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POST IMPLEMENTATION COLLISION RISK ASSESSMENT FOR RVSM IN THE AFRICA INDIAN OCEAN REGION

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Executive summary

POST IMPLEMENTATION COLLISION RISK ASSESSMENT FOR RVSM IN THE AFRICA INDIAN OCEAN REGION

Problem area
This report presents the first post-implementation collision risk assessment for the implementation of a Reduced Vertical Separation Minimum (RVSM) in the Africa - Indian Ocean (AFI) Region. It addresses two of the AFI RVSM Safety Policy objectives, namely an assessment of the technical vertical collision 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 collision risk against a TLS of 5×10^{-9} fatal accidents per flight hour.

Description of work
The technical and total vertical collision risk assessments are based on the data and information available after the first year of AFI RVSM operations.

Collision risk models developed as a part of the pre-implementation assessments have been re-used with updated parameter values to estimate the vertical collision risk under AFI RVSM.

Results and conclusions
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.

The total vertical TLS was found to be exceeded by a factor of approximately 6. The dominant component of the total vertical risk was the risk due to aircraft having levelled off at a wrong flight level. This had to be estimated conservatively due to a lack of precise information on the duration of the pertinent events. There remain several factors that require the estimate of the total vertical collision risk to be treated with caution. The estimate is most likely affected by under-reporting of vertical incidents involving large height deviations. Measures are required to ensure proper incident reporting.

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.

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CONTENTS

ABBREVIATIONS

AAD	Assigned Altitude Deviation
ACAS	Airborne Collision Avoidance System
ACC	Area Control Centre
AFI	Africa – Indian Ocean
AIAG	ATS Incident Analysis working Group
APIRG	Africa – Indian Ocean Planning and Implementation Regional Group
AR	Area of Routing
ARMA	African Regional Monitoring Agency
ASE	Altimetry System Error
ATC	Air Traffic Control
ATCU	Air Traffic Control Unit
ATM	Air Traffic Management
ATS	Air Traffic Services
CC	Crossing FL Crossing tracks
CO	Crossing FL Opposite direction tracks
CRA	Collision Risk Assessment
CS	Crossing FL Same direction tracks
CVSM	Conventional Vertical Separation Minimum
DME	Distance Measuring Equipment
DRC	Democratic Republic of Congo
EUR	Europe(an)
FIR	Flight Information Region
FL	Flight Level
Ft	Foot
FTE	Flight Technical Error
GMU	GPS-based Monitoring Unit
GNSS	Global Navigation Satellite System
H	Horizontal
HMU	Height Monitoring Unit
H(SFL)	Horizontal (same route, following another aircraft)
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFBP	In Flight Broadcasting Procedure
IFR	Instrument Flight Rules

LHD	Large Height Deviation
NAT	North Atlantic
NLR	National Aerospace Laboratory
NM	Nautical Mile
OAG	Official Airline Guide
OB	Outside flight level Band
PISC	Pre Implementation Safety Case
PANS	Procedures Air Navigation Services
RA	Resolution Advisory
RNAV	Area Navigation
RNP	Required Navigation Performance
RVSM	Reduced Vertical Separation Minimum
TA	Traffic Advisory
TAG	(AFI) Tactical Action Group
TF	Task Force
TLS	Target Level of Safety
TVE	Total Vertical Error
UCR	Unsatisfactory Condition Report (AFI TAG Terminology)
UIR	Upper (Flight) Information region
VOR	Very high frequency Omni-directional Range
WC	Wrong level Crossing tracks
WO	Wrong level Opposite direction tracks
WS	Wrong level Same direction tracks

1 INTRODUCTION

This report presents the first post-implementation Collision Risk Assessment (CRA) for the implementation of a Reduced Vertical Separation Minimum (RVSM) in the Africa - Indian Ocean (AFI) Region. It covers the period of time from the start of RVSM operations in the AFI Region on 25 September 2008 up to and including 30 September 2009.

The report addresses two specific safety objectives from the AFI RVSM Safety Policy (Ref. 1), namely an assessment of the technical vertical collision risk against the technical vertical Target Level of Safety (TLS) of 2.5×10^{-9} fatal accidents per flight hour, and an assessment of the total vertical collision risk against the total vertical TLS of 5×10^{-9} fatal accidents per flight hour. Results, conclusions, and recommendations from the report will also be incorporated in the AFI RVSM Post-Implementation Safety Case (POSC) (Ref. 2), which addresses all the safety objectives and requirements from the AFI RVSM Safety Policy. In line with the RVSM guidance material from reference 3 and with previous RVSM collision risk assessments, the current two assessments are based on collision risk models appropriate for the AFI Region. More specifically, this AFI RVSM post-implementation CRA has used essentially the same methods and models as the AFI RVSM pre-implementation CRAs (Refs. 4 – 6). The pertinent collision risk models will be recalled from reference 6 and the reader is referred to reference 4 for further details.

Section 2 presents the assessment of the technical vertical collision risk and section 3 presents the assessment of the total vertical collision risk, i.e. the vertical collision risk due to all causes, operational and technical. Conclusions and recommendations are given in section 4.

2 ASSESSMENT OF TECHNICAL VERTICAL RISK

2.1 INTRODUCTION

This section deals with the assessment of the technical vertical collision risk under RVSM in the AFI Region. Technical vertical collision 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 accordance with the AFI RVSM Safety Policy (Ref. 1), the technical vertical collision risk will be assessed against a technical vertical 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 typical aircraft height deviations will be examined in section 3.

Whilst the pre-implementation CRAs (Refs. 4 – 6) showed that the technical vertical TLS was met, it is necessary to confirm that this TLS has continued to be met on the basis of recent post-implementation data on the first year of AFI RVSM operations. For the technical vertical collision risk assessment, this data concerns the aircraft population on the one hand and the traffic flows on the other. The aircraft population plays a part with regard to the overall Altimetry System Error (ASE) distribution, the lateral navigation accuracy, and the definition of average aircraft dimensions. Traffic flows (together with navigation accuracy) determine the exposure of the aircraft to the loss of vertical separation.

Section 2.2 recalls the technical vertical collision risk model and its parameters. Updated estimates for the various model parameters are given in sections 2.3 – 2.6. Estimates of the technical vertical collision risk are then presented and compared with the TLS in section 2.7.

2.2 COLLISION RISK MODEL

Following reference 6, the model for technical vertical collision risk for aircraft at adjacent flight levels of the <u>same route</u>, flying in either the <u>same</u> or the <u>opposite</u> direction is given by

$$N_{az} = 2P_z(S_z)P_y(0)\left[n_x(same)\left\{1+\frac{2\lambda_x}{2\lambda_y}\frac{\overline{|\dot{y}|}}{\overline{|\Delta V|}}+\frac{2\lambda_x}{2\lambda_z}\frac{\overline{|\dot{z}|}}{\overline{|\Delta V|}}\right\}+n_x(opp)\left\{1+\frac{2\lambda_x}{2\lambda_y}\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{2\lambda_x}{2\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}\right] \tag{2.1}$$

The left-hand side variable N_{az} represents the expected number of aircraft accidents per flight hour due to normal technical height deviations of RVSM approved aircraft for the given traffic geometry. All parameters in the model of eq. (2.1) are defined in table 2.1.

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 at adjacent flight levels
$P_y(0)$	The probability of lateral overlap for aircraft nominally flying on the same route
$n_x(same)$ [1]	The frequency with which same direction aircraft at adjacent flight levels of the same route are in longitudinal overlap
$n_x(opp)$	The frequency with which opposite direction aircraft at 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 2.1 Definition of parameters of the vertical collision risk model of eq. (2.1)

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[1] The subscript “z” in the same and opposite direction passing frequency symbols has been replaced by the subscript “x” to emphasize the longitudinal element of a passing event rather than the aircraft flying at adjacent flight levels.

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 $n_x(same)$ and $n_x(opp)$ 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. (2.1).

Each of the terms inside the accolades in eq. (2.1) 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.)

The model for technical vertical collision risk for aircraft on adjacent flight levels of two routes intersecting at an angle θ and cylindrical aircraft models is given in reference 6 as

$$N_{az} = 2P_z(S_z)n_{xy}(\theta)\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{2\lambda_z}\frac{\overline{|\dot{z}|}}{V_{rel}(\theta)}\right\} \tag{2.2}$$

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

$$V_{rel}(\theta) = \overline{V}\sqrt{2(1-\cos\theta)} \tag{2.3}$$

The new parameters are defined in table 2.2. Notice that for intersecting routes the lateral overlap probability $P_y(0)$ no longer appears explicitly in the model as it is effectively included within the intersecting-routes frequency of horizontal overlap $n_{xy}(\theta)$. Indeed, for intersecting routes, it is more convenient to combine the head/tail and sideways collision directions into a combined horizontal direction. The quantity $\frac{\pi}{2}\lambda_{xy}$ in eq. (2.2) represents the average length of a horizontal overlap between two typical aircraft on intersecting 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
$n_{xy}(\theta)$ [2]	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 θ

Table 2.2 Definition of additional parameters for vertical collision risk model of eq. (2.2)

For the case of n pairs of routes intersecting at different angles $\theta_i, i=1,\ldots,n$, the collision risk model of eq. (2.2) can be extended to

$$N_{az} = 2P_z(S_z)\sum_{i=1}^{n} n_{xy}(\theta_i)\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{2\lambda_z}\frac{\overline{|\dot{z}|}}{V_{rel}(\theta_i)}\right\} \qquad (2.4)$$

Combining the models in eqs. (2.1) and (2.4) gives the full technical vertical collision risk model for AFI RVSM:

$$N_{az} = 2P_z(S_z)P_y(0)\left[n_x(same)\left\{1+\frac{2\lambda_{xy}}{2\lambda_{xy}}\frac{\overline{|\dot{y}|}}{\overline{|\Delta V|}}+\frac{2\lambda_{xy}}{2\lambda_z}\frac{\overline{|\dot{z}|}}{\overline{|\Delta V|}}\right\}+n_x(opp)\left\{1+\frac{2\lambda_{xy}}{2\lambda_{xy}}\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{2\lambda_{xy}}{2\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\}\right]+$$
$$+2P_z(S_z)\sum_{i=1}^{n} n_{xy}(\theta_i)\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)}\frac{\overline{|\dot{z}|}}{2\lambda_z}\right\} \qquad (2.5)$$

Notice that for the same- and opposite-direction components the original aircraft length and width λ_x and λ_y have been replaced by a diameter λ_{xy}. The lateral overlap probability parameter $P_y(0)$ may be combined with the same-direction and opposite-direction longitudinal overlap frequencies $n_x(same)$ and $n_x(opp)$ respectively to give

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[2] The subscript "z" in the intersecting (crossing) route passing frequency symbol has been replaced by the subscript "xy" to emphasize the horizontal element of a passing event rather than the aircraft flying on adjacent flight levels.

frequencies of horizontal overlap for these two traffic types (comparable to the horizontal overlap frequency $n_{xy}(\theta_i)$ for traffic on intersecting routes).

Aside from $P_z(S_z)$, the impact of any opposite-direction passing on the vertical collision risk is determined by the probability of lateral overlap $P_y(0)$ and the kinematic factor $\left\{1+\overline{|\dot{y}|}\big/2\bar{V}+\lambda_{xy}\big/\lambda_z\times\overline{|\dot{z}|}\big/2\bar{V}\right\}$. Thus, any same-direction passing event included in $n_x(same)$ and any intersecting-routes traffic passing included in $n_{xy}(\theta_i)$ may be translated into an equivalent opposite-direction passing by means of these two factors, i.e.

$$\begin{aligned}
N_{az} = {} & 2P_z(S_z)P_y(0)n_x(opp)\left\{1+\frac{\overline{|\dot{y}|}}{2\bar{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\bar{V}}\right\}+\\
& 2P_z(S_z)P_y(0)n_x(same)\left\{1+\frac{\overline{|\dot{y}|}}{2\bar{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\bar{V}}\right\}\frac{\left\{1+\dfrac{\overline{|\dot{y}|}}{\overline{\Delta V}}+\dfrac{\lambda_{xy}}{\lambda_z}\dfrac{\overline{|\dot{z}|}}{\overline{|\Delta V|}}\right\}}{\left\{1+\dfrac{\overline{|\dot{y}|}}{2\bar{V}}+\dfrac{\lambda_{xy}}{\lambda_z}\dfrac{\overline{|\dot{z}|}}{2\bar{V}}\right\}}+\\
& 2P_z(S_z)P_y(0)\frac{1}{P_y(0)}\sum_{i=1}^{n}n_{xy}(\theta_i)\left\{1+\frac{\overline{|\dot{y}|}}{2\bar{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\bar{V}}\right\}\frac{\left\{1+\dfrac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)}\dfrac{\overline{|\dot{z}|}}{2\lambda_z}\right\}}{\left\{1+\dfrac{\overline{|\dot{y}|}}{2\bar{V}}+\dfrac{\lambda_{xy}}{\lambda_z}\dfrac{\overline{|\dot{z}|}}{2\bar{V}}\right\}}
\end{aligned} \tag{2.6}$$

or

$$\begin{aligned}
N_{az} = 2P_z(S_z)P_y(0)\Bigg\{ & n_x(opp)+n_x(same)\frac{\dfrac{\overline{|\dot{y}|}}{\overline{|\Delta V|}}+\dfrac{\lambda_{xy}}{\lambda_z}\dfrac{\overline{|\dot{z}|}}{\overline{\Delta V}}}{\left\{1+\dfrac{\overline{|\dot{y}|}}{2\bar{V}}+\dfrac{\lambda_{xy}}{\lambda_z}\dfrac{\overline{|\dot{z}|}}{2\bar{V}}\right\}}+\\
& \frac{1}{P_y(0)}\sum_{i=1}^{n}n_{xy}(\theta_i)\frac{\left\{1+\dfrac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)}\dfrac{\overline{|\dot{z}|}}{2\lambda_z}\right\}}{\left\{1+\dfrac{\overline{|\dot{y}|}}{2\bar{V}}+\dfrac{\lambda_{xy}}{\lambda_z}\dfrac{\overline{|\dot{z}|}}{2\bar{V}}\right\}}\Bigg\}\left\{1+\frac{\overline{|\dot{y}|}}{2\bar{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\bar{V}}\right\}
\end{aligned} \tag{2.7}$$

Defining

$$n_x(equiv) = n_x(opp) + n_x(same)\frac{\dfrac{\overline{|\dot{y}|}}{\overline{\Delta V}} + \dfrac{\lambda_{xy}}{\lambda_z}\dfrac{\overline{|\dot{z}|}}{\overline{|\Delta V|}}}{\left\{1 + \dfrac{\overline{|\dot{y}|}}{2\overline{V}} + \dfrac{\lambda_{xy}}{\lambda_z}\dfrac{\overline{|\dot{z}|}}{2\overline{V}}\right\}} + \frac{1}{P_y(0)}\sum_{i=1}^{n} n_{xy}(\theta_i)\frac{\left\{1 + \dfrac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)}\dfrac{\overline{|\dot{z}|}}{2\lambda_z}\right\}}{\left\{1 + \dfrac{\overline{|\dot{y}|}}{2\overline{V}} + \dfrac{\lambda_{xy}}{\lambda_z}\dfrac{\overline{|\dot{z}|}}{2\overline{V}}\right\}} \tag{2.8}$$

eq. (2.7) can be written in the so-called equivalent opposite-direction passing frequency form as

$$N_{az} = 2P_z(S_z)P_y(0)n_x(equiv)\left\{1 + \frac{\overline{|\dot{y}|}}{2\overline{V}} + \frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\} \tag{2.9}$$

The last expression is precisely of the opposite-direction traffic form, whereas numerically it takes account of all the different types of traffic geometries through the equivalent opposite direction passing frequency $n_x(equiv)$.

With the form of the technical vertical collision risk model specified by eqs. (2.8) and (2.9), it remains to update the estimates of the various parameters in the model. This will be addressed in the subsequent subsections, starting with the probability of vertical overlap $P_z(S_z)$ in section 2.3 and followed by passing frequency $n_x(equiv)$ in section 2.4. 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 2.5 and 2.6.

2.3 PROBABILITY OF VERTICAL OVERLAP

The probability of vertical overlap $P_z(S_z)$ for aircraft flying at adjacent flight levels (separated by S_z) of the same route or intersecting routes is calculated from the probability distribution of normal, or typical, height deviations of RVSM approved aircraft. These aircraft height deviations are usually defined in terms of Total Vertical Error (TVE) (in geometric feet) with:

$$TVE = actual\ pressure\ altitude\ flown\ by\ an\ aircraft - assigned\ altitude \tag{2.10}$$

In the same manner as for the pre-implementation CRAs, the components approach is used to express TVE as the (statistically independent) sum of Altimetry System Error (ASE) and Flight Technical Error (FTE) or Assigned Altitude Deviation (AAD), i.e.

$$TVE = ASE + FTE \tag{2.11}$$

$$TVE \approx ASE + AAD \tag{2.12}$$

The error components ASE, FTE, and AAD are defined by

$$ASE = actual\ pressure\ altitude\ flown\ by\ an\ aircraft - displayed\ altitude \tag{2.13}$$

$$FTE = displayed\ altitude - assigned\ altitude \tag{2.14}$$

and

$$AAD = transponded\ altitude - assigned\ altitude \tag{2.15}$$

Within the components approach, the TVE probability density follows from the ASE and AAD probability densities by means of the convolution integral

$$f^{TVE}(z) = \int_{-\infty}^{\infty} f^{ASE}(a) f^{AAD}(z-a)da \tag{2.16}$$

The key part of the calculation is formed by the overall ASE probability density $f^{ASE}(a)$ of the RVSM approved aircraft population operating in AFI RVSM airspace. Assuming that this population is made up of n_{MG} aircraft monitoring groups with ASE probability densities $f_i^{ASE}(a)$, $i = 1,\ldots,n_{MG}$, the overall ASE probability density can be written as a weighted mixture of the ASE densities by monitoring group, i.e.

$$f^{ASE}(a) = \sum_{i=1}^{n_{MG}} \beta_i f_i^{ASE}(a) \tag{2.17}$$

where the weighting factors β_i, $i = 1,\ldots,n_{MG}$, are the proportions of flight time contributed by monitoring group i.
Height monitoring data is required to determine the individual monitoring groups' ASE probability densities $f_i^{ASE}(a)$ whereas the flight time proportions β_i can, in principle, be derived from the ARMA Form 4 traffic flow data.

