	0.000020
L101	0.003934	(C130)	0.000018
FA50	0.003715	ATR	0.000011
GLF4	0.002729	YK42	0.000009
A310-GE	0.002664	DC85	0.000008
A310-PW	0.002664	(YK40)	0.000004
DC95	0.002430	(DH8)	0.000003
B773	0.001858	L29B-2	0.000001
DC86-7	0.001567	(G159)	0.000001
B703	0.001556		
IL62	0.001258		
GLF5	0.000909		
GLF3	0.000836		

Table A.1 Flight time proportions by aircraft monitoring group for the benefit of the overall ASE probability distribution model

A.3 Flight time proportions for average aircraft dimensions and cruising speed

Each ICAO code (aircraft designator) represents a particular aircraft name or model that may be made up of different aircraft types and/or series. The dimensions may vary by type and series of a given name or model. Since the traffic flow data collected in Form 4 does not distinguish between aircraft types or series under a given ICAO code, the variation in dimensions by type or series needs to be accounted for in some manner. Two straightforward possibilities are an un-weighted average or the maximum dimensions. The latter option has been adopted here. Following that, the proportions of flight time by ICAO code have been used as weighting factors for the calculation of average aircraft dimensions. The resulting average dimensions are given in table A.2.

An average cruising speed has also been calculated as 466 kts.

Aircraft Dimension	**Value (ft)**
Length	168.7198
Width	158.7086
Height	49.2546

Table A.2 Average aircraft dimensions projected for AFI RVSM airspace

Appendix B Passing frequency estimation

B.1 Introduction

An aircraft pair that has lost vertical separation can only collide when both aircraft are at the same location in the horizontal plane. For aircraft on the same route, the latter event may generally be split into the aircraft passing each other (in the longitudinal direction) and in them being at the same lateral location with respect to the route. The number of times per flight hour that an average or typical aircraft passes another aircraft at an adjacent flight level is called the passing frequency parameter of the vertical collision risk model. In a radar environment, passing frequency can be estimated using the radar tracks of all the aircraft operating in the airspace. In a non-radar environment, passing frequency needs to be estimated using flight progress information.

A method for estimating passing frequency, or actually for estimating a related parameter called occupancy, was developed in the 1960s for the North Atlantic. The method is described in Appendix C to Chapter 4 of Section 2 of Part II of the ICAO Air Traffic Services Manual, Doc 9426-AN/924. The basic information for both passing frequency and occupancy estimation are the reporting times at waypoints. The following paragraph has been quoted from Doc 9426, but "translated" from the lateral dimension to the vertical dimension.

For a given day in the sample, the progress information for all flights is examined and the times reported at each required point in the system are grouped by route. The objective of the analysis is to determine the number of aircraft pairs on the same route at adjacent flight levels that are within the distance $\tilde{S}_x$ referenced in the definition of occupancy. This distance is translated into a time interval, 15 minutes being the standard period. The analysis procedure is straightforward: two counters, one for each same and opposite direction occupancy, are initialised to zero; the reported time of each aircraft in turn is compared to the reported times of all aircraft on the appropriate adjacent flight level of the same route; whenever the absolute value of the difference between the two times is 15 minutes or less, the appropriate directional counter is incremented by one. After all aircraft have been examined, the counters are multiplied by 2 and divided by the total number of aircraft reported crossing the waypoint considered.

The distance $\tilde{S}_x$ referred to in the previous paragraph is called the proximity distance. Characteristic of the proximity distance $\tilde{S}_x$ is that it is much larger than the length λ_x of an aircraft. As a result, proximity events are occurring much more frequently and can be estimated much more effectively than passing events, especially for same direction traffic and crossing traffic. A correction factor needs to be determined to convert the frequency of proximate events into the frequency of passing events.

The following subsections provide some details of the passing frequency calculations.

B.2 General implementation aspects of passing frequency estimation

The passing frequency parameter of the vertical collision risk model is determined by counting the number of passings between two aircraft on adjacent flight levels and dividing by the total flying time. In order to do this, traffic data is required for each route segment in a FIR/UIR. Based on the traffic flow data reported in Form 4, the entry and exit times and flight levels can be estimated for each aircraft for each segment. For each aircraft the following items are determined for each route segment:

1. Callsign;
2. Route segment indicator;
3. Date/time, flight level and entry waypoint for the segment;
4. Date/time, flight level and exit waypoint for the segment; and
5. Average speed.