The flight time proportions have been updated as set out in Appendix A. A total of 120 monitoring groups have been inferred from the ARMA Form 4 data. This is about twice the number of monitoring groups (58) taken into account in CRA 3, the last pre-implementation CRA. The increase may be explained from the fact that CRA 3 had to predict a candidate AFI RVSM aircraft population on the basis of the RVSM aircraft/operator approval status as per 5 May 2008. Apparently, aircraft approvals from many monitoring groups have been registered since.

The monitoring groups' ASE probability densities $f_i^{ASE}(a)$, $i = 1,\ldots,n_{MG}$, 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, since the normal height-keeping 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 the monitoring groups' ASE probability densities $f_i^{ASE}(a)$, $i = 1,\ldots,n_{MG}$. Notice that the overall ASE probability density defined by eq. (2.17) will vary from region to region due to different sets of weighting factors β_i, $i = 1,\ldots,n_{MG}$, resulting from the pertinent composition of each region's aircraft population.

ASE probability densities $f_i^{ASE}(a)$, $i = 1,\ldots,n_{MG}$, have been used based on European height monitoring data (supplemented with some North Atlantic data) collected between 1 January 2007 and 31 December 2008 inclusive. For each monitoring group, the parameters of the group's within airframe ASE and between airframe ASE probability densities are estimated on the basis of the height monitoring data pertaining to the group, after which these two component densities are numerically combined to the monitoring group's ASE probability density $f_i^{ASE}(a)$, $i = 1,\ldots,n_{MG}$. Following this, the overall ASE probability density $f^{ASE}(a)$ is determined for the AFI RVSM aircraft population by means of eq. (2.17). See Appendix A for the resulting probability density.

The type of AAD probability density and the corresponding parameter value(s) have been reviewed and it was decided to retain the double exponential AAD probability density model from the pre-implementation CRAs. Based on the latest height monitoring data, a slightly larger standard deviation of typical AAD has been taken, viz. $\sigma_{AAD} = 42.7$ ft.

Figures 2.1 and 2.2 show two copies of the resulting TVE probability density $f^{TVE}(z)$ separated by 1000 ft, plotted against a linear and a logarithmic scale respectively. The interaction between the two curves determines the probability density of the vertical distance between two aircraft nominally separated by 1000 ft, which in turn determines the probability of vertical overlap.

In formula, the probability of vertical overlap for aircraft at adjacent flight levels separated by S_z is calculated by means of the expression

$$P_z(S_z) = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f^{TVE}(z_1) f^{TVE}(S_z + z_1 - z) dz_1 dz \qquad (2.18)$$

where $f^{TVE}(z)$ denotes the TVE probability of an aircraft given by eq. (2.16) and the inner integral represents the probability density of the vertical distance between two aircraft at adjacent flight levels . The resulting value was found to be

$$P_z(1000) = 1.2 \times 10^{-8} \qquad (2.19)$$

This value is a factor of six larger than the one obtained for the last pre-implementation CRA 3. It is not possible to identify a single cause for the increase since so many parameters play a part, i.e. both flight time proportions and (within and between airframe) ASE probability density parameters. It should be remarked, however, that the current estimate still lies approximately 50% below the upper bound of 1.7×10^{-8} specified by the global height-keeping performance specification for RVSM (Ref. 3).

Figure 2.1 Two TVE probability densities (defined by eq. (2.16)) separated by 1000 ft

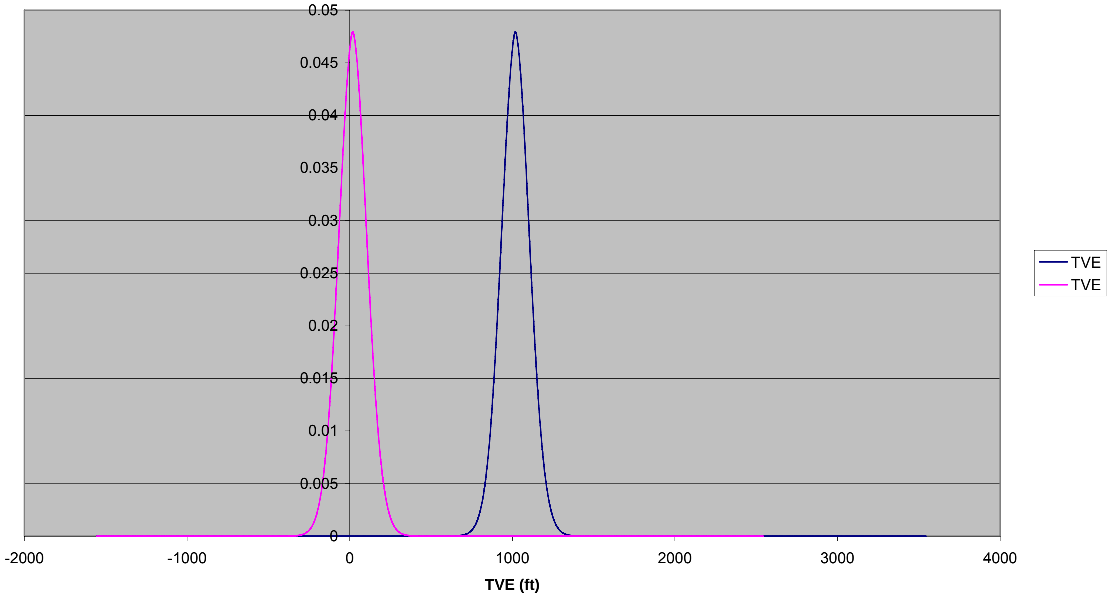
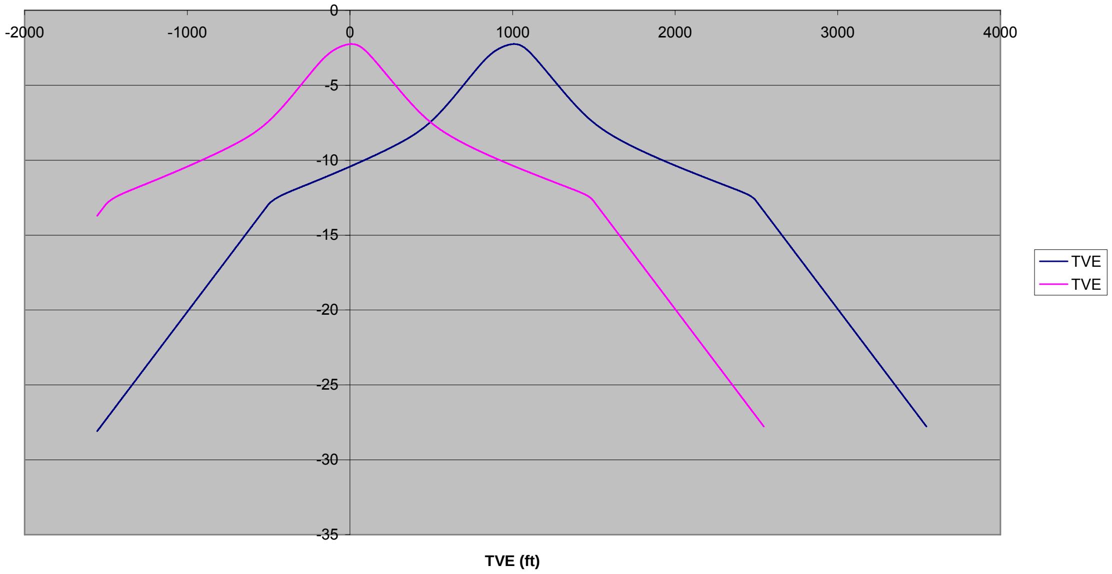


Figure 2.2 Logarithm (base 10) of two TVE probability densities (defined by eq. (2.16)) separated by 1000 ft



2.4 PASSING FREQUENCY

2.4.1 RESULTS

The distribution of the aircraft over 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, $n_x(same)$, $n_x(opp)$, and $n_{xy}(\theta_i)$ in the collision risk model of eqs. (2.8) and (2.9). 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. 3) 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 3 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. 7 and 8). The need for this and other monitoring data has been duly recognised and confirmed by the AFI RVSM programme in the conclusions of its successive Task Force meetings, see e.g. reference 9 – conclusions 13.1 and 13.2. Many, but not all, States have provided the monthly traffic flow data in one form or another. Prior to any data being available for the first pre-implementation collision risk assessment CRA 1, some operational judgement was applied to identify the three busiest adjacent ACCs by specifying the following four clusters of adjacent States 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 clusters provides a kind of east-west cross-section through the major north-south routes in the AFI Region with the associated FIR/UIRs being:

- Algiers, Tripoli, Cairo;
- Brazzaville/ N'Djamena, Kano, Cairo;

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

The above clusters have been used as a guideline for each of the pre-implementation CRAs, though it was recognised that data from each ACC is really necessary to be able to perform the passing frequency estimation properly. It should also be remarked that Cairo FIR is a part of the Middle East RVSM airspace.

Another look at the ACCs covering the region's busiest traffic flows or highest passing frequencies is based on the six Areas of Routing (ARs) to, from, and within Africa, defined by the Africa - Indian Ocean Planning and Implementation Group (APIRG), namely:

- AR-1: Europe South Atlantic;
- AR-2: Atlantic Ocean;
- AR-3: Europe – Eastern Africa (including Oceanic Areas);
- AR-4: Europe – Southern Africa, including continental Southern Africa routes;
- AR-5: Continental Western Africa including coastal areas; and
- AR-6: Trans-Indian Ocean.

See figure D-1 of reference 10. The three continental ARs AR-3, AR-4, and AR-5 are of relevance to the passing frequency assessment as prescribed by reference 3. The FIR/UIRs making up these three ARs are

- AR-3: Addis Ababa, Asmara, Cairo, Dar Es Salaam, Entebbe, Khartoum, Mogadishu, Nairobi, and Tripoli;
- AR-4: Brazzaville, Cape Town, Gaborone, Harare, Johannesburg, Kano, Kinshasa, Luanda, Lusaka, N'Djamena, Niamey, Tripoli, and Windhoek; and
- AR-5: Accra, Brazzaville, Dakar, Kano, Niamey, N'Djamena, and Roberts.

In the pre-implementation CRAs, the traffic flow data was collected in the AFI Region under the conventional vertical separation minimum (CVSM) and an assumption had to be made as to how the traffic would be redistributed across the RVSM flight levels. A conservative assumption was made, viz. that the passing frequency values under CVSM would not decrease under RVSM.

For the post-implementation CRA of the POSC, the traffic flow data has been collected under RVSM and the redistribution of the traffic across the RVSM flight levels is directly reflected, therefore, in the traffic flow data. Though it may be of interest from an operational point of view to examine the reduction in traffic load per flight level and, hence, in passing frequency, it does not make much sense to compare pre- and post-implementation passing frequency values from a risk assessment point of view.

In accordance with the cruising levels (at or above FL290) in use in (most of) the FIR/UIRs in the AFI Region under RVSM, no same-direction passings between aircraft at adjacent flight levels were found, i.e. $n_x(same)=0$ in the collision risk model of eqs. (2.8) and (2.9). Table 2.3 summarizes the opposite-direction and equivalent opposite-direction passing frequencies obtained from the ARMA Form 4 traffic flow data for the various FIR/UIRs. Notice that useful data for the passing frequency calculations was <u>not</u> obtained from 14 out of the 30 participating FIR/UIRs. Details of the underlying processing can be found in Appendix B. Recall that equivalent opposite-direction passing frequency allows comparing the relative risk associated with an opposite-direction passing and an aircraft passing on intersecting routes. All passing frequencies can be seen to have decreased significantly from the (conservative) values obtained for the pre-implementation CRA 3. The difference between the equivalent opposite-direction passing frequency $n_x(equiv)$ and the opposite-direction passing frequency $n_x(opp)$ for an FIR/UIR determines the effect of intersecting routes traffic on the exposure to the technical vertical collision risk. Traffic on intersecting routes is seen to have a marginal effect.

In addition to the data limitations to be summarised in section 2.4.2, the following should be remarked. Passing frequency refers to aircraft at <u>adjacent</u> flight levels passing one another in the horizontal plane. The passing frequency calculations consider all aircraft pairs and then check for each pair the vertical distance between the aircraft. The “default” vertical distance for a pair is, of course, the vertical separation minimum of 1000 ft. However, as a matter of interest, separate numbers of passings are also calculated when the vertical distance between the aircraft is 0 ft (both aircraft at the same flight level) or 2000 ft (second aircraft at next adjacent flight level). Given the semi-circular flight level system, aircraft at adjacent flight levels of the same route should be flying in opposite directions and an aircraft at the next adjacent flight level should again be flying in the same direction as the first aircraft. However, the flight directions that can be inferred from the traffic flow data in ARMA Form 4 suggest for a non-negligible number of cases that an aircraft flying at the next adjacent flight level is flying in the opposite direction with respect to the first aircraft. Similarly, based on the flight directions inferred from the ARMA Form 4 traffic flow data, opposite-direction passings between aircraft at the same flight level have been found for a non-negligible number of cases. The source of these apparent inconsistencies should be investigated. The (artificial) additional opposite direction passings between aircraft separated by 0 ft and 2000 ft were included in the passing frequencies calculated in the pre-implementation CRAs but have been excluded from the current CRA. This may be one of the reasons for the decrease in passing frequency noted above, in addition to the redistribution of the traffic over the RVSM flight levels.

FIR/UIR	POSC		CRA 3	
	n_x(opp)	n_x(equiv)	n_x(opp)	n_x(equiv)
Accra	-	-	-	-
Addis Ababa	0.08922	0.08922	-	-
Algiers	0.07392	0.07410	0.1093	0.1701
Antananarivo	-	-	0.03534	0.03594
Asmara	0.005977	0.005977	0.02624	0.02624
Beira	0.07037	0.07037	0.08216	0.09493
Brazzaville	-	-	-	-
Canarias [1]				
Cape Town	-	-	-	-
Dakar	0.04112	0.04112		
Dakar Oceanic [1]				
Dar Es Salaam	0.04532	0.04537	0.1045	0.1369
Entebbe	0.007504	0.007567	-	-
Gaborone	0.05986	0.05988	-	-
Harare	*	*	*	*
Johannesburg	-	-	-	-
Johannesburg Oceanic	-	-		
Kano	0.1015	0.1022	0.1906	0.2237
Khartoum	-	-	-	-
Kinshasa	-	-	0.02818	0.03857
Lilongwe	0.01305	0.1309	-	-
Luanda	-	-	-	-
Lusaka	0.01729	0.01730	0.02275	0.02275
Mauritius	0.009333	0.009333	0.02776	0.02852
Mogadishu	0.02438	0.02443	0.05281	0.06961
Nairobi	0.01040	0.01041	-	-
N'Djamena	-	-	-	-
Niamey	-	-	-	-
Roberts	0.01080	0.01082	0.03218	0.03892
Sal Oceanic [1]			-	-
Seychelles	-	-	-	-
Tripoli	-	-	-	-
Windhoek	0.001047	0.001047	-	-

Table 2.3 Summary of passing frequency values for the AFI RVSM POSC CRA

Remark [1]: Included in Doc 7030 AFI Regional Supplementary procedures RVSM, but non-participating AFI RVSM FIR/UIR.

Remark *: Form 4 traffic flow data provided in non-electronic form

As follows from table 2.3, the required traffic flow data was not received from all the ACCs involved in the preliminary and AR-based clusters of busiest ACCs. As a result, the intended averaging over the ACCs included in each cluster could only be applied to the ACCs for which data was available. In principle, averaging over fewer ACCs in a cluster tends to be conservative (less smoothing) unless the ACC(s) excluded from the averaging due to missing data actually have the larger passing frequencies. Table 2.4 summarises the equivalent opposite direction passing frequencies for the four initial and three AR-based clusters of busy adjacent ACCs specified above where the names of the ACCs for which no data were available have been put in brackets.

Cluster of busy ACCs	Equivalent opposite direction passing frequency values
Algiers, (Tripoli), (Cairo)	0.07410
(Brazzaville)/(N'Djamena), Kano, (Cairo)	0.1022
Kano, (N'Djamena), (Brazzaville)	0.1022
(Johannesburg), (Cape Town), Gaborone, (Kinshasa)/(Luanda)	0.05988
AR-3: Addis Ababa, Asmara, (Bujumbara), (Cairo), Dar Es Salaam, Entebbe, (Khartoum), (Kigali), Mogadishu, Nairobi, (Tripoli)	0.08922, 0.005977, 0.04537, 0.007567, 0.02443, 0.010, 0.00104741
AR-4: (Brazzaville), (Cape Town), Gaborone, (Harare), (Johannesburg), Kano, (Kinshasa), (Luanda), Lusaka, (N'Djamena), (Niamey), (Tripoli), Windhoek	0.05988, 0.1022, 0.0173
AR-5: (Accra), (Brazzaville), Dakar, Kano, (Niamey), (N'Djamena), Roberts	0.04112, 0.1022, 0.01082

Table 2.4 Summary of equivalent opposite-direction passing frequency values for seven clusters of busy ACCs

The upper part of table 2.4 shows that data for the four initially identified clusters were available only from Algiers, Gaborone, and Kano. Consequently, the averaging over each cluster reduces to a rather trivial operation on a single value. The largest value is that for Kano, viz. 0.1022. For the AR-3 based cluster, a total of nine triples of adjacent ACCs were identified and for each triple a (weighted) average equivalent opposite-direction passing frequency was calculated. The calculated values ranged from 0.01621 to 0.04885. For the AR-4 based cluster, a (weighted) average equivalent opposite-direction passing frequency of 0.03771 was calculated for the three adjacent FIR/UIRs Gaborone, Lusaka, and Windhoek. The three FIR/UIRs in the AR-5 cluster for which data were available are not adjacent. A (weighted) average equivalent opposite-direction passing frequency of 0.05501 was calculated for these FIR/UIRs.