In order to determine a possible passing between two aircraft on adjacent flight levels, it should be noted that a passing can only occur

- on a segment between two consecutive waypoints when flying in opposite direction; or
- at a waypoint where two different routes cross each other.

Since “same directional routes” do not (yet) exist in the AFI Region, a same directional passing on adjacent flight levels has to be caused by an operational error.

When considering a waypoint A, say, at which a potential passing could occur, two consecutive segments needs to be considered: the segment before waypoint A and the segment after the waypoint A. For two aircraft, this leads to the following generic situation.

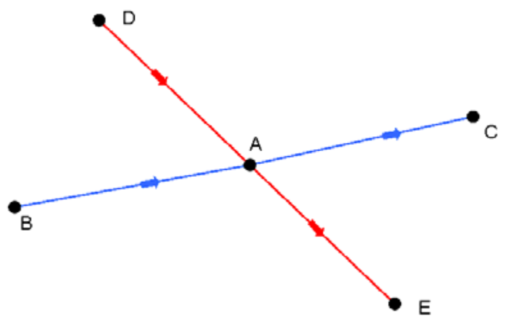


Figure B.1 Illustration of a potential passing at waypoint A

Note that all possible scenarios can be represented by assuming that one or more waypoints coincide, e.g.

- B=D;
- E=C;
- D=C or, equivalently, B=E;
- D=C and B=E; or
- B=D and C=E.

Determining whether a passing has occurred on a (same) segment, can be done by comparing the entry and exit times for that segment for both aircraft. When these time intervals overlap an opposite passing has occurred.

Since a crossing exactly at a waypoint is a rare event, one looks at a crossing in the proximity of a waypoint. A crossing is said to occur in the proximity a waypoint, when, at some point of time, two aircraft crossing that waypoint are both less than a distance R, say, from the waypoint. In a radar environment, R may be taken in the order of the radar separation minimum, e.g. 2.5 NM or 5 NM. In a procedural environment, it may be taken as the distance based longitudinal separation minimum or as a distance equivalent of the time based separation minimum. Thus, if a circle with radius R is drawn about the waypoint A, a crossing in the proximity of A occurs if both aircraft are within this circle.

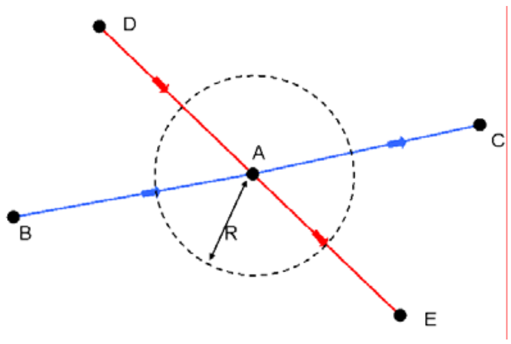


Figure B.2 Top view of a proximity at waypoint A

To determine if both aircraft are within the circle, two cases are considered: aircraft 1 reaches waypoint A first or aircraft 2. By renumbering the aircraft it can be assumed that aircraft 1 reaches waypoint A always first. Let t_1 denote the time at which aircraft 1 enters the circle, t_2 the time at which it reaches waypoint A and t_3 the time at which it leaves the circle again. Similarly define t_4, t_5 and t_6 for aircraft 2. Since aircraft 1 reaches waypoint A first it holds that $t_2 \leq t_5$.

If one draws the distance of the aircraft to waypoint A as a function of time, two V-shaped functions are obtained: the left one for aircraft 1 (in red) and the right one for aircraft 2 (in blue).