Based on the foregoing discussion, particularly the lack of data from a considerable number of FIR/UIRs, the passing frequency estimate for the Kano FIR from the second and third cluster in table 2.4 is considered to best address the problem of ACCs with high traffic flows where higher-than-average collision risk may pertain. Hence, the overall value to be used for the vertical collision risk assessment for the AFI region becomes

$$n_x^{AFI}(equiv) = 0.1022 \qquad (2.20)$$

This value is approximately 20% smaller than the value of 0.1254 equivalent opposite-direction passings per flight hour utilised in the last pre-implementation CRA 3.

It is remarked once more that the above analysis is unsatisfactory in that its results may be strongly affected by the missing data from 14 participating FIR/UIRs. This complication would be avoided, if all the required and agreed data would be available.

2.4.2 SUMMARY OF DATA LIMITATIONS

It should be clear that in order to produce a representative post-implementation estimate of the technical vertical collision risk in AFI RVSM airspace, it is necessary to collect data on all flights 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 on the one hand and the number of horizontal passing events (of each of the different types) on the other. The data collection is performed through ARMA Form 2 (monthly movements) and ARMA Form 4 (traffic flow data). Provided the information in ARMA Form 4 is complete, flying time can be derived from it and can be cross-checked against the flying time reported in ARMA Form 2.

A key element of the traffic flow data information in ARMA Form 4 is the actual flight progress information, i.e. waypoint identification, reporting time at waypoint, and flight level at waypoint. 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 an FIR/UIR is required.

Data has only been received from a limited number of FIR/UIRs. For 16 FIR/UIRs, the quality of the data was such that the passing frequency and aircraft population could be determined. In total, 121 months worth of data have been processed. This constitutes only 34% of the total that should have been available from the 30 participating FIR/UIRs. The quality of the available information varied strongly. Appendix B lists for each FIR/UIR all the limitations in the data.

Figure 2.3 below shows, for illustration purposes, a graphical representation of the amount of data received from States for the post-implementation CRA. The borders represent State' borders rather than FIR/UIR borders. The airspace of grey coloured States is not part of AFI RVSM airspace. Green coloured States concern States from which information was available and the information could be successfully processed. Yellow marks those States that did make information available, but whose information could not be successfully processed. Lavender indicates the States from which simply no information was available.

Based on the available and processable data set, a total of 313,652 flight hours for the AFI region has been calculated for the RVSM flight level band FL290 – FL410 inclusive for a one-year period of time from 25 September 2008 to 24 September 2009 inclusive. This appears to represent only a very limited proportion of the total. For example, the number of scheduled flights in the AFI region for the year 2003 was estimated in the initial CRA (CRA 1) as 1,108,000 flights (Ref. 4). It must be concluded, therefore, that the available set of information represents only a fraction of all flights in the AFI region.

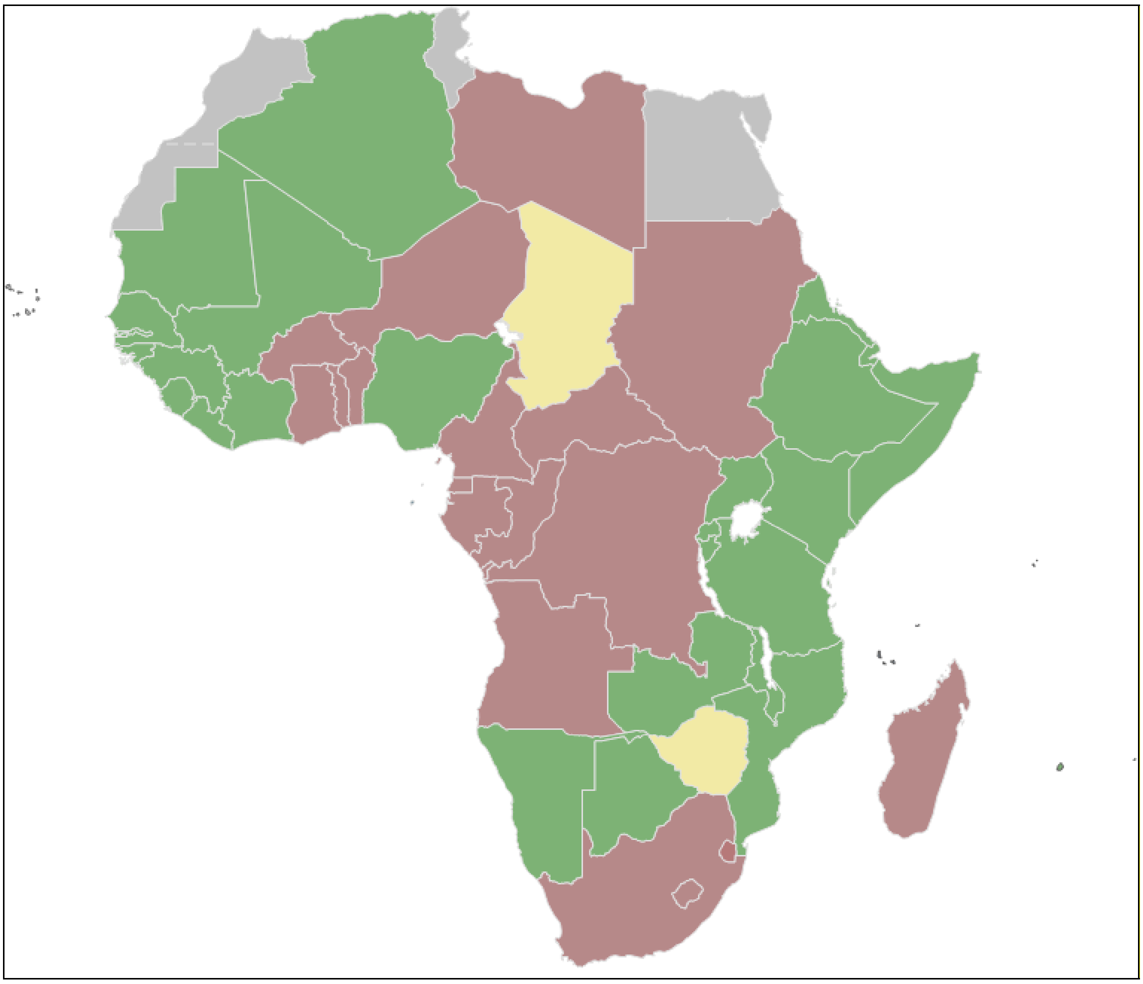


Figure 2.3 Summary of available data for AFI RVSM post-implementation CRA Colours represent the following. Green: information was available and could be successfully processed. Yellow: information was available but could not be processed. Lavender: no information was available. Grey: not a part of AFI RVSM airspace.

2.5 PROBABILITY OF LATERAL OVERLAP

Lateral navigation accuracy has an essential influence on the likelihood of a collision between two aircraft once vertical separation has been lost. This influence is expressed as the probability of lateral overlap for aircraft nominally flying at (adjacent flight levels of) the same route, $P_y(0)$, and is defined by

$$P_y(0) = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f_Y(y_1) f_Y(y_1 - y) dy_1 dy \tag{2.21}$$

where λ_y denotes the average width of the aircraft (cf. table 2.1) and $f_Y(y)$ denotes the probability density of the lateral deviations from route centre line. The probability density $f_Y(y)$ is dependent on the type of navigation equipment being used in the airspace under consideration. To quantify $P_y(0)$, the same approach has been followed as for the pre-implementation CRAs.

The approach followed was to assume that a proportion α, $0 \le \alpha \le 1$, of the AFI RVSM airspace users is using GNSS navigation and that the remaining proportion $1-\alpha$ is using VOR/DME navigation. The following mixture distribution was then specified

$$f_Y(y) = (1-\alpha)\frac{1}{\sigma_{VOR/DME}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y}{\sigma_{VOR/DME}}\right)^2} + \alpha \frac{1}{\sigma_{GNSS}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y}{\sigma_{GNSS}}\right)^2} \tag{2.22}$$

with

$$\sigma_{VOR/DME} = 0.3NM \tag{2.23}$$

$$\sigma_{GNSS} = 0.06123NM \tag{2.24}$$

The resulting model was used to calculate the probability of lateral overlap as a function of the proportion α of the AFI RVSM airspace users using GNSS navigation. Table 2.5 below (based on an average aircraft width $\lambda_y = 158.71$ ft) has been reproduced from reference 4.

The first pre-implementation CRA, CRA 1, used a value of $\alpha = 0.5$ for the proportion of GNSS flying time. At the time, this value was judged to be slightly conservative. Following the presentation of CRA 1 at the AFI RVSM TF/7 meeting in Dakar, August 2005, it was suggested to assume that the full aircraft population would be using GNSS and to thus take $\alpha = 1.0$ for the next CRA. This suggestion, however, was believed to be overly optimistic at the time of drafting of both CRA 2 and CRA 3 and it was decided then to retain the value of $\alpha = 0.5$ for the proportion of GNSS flying time for those CRAs. The same argument is believed to be still valid, and $\alpha = 0.5$ will also be used for the (first) post-implementation CRA. A minor correction to $P_y(0)$ will be applied in section 2.7 to account for a minor change in the average aircraft dimensions (see table 2.6).

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 2.5 The probability of lateral overlap, $P_y(0)$, as a function of the proportion α of GNSS flying time (Reproduced from reference 4, based on $\lambda_y = 158.71$ ft)

$P_y(0)$ multiplied by $n_x(equiv)$ determines the exposure to the risk of collision due to the loss of vertical separation. When the aircraft height-keeping performance just meets the limit value of $P_z(1000) = 1.7 \times 10^{-8}$, the global system performance specification for RVSM (Ref. 3) shows that twice this exposure needs to be less than $0.058 \times 2.5 = 0.145$ to be able to meet the technical vertical TLS of 2.5 × 10^{-9} fatal accidents per flight hour. This global upper bound of 0.145, applied to the local value of $P_y(0) = 0.109$, gives a local upper bound of only 0.67 for the (equivalent) opposite direction passing frequency for RVSM in the AFI Region. This is a direct consequence of the product of passing frequency and probability of lateral overlap being constrained by the global system performance specification. Put simply, the better the lateral navigation accuracy the fewer passings are allowed. Notice that the average passing frequency value of $n_x^{AFI}(equiv) = 0.1022$ (eq. (2.20)) calculated in section 2.4 is well below the local bound of 0.67 opposite direction passings per flight hour.

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 section 15.2.4 of the PANS-ATM (Ref. 11). To be able to take the risk mitigating effect of lateral offsets on $P_y(0)$ into account, it needs to be known to what extent the offsets are actually used in practice. Since this knowledge is currently unavailable, the beneficial effects of lateral offsets have not been taken into account in this report.

2.6 AIRCRAFT DIMENSIONS AND RELATIVE SPEEDS

2.6.1 RELATIVE SPEEDS

The vertical collision risk model of eqs. (2.8) and (2.9) contains four basic relative speed parameters, $2|V|$, $|\Delta V|$, $|\dot{y}|$ and $|\dot{z}|$. An updated estimate of the average aircraft speed has been calculated in Appendix A.5 as $\overline{V} = 463.4$ kts, which is clearly equivalent to the value of 463.6 kts used in CRA 3. The other relative speed parameter values have not been revised since no data directly from AFI RVSM airspace were available. Thus the following initial values from references 4 - 6 have been retained: $\overline{|\Delta V|} = 20$ kts, $|\dot{y}| = 20$ kts, and $|\dot{z}| = 1.5$ kts.

2.6.2 AIRCRAFT DIMENSIONS

Updated weighted average aircraft dimensions have been calculated as described in Appendix A.5. The resulting dimensions for a typical aircraft in AFI RVSM airspace are shown in Table 2.6. Notice that the updated values are virtually the same as the previous ones. The values for the AFI region are larger than those for the EUR Region and smaller than those for the NAT Region (see reference 4, table 3.18).

Aircraft dimension	Parameter	Value (ft)				Value (NM)
		CRA 1	CRA 2	CRA 3	POSC	POSC
Length	λ_x	168.72	173.51	173.81	171.49	0.028223
Width	λ_y	158.71	163.35	165.32	163.81	0.026959
Height	λ_z	49.25	51.07	50.93	50.29	0.008277
Diameter	λ_{xy}	168.72	173.51	173.81	171.49	0.028223

Table 2.6 Typical aircraft dimensions for the AFI Region

2.7 TECHNICAL VERTICAL COLLISION RISK

Recall the technical vertical collision risk model specified in eq. (2.9) of section 2.2, i.e.

$$N_{az} = 2P_z(S_z)P_y(0)n_x(equiv)\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\} \tag{2.9}$$

Table 2.7 summarises the main parameter estimates for this model.

Parameter	Value
S_z	1000
$P_z(S_z)$	1.2×10^{-8}
$P_y(0)$	0.109
$n_x(equiv)$	0.1022
$\left\{1+\frac{\overline{\lvert\dot{y}\rvert}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{\lvert\dot{z}\rvert}}{2\overline{V}}\right\}$	1.0271

Table 2.7 Summary of parameter values for vertical collision risk model of eq. (2.9)

Substitution of the table 2.7 values into eq. (2.9) gives

$$\boxed{N_{az} = 2\times1.2\times10^{-8}\times0.109\times0.1022\times1.0271 = 2.7\times10^{-10}} \tag{2.25}$$

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 met. Moreover, it is being met with a factor of approximately 10.

The margin between the technical vertical TLS and the current estimate of the technical vertical collision risk needs to be considered in the context of several uncertainties like the data limitations summarised in section 2.4.2, the proportion of GNSS navigation and increases in traffic volume. The effect of the proportion of GNSS navigation can easily be quantified, see table 2.5, and would be a factor of approximately two when nearly all aircraft would be using GNSS navigation. In first approximation, passing frequency increases proportionally to traffic volume. For example, a 5% annual traffic growth would, over ten years, in first approximation, lead to a 60% increase in passing frequency. The uncertainty associated with the data limitations is rather difficult to quantify but is not believed to be an order of magnitude. Moreover, proper use of the Strategic Lateral Offset Procedure under RVSM would counteract the adverse effect on the vertical risk of GNSS navigation accuracy. Thus, the current margin is deemed to be sufficient to cover the effect of the data limitations from section 2.4.2 and the other uncertainties.

3 ASSESSMENT OF TOTAL VERTICAL RISK

3.1 INTRODUCTION

Section 2 dealt with the assessment of the technical vertical collision risk under RVSM in the AFI Region. There may exist additional causes of vertical collision risk, however, and the combined effect of all those potential causes and the normal technical cause is to be assessed against the total vertical TLS of 5×10^{-9} fatal accidents per flight hour. Suitable collision risk models for the risk due to all the additional causes developed for the pre-implementation CRAs have been re-used for the current CRA.

Section 3.2 recalls the pertinent models. This is followed by a detailed examination of the data available for the post-implementation CRA in section 3.3. Data on large atypical height deviations in AFI RVSM airspace have been obtained via ARMA from the African States and from IATA. Finally, section 3.4 presents estimates of the total vertical collision risk under AFI RVSM.

3.2 TOTAL VERTICAL COLLISION RISK MODELS

Background

In the same manner as for the pre-implementation CRAs (CRA 1- CRA 3), incident data will be used to estimate the vertical collision risk due to causes other than the normal typical height deviations of RVSM approved aircraft. The following broad categories of potential causes of total vertical collision risk have been distinguished in references 4 - 6:

- ATC error;
- Pilot error;
- ACAS events;
- Non-RVSM approved aircraft;
- Equipment failure;
- Turbulence/weather;
- Unknown civil aircraft;
- Unknown military aircraft operating outside designated military areas; and
- 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, say, 300 ft or more. It is essentially 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.

As before, 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 very 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. 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, say, 300 ft. 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.

Following the pre-implementation CRAs (Refs. 4 – 6), three sub-models will be used 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.

Large height-deviations not involving whole numbers of flight levels

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.

$$N_{az}^{non-whl} = 2P_z(S_z)^{non-whl} P_y(0) n_x(equiv)\left\{1 + \frac{\overline{|\dot{y}|}}{2\overline{V}} + \frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}|}}{2\overline{V}}\right\} \tag{3.1}$$

A superscript “non-whl” is used to distinguish this type of vertical collision risk from the technical vertical collision risk. The basic method to estimate the probability of vertical overlap $P_z(S_z)^{non-whl}$ due to large height deviations not involving whole numbers of flight levels is to model assigned altitude deviation (AAD) by means of a mixture distribution as described in section 4.3.2.2 of reference 4. The method requires large height deviation data observed over a fairly broad range. It fails when the data available is heavily concentrated at one (or a few) value(s) as in the current case of a single 400 ft value (see table 3.8). Therefore, in the same manner as for the last pre-implementation CRA 3 (Ref. 6), an alternative method to estimate $P_z(S_z)^{non-whl}$ has been used as outlined in the following five paragraphs.

Recall from section 2.3 that for the technical risk the TVE of a typical RVSM approved aircraft is modelled as the sum of typical ASE and typical AAD. Both error components are assumed to be random variables with the ASE probability density of a typical aircraft given by eq. (2.17) of section 2 and the probability density of typical AAD being double exponential with a standard deviation of 42.7 ft.

A large height deviation over a relatively long period of time is modelled by taking the AAD as a (large) constant value. Thus, the TVE of any aircraft involved in a large height deviation of the non-whole numbers of flight levels type will be modelled as

$$TVE_{LHD} = AAD_{LHD} + ASE \tag{3.2}$$

where AAD_{LHD} is now a constant and ASE continues to be random with probability density given by eq. (2.17).

The probability of vertical overlap between a typical RVSM approved aircraft and an RVSM approved aircraft involved in a large height deviation of the non-whole numbers of flight levels type is then calculated by the following variant of eq. (2.18),

$$P_z(S_z)_{LHD} = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f^{TVE}(z_1) f^{TVE_{LHD}}(S_z + z_1 - z) dz_1 dz \tag{3.3}$$

or

$$P_z(S_z)_{LHD} = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f^{TVE}(z_1) f^{ASE}(S_z - AAD_{LHD} + z_1 - z) dz_1 dz \tag{3.4}$$

The inner integral represents the probability density of the vertical distance between the two aircraft where the aircraft are nominally separated by S_z and where one of the aircraft is assumed to have a large AAD. This constant large AAD effectively reduces the nominal separation S_z by an amount of AAD_{LHD}. In addition to the large constant AAD, the pertinent aircraft is assumed to have a normal random ASE.

Suppose now that there are n_{LHD} large height deviations of the non-whole numbers of flight levels type with magnitudes AAD_{LHDi} and duration t_{LHDi}, $i = 1,\dots,n_{LHD}$, during a period of time of T flight hours. The probability of vertical overlap due to these deviations is then estimated by

$$P_z(S_z)^{non-whole} = \sum_{i=1}^{n_{LHD}} \frac{t_{LHDi}}{T} P_z(S_z)_{LHDi} \tag{3.5}$$

Large height-deviations involving aircraft climbing or descending through a flight level

The probability of vertical overlap due to an aircraft climbing or descending (cl/d) through a single flight level can be given by

$$P_z(S_z)_{FL}^{cl/d} = \frac{2\lambda_z / \overline{|\dot{z}_c|}}{T} \tag{3.6}$$

and the probability of vertical overlap due to climbing or descending through $n^{cl/d}$ flight levels by

$$P_z(S_z)^{cl/d} = \frac{n^{cl/d} \times 2\lambda_z / \overline{|\dot{z}_c|}}{T} \tag{3.7}$$

where λ_z denotes the average aircraft height, $\overline{|\dot{z}_c|}$ is the average relative vertical speed between the aircraft and T the total flight time. See table 3.1. The probabilities of vertical overlap in eqs. (3.6) and (3.7) are the same for an aircraft climbing (or descending) through an opposite- or same-direction flight level and also for a flight level of an intersecting route.

When an aircraft climbs or descends through a number of flight levels of a bidirectional route, the numbers of same- and opposite-direction flight levels crossed, say, $n_{same}^{cl/d}$ and $n_{opp}^{cl/d}$, need to be determined as well as the probability of the subject aircraft being in longitudinal overlap at each same- and opposite-direction flight level crossed. With opposite-direction traffic at adjacent flight levels, it is assumed that the probability of longitudinal overlap is the same for each opposite-direction flight level crossed. Similarly, it is assumed that the probability of longitudinal overlap is the same for each same-direction flight level crossed. The probability of joint vertical and longitudinal overlap between two aircraft due to one aircraft climbing or descending through a flight level is taken as the product of the probability of vertical overlap and the probability of longitudinal overlap defined by the flight level direction.

Thus, the conventional vertical collision risk model for aircraft climbing or descending through a flight level without (proper) clearance is given by:

$$
\begin{aligned}
N_{az}^{cl/d} = {} & 2P_z(S_z)_{opp}^{cl/d}\,P_y(0)\,n_x(opp)\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}_c|}}{2\overline{V}}\right\}+ \\
& 2P_z(S_z)_{same}^{cl/d}\,P_y(0)\,n_x^{*}(same)\left\{1+\frac{\overline{|\dot{y}|}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{|\dot{z}_c|}}{\overline{\Delta V}}\right\}+ \\
& 2\sum_{i}^{n}P_z(S_z)_{\theta i}^{cl/d}\,n_{xy}(\theta_i)\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)}\frac{\overline{|\dot{z}_c|}}{2\lambda_z}\right\}+ \\
& 2\sum_{i}^{n}P_z(S_z)_{\pi-\theta i}^{cl/d}\,n_{xy}^{*}(\pi-\theta_i)\left\{1+\frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\pi-\theta_i)}\frac{\overline{|\dot{z}_c|}}{2\lambda_z}\right\}
\end{aligned}
\tag{3.8}
$$

where the superscript “cl/d” refers to an aircraft climbing or descending through a flight level without a proper clearance and the various probabilities of vertical overlap are given by

$$P_z(S_z)_{opp}^{cl/d} = \frac{n_{opp}^{cl/d}\times 2\lambda_z/\overline{|\dot{z}_c|}}{T} \tag{3.9}$$

$$P_z(S_z)_{same}^{cl/d} = \frac{n_{same}^{cl/d}\times 2\lambda_z/\overline{|\dot{z}_c|}}{T} \tag{3.10}$$

$$P_z(S_z)_{\theta i}^{cl/d} = \frac{n_{\theta i}^{cl/d}\times 2\lambda_z/\overline{|\dot{z}_c|}}{T} \tag{3.11}$$

$$P_z(S_z)_{\pi-\theta i}^{cl/d} = \frac{n_{\pi-\theta i}^{cl/d}\times 2\lambda_z/\overline{|\dot{z}_c|}}{T} \tag{3.12}$$

The new parameters of the collision risk model of eqs. (3.8) – (3.12) are defined in table 3.1. (See tables 2.1 and 2.2 for the previously defined parameters.) Notice that opposite- and same-direction flight levels of a single route constitute a special case of routes intersecting at an angle $\theta = 180^\circ$ (with supplementary angle $\pi - \theta = 0^\circ$). Notice also that an additional superscript “*” is used on $n_x^{*}(same)$ and $n_{xy}^{*}(\pi-\theta_i)$ to emphasize that these passing frequencies concern longitudinal/horizontal passings between aircraft at flight levels separated by twice the vertical separation minimum S_z.

The above model of eqs. (3.8) – (3.12) may be compared with the model used in the last pre-implementation CRA 3, i.e. eq. (3.11) of reference 6. Two differences are worth noting. The first difference concerns the vertical collision risk due to improper flight level crossings, if any, on intersecting routes. This difference is essentially optical in the sense that this risk has now been written out explicitly in terms of the intersecting-routes passing frequencies $n_{xy}(\theta_i)$ and $n^*_{xy}(\pi-\theta_i)$ rather than it being covered by the equivalent opposite direction passing frequency $n_x(equiv)$ of eq. (2.8). The second difference concerns the counting of opposite- and same-direction flight levels crossed without proper clearance in the probabilities of vertical overlap given by eqs. (3.9) – (3.12). In the "old" model, all opposite- and same-direction flight levels were added together in $P_z(S_z)^{cl/d}$, after which $P_z(S_z)^{cl/d}$ was applied to both the opposite- and same-direction passing frequencies. This may lead to an unintended over-estimation of the vertical collision risk due to improper flight level crossings, the amount of over-estimation being dependent on the ratio between the numbers of opposite- and same-direction flight levels crossed.

Parameter	Definition
$N^{cl/d}_{az}$	Expected number of fatal aircraft accidents per flight hour due to aircraft climbing or descending through a flight level without a proper clearance
$P_z(S_z)^{cl/d}_{opp}$	Probability of vertical overlap due to aircraft climbing or descending through an opposite direction flight level without a proper clearance
$P_z(S_z)^{cl/d}_{same}$	Probability of vertical overlap due to aircraft climbing or descending through a same direction flight level without a proper clearance
$P_z(S_z)^{cl/d}_{\theta i}$	Probability of vertical overlap due to aircraft climbing or descending without a proper clearance through a flight level of a route intersecting at an angle θ_i
$P_z(S_z)^{cl/d}_{\pi-\theta i}$	Probability of vertical overlap due to aircraft climbing or descending without a proper clearance through a flight level of a route intersecting at supplementary angle $\pi-\theta_i$
$n^{cl/d}_{opp}$	Number of aircraft climbing or descending through an opposite-direction flight level without a proper clearance during a period of time with T flying hours
$n^{cl/d}_{same}$	Number of aircraft climbing or descending through a same-direction flight level without a proper clearance during a period of time with T flying hours
$n^{cl/d}_{\theta i}$	Number of aircraft climbing or descending without a proper clearance through a flight level of a route intersecting at an angle θ_i

$n^{cl/d}_{\pi-\theta_i}$	Number of aircraft climbing or descending without a proper clearance through a flight level of a route intersecting at supplementary angle $\pi-\theta_i$
$n_x^*(same)$	Same direction passing frequency for same direction aircraft nominally separated by twice the vertical separation minimum S_z
$n_{xy}^*(\pi-\theta_i)$	Passing frequency for aircraft nominally separated by twice the vertical separation minimum S_z on routes intersecting at supplementary angle $\pi-\theta_i$
$\overline{\lvert \dot{z}_c \rvert}$	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 3.1 Definition of additional parameters of the vertical collision risk model of eqs. (3.8) - (3.12)

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 12 and 13, for example, 20 kts and 15 kts respectively for a normal climb/descent. Both references specify a value of 50 kts in case of pressurisation failure, and 2 - 5 kts for engine failures. Since the probabilities of vertical overlap are inversely proportional to the vertical speed, a value of 15 kts will be used for normal climb/descents when specific information is missing in the incident report. The common references 12 and 13 values will be used for the other cases, where the distinction between 2 kts and 5 kts depends on the aircraft being triple (or more) engined or twin engined.

<u>Large height-deviations involving aircraft levelled off at a wrong flight level</u>

The probability of vertical overlap due to an aircraft levelling off at a wrong flight level can be given by

$$P_z(S_z)^{wl}_{FL} = \frac{t^{wl} \times P_z(0)}{T} \tag{3.13}$$

and the probability of vertical overlap due to n^{wl} aircraft having levelled off at a wrong flight level by

$$P_z(S_z)^{wl} = \frac{n^{wl} \times \bar{t}^{wl} \times P_z(0)}{T} \tag{3.14}$$

where the new parameters t^{wl} and $\bar{t}^{wl}$ denote the sojourn time of a single aircraft and the average sojourn time of aircraft at a wrong flight level respectively and $P_z(0)$ denotes the probability of vertical overlap for aircraft at the same flight level. See table 3.2. The vertical overlap probabilities in eqs. (3.13) and (3.14) are the same for an aircraft levelling off at a same- or opposite-direction flight level. They are also valid for the case of an aircraft levelling off at a wrong flight level and the aircraft's route intersecting another route.

When an aircraft levels off at a wrong flight level, the sojourn time at the wrong level needs to be determined as well as the probability of the subject aircraft being in longitudinal overlap at the wrong flight level, which may be either same or opposite direction, of the assigned route. When the aircraft levels off at an opposite-direction flight level, it is assumed that the probability of longitudinal overlap is the same as that for opposite-direction traffic at adjacent flight levels. Similarly, when the aircraft levels off at a same-direction flight level, it is assumed that the probability of longitudinal overlap is the same as that for same-direction traffic at flight levels separated by twice the vertical separation minimum S_z on the same route.

When the route with the aircraft levelled off at a wrong flight level intersects another route, there is also an intersecting routes vertical collision risk due to the loss of vertical separation and the probability of the subject aircraft being in horizontal overlap at the intersection at the wrong flight level is needed. Dependent on the aircraft having levelled off at an opposite- or same-direction flight level, the probability of horizontal overlap will be taken as the probability of horizontal overlap for aircraft at adjacent flight levels of intersecting routes or as the probability of horizontal overlap for aircraft at flight levels separated by twice the vertical separation minimum S_z on intersecting routes.

In all cases, the probability of joint vertical and longitudinal, or horizontal, overlap between two aircraft due to one aircraft levelling off at a wrong flight level is taken as the product of the probability of vertical overlap and the probability of longitudinal, or horizontal, overlap defined by the flight level direction.
Thus, the conventional vertical collision risk model for aircraft levelling off at a wrong flight level is given by:

$$
\begin{aligned}
N_{az}^{cl/d} = {} & 2P_z(S_z)_{opp}^{wl} P_y(0) n_x(opp) \left\{ 1 + \frac{\overline{|\dot{y}|}}{2\overline{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{\overline{|\dot{z}_c|}}{2\overline{V}} \right\} + \\
& 2P_z(S_z)_{same}^{wl} P_y(0) n_x^*(same) \left\{ 1 + \frac{\overline{|\dot{y}|}}{2\overline{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{\overline{|\dot{z}_c|}}{\overline{\Delta V}} \right\} + \\
& 2\sum_i^n P_z(S_z)_{opp,\theta i}^{wl} n_{xy}(\theta_i) \left\{ 1 + \frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)} \frac{\overline{|\dot{z}_c|}}{2\lambda_z} \right\} + \\
& 2\sum_i^n P_z(S_z)_{same,\theta i}^{wl} n_{xy}^*(\theta_i) \left\{ 1 + \frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)} \frac{\overline{|\dot{z}_c|}}{2\lambda_z} \right\}
\end{aligned}
\tag{3.15}
$$

where the superscript “wl” refers to an aircraft levelling off at a wrong flight level and the various probabilities of vertical overlap are given by

$$P_z(S_z)_{opp}^{wl} = \frac{n_{opp}^{wl} \times \bar{t}_{opp}^{wl} \times P_z(0)}{T} \tag{3.16}$$

$$P_z(S_z)_{same}^{wl} = \frac{n_{same}^{wl} \times \bar{t}_{same}^{wl} \times P_z(0)}{T} \tag{3.17}$$

$$P_z(S_z)_{opp,\theta i}^{wl} = \frac{n_{opp,\theta i}^{wl} \times \bar{t}_{opp,\theta i}^{wl} \times P_z(0)}{T} \tag{3.18}$$

$$P_z(S_z)_{same,\theta i}^{wl} = \frac{n_{same,\theta i}^{wl} \times \bar{t}_{same,\theta i}^{wl} \times P_z(0)}{T} \tag{3.19}$$

The new parameters of the collision risk model of eqs. (3.15) - (3.19) are defined in table 3.2. (See tables 2.1 and 2.2 for the previously defined parameters.)

Not surprisingly, the number of times an aircraft levels off at a wrong level and 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. 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 probability of vertical overlap $P_z(S_z)$ due to normal technical height deviations by putting $S_z = 0$ in eq. (2.18).

Parameter	Definition
$N_{az}^{cl/d}$	Expected number of fatal aircraft accidents per flight hour 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
$P_z(S_z)_{opp}^{wl}$	Probability of vertical overlap due to aircraft levelling off at a wrong, opposite direction, flight level
$P_z(S_z)_{same}^{wl}$	Probability of vertical overlap due to aircraft levelling off at a wrong, same direction, flight level
$P_z(S_z)_{opp,\theta_i}^{wl}$	Probability of vertical overlap due to aircraft levelling off at a wrong, opposite direction, flight level of a route intersecting another route at an angle θ_i
$P_z(S_z)_{same,\theta_i}^{wl}$	Probability of vertical overlap due to aircraft levelling off at a wrong, same direction, flight level of a route intersecting another route at an angle θ_i
n_{opp}^{wl}	Number of aircraft levelling off at a wrong, opposite direction, flight level during a period of time with T flying hours
n_{same}^{wl}	Number of aircraft levelling off at a wrong, same direction, flight level during a period of time with T flying hours
n_{opp,θ_i}^{wl}	Number of aircraft levelling off at a wrong, opposite direction, flight level of a route intersecting another route at an angle θ_i
n_{same,θ_i}^{wl}	Number of aircraft levelling off at a wrong, same direction, flight level of a route intersecting another route at an angle $\pi-\theta_i$
$\bar{t}_{opp}^{wl}$	Average sojourn time (hours) of an aircraft at a wrong, opposite direction, flight level after incorrectly levelling off
$\bar{t}_{same}^{wl}$	Average sojourn time (hours) of an aircraft at a wrong, same direction, flight level after incorrectly levelling off
$\bar{t}_{opp,\theta_i}^{wl}$	Average sojourn time (hours) of an aircraft at a wrong, opposite direction, flight level of a route intersecting another route at an angle θ_i after incorrectly levelling off
$\bar{t}_{same,\theta_i}^{wl}$	Average sojourn time (hours) of an aircraft at a wrong, same direction, flight level of a route intersecting another route at an angle θ_i after incorrectly levelling off

Table 3.2 Definition of additional parameters of the vertical collision risk model of eqs. (3.15) - (3.19)

Each of the three collision risk models of eqs. (3.1), (3.8) and (3.15) 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 net is not allowed to be accounted for in collision risk assessment (Ref. 14).