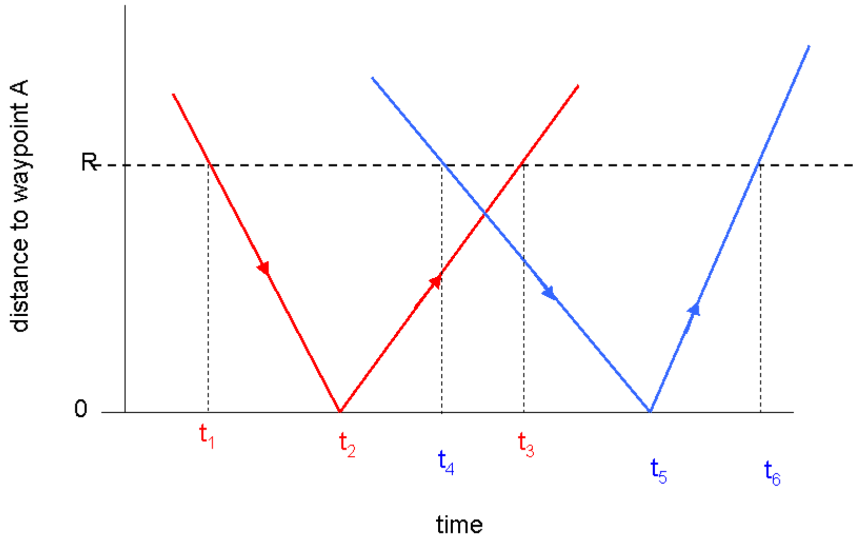


Figure B.3 Distance to waypoint A versus time for two aircraft

A crossing in the proximity of A occurs if at some point in time both aircraft have a distance to waypoint A less than R. In the graph, this corresponds with the right line of the left V-shape intersecting with the left line of the right V-shape (assuming that $t_2 \le t_5$) beneath the line R. This is equivalent to verifying that $t_4 \le t_3$.

Hence, it is sufficient to only consider segments which have one waypoint in common where one aircraft is entering the waypoint and the other aircraft is exiting the waypoint (which corresponds to the left line of the right V-shape and the right line of the left V-shape in the above graph) and verify whether at some point in time both aircraft are a distance less than R from waypoint A.

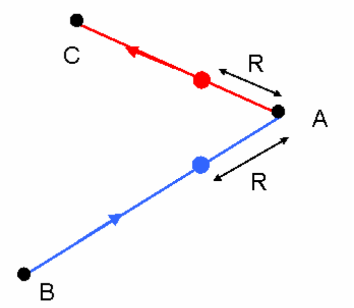


Figure B.4 Top view of a proximity at waypoint A in terms of route segments

Since flight level information is only known for the entry waypoint and exit waypoint for a segment, it is assumed that two aircraft pass each other on the largest possible difference between the entry en exit waypoint combinations.

B.3 FIR/UIR specific aspects of passing frequency estimation

B.3.1 Introduction

Since States have provided the data in slightly different formats, it has been necessary to process the data differently in order to obtain the required information. Some data has been discarded due to:

- Missing reporting times, waypoints or flight level information;
- Flights outside the FL290-FL410 band;
- Wrong entry-exit time combinations resulting in unrealistic speeds; or
- Unknown routes or inability to reconstruct the routes.

Less than 10% of the flights have had to be excluded from further processing due to these problems. Specific details of the data processing by FIR/UIR are given in the remainder of this subsection.

B.3.2 Algiers

The traffic flow data for Algiers has been provided in a format with reporting times at all the waypoints along the routes. Some pre-processing was necessary to correct unrealistic reporting times which were potentially a result of typing errors. About 50 reporting times have been corrected per month.

B.3.3 N'Djamena and Brazzaville

The traffic flow data in Form 4 for N'Djamena and Brazzaville was provided in “FIR entry” and “FIR exit” point format. Only one flight level was given. It has been assumed, therefore, that all flights remained on their initial flight level.

For almost every FIR entry and exit point combination a most likely route has been constructed. Based on the total length of this route and the FIR entry and exit times, an average speed was determined. Using this average speed, passing times at each waypoint for each segment were determined.

B.3.4 Kano

For the Kano FIR only one reporting waypoint was given for each flight. Based on the route and the flight level, the segments and the direction of the flight have been determined. Based on the aircraft code, a typical speed was obtained from a database. Hence it has been assumed that all aircraft were flying on the correct flight level and no level changes occurred. If the aircraft code was unknown or the route was unknown, the pertinent flight was discarded.

B.3.5 Johannesburg and Cape Town

For the Johannesburg FIR and the Cape Town East and West FIRs only one waypoint was reported for each flight. Based on the number of flights in the FL290-FL410 band as reported in Form 2, it is remarked that the number of flights obtained from Form 4 was substantially smaller. Furthermore, due to a significant change in the route structures in these FIRs (effective from 17th February 2005) only traffic flow data from the period of time after this change has been analysed.