Total vertical collision risk

The total vertical collision risk due to all causes under AFI RVSM is the sum of the three risk components $N_{az}^{non-whl}$, $N_{az}^{cl/d}$, and N_{az}^{wl} given by eqs. (3.1), (3.8), and (3.15) plus the technical vertical collision risk given by eq. (2.25), i.e.

$$N_{az}^{total} = N_{az}^{non-whl} + N_{az}^{cl/d} + N_{az}^{wl} + N_{az} \tag{3.20}$$

3.3 INCIDENT DATA

3.3.1 INTRODUCTION

This subsection examines the data that were available for the assessment of the total vertical collision risk in the first year of AF RVSM operations from 25 September 2008 to 30 September 2009 inclusive. Data collected by ARMA from States in the monthly forms will be presented first, i.e. Form 1, large height deviations, and Form 3, other operational considerations. Following that, some data from the AFI ATS Incident Analysis Working Group (AIAG) will be presented and analysed. The AIAG data, supplemented with some data from ARMA Form 1, will be used for the current assessment of the total vertical collision risk under AFI RVSM.

An important issue with regard to the 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.

As regards the type of data, data on the occurrence frequency of each type of cause is needed in the first place. 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 deviations are needed.

3.3.2 ARMA FORM 1 – LARGE HEIGHT DEVIATIONS

Recall that Form 1 is to be used for the reporting of **all** height deviations of 300 ft or more on the basis of conclusion 3/4 of the RVSM/RNAV/RNP/TF/3 meeting (Ref. 15). Where applicable, this data should be collected by radar (conclusion 3/13 of the same meeting) and otherwise by the institution of suitable procedures for reporting data, incidents and conditions necessary for the vertical collision risk assessment.

Table 3.3 summarises the height deviations reported to ARMA in Form 1 over the period of time from 25 September 2008 to 30 September 2009 inclusive. Notice first that eight out of the thirty FIR/UIRs did not provide any information in Form 1. Three more FIR/UIRs did not provide any information for the pertinent months in 2009.

One FIR/UIR reported nil deviations for every month and ten FIR/UIRs reported nil deviations for some months whilst not providing any information for the remaining months. The remaining eleven FIR/UIRs reported a total of 36 height deviations, approximately half of which (17) were reported by Johannesburg. Compared with the last pre-implementation CRA (CRA 3, Ref. 6), the number of FIR/UIRs actually reporting one or more deviations in ARMA Form 1 has increased from 4 to 11 and the number of reported deviations increased approximately in proportion from 13 to 36.

With reference to the table, it is hypothesized that there continues to be a serious problem of under-reporting in ARMA Form 1. In addition to the 27% non-reporting FIR/UIRs, the large number of nil height deviations does not appear to be consistent with the number of pilot reported incidents in the AIAG data set to be presented in section 3.3.4. The latter data set will be used as an additional source of data on incidents/large height deviations in the AFI Region and, in fact, it may be seen as the main data source for the assessment of the total vertical risk under AFI RVSM.

It should be remarked that the September 08 – November 08 entries in table 3.3 for the Seychelles and Windhoek FIR/UIRs show "no information provided", though the ARMA Form 1 reports stated "No height deviation". The particular classification was used since the pertinent Forms 1 referred to the months September – November of the

FIR/UIR	Sep 08	Oct 08	Nov 08	Dec 08	Jan 09	Feb 09	Mar 09	Apr 09	May 09	Jun 09	Jul 09	Aug 09	Sep 09	Total
Accra	-	-	-	-	-	1	-	-	-	-	-	-	-	1
Addis Ababa	0	0	0	0	-	-	-	-	-	-	-	-	-	-
Algiers	0	0	0	0	0	0	0	0	0	-	0	0	0	-
Antananarivo	0	-	-	-	-	-	-	-	-	-	-	-	-	-
Asmara	-	-	-	-	0	0	0	0	0	0	-	-	-	-
Beira	0	0	0	0	-	1	1	-	-	-	-	-	-	2
Brazzaville	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cape Town	0	0	0	0	-	-	1	-	4	-	-	-	-	5
Dakar	-	-	0	0	0	0	0	-	-	0	-	-	-	-
Dar Es Salaam	0	0	0	0	-	-	-	-	-	-	-	-	-	-
Entebbe	0	0	0	0	0	0	0	0	0	0	0	-	-	-
Gaborone	-	0	-	-	0	0	1	0	0	0	0	0	0	1
Harare	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Johannesburg	0	1	1	0	1	4	3	2	4	1	-	-	-	17
Johannesburg Oceanic	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kano	0	0	0	0	0	0	0	-	-	-	-	-	-	-
Khartoum	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kinshasa	-	-	-	-	-	-	-	1	-	-	-	-	-	1
Lilongwe	-	-	-	-	-	-	1	-	-	-	-	-	-	1
Luanda	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lusaka	-	-	-	-	-	-	1	-	-	-	-	-	-	1
Mauritius	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mogadishu	0	0	0	0	0	0	0	0	0	0	0	0	-	-
Nairobi	-	-	-	2	1	-	-	-	-	-	-	-	-	3
Niamey	-	-	-	-	-	-	-	-	-	-	-	-	-	-
N'Djamena	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Roberts	0	0	0	0	0	0	0	0	-	-	-	-	-	-
Seychelles	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tripoli	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Windhoek	-	-	-	0	1	-	-	2	-	-	-	-	-	3

Table 3.3 Summary of large height deviations reported in ARMA Form 1 by 30 participating FIR/UIRs

year 2007 rather than 2008[3]. It should also be remarked that the five months with “zero” height deviations for Dakar pertain to the Nouakchott ACC of Mauritania only. The 36 height deviations reported in Form 1 are briefly described below, followed by a summary in table 3.4.

Accra

The height deviation reported by Accra is also included in the AIAG data set (UCR 26: 1275 AIRPROX, ARMA Ref 13) and is included in the CRA accordingly.

Beira

Both reports were not simultaneously included in the AIAG data set. One height deviation was due to an error in ATCU co-ordination. The report provides insufficient information for the event to be included in the CRA. However, the event should be duly noted with a view to risk reduction, i.e. prevention of future occurrences. The report on the other height deviation is ambiguous about convergence in the horizontal plane or the vertical plane. If it were the latter, the height deviation might be classified as an incorrect (opposite direction) flight level crossing (CO, see section 3.3.4). Due to the ambiguity, and some apparent ATC involvement (radar), the event has not been included in the CRA.

Cape Town

None of the five reports were included in the AIAG data set. One report concerned an aircraft being no longer RVSM capable. The flight crew and ATC took appropriate action and the event is considered no-risk bearing and is not included in the CRA. The other four reports concern two formation flights, each formation made up of two aircraft. Formation flights are not allowed in AFI RVSM airspace. The events will not be included in the CRA since no details about the formation flights are available such as RVSM approval status or vertical offset, if any, between the aircraft. However, the events should be duly noted for risk reduction, i.e. preventing the recurrence of formation flights in AFI RVSM airspace in the future.

Gaborone

The report, not simultaneously included in the AIAG data set, concerns a State aircraft without RVSM approval. Non-RVSM approved State aircraft are allowed in RVSM airspace but need to be provided with 2000 ft vertical separation from

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[3] Subsequent information from ARMA confirmed that the correct year should have been 2008. The table 3.3 classification has been maintained to preserve the consistency between the data sources (Ref. 16 and 17) and the AFI RVSM POSC CRA report.

other aircraft. It is not clear from the report whether, or not, the proper vertical separation minimum was applied. However, the report does state that the aircraft, according tot he semi-circular rule, flew at an incorrect RVSM flight level for 12 minutes. This part of the height deviation report will be included in the CRA.

Harare

The report, not included in the AIAG data set, concerns an aircraft without RVSM approval flying in RVSM airspace at FL290. The report does not provide any details of the duration of this flying which makes it impossible to include the event in the CRA. As before, the report should be duly noted for risk reduction/prevention purposes.

Johannesburg

A total of 17 height deviations were reported for Johannesburg. Although some of these deviations will, for a variety of reasons, not be included in the CRA, they should nonetheless be duly noted for the benefit of risk reduction/prevention.

The first height deviation report in Form 1 for Johannesburg (October 2008) concerned a 300 ft height deviation for an aircraft reporting a faulty altimeter and hence unable RVSM. The aircraft was subsequently re-cleared to FL280. Since a 300 ft deviation is on the verge of typical/atypical performance and because of the appropriate re-clearance, the event will not be included in the CRA. The second height deviation reported in Form 1 (November 2008) concerned an aircraft observed deviating from its assigned flight level on two occasions and requested to adjust to assigned level. Since neither the duration nor the magnitude of the height deviations are included in the report, it is not possible to include the event in the CRA. The third height deviation (January 2009) concerned a case of an aircraft pressurisation problem. The problem was handled by the flight crew and ATC according to the prevailing procedures. Consequently, the event does not need to be included in the CRA.

Four events were reported for Johannesburg in February 2009. Two of these concerned aircraft pressurisation problems similar to the one above. One report seems to concern a flight plan request for FL350 from an unqualified flight crew/aircraft. The report suggests that the aircraft climbed to FL280 only, i.e. did not enter into AFI RVSM airspace. These three events, therefore, do not need to be included in the CRA. The remaining report involves a descent from FL410 to

FL371 with no descent clearance issued, followed by a descent to FL250 under ATC control. The first part of this event will be included in the CRA.

Three height deviation reports are available for Johannesburg in March 2009. However, two reports appear to be identical and concern an aircraft reporting unable to comply with RVSM and requesting descent. ATC descended the flight to FL280 and the event does not need to be accounted for in the CRA. The third report concerns a non-RVSM approved aircraft observed flying in AFI RVSM airspace. In fact, the aircraft involved is the same one discussed above for Harare! Since (again) the report does not provide any details of the duration of the event, it is impossible to include it in the CRA. It should be clear, however, that the report should be duly noted for risk reduction/prevention purposes.

ARMA Form 1 lists two height deviations for Johannesburg in April 2009. One report concerns a lateral deviation from track rather than a vertical deviation from assigned flight level. The other report appears to be missing[4].

ARMA Form 1 lists four height deviations for Johannesburg in May 2009. One report concerns a non-RVSM approved aircraft operating in AFI RVSM airspace. Since the report does not provide any details of the event, it cannot be included in the CRA. The other three reports appear to be missing[5].

One height deviation report is available for Johannesburg in June 2009. It concerns another case of a non-RVSM approved aircraft operating in AFI RVSM airspace. Due to missing details, it is again not possible to include the event in the CRA.

Kinshasa

The height deviation reported by Kinshasa is simultaneously included in the AIAG data set (UCR 43: 1292 AIRPROX). However, the AIAG data set review (section 3.3.4) classified the event as a horizontal (H) event and the event will thus not be included in the CRA.

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[4] Subsequent information from ARMA confirmed that the correct number of reports was 1 for April 2009 as well as 1 for May 2009. Report text has been maintained to preserve the consistency between the data sources (Ref. 16 and 17) and the AFI RVSM POSC CRA report.

Lilongwe

The height deviation reported by Lilongwe is simultaneously included in the AIAG data set (UCR 41: 1290 AIRPROX, ARMA Ref 19) and is included in the CRA accordingly.

Lusaka

The report concerns a non-RVSM approved aircraft observed flying in AFI RVSM airspace. In fact, the aircraft involved is the same one discussed above for Harare and Johannesburg, i.e. the **third** report on a single aircraft, all on the same day with two reports on the same flight! Since (again) the report does not provide any details of the duration of the event, it is impossible to include it in the CRA.

Nairobi

A total of 3 height deviations were reported for Nairobi. Two large height deviations occurred in December 2008 and were reported to be due to turbulence and resulted in deviations of the whole numbers of flight levels type (WS, see section 3.3.4). Both reports include the magnitude of the deviation and one report includes the duration of the large height deviation. Both events will be included in the CRA where the unknown duration of one event will be assumed to be the same as the known duration of the other. The third report talks about “conflicting traffic” only, without any further details. It must be concluded, therefore, that it is not possible to include the event concerned in the CRA.

Windhoek

A total of 3 height deviations were reported for Windhoek. The January 2009 height deviation report talks about an aircraft entering the Johannesburg FIR at an incorrect semi-circular flight level with a total height deviation of 1000 ft. Although the report is ambiguous by listing FL370 as the assigned flight level as well as the observed flight level, the event will be included in the CRA as a large height deviation of the wrong flight level opposite direction type (WO, see section 3.3.4). The other two reports concern non-RVSM approved aircraft operating in AFI RVSM airspace. Due to missing details, it is again not possible to include these two events in the CRA.

Table 3.4 summarises which of the 36 height deviations reported in Form 1 have been included in the post-implementation CRA and which ones have not been included. Although some height deviations will not be used for risk estimation, their reporting continues to be very important with regard to risk mitigation, i.e. preventing their recurrence in future.

Height deviations reported in ARMA Form 1 and included in CRA			
FIR/UIR	**Date**	**Type**	**Description/comment**
Accra	February 2009	CO	See AIAG analysis
Gaborone	March 2009	WO	Unapproved State aircraft
Johannesburg	February 2009	CS	
Lilongwe	March 2009	CS	See AIAG analysis
Nairobi	December 2008	WS	Due to turbulence
Nairobi	December 2008	WS	Due to Turbulence
Windhoek	January 2009	WO	

Height deviations reported in ARMA Form 1 and NOT included in CRA		
FIR/UIR	**Date**	**Rationale for non-inclusion**
Beira	February 2009	Insufficient information
Beira	March 2009	Ambiguous information and some positive ATC involvement
Cape Town	March 2009	Altimetry problem, correct procedures followed
Cape Town (2)	May 2009	Formation flight, insufficient information
Cape Town (2)	May 2009	Formation flight, insufficient information
Harare	March 2009	Non-RVSM approved aircraft
Johannesburg	October 2008	Altimetry problem, correct procedures followed
Johannesburg	November 2008	Insufficient information, under radar control (?)
Johannesburg	January 2009	Pressurisation problem, correct procedures followed
Johannesburg	February 2009	Pressurisation problem, correct procedures followed
Johannesburg	February 2009	FL280
Johannesburg	February 2009	Pressurisation problem, correct procedures followed
Johannesburg	March 2009	Pressurisation problem, correct procedures followed

Johannesburg	March 2009	Duplicate report of previous one
Johannesburg	March 2009	Non-RVSM approved aircraft
Johannesburg	April 2009	Horizontal problem
Johannesburg	April 2009	Form 1 missing?
Johannesburg	May 2009	Non-RVSM approved aircraft
Johannesburg	May 2009	Form 1 missing
Johannesburg	May 2009	Form 1 missing
Johannesburg	May 2009	Form 1 missing
Johannesburg	June 2009	Non-RVSM approved aircraft
Kinshasa	April 2009	Horizontal event, see AIAG analysis
Lusaka	March 2009	Non-RVSM approved aircraft
Nairobi	January 2009	Insufficient information
Windhoek	April 2009	Non-RVSM approved aircraft
Windhoek	April 2009	Non-RVSM approved aircraft

Table 3.4 Treatment of 36 height deviations reported in ARMA Form 1 for AFI RVSM post-implementation CRA

3.3.3 ARMA FORM 3 – OTHER OPERATIONAL CONSIDERATIONS

Table 3.5 summarises “other operational considerations” as reported to ARMA in Form 3. Although ARMA Form 3 contains fields for four specific operating conditions, it should also be used in case of any other operational circumstances that might have an impact upon the safety of RVSM operations in the AFI Region. The four specific conditions are:

- Coordination failures;
- Communication failures;
- Turbulence; and
- ACAS events.

The entries in table 3.5 have been coded with regard to these four conditions as follows. The general form of an entry is “abcd” where “a” denotes the <u>number</u> of coordination failures, “b” denotes the <u>number</u> of communication failures, “c” denotes the <u>number</u> of turbulence event reports, and “d” denotes the <u>number</u> of ACAS event reports. (The duration of communication failures and turbulence events is also to be provided in ARMA Form 3, but this information has not been included in table 3.5.) When any number of event reports is larger than 9, it is enclosed between dots, e.g. “.10.”. A single value of “0” rather than “0000” is used when all the four conditions have zero reports. A dash, “-“, is used when information on a specific condition is missing. In addition, a single dash "-" rather than "----" is used when all information on the four conditions is missing.

Consider, for example, the month of January 2009. The entry 0.87.-- for Algiers represents 0 coordination failures, 87 communication failures, and no information about turbulence or ACAS events. The entry .19.11.60 for Kano represents 19 coordination failures, 11 communication failures, 6 turbulence event reports, and 0 ACAS event reports. As a final example, the entry 30.21.0 for Nairobi represents 3 coordination failures, 0 communication failures, 21 turbulence event reports, and 0 ACAS event reports.

A comparison between table 3.3 and table 3.5 shows that FIR/UIRs that provided little or no response in ARMA Form 1 provided also little response in ARMA Form 3.

It should be remarked that the September 08 – December 08 entries in table 3.5 for Windhoek show "no information provided", though the Form 3 reports stated "0 events". The particular classification was used since the pertinent Forms 3 referred to the months September – December of the year 2007 rather than 2008. It should also be remarked that the six months for which information was available for Dakar pertain to the Nouakchott ACC of Mauritania only. Cf. similar remarks on table 3.3.

Larger numbers of coordination errors have been reported by Dakar, Johannesburg, and, particularly, Kano over several months, and to a lesser extent by Nairobi. Notice that the entries for Kano may suggest some correlation between communication failures and coordination errors.

In a similar manner as for the pre-implementation CRAs, Algiers has provided quite detailed information about communication failures. Other FIR/UIRs that have reported relatively large numbers of communication failures are Dakar, Kano, Luanda (September 2008), and Mogadishu. Nairobi reported the largest number of turbulence events in a single month, viz. 21. Turbulence was also reported by Cape Town, Harare, Kano, Mauritius, and Mogadishu. The full impact of the communication failures and turbulence events depends, of course, on both the number and duration/severity of the events. Notice that not any ACAS events have been reported in ARMA Form 3.

FIR/UIR	Sep 08	Oct 08	Nov 08	Dec 08	Jan 09	Feb 09	Mar 09	Apr 09	May 09	Jun 09	Jul 09	Aug 09	Sep 09
Accra	-	-	-	-	-	-	-	-	-	-	-	-	-
Addis Ababa	-	-	-	-	-	-	-	-	-	-	-	-	-
Algiers	1.121.--	3.202.--	0.97.--	0.98.--	0.87.--	0.72.--	1.110.--	0.105.--	0.94.--	-	0.65.--	0.44.--	-
Antananarivo	-	-	-	-	-	-	-	-	-	-	-	-	-
Asmara	-	-	-	-	0	0	0	0	0	0	-	-	-
Beira	-	-	-	-	-	-	-	-	-	-	-	-	-
Brazzaville	-	-	-	-	-	-	-	-	-	-	-	-	-
Cape Town	0001	000-	0061	0080	-	-	-	-	-	-	-	-	-
Dakar	-	-	.10.000	.10.000	.11.800	.10.000	2800	-	-	6200	-	-	-
Dar Es Salaam	1200	1200	0100	1200	-	-	-	-	-	-	-	-	-
Entebbe	-0-0	-000	-0-0	-0-0	-0-0	-000	-000	-000	-000	-000	-000	-	-
Gaborone	-	0	-	-	0	0	0	0	0	0	0	0	0
Harare	0020	00-0	0010	0	0	0	0	0	0	0010	0040	0	0
Johannesburg	3000	.11.000	5000	2000	8000	4000	1000	2000	-	-	-	-	-
J'burg Oceanic	-	-	-	-	-	-	-	-	-	-	-	-	-
Kano	.15.920	.15.810	.11.610	4220	.19.11.60	.16.820	.19.12.30	-	-	-	-	-	-
Khartoum	-	-	-	-	-	-	-	-	-	-	-	-	-
Kinshasa	-	-	-	10--	-2--	-4--	-	-	-	-	-	-	-
Lilongwe	-	-	-	-	-	-	-	-	-	-	-	-	-
Luanda	0.10.00	-	-	-	-	-	-	-	-	-	-	-	-
Lusaka	-	-	-	-	-	-	-	-	-	-	-	-	-
Mauritius	0	0300	0	0	0	0	0	1400	1100	0	1000	1220	0010
Mogadishu	0100	0120	0	0200	0600	0400	0800	0700	0200	0700	4410	0300	1100
Nairobi	-	-	-	--20	30.21.0	0020	0	0	1030	3000	-	-	-
Niamey	-	-	-	-	-	-	-	-	-	-	-	-	-
N'Djamena	-	-	-	-	-	-	-	-	-	-	-	-	-
Roberts	0	0	0	0	0	0	0	0	-	-	-	-	-
Seychelles	0	0	0	-	-	-	0100	-	-	-	-	-	-
Tripoli	-	-	-	-	-	-	-	-	-	-	-	-	-
Windhoek	0	0	0	0	-	-	-	-	-	-	-	-	-

Table 3.5 Summary of other operational considerations reported in ARMA Form 3 for the period of time from September 2008 to 30 September 2009 inclusive

The information in Form 3 as summarised in table 3.5 is not directly taken into account into the collision risk estimation process for CRA 3. Currently, its main role is to gain a better insight into the actual operating conditions in the AFI Region.

3.3.4 AFI ATS Incident Analysis Working Group (AIAG) data

AIRPROX reports for the years 2008 and 2009 have been made available by ARMA and IATA (Refs. 16 and 17). The reports concerned various phases of flight and types of airspace. The 2008 reports were numbered from 1100 – 1213[5]. The data prior to the implementation of RVSM in the AFI Region on 25 September 2008 have not been utilized. The first event report listing a date of occurrence after the start of RVSM operations in the AFI Region (28 September 2008) carried sequence number 1175. Thus, event reports 1175 – 1213 have been considered for the benefit of the post-implementation CRA. One empty report was included in the series of 39 reports and eight reports in this series with an occurrence date prior to 25 September 2008 have been excluded from further processing, leaving a number of 30 reports for 2008.

The numbering of the 2009 AIRPROX reports may be subdivided into two parts. The first series of reports were consecutively numbered from 2/1250 to 62/1311 (number 1/1249 was missing). The occurrence date of the 2/1250 report was 6 January 2009 (first date in the first part) and the occurrence date of the 62/1311 report was 23 June 2009 (last date in the first part). There were no late 2008 reports included in this series. The second series of reports were numbered from 65/65 ATS to 315 and contained many gaps. The reason for the gaps is not known. The actual number of reports contained in this series was 37. The occurrence date of the 65/65 ATS AIRPROX report event was 23 June 2009 and the occurrence date of the 315 AIRPROX report event was 19 February 2009. The first and last occurrence dates in this series were 16 January and 29 September respectively. Some reports concerning events that occurred during the period of time 1 January 2009 – 30 September might still be missing, but there is no clear evidence of this.

The total number of AIRPROX reports thus amounts 30+62+37=129. Out of these 129 reports, a total of 59 reports pertained to events that occurred outside of the FL290 – FL410 band, leaving 70 events for further processing. (The corresponding numbers for the last pre-implementation CRA were 95, 48, and 47.)

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[5] The numbering is not necessarily chronological.

The available AIRPROX reports concerning vertical events will be seen not to cover all the FIR/UIRs in the AFI Region (see section 3.4, table 3.9), and **there is some concern as to the completeness and representation of the operational incident data.**

In a similar manner as for the pre-implementation CRAs, the AIRPROX reports have been classified into one of the categories shown in table 3.6. The first six categories concern “vertical events” of the “whole numbers of flight levels” type (cf. section 3.2). The “crossing through FL” category should be self-explanatory. For the “wrong FL” category, the incorrectness of the flight level was inferred from the AIRPROX report and the applicable cruising levels. The next vertical category covers all Large Height Deviations (LHDs) of the “non-whole numbers of flight levels” type where “X” represents the magnitude of the deviation.

Event type	Event Code
Crossing through FL, opposite direction	CO
Crossing through FL, same direction	CS
Crossing through FL, intersecting routes	CC
Wrong FL, opposite direction	WO
Wrong FL, intersecting (crossing) routes	WC
Wrong FL, same direction	WS
Large Height Deviation of X ft	X ft
Horizontal (intersecting routes)	H
orizontal (same route, following another a/c)	H(SFL)

Table 3.6 Event types and coding

There are two “horizontal categories”. The first category, coded H, concerns aircraft at the same flight level of intersecting routes. When the flight directions were in conformity with the applicable cruising levels, it was assumed that the aircraft were to be horizontally separated at the intersection unless the AIRPROX report indicated that the aircraft had actually been intended to be vertically separated at the intersection (in which case the classification WC was applied). The second horizontal category, coded H(SFL), concerns pairs of in-trail aircraft on the same flight path where the actual longitudinal separation was less than the applicable longitudinal separation minimum.

Table 3.7 provides the results of the classification applied to the 70 AIRPROX reports ultimately analysed, namely 41 vertical events, 20 horizontal events, 5 no error/risk events, and 4 TCAS nuisance alerts. This shows a considerable <u>increase</u> in the <u>number</u> of <u>vertical</u> events compared with that for the last pre-implementation CRA 3, for which there were 13 vertical reports and 34 horizontal reports.

Table 3.7 also lists some additional information from the event reports. All information in the table other than “Event Code” is a straight copy of the information provided in the pertinent fields in the AIRPROX report forms. Notice the different format used in the 2008 and 2009 reports.

Reference		Event Code	Phase of flight	Type of airspace	IFBP use	ACAS
	1175	CS	Cruise	FIR	Unkn	Unkn
	1183	CS	Cruise	FIR	½	Unkn
	1188	400ft	Cruise	FIR	Yes	RA
	1191	H	Cruise	FIR	Yes	Unkn
	1192	No vertical risk				
	1193	CO	Cruise	FIR	½	RA
	1195	CO	Climb	FIR	YES	YES
	1196	CC	Cruise	FIR	Unkn	RA
	1198	TCAS nuisance	Descent	FIR	Unkn	TA
	1199	CO	Cruise	CTR	Yes	Yes
	1200	WO	Cruise	FIR	Yes	Yes
	1201	CC	Cruise	FIR	Yes	Yes
	1203	H	-	-	-	-
	1204	CO	-	-	-	-
	1212	WC	Cruise	FIR	Unkn	-
					Location Summary	
2	1250	no error	En-route and cruise		Niamey FIR	
3	1251	CS	En-route and cruise		Seychelles FIR	
4	1252	CS	En-route and cruise		Dakar FIR	
5	1253	H	En-route and cruise		Niamey FIR	
6	1254	H	-		Ndjamena FIR	
7	1255	no error			Ndjamena FIR	
9	1257	CO	En-route and cruise		Addis Ababa FIR	
11	1259	CO	en-route and climb to cruisi		Luanda FIR	
12	1260	H	En-route and cruise		Adena FIR	
16	1264	H			Luanda FIR	
18	1266	WO	en-route and cr		Nairobi FIR	
20	1268	CO	en-route and climb to cruising		Accra FIR	
21	1269	TCAS nuisance			Nairobi FIR	
22	1271	CS	En-route and cruise		Brazzaville FIR	
24	1273	CO			Beira FIR	
26	1275	CO	-		Accra FIR	
27	1276	CC	-		Brazzaville FIR	
28	1277	H	En-route and cruise		Kinshasa FIR	

29	1278	H	-	Kinshasa FIR
30	1279	WC		Nairobi FIR
33	1282	H	en-route and climb to cruisi	Entebbe FIR
34	1283	CC	en-route and climb to crui	Tripolis FIR
39	1288	CO	en-route and climb to cru	Nairobi FIR
40	1289	TCAS nuisance	En-route and norma descent	Dakar FIR
41	1290	CS	approach and initial ap	Lilongwe FIR
43	1292	H	En-route and cruise	Kinshasa FIR
47	1296	TCAS nuisance	en-route and change of	Brazzaville FIR
48	1297	H	En-route and cruise	Kinshasa FIR
52	1301	CO	-	Kano FIR
54	1303	CS	Take-off and initial climb	Niamey FIR
55	1304	H	-	Khartoum FIR
57	1306	H	En-route and cruise	Nairobi FIR
58	1307	CO	En-route and cruise	Brazzaville FIR
65	65 ATS	CS	En-route and cruise	Gaborone FIR
68	68 ATS	H	En-route and cruise	Ndjamena FIR
78		WS	en-route and climb to cruis	Dar Es Salaam FIR
80		CS	en-route and climb to cruising	Ndjamena FIR
101		CS	take-off and climb into traffic	Brazzaville FIR
120		no error		Beira FIR
151		H(SFL)	En-route and cruise	Kinshasa FIR
162		H	En-route and cruise	Kano FIR
183		CS		Seychelles FIR
186		CO	take-off and climb into traffic p	Nairobi FIR
207		WC	-	Addis Ababa FIR
208		CS	En-route and cruise	Khartoum FIR
209		WO	En-route and cruise	Niamey FIR
219		CO	en-route and change of cruise lev	Tripolis FIR
223		CO	En-route and cruise	Luanda FIR
225		CO	En-route and cruise	Ndjamena FIR
234		H	-	Kinshasa FIR
272		CS	-	Kinshasa FIR
281		H		Dar Es Salaam FIR
287		H	En-route and cruise	Kano FIR
311		H	En-route and cruise	Kano FIR
315		no error	-	Kinshasa FIR

Table 3.7 Some details of the 70 AIRPROX reports for the FL290 - FL410 band

It should be remarked that there may be various reasons for classifying an event reported in an AIRPROX report as “no error”, “no vertical risk”, or “TCAS nuisance event”. An example of the “no error” classification is an AIRPROX report in which it was stated that the minimum vertical separation was 2000 ft with a horizontal separation of approximately 30 NM. An example of the “no vertical risk” classification is an AIRPROX report stating that ATC requested to reduce the aircraft’s rate of climb due to traffic crossing over at 6000 ft vertical separation. “TCAS nuisance events” generally refer to resolution advisories concerning adjustments of vertical speed without a particular (large) height deviation.

Consider now the vertical events in some more detail. Recall from section 3.1 that two types of large height deviations involving whole numbers of flight levels are distinguished, namely aircraft climbing/descending incorrectly through another aircraft’s flight level and aircraft levelling off at an incorrect flight level. Table 3.8 shows in the second column that 33 out of the 41 vertical events are of the improper flight level crossing type, where 16 events involved aircraft flying in opposite directions (CO), 13 events involved aircraft flying in the same direction (CS), and 4 events involved aircraft on intersecting (crossing) routes (CC). Seven AIRPROX reports involved aircraft flying at a wrong flight level, with 3 aircraft flying in the opposite direction (WO), 1 in the same direction (WS) and 3 at a wrong level of a pair of intersecting (crossing) routes (WC). Finally, there was 1 LHD of 400 ft.

An AIRPROX report of the incorrect flight level crossing type (CO, CS, or CC) may involve the crossing of more than a single flight level and, hence, multiple exposure of other aircraft to the risk of a collision. For example, when an aircraft would incorrectly change level from FL290 to FL370, it would traverse three intermediate same-direction levels and four opposite-direction levels. Therefore, the number of flight levels crossed needs to be determined for each AIRPROX report of this type. It should be remarked that an exact determination may not always be possible, e.g. when information is not included in the AIRPROX report on both the initial and final flight levels of the climbing/descending aircraft. Some reasonable judgement will then have to be applied.

Table 3.8 shows the different numbers of flight levels crossed, together with the additionally required information for the collision risk model, i.e. climb/descent rate of the aircraft during the event and the relative heading between the aircraft tracks. (The wrong flight level type of events and the LHD have also been included for completeness but, obviously, without numbers of flight levels crossed.) Unfortunately, not any information on climb/descent rates was available in the AIRPROX reports and default values will therefore have to be used. Notice that 2 of the CO type events involved a major level change for the climbing/descending aircraft inside AFI RVSM airspace. Most of the CS type events have several same and opposite direction flight levels listed. Event 1183 concerns an aircraft traversing completely through AFI RVSM airspace to FL450. There are also two cases of an aircraft descending out of AFI RVSM airspace from, say, FL360 and two cases of aircraft entering into AFI RVSM airspace with a clearance for, say, FL360. Finally, the CC type of event 1196 also concerns a descent out of AFI RVSM airspace from FL390.

Reference		AIRPROX report event code	Number of FLs crossed for CRA			Aircraft type; climb/descent rate (kts)	Crossing angle
			Same	Opposite	Crossing		
	1193	CO	0	1	-	Unkn	180°
	1195	CO	0	1	-	Unkn	180°
	1199	CO	0	1	-	Unkn	180°
	1204	CO	0	1	-	Unkn	180°
9	1257	CO	0	1	-	A310/Unkn	180°
11	1259	CO	0	1	-	Unkn	180°
20	1268	CO	4	5	-	Unkn	180°
24	1273	CO	0	1	-	Unkn	180°
26	1275	CO	0	1	-	A310/Unkn	180°
39	1288	CO	0	1	-	Unkn	180°
52	1301	CO	4	5	-	Unkn	180°
58	1307	CO	0	1	-	Unkn	180°
186		CO	0	1	-	A340/Unkn	180°
219		CO	1	2	-	Unkn	180°
223		CO	0	1	-	Unkn	180°
225		CO	0	0	-	Unkn	180°
	1175	CS	3	3	-	Unkn	0°
	1183	CS	7	6	-	Learjet 45/Unkn	0°
3	1251	CS	1	2	-	Unkn	0°
4	1252	CS	1	2	-	Unkn	0°
22	1271	CS	2	3	-	Falcon 900/Unkn	0°
41	1290	CS	4	4	-	Unkn	0°
54	1303	CS	1	1	-	Unkn	0°
65	65 ATS	CS	1	1	-	Unkn	0°
80		CS	1	1	-	Unkn	0°
101		CS	3	4	-	Unkn	0°
183		CS	1	1	-	B772/Unkn	0°
208		CS	3	3	-	Unkn	0°
272		CS	1	1	-	Unkn	0°

	1196	CC	-	-	10	Unkn	Unkn
	1201	CC	-	-	1	Unkn	153°
27	1276	CC	-	-	3	Unkn	150°
34	1283	CC	-	-	1	Unkn	105°
	1200	WO	-	-	-	Unkn	180°
18	1266	WO	-	-	-	Unkn	180°
209		WO	-	-	-	Unkn	180°
78		WS	-	-	-	A332/Unkn	0°
	1212	WC	-	-	-	Unkn	37°
30	1279	WC	-	-	-	Unkn	111°
207		WC	-	-	-	Unkn	128°
	1188	400 ft	-	-	-	Unkn	180°

Table 3.8 Some further details of the 41 vertical AIRPROX reports

3.4 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 for the period of time over which the incident reports (both ARMA Form 1 and AIAG data) were generated is needed. In principle, this estimate can be obtained from the flight hours in the FIR/UIRs concerned by means of the information as collected in ARMA Form 2 and Form 4 for the period 25 September 2008 – 30 September 2009. However, as mentioned in section 2.4.2 on data limitations, the required information was not provided by a significant number of FIR/UIRs.