Due to the new route structure, the number of waypoint-origin-destination combinations is very limited. Therefore, for each waypoint-origin-destination combination the segments were determined. Since many of the origins and destinations were within South Africa, it has been assumed that the routes stop at the TMA boundary. Based on the aircraft code, a typical speed was obtained from a database. If the aircraft code was unknown or the waypoint-origin-destination combination was not a logical combination, the flight was discarded. Since only one flight level was given, it has been assumed that all flights remained on their initial flight level.

B.3.6 Gaborone

The data included overflights as well as some flights to and from Gaborone and Maun. Since the Gaborone traffic flow data in Form 4 was given in non-electronic form, four sample days were selected namely the 4th, 12th, 20th and 28th of each month. The data was provided in “single waypoint” format. It was inferred that the waypoints used were FIR/UIR entry points. From the combination of entry point, route, departure airport and destination airport, a FIR/UIR exit point was determined for each flight. For most flights, there was only a single conncection between entry point and exit point, e.g. between TAVLA and DANAM on the UG655. For overflights entering on the UB733 (BUGRO or ETOSA) or on the UG853 (AGRAM, RUDAS), it has been assumed that these would be exiting on the same route.

For each flight, a FIR/UIR exit time was calculated from the route length between FIR/UIR entry point and exit point and an average aircraft speed. Te same procedure was used for intermediate waypoints, if any. Average aircraft speeds of 480 and 420 kts have been used with very little influence on the passing frequency values. A more refined procedure would be based on an average aircraft speed by aircraft type. Subsequently, opposite direction and crossing traffic passing frequencies have been calculated for each route segment and for each crossing point.

Some pre-processing of the traffic flow data was necessary to correct for:

1. Missing entry point reporting times;
2. Missing entry point flight levels;
3. BUGRO entry point, route G853;
4. TAVAS entry point, route UB733 or UG653; and
5. A few more irregularities.

The pertinent flights have been deleted from the sample. This concerned about 10% of the data. A number of flights from Johannesburg into Namibia had the FIR entry point labelled as “FIR”. This has been taken as ETOSA. For a number of flights entering Botswana from Johannesburg the entry reporting was listed at NEJEK in South Africa. No correction was made for this.

B.3.7 Luanda

For the Luanda FIR only one waypoint was reported per flight. Furthermore, most of the routes were not given in Form 4. Due to the geographical location of the Luanda FIR, the number of origins or destinations located to the South of Luanda is very limited: most of the origins or destinations were either in the South (direction of Windhoek or Cape Town) or to the Southeast (direction of Johannesburg). By classifying the origins and destinations of the flights into: "South", "Southeast" or "Other" almost all routes could be determined in combination with the reported waypoint since the number of waypoint-origin-destination combinations was limited after the classification. If both the origin and destination were labelled as "Other", the flight direction was inferred from the flight level. Since only one flight level was given, it was assumed that all flights remained on their initial flight level.

B.3 Conceptual aspects of passing frequency estimation

B.3.1 Opposite direction passing frequency

Consider two aircraft flying in opposite direction at adjacent flight levels of a route segment of length L, see figure B.5.

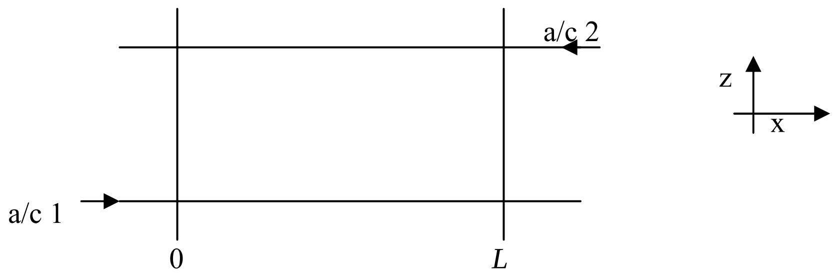


Figure B.5 Opposite direction traffic on a route segment of length *L*

The aircraft are in longitudinal overlap at time t^* when

$$\left|x_1(t^*) - x_2(t^*)\right| \leq \lambda_x \qquad \text{(B.1)}$$

where $x_1(t)$ and $x_2(t)$ denote the locations of the (longitudinal) centres of the aircraft at time t. For simplicity, only the point of passing of the centres of the two aircraft will be considered, i.e.

$$x_1(t^*) - x_2(t^*) = 0 \qquad \text{(B.2)}$$

It is assumed that each aircraft travels with a constant speed. (Different aircraft may have different, constant, speeds.)