Recall from sections 3.3.2 (table 3.4) and 3.3.4 (table 3.8) respectively that 7 height deviations reported in ARMA Form 1 and 41 height deviations reported in the AIAG data set will be included in the post-implementation assessment of the total vertical collision risk under AFI RVSM. Since 2 events were jointly included in both data sets, the ultimate number of events to be utilized amounts 46. Table 3.9 lists the 23 FIR/UIRs in which the reported height deviations occurred, together with some additional information. As can be seen in the fourth and fifth columns of the table, not any (useable) 2008 – 2009 flight hour information was provided in Form 2 or Form 4 for 12 out of the 23 FIR/UIRs, namely: Accra, Brazzaville, Cape Town, Johannesburg, Khartoum, Kinshasa, Luanda, N'Djamena, Niamey, Sal Oceanic, Seychelles, and Tripoli. Where possible, additional information has been used as described below. All estimates in table 3.9 have been obtained from pertinent annual flight hour estimates, corrected by a factor of 371/365 (i.e. approximately 1.6%) to cover the full period of time from 25 September 2008 – 30 September 2009. See also table 3.10.

See FIR/UIR	Vertical AIAG AIRPROX reports	ARMA Form 1 LHDs	Estimated number of flight hours for time period 25 September 2008 – 30 September 2009			
			ARMA Form 4 2008 - 2009	ARMA Form 2 2008 - 2009	Other estimate	Source of other estimate
Accra	2	1 (1) *	-	-	71035	ARMA Form 4, 2005 – 2006
Addis Abbaba	2	-	17697	-		
Beira	2	2 (0)	22303	-		
Brazzaville	7	-	-	-	21035	ARMA Form 4, 2006
Cape Town &	-	5 (0)	-	-	369072	ARMA
Johannesburg	-	17 (1)				
Dakar	3	-	-	49978		
Dar Es Salaam	1	-	26914			
Gaborone	1	1 (1)	19398			
Harare		1 (0)		22724		
Kano	2	-	11013			
Khartoum	3	-	-	-	≥11845	Lower bound from CRA 3 (Ref. 6)
Kinshasa	3	1 (0)	-	-	35489	ARMA Form 4, 2007
Lilongwe	1	1 (1)	2002			
Luanda	4	-	-	-	27859	ARMA Form 2, 2006 (Ref. 5)
Lusaka	-	1 (0)	10702			
Nairobi	6	3 (2)	46424			
N’Djamena	3	-	-	-	29004	ARMA Form 4, 2006 (Ref. 5)
Niamey	4	-	-	-	28180	ARMA Form 2, 2004 – 2005 (Ref. 4)
Sal Oceanic	1		-	-		
Seychelles	2		-	-	13702	ARMA Form 4, 2005 (Ref.5)
Tripoli	3		-	-	≥ 8920	Lower bound from CRA 3 (Ref. 6)
Windhoek	-	3 (1)	7410			

Table 3.9 Estimated numbers of flight hours for FIR/UIRs with vertical incidents listed in table 3.4 and 3.8 for the period 25 September 2008 – 30 September 2009

Remark *: Numbers in brackets refer to numbers of LHDs actually included in CRA

For the **Accra** FIR, not any information was provided in either Form 4 or Form 2 for the years 2008 – 2009 (or 2007). However, the Accra 2006 Form 4, though not useable for the passing frequency calculations at the time, did provide information about the number of movements in the RVSM flight level band for the months of July 2005 – January 2006 plus July and August 2006. The successive numbers were: 2527, 1584, 1574, 2525, 2521, 2800, 2780, 3015, and 3113. In addition, a single Form 2 was available for June 2005, listing 2520 movements between FL290 and FL410 inclusive and an average time per movement in this level band of 2 hours and 20 minutes. From this information, an annual number of 29951 movements in the RVSM flight level band in the Accra FIR was estimated for the year 2007, producing 69886 flight hours (Ref. 6). This value will be used as the base estimate for the post implementation CRA.

See table 3.9. The value to be used is conservative when it is assumed that some traffic growth may have occurred from 2005 up to and including 2009, since the amount of flying time appears in the denominator of the equations for the probability of vertical overlap, cf. eqs. (3.5), (3.9), and (3.16).

For the **Addis Abbaba** FIR, traffic flow data was provided for 9 months in ARMA Form 4 and no information was provided in ARMA Form 2. The Form 4 data produced an estimate of the number of flight hours for the period October 2008 – September 2009 of 17411 hours. It should be remarked that this value is much lower than the estimate of 43832 hours obtained in CRA 3 from ARMA Form 2 data for the year 2007 (Ref. 6).

For the **Beira** UIR, traffic flow data was provided for 3 months in ARMA Form 4, but no information was provided in ARMA Form 2. The Form 4 data resulted in an estimate of the number of flight hours for the period October 2008 – September 2009 of 21942 hours. This estimate compares well with the CRA 3 estimate of 19074 hours based on ARMA Form 4 data for the year 2007 (Ref. 6).

For the **Brazzaville** UIR, no information was provided in either Form 4 or Form 2 for the years 2008 – 2009, or 2007. Therefore, the same estimate as used for the pre-implementation CRA 2 (Ref. 5) based on ARMA Form 4 2006 data will be used for the current CRA, viz. 20695 hours. This is again conservative in light of traffic growth, if any.

For the **Cape Town** and **Johannesburg** FIRs, not any information was provided in Form 2 or Form 4 for the years 2008 – 2009. Therefore, the ARMA estimate initially provided for the last pre-implementation CRA 3 for the Cape Town and Johannesburg FIRs jointly for the year 2007 and subsequently confirmed for the current CRA has been re-used, i.e. 363103 flight fours in the RVSM flight level band.

For the **Dakar** UIR, data was provided for 6 months in ARMA Form 4 and Form 2. Since the quality of the Form 4 data was very low, only the Form 2 data has been used. This comprised the following numbers of flights in the RVSM band: 2595 (November 2008, converted from 865 flights between 20 and 30 November), 2403 (December 2008), 2206 (January 2009), 2031 (February 2009), 2269 (March 2009), and 2282 (June 2009). The average flight duration in the RVSM flight level band was given as 1 hour and 47 minutes. The resulting flight hour estimate for the period October 2008 – September 2009 amounts 49170 hours. It should be remarked that according to the Form 2 headings, the data pertains to the Nouakchott ACC of Mauritania.

For the **Dar Es Salaam** FIR, data was provided in ARMA Form 4 for 5 months and in ARMA form 2 for 3 months. Based on the ARMA Form 4 data, the flight hour estimate for the period of time October 2008 – September 2009 amounts 26479 hours whereas based on the ARMA Form 2 data the corresponding flight hour estimate amounts 50143 hours. The former value will be used for the current CRA because the Form 4 data is generally believed to be more accurate.

Data was provided for the **Gaborone** FIR for 10 months in both ARMA Form 4 and in ARMA Form 2, with excellent consistency between the numbers of flights in the two forms. Based on the ARMA Form 4 data, the flight hour estimate for the period of time October 2008 – September 2009 amounts 19084. (There was no useable information about the average flight duration in Gaborone RVSM airspace available in Form 2.)

Though no electronic ARMA Form 4 information was available for the **Harare** UIR, the ARMA Form 2 information provided for each month of the period September 2008 – September 2009 was very useful for the estimation of the number of flight hours, viz. 22356 hours.

For the **Kano** FIR, data was provided for 7 months in both ARMA Form 2 and Form 4, with a reasonable to good level of consistency between the numbers of flights reported in the two forms. Based on the ARMA Form 4 data processed, the flight hour estimate for the period of time October 2008 – September 2009 amounts 10835 hours whereas based on the ARMA Form 2 data the corresponding flight hour estimate amounts 12617 hours. The Form-4-based value is approximately 14% smaller than the Form-2-

based value (cf. a 24% difference in CRA 3 (Ref. 6)) and will be used for the CRA because the Form 4 data is generally believed to be more accurate.

Not any information was provided for the **Khartoum** UIR in either ARMA Form 4 or Form 2 for the years 2008-2009. Therefore, the lower bound for the Khartoum flight hours derived in the last pre-implementation CRA 3 (Ref. 6) has been re-used. This lower bound was obtained using the following approach. Using the OAG database for 2007 (Ref. 18), the number of international scheduled flights with either a departure or an arrival airport inside the Khartoum FIR was inferred. For each flight, the most likely flown route was also estimated, together with the distance flown inside the Khartoum FIR. The distances were then converted into flight hours using an average aircraft speed of 463.6 kts (cf. section 2.6.1 of reference 6) and the flight hours added up to obtain a total of 11653 hours for the year 2007. Though no correction was made for climb/descent below FL290, the value of 11653 hours was believed to be a lower bound, since neither over-flights nor non-scheduled flights were included. Domestic flights at and above FL290, if any, were not included either. Since this approach only results in a lower bound for the number of flight hours, no attempt has been made to come up with an update based on OAG data for 2008 or 2009.

For the **Kinshasa** UIR, not any information was provided in ARMA Form 2 or Form 4 for the years 2008 – 2009. However, some ARMA Form 4 data from CRA 3 for four month in 2007 have been able to be used and resulted in an estimate of 34915 hours for the period October 2008 – September 2009. No attempt was made to adjust for traffic growth, if any, over the years 2008 – 2009.

For the **Lilongwe** FIR, traffic flow data was provided for 7 months in ARMA Form 4, but no information was provided in ARMA Form 2. The Form 4 data provided an estimate of the number of flight hours for the period October 2008 – September 2009 of 1970 hours.

Not any information has been provided for the **Luanda** UIR in either ARMA Form 2 or Form 4. The only data available for Luanda concerns ARMA Form 2 data for 2006 from CRA 2 (Ref. 5). The pertinent flight hour estimate of 27408 hours has been re-used for the current post-implementation CRA, again without correcting for traffic growth, if any.

For the **Lusaka** FIR/UIR, traffic flow data was provided for 6 months in ARMA Form 4, but no information was provided in ARMA Form 2. The Form 4 data provided an estimate of the number of flight hours for the period October 2008 – September 2009 of 10529 hours.

Data was provided for the **Nairobi** FIR for 7 months in both ARMA Form 4 and in ARMA Form 2, with good consistency between the two data sets. Based on the ARMA Form 4 data, the flight hour estimate for the period October 2008 – September 2009 amounts 45673 hours. (There was no readily useable information about the average flight duration in Nairobi RVSM airspace available in Form 2.) It is worth remarking that the value of 45673 hours is significantly larger than the 34749 hours used in the last pre-implementation CRA 3, based on ARMA Form 2 data for the year 2007 (Ref. 6).

Not any information has been provided for the **N'Djamena** UIR in either ARMA Form 2 of Form 4, except for a single pdf copy of Form 4 for January 2009. The only supporting data available for N'Djamena concerns ARMA Form 4 data for 2006 from CRA 2 (Ref. 5). The pertinent flight hour estimate of 28535 hours has been re-used for the current post-implementation CRA, again without a correction for traffic growth, if any.

For the **Niamey** UIR, no information has been provided in either ARMA Form 2 or ARMA Form 4. The only supporting data available for Niamey concerns ARMA Form 2 data for the years 2004 - 2005 from CRA 1 (Ref. 4). The pertinent flight hour estimate of 27724 hours has been re-used for the current post-implementation CRA, without any correction for traffic growth over the years 2005 - 2009.

Although **Sal Oceanic** FIR is part of AFI RVSM airspace, it is not a participating AFI RVSM FIR and not any ARMA Form 2 or Form 4 data is available for it.

Not any information has been provided for the **Seychelles** FIR/UIR in either ARMA Form 4 or ARMA Form 2 for the years 2008 – 2009. The only available data for Seychelles concerns ARMA Form 4 traffic flow data for the months of June 2005 – December 2005 (Ref. 5). As described in reference 5, the quality of the data was rather poor for three out of the seven months. Based on the data for the remaining four months, the number of Seychelles flight hours for the year 2005 has been estimated as 13480 hours. This value will also be used for the current CRA hours. This is again conservative in light of traffic growth, if any, over time.

No information was provided for the **Tripoli** FIR in either Form 4 or Form 2 for the years 2008 - 2009 and the same procedure as described above for Khartoum has been used to obtain a lower bound for the number of flight hours. The resulting estimate was 8776 hours for the RVSM flight level band in the Tripoli FIR for the year 2007 (Ref.

6). This value has also been used for the current CRA, again without any correction for possible traffic growth over time.

For the **Windhoek** FIR, traffic flow data was provided for 11 months in ARMA Form 4, but no information was provided in ARMA Form 2. The Form 4 data provided an estimate of the number of flight hours for the period October 2008 – September 2009 of 7290 hours.

Table 3.10 summarises the analysis above. It follows that a **lower bound** for the number of flying hours in the period 25 September 2008 – 30 September 2009 for the 23 FIR/UIRs of which the vertical AIAG AIRPROX reports and the large height deviations reported in ARMA Form 1 have been taken into account is 852706 hours. This number is a lower bound due to the lack of data from three FIR/UIRs, namely Khartoum, Sal Oceanic, and Tripoli. The current value is approximately 38% larger than the last pre-implementation estimate of 616644 hours utilized in CRA 3 (Ref. 6). One of the contributory factors to the increase is the larger number of FIR/UIRs from which vertical incident data were available, i.e. 23 rather than 11. It should be noted, however, that the flight hour estimate continues to be dominated by the flight hours, approximately 43% (60% in CRA 3), from the Cape Town and Johannesburg FIRs.

When the flight hour estimate is combined with the 50 vertical AIAG AIRPROX report events and the 7 ARMA Form 1 large height deviations that will be included in the CRA, a vertical event rate of approximately 6.7×10^{-5} incidents per flight hour may be obtained. This rate is approximately twice as large as the vertical event rate of 3.1×10^{-5} incidents per flight hour found in the last pre-implementation CRA 3. This increase is the combined effect of a tripling of the number of vertical events, dampened by a flight hour increase by a factor of approximately 1.4.

FIR/UIR	Vertical AIAG AIRPROX reports	ARMA Form 1 LHDs	Estimated number of flight hours for time period 25 September 2008 – 30 September 2009
Accra	2	1 (1) *	71035
Addis Abbaba	2	-	17697
Beira	2	2 (0)	22303
Brazzaville	7	-	21035
Cape Town & Johannesburg	-	5 (0) 17 (1)	369072
Dakar	3	-	49978
Dar Es Salaam	1	-	26914

Gaborone	1	1 (1)	19398
Harare		1 (0)	22724
Kano	2	-	11013
Khartoum	3	-	≥11845
Kinshasa	3	1 (0)	35489
Lilongwe	1	1 (1)	2002
Luanda	4	-	27859
Lusaka	-	1 (0)	10702
Nairobi	6	3 (2)	46424
Ndjamena	3	-	29004
Niamey	4	-	28180
Sal Oceanic	1		-
Seychelles	2		13702
Tripoli	3		≥ 8920
Windhoek	-	3 (1)	7410
Total	**50**	**36 (7)**	**≥ 852706**

Table 3.10 Summary of numbers of flight hours, AIRPROX reports, and large height deviations (LHDs) for AFI RVSM POSC CRA

Remark *: Numbers in brackets refers to numbers of LHDs actually included in CRA

3.5 TOTAL VERTICAL COLLISION RISK

In this subsection, the conventional vertical collision risk models will be applied to obtain the first post-implementation estimate 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 5×10^{-9} fatal accidents per flight hour.

The total vertical collision risk estimate is made up of the following contributions (cf. tables 3.4 and 3.8):

1. Risk due to AIRPROX reports coded CO, CS, and CC;
2. Risk due to AIRPROX reports coded WO, WS, and WC;
3. Risk due to a single 400 ft Large Height Deviation; and
4. Technical vertical risk.

AIRPROX reports coded CO, CS, and CC

Table 3.11 below summarises the parameter values for the collision risk model of eqs. (3.8) – (3.12). Most values follow relatively easily from the information presented in previous tables and equations. For example, $n_{same}^{cl/d} = 40$ and $n_{opp}^{cl/d} = 57$ follow directly from the numbers in the fourth and fifth columns of table 3.8 and the 2 same- and 2 opposite-direction flight levels crossed improperly in the Johannesburg ARMA Form 1 CS type event (cf. table 3.4 and summary in next paragraph). The values of $n_{\theta i}^{cl/d}$ and $n_{\pi-\theta i}^{cl/d}$ are discussed by event below. The same direction passing frequency $n_x^*(same)$ for aircraft separated by twice the vertical separation minimum S_z has not been estimated directly from the ARMA Form 4 traffic flow data but has been obtained from the opposite-direction passing frequency for aircraft at adjacent flight levels by means of the equation $n_x^*(same) \approx n_x(opp) \times \overline{|\Delta V|} / 2\overline{V}$. This relationship is an approximation based on a steady state system with uniformly-loaded flight levels. Since data on intersecting-route passing frequencies $n_{xy}(\theta_i)$ and $n_{xy}^*(\pi-\theta_i)$, $i = 1,\ldots,4$ (cf. table 3.8) for specific intersection angles are rare, the pertinent values for the four CC type events from table 3.8 have been conservatively approximated by overall values, say $\overline{n}_{xy}$ and $\overline{n}_{xy}^*$, obtained over all intersection angles available in the ARMA Form 4 traffic flow data, unless an AIRPROX report suggested otherwise. A less conservative approximation would be to assign an equal proportion of the overall value to each of the four events, but this has not been done because the contribution of the CC type events to the vertical collision risk due to improper flight level crossings will be seen to be relatively small. See eq. (3.21) below. The value obtained for $\overline{n}_{xy}$ over all intersections was $\overline{n}_{xy} = 1.08 \times 10^{-5}$. However, 85% of the intersecting-routes passing events occurred in the Algiers FIR with a passing frequency value for Algiers of $n_{xy}^{Algiers} = 2.25 \times 10^{-5}$. The latter value has been used as a conservative estimate for $\overline{n}_{xy}$. The corresponding values for $\overline{n}_{xy}^*$ and $n_{xy}^{*Algiers}$ are $\overline{n}_{xy}^* = 2.64 \times 10^{-5}$ and $n_{xy}^{*Algiers} = 5.11 \times 10^{-5}$. The latter value has been used as a conservative estimate for $\overline{n}_{xy}^*$. For each of the CC type events, the kinematics factor has been based on the prevailing intersection angle (or its supplement).