For a passing to occur on the route segment between $x = 0$ and $x = L$ inclusive or, equivalently, at a point of time t^* between the aircraft entry and exit times,

$$t_{1_{in}} \leq t^* \leq t_{1_{out}} \qquad \text{(B.3)}$$

$$t_{2_{in}} \leq t^* \leq t_{2_{out}} \qquad \text{(B.4)}$$

it must hold that either

$$t_{2_{in}} \leq t_{1_{in}} \leq t_{2_{out}} \qquad \text{(B.5)}$$

or

$$t_{1_{in}} \leq t_{2_{in}} \leq t_{1_{out}} \qquad \text{(B.6)}$$

Eqs. (B.5) and (B.6) have a clear operational interpretation. For the passing to occur it is simply necessary that the aircraft entering the segment last (regardless of whether it is labelled 1 or 2) enters during the time interval in which the aircraft that entered first is flying along the segment.

Notice that the reporting times of the aircraft at both the waypoints defining a route segment are needed to determine whether or not an opposite direction passing event has occurred on the route segment.

The only estimation error that may play a part with the use of the requirements of eqs. (B.5) and (B.6) is related to inaccuracies in the waypoint reporting times. Additional errors will be present when only limited information is available, e.g. only the segment entry times of both aircraft or the reporting times (entry and exit times respectively) at only one end of the route segment.

A question of some interest is how many opposite direction passings one might expect for a given route segment during a certain period of time. Obviously, this will depend on the route segment length, the aircraft speeds and the separation between the aircraft entering each of the flight levels. (Since the aircraft are vertically separated, each flight level is loaded independently from the other flight levels.) It can be shown that in a stationary situation where on each level the aircraft are separated by precisely the longitudinal separation minimum, for each aircraft the likelihood of passing at least one other aircraft on an adjacent flight level is approximately equal to one. In practice, this likelihood will be smaller due to larger separations between aircraft on the same level, but there is no need for the proximity concept, i.e. the aircraft being within a much larger distance $\widetilde{S}_x$, say, then the aircraft length λ_x for opposite direction traffic.

B.3.2 Same direction passing frequency

Consider now two aircraft flying in the same direction at adjacent flight levels of a route segment of length L, see figure B.6.

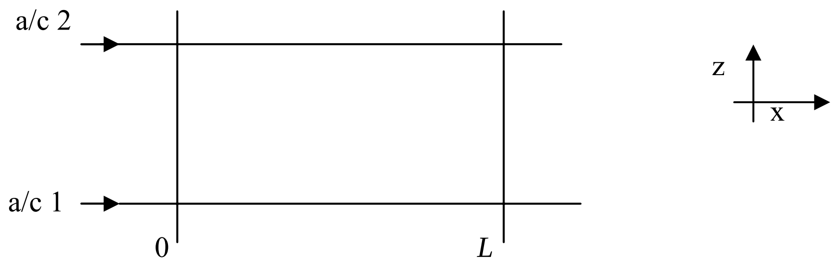


Figure B.6 Same direction traffic on a route segment of length *L*

In the same way as for the opposite direction case, the pair of aircraft are in longitudinal overlap at time t^* when

$$|x_1(t^*) - x_2(t^*)| \le \lambda_x \tag{B.1}$$

and the centres of the two aircraft are passing at time t^* when

$$x_1(t^*) - x_2(t^*) = 0 \tag{B.2}$$

The point of time t^* must again satisfy the set of inequalities

$$t_{1_{in}} \le t^* \le t_{1_{out}} \tag{B.3}$$
$$t_{2_{in}} \le t^* \le t_{2_{out}} \tag{B.4}$$

The same direction case differs from the opposite direction case in that it is necessary to distinguish between the aircraft having the same speed and the aircraft having different speeds.

If the aircraft (are known to) have the same speed, then their being in longitudinal overlap at time t^* implies that they must be in longitudinal overlap at any point of time during their journey along the route segment. Specifically, they must be in overlap on entry and exit of the segment. The likelihood of this happening is very small. For a longitudinal separation minimum of 10 minutes, this likelihood is approximately $(1/10)\times(2\lambda_x/V)$.

Assume now that the aircraft have different (constant) speeds. It follows that for a same direction passing to occur on the route segment subject to the inequalities (B.3) and (B.4) it must hold that either

$$t_{1_{out}} \le t_{2_{out}} \text{ and} \tag{B.7}$$
$$t_{2_{in}} \le t_{1_{in}} \tag{B.8}$$

or

$$t_{2_{out}} \le t_{1_{out}} \text{ and} \tag{B.9}$$
$$t_{1_{in}} \le t_{2_{in}} \tag{B.10}$$

These requirements may also be written in the form

$$t_{2_{in}} \le t_{1_{in}} \le t_{1_{out}} \le t_{2_{out}} \tag{B.11}$$

or

$$t_{1_{in}} \le t_{2_{in}} \le t_{2_{out}} \le t_{1_{out}} \tag{B.12}$$

Like eqs. (B.5) and (B.6), eqs. (B.11) and (B.12) have a clear operational interpretation. For a same direction passing to occur, it is simply necessary that the aircraft entering the segment last is leaving the segment first.

Also, the reporting times of the aircraft at both the waypoints defining a route segment are needed to determine whether a same direction passing event has occurred on the route segment.

Eqs. (B.11) and (B.12) have an interesting feature in that they allow to infer which of the two aircraft was flying faster, i.e. aircraft 1 in case of eq. (B.11) and aircraft 2 in case of eq. (B.12).

The relative speed between the two aircraft travelling in the same direction also plays a part when considering how many same direction passings one might expect for a given route segment during a certain period of time. Under the same stationarity assumption as used for opposite direction traffic, it can be shown that the likelihood of observing a same direction passing event between aircraft with different speeds is about 5% for a 5% speed difference,. Clearly, this is much smaller than for opposite direction traffic. In practise, this likelihood will even be much smaller due to larger separations between the aircraft on each level. As a result, estimating longitudinal passings between same direction aircraft is rather difficult in practice. To overcome this difficulty, the concept of proximity, i.e. using $\tilde{S}_x$ rather than λ_x has been developed as a measure for the closeness of same direction aircraft in a pair. For same direction traffic, the proximity distance can be converted directly into a difference in time. The proximity concept needs to be supplemented by the concept of the conditional probability of an aircraft pair being in longitudinal overlap, given that it is in proximity. As a first approximation, this conditional probability may be taken as $\lambda_x / \tilde{S}_x$.

B.3.3 Crossing traffic passing frequency

Figure B.7 shows two routes crossing at an angle θ. Assume that the aircraft are at adjacent flight levels, one on route 1 and the other on route 2.

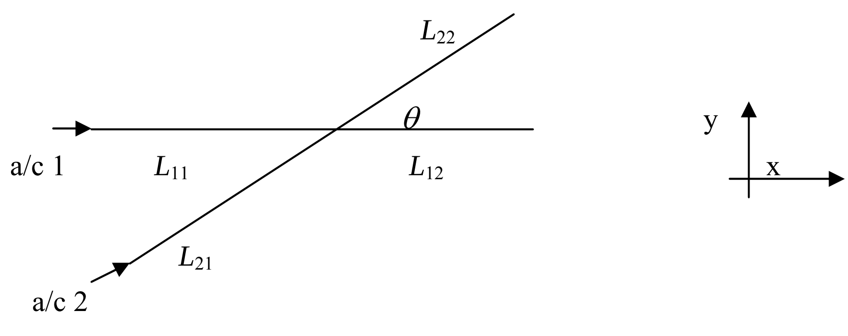


Figure B.7 Crossing traffic

Formally, a pair of aircraft on adjacent flight levels of crossing routes is in horizontal overlap at time t^* when

$$\sqrt{\left(x_1(t^*) - x_2(t^*)\right)^2 + \left(y_1(t^*) - y_2(t^*)\right)^2} \le \lambda_x \tag{B.13}$$

and the centres of the two aircraft are in a horizontal passing at time t^* when

$$x_1(t^*) - x_2(t^*) = 0 \tag{B.14}$$

and

$$y_1(t^*) - y_2(t^*) = 0 \tag{B.15}$$

subject to the constraints

$$t_{1_{in}} \le t^* \le t_{1_{out}} \tag{B.3}$$
$$t_{2_{in}} \le t^* \le t_{2_{out}} \tag{B.4}$$

The crossing track case differs from the opposite direction and same direction cases in that it fixes the point at which a horizontal passing needs to take place, viz. the crossing point. If the crossing times are denoted as t_1^* and t_2^*, then for a horizontal passing to occur it must hold that

$$t_1^* = t_2^* \tag{B.16}$$

i.e. the aircraft must be arriving at the crossing at the same time.

The crossing times may be expressed in the segment entry times as

$$t_1^* = t_{1_{in}} + \frac{L_{11}}{V_1} \tag{B.17}$$

$$t_2^* = t_{2_{in}} + \frac{L_{21}}{V_2} \tag{B.18}$$

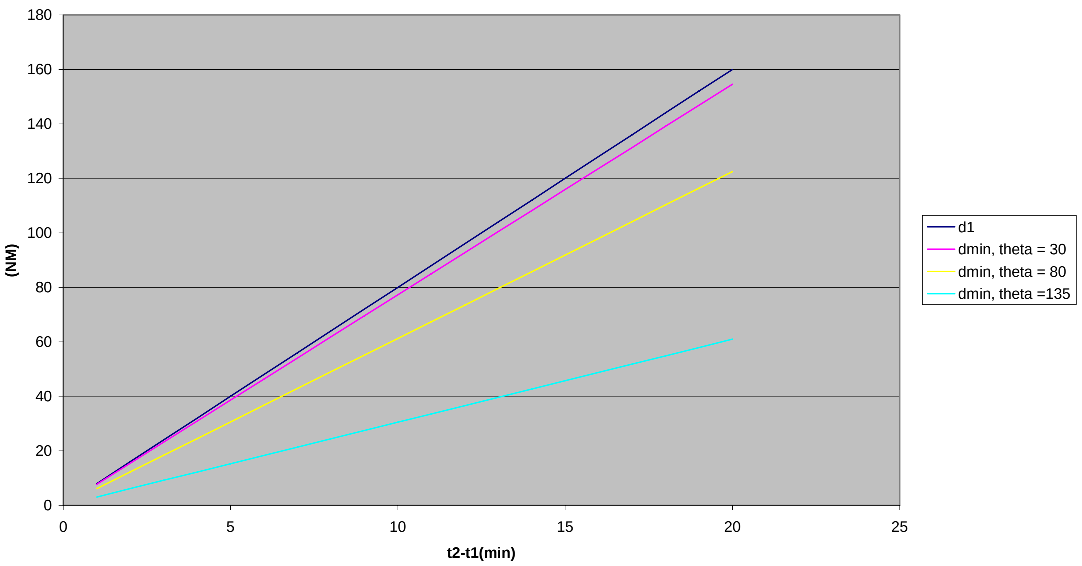
The above two equations are useful to calculate the likelihood of eq. (B.16) being satisfied. Assuming a steady state as for the previous two passing frequency cases, together with a longitudinal separation minimum of ten minutes, this likelihood is approximately $\left(1/10\right) \times \left(2\lambda_x / V\right)$ and is very small.

Thus, a crossing traffic horizontal passing is a rare event whose frequency estimation may be improved by using a related but more easily observable event, the crossing track proximity event. Considering eq. (B.16), it might be tempting to use a requirement of the form

$$\left|t_1^* - t_2^*\right| \leq \Delta t \qquad \text{(B.19)}$$

with Δt of the order of magnitude of several minutes, e.g. 10 or 15 minutes in a similar way as the same direction proximity. However, for crossing traffic, a given time difference translates into a different minimum horizontal distance between the aircraft during the crossing, dependent on the crossing angle θ. This is illustrated for crossing angles of 30˚, 80˚ and 135˚ in figure B.8.

Figure B.8 Distance to crossing and minimum distance between aircraft as a function of difference in reporting times for varous crossing angles



The d1-curve represents the distance between the aircraft when the first aircraft passes the crossing (based on an aircraft speed of 480 kts) whereas the other three curves represent the minimum horizontal distance between two crossing aircraft as a function of the reported time difference at the crossing. For crossing traffic, two methods that may be used for proximity at a crossing are:

Requiring both aircraft to be simultaneously within a distance $\tilde{S}_x$ from the crossing point; and

Requiring the minimum distance between two aircraft at the crossing to be less than $\tilde{S}_x$.

(The two methods may require different values for $\tilde{S}_x$.)