There was one CS type event in table 3.4 for ARMA Form 1 for Johannesburg in February 2009. According to the report, an aircraft was observed descending through FL371 whilst no descent clearance had been issued. The report showed FL410 as the assigned flight level. Assuming that the aircraft continued its descent through FL370 without ATC control, 2 opposite-direction and 2 same-direction flight level crossings have been counted for this event.

The first CC type event in table 3.8 is AIRPROX report 1196. It involved an aircraft descending out of AFI RVSM airspace, starting at FL390. It is assumed, therefore, that 10 flight levels might have been crossed. Unfortunately, the AIRPROX report is not clear about the angle of intersection between the two routes. In fact, the reporting aircraft was on a direct route and the intruder aircraft was descending from left to right. Therefore, taking into account the minimum and maximum kinematics factors of 1.0768 and 4.5571 for opposite and same direction traffic (see last row in table 3.11), $\theta_1 = 180^\circ$ has been taken with supplementary angle $\pi - \theta_1 = 0^\circ$ and it has been assumed that for each of the two angles 5 flight levels would be crossed, i.e. $n_{180}^{cl/d} = 5$ and $n_0^{cl/d} = 5$. The overall intersecting-routes passing frequencies $\overline{n}_{xy}$ and $\overline{n}_{xy}^*$ have been used for this event.

The second CC type event in table 3.8 is AIRPROX report 1201. Though the AIRPROX report does not provide any information about the initial flight level of the intruder aircraft, it appears reasonable to assume that only a single flight level was crossed improperly and thus $n_{153}^{cl/d} = 1$ and $n_{27}^{cl/d} = 0$. The overall intersecting-routes passing frequencies $\overline{n}_{xy}$ and $\overline{n}_{xy}^*$ have been used for this event.

The third CC type event in table 3.8 is AIRPROX report 1276. The AIRPROX report suggests a convergence angle of 30° between the track of the reporting aircraft and the other aircraft. The numbers of flight levels crossed improperly are $n_{30}^{cl/d} = 1$ and $n_{150}^{cl/d} = 2$. The overall intersecting-routes passing frequencies $\overline{n}_{xy}$ and $\overline{n}_{xy}^*$ have been used for this event.

The fourth CC type event in table 3.8 is AIRPROX report 1283. Since the report does not provide any information about the initial flight level of the climbing aircraft, it is assumed that only a single flight level would be crossed improperly and thus $n_{105}^{cl/d} = 1$ and $n_{75}^{cl/d} = 0$. The overall intersecting-routes passing frequencies $\overline{n}_{xy}$ and $\overline{n}_{xy}^*$ have been used for this event.

Parameter	Estimated value	Parameter	Estimated value
$n_{opp}^{cl/d}$	57 (55+2)	$P_z(S_z)_{opp}^{cl/d}$	7.38 × 10^{-8}
$n_{same}^{cl/d}$	40 (38+2)	$P_z(S_z)_{same}^{cl/d}$	5.18 × 10^{-8}
$n_{\theta i}^{cl/d}$, $i=1,\ldots,4$	5, 1, 1, 1	$P_z(S_z)_{\theta i}^{cl/d}$, $i=1,\ldots,4$	(6.5, 1.3, 1.3, 1.3) × 10^{-9}
$n_{\pi-\theta i}^{cl/d}$, $i=1,\ldots,4$	5, 0, 2, 0	$P_z(S_z)_{\pi-\theta i}^{cl/d}$, $i=1,\ldots,4$	(6.5, 0, 2.6, 0) × 10^{-9}
$n_x(opp)$	0.1015	$n_{xy}(\theta_i)$	2.25 × 10^{-5}
$n_x^*(same)$	0.002190	$n_{xy}^*(\pi-\theta_i)$	5.11 × 10^{-5}
λ_z (NM)	0.008277	$\overline{\lvert\dot{z}_c\rvert}$ (kts)	15
λ_{xy} (NM)	0.02822	$\overline{\lvert\dot{y}\rvert}$ (kts)	20
$P_y(0)$	0.109	$\overline{V}$ (kts)	463.4
T (hrs)	852706	$\overline{\lvert\Delta V\rvert}$ (kts)	20
$\left\{1+\frac{\overline{\lvert\dot{y}\rvert}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{\lvert\dot{z}_c\rvert}}{2\overline{V}}\right\}$	1.0768	$\left\{1+\frac{\overline{\lvert\dot{y}\rvert}}{\overline{\lvert\Delta V\rvert}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{\lvert\dot{z}_c\rvert}}{\overline{\lvert\Delta V\rvert}}\right\}$	4.5571

Table 3.11 Summary of parameter estimates for collision risk model of eqs. (3.8) - (3.12)

Substitution of the table 3.11 values into the model gives

$$N_{az}^{cl/d}=1.76\times10^{-9}+1.13\times10^{-10}+5.03\times10^{-13}+3.29\times10^{-12}=1.9\times10^{-9} \tag{3.21}$$

The risk estimate of $N_{az}^{cl/d}=1.9\times10^{-9}$ is approximately 12% larger than its counterpart of 1.7×10^{-9} fatal accidents per flight hour from the last pre-implementation CRA 3.

The main contribution to the collision risk due to improper flight level crossings is seen to come from aircraft traversing through opposite-direction flight levels. This is the result of two factors, firstly the large number of 57 opposite-direction flight levels crossed without a proper clearance and secondly the larger probability of being in longitudinal overlap ($n_x(opp)$).

Compared with CRA 3, the probability of vertical overlap $P_z(S_z)^{cl/d}_{opp}$ has increased from $P_z(S_z)^{cl/d} = 2.18 \times 10^{-8}$ (Ref. 6) to $P_z(S_z)^{cl/d}_{opp} = 7.38 \times 10^{-8}$, i.e. by a factor of 3.4. This factor is the result of an increase in the number of flight levels crossed from 12 to 57 (factor of 4.8) and an increase in the number of flight hours from 616644 to 852706 (factor of 1.4). Since the probability of vertical overlap is inversely proportional to the number of flight hours, the combined effect is an increase by a factor of $4.8/1.4 = 3.4$. The increase in this collision risk model parameter is largely counteracted by a very significant decrease in the same direction passing frequency $n^*_x(same)$ from 0.04894 in CRA 3 (Ref. 6) to 0.002190 in the current CRA. Dependent on the specific values of $n_x(opp)$ and $n^*_x(same)$, the risk estimate $N^{cl/d}_{az}$ is somewhat sensitive to $n^*_x(same)$ because the kinematics factor for the same-direction component is approximately 4 times larger than that of the opposite-direction component. (See last row in table 3.11.)

Eq. (3.21) suggests that the individual $N^{cl/d}_{az}$ component of the total vertical collision risk meets the total vertical TLS of 5 × 10^{-9} fatal accidents per flight hour with some margin. However, some care is necessary with regard to the sensitivity of this risk component to the various model parameters, e.g. the number of AIRPROX reports (and thus the number of flight levels crossed wrongly) and the annual number of flying hours. Recall from section 3.4, for example, that without the data from the Cape Town and Johannesburg FIRs, the number of flight hours would have been smaller by nearly 43%. As a result, the risk estimate would, very roughly, increase by 50%.

AIRPROX reports coded WO, WS, and WC

There are 7 AIAG AIRPROX reports coded WO, WS, or WC in table 3.8 and 4 ARMA Form 1 events coded WO or WS in table 3.4. The parameters n^{wl}_{opp} , n^{wl}_{same}, $n^{wl}_{opp,\theta i}$, $n^{wl}_{same,\theta i}$, $\bar{t}^{wl}_{opp}$, $\bar{t}^{wl}_{same}$, $\bar{t}^{wl}_{opp,\theta i}$, and $\bar{t}^{wl}_{same\,\theta i}$ need to be inferred from the reports. Unfortunately, the reports did generally not specify for how long the aircraft in error had been flying at a wrong flight level. The strategy used in the pre-implementation CRAs (Refs. 4 – 6) in similar cases was to assume that an aircraft in error had been on a wrong level since its last passed compulsory reporting point. The same strategy has been used here for the post-implementation CRA, unless an AIRPROX report suggested otherwise. Opposite- and same-direction passing frequency values of $n_x(opp)$ and $n^*_x(same)$ are the same as for the improper flight level crossing CO and CS type events. For the WC type events, the kinematics factors and the intersecting-routes passing frequencies have been treated in the same manner as for the CC type events. Table 3.12 summarises the various parameter values whereas the following paragraphs provide some background information. The total time spent at a wrong, opposite direction, flight level was 138.4 minutes and the total time spent at a wrong, same direction flight level was 145.4 minutes.

The first WO type event in table 3.8 is AIRPROX report 1200. According to the report, opposite direction traffic at the same flight level was seen on ACAS between TERAS and INEPA on the UM608 in the Niamey UIR. More precise aircraft locations were not included in the report. Assuming an ACAS range of 30 NM and a TERAS - TERIN segment length of 25 NM, a conservative assumption has been made that the conflicting aircraft was at a wrong level for all of the route segment INEPA - TERIN. Using an average aircraft speed of 463.4 kts, the route segment length of 244 NM equates to a time at wrong level of $t_{opp}^{wl}(1) = 31.6$ minutes.

The second WO type event in table 3.8 is AIRPROX report 1266. The event occurred on the route segment NAK - NV in the Nairobi FIR. Since the AIRPROX report did not specify the precise locations of either aircraft on the route segment, it is conservatively assumed that the full segment was flown by one of the aircraft at a wrong opposite-direction flight level. For a segment length of 77 NM this is equivalent to $t_{opp}^{wl}(2) = 10.0$ minutes at an average aircraft speed of 463.4 kts.

The third and last WO type event in table 3.8 is AIRPROX report 209. The event occurred 40 NM north of AGADES on the EDAGO - AGADES segment of the UR978 in the Niamey UIR at 20 NM separation. It has thus been assumed that the conflicting aircraft had been flying on a wrong opposite-direction flight level since AGADES for 152 - 60 = 92 NM or, equivalently, $t_{opp}^{wl}(3) = 11.9$ minutes at an average aircraft speed of 463.4 kts.

The first WO type event in table 3.4 for ARMA Form 1 concerns the Gaborone March 2009 report. The report stated that a non-RVSM approved State aircraft was observed flying in AFI RVSM airspace, initially flying an incorrect semi-circular RVSM flight level for 12 minutes. Apart from the latter, it is assumed that the State aircraft was provided with the required 2000 ft vertical separation. Hence, only the 12 minute flying at a wrong opposite-direction flight level will be included in the CRA. As follows from the model of eq. (3.16), the risk associated with this event involves $P_z(0)$, the probability of vertical overlap for aircraft at the same flight level. For this particular event, $P_z(0)$ has to be estimated for a pair of aircraft of which one aircraft is RVSM approved and the other is non-RVSM approved. In the absence of any data on the height-keeping performance of non-RVSM approved aircraft, the "default" $P_z(0)$ for a pair of RVSM approved aircraft has been used. This approach is conservative, since the height-keeping performance of a non-RVSM approved aircraft is likely to be worse than that of an RVSM approved aircraft.

The second WO type event in table 3.4 for ARMA Form 1 concerns the Windhoek January 2009 report. The report stated that Windhoek had negative contact with an aircraft throughout its FIR resulting in the aircraft entering the Johannesburg FIR at KEBAT at an incorrect semi-circular flight level. The total height deviation was listed as 1000 ft, but the duration was not specified. Based on the described negative contact with the aircraft throughout the Windhoek FIR, it has been assumed that the aircraft was flying at a wrong opposite-direction flight level through the whole FIR. Given the FIR exit point, it has been assumed that the aircraft flew the whole segment ANVAG – KEBAT (563 NM) on a wrong, opposite-direction, semi-circular flight level. This equates to 72.9 minutes at an average aircraft speed of 463.4 kts.

Table 3.8 shows one event of the WS type, viz. AIRPROX report 78. The event occurred on the route segment APNAD – IBGEN on the UG656 in the Dar Es Salaam FIR. The AIRPROX report suggests that the aircraft at the wrong same-direction flight level should have climbed to the next applicable level 2 minutes after passing NN (Entebbe). Since the report did not specify the precise aircraft locations on the route segment NN - IBGEN, it has been assumed that the aircraft was on a wrong level for all of the segment NN – IBGEN, approximately 200 NM, minus 2 minutes, i.e. $t_{same}^{wl}(1) = 23.9$ minutes at an average aircraft speed of 463.4 kts.

The ARMA Form 1 data in table 3.4 shows two events of the WS type for the Nairobi FIR in December 2008. The total height deviation of the first event was 4000 ft and that of the last event was 2000 ft. The total time of the latter deviation was reported as 10 minutes whereas that of the former was reported as “unknown”. Thus, in the absence of any other information, the duration of the first event has also been assumed to be 10 minutes.

The first WC type event in table 3.8 is AIRPROX report 1212. The event occurred at DITAR on the boundary between the Tripoli and Cairo FIRs. One of the aircraft was at a wrong same-direction level on the ARADA – DITAR segment (290 NM) of the R2. The event constitutes two risk components, namely same-direction risk and intersecting-routes risk for an intersection angle of $\theta_1 = 37^\circ$. The duration of the event has been taken as 37.5 minutes (based on an average aircraft speed of 463.4 kts), i.e. $t_{same}^{wl}(1) = 37.5$ minutes and $t_{same,\theta 1}^{wl} = 37.5$ minutes.

The second WC type event in table 3.8 is AIRPROX report 1279. The event occurred at PATAR on the UB612 in the Nairobi FIR. One of the aircraft was at a wrong same-direction level on the NABRO – PATAR segment (57 NM) of the UA408. Since, according to the AIRPROX report, this aircraft had been in contact with Nairobi approximately 10 minutes before PATAR, it has been assumed that it had been on a wrong same-direction level for the larger segment NN – PATAR (207 NM) rather than just NABRO – PATAR. Like the previous WC type event, the current event constitutes two risk components, namely same-direction risk and intersecting-routes risk for an intersection angle of $\theta_2 = 111^\circ$. For the same-direction risk model $t_{same}^{wl}(2) = 26.8$ minutes was taken (based on an average aircraft speed of 463.4 kts) and similarly $t_{same,\theta 2}^{wl} = 26.8$ minutes for the intersecting-routes vertical collision risk model.

The third and last WC type event in table 3.8 is AIRPROX report 207. The event occurred at IBTAN on the UM977 in the Addis Ababa FIR. The ICAO Caretaker feedback in the AIRPROX report indicates that one of the aircraft was at a wrong same-direction level to IBTAN from TULAP on the UM665 onwards (287 NM). Like the previous two WC type events, the current event constitutes two risk components, namely same-direction risk and intersecting-routes risk for an intersection angle of $\theta_3 = 128^\circ$. For the same-direction risk model $t_{same}^{wl}(3) = 37.2$ minutes was taken (based on an average aircraft speed of 463.4 kts) and similarly $t_{same,\theta 2}^{wl} = 37.2$ minutes for the intersecting-routes vertical collision risk model.

Parameter	Estimated value	Parameter	Estimated value
n_{opp}^{wl}	5	$P_z(S_z)_{opp}^{wl}$	1.22 × 10^{-6}
n_{same}^{wl}	3+3	$P_z(S_z)_{same}^{wl}$	1.28 × 10^{-6}
$n_{opp,\theta i}^{wl}$	0	$P_z(S_z)_{opp,\theta i}^{wl}$	0
$n_{same,\theta i}^{wl}$, $i = 1,\ldots 3$	1, 1, 1	$P_z(S_z)_{same,\theta i}^{wl}$, $i = 1,\ldots 3$	(3.3, 2.4, 3.3) × 10^{-7}
$\bar{t}_{opp}^{wl}$ (min)	27.67	$n_x(opp)$	0.1015
$\bar{t}_{same}^{wl}$ (min)	24.23	$n_x^*(same)$	0.002190
$\bar{t}_{opp,\theta i}^{wl}$ (min)	0	$n_{xy}(\theta_i)$	2.25 × 10^{-5}
$\bar{t}_{same,\theta i}^{wl}$, $i = 1,\ldots 3$ (min)	33.84	$n_{xy}^*(\theta_i)$	5.11 × 105^{6}
λ_z (NM)	0.008277	$\bar{V}$ (kts)	463.4
λ_{xy} (NM)	0.02822	$\overline{\lvert \Delta V \rvert}$ (kts)	20
$P_y(0)$	0.105	$\overline{\lvert \dot{y} \rvert}$ (kts)	20

$P_z(0)$	0.45	$\overline{\lvert\dot{z}\rvert}$ (kts)	1.5
$\left\{1+\frac{\overline{\lvert\dot{y}\rvert}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{\lvert\dot{z}\rvert}}{2\overline{V}}\right\}$	1.0271	$\left\{1+\frac{\overline{\lvert\dot{y}\rvert}}{2\overline{V}}+\frac{\lambda_{xy}}{\lambda_z}\frac{\overline{\lvert\dot{z}\rvert}}{\overline{\lvert\Delta V\rvert}}\right\}$	2.2557
T (hrs)	852706		

Table 3.12 Summary of parameter estimates for collision risk model of eqs. (3.15) - (3.19)

Substitution of all the parameter values into the collision risk model of eqs. (3.15) - (3.19) results in

$$N_{az}^{wl} = 2.766\times10^{-8} + 1.311\times10^{-9} + 0 + 9.20\times10^{-11} = 2.9\times10^{-8} \qquad (3.22)$$

The risk estimate of $N_{az}^{wl} = 2.9\times10^{-8}$ is 8.5 times larger than its counterpart of 3.4×10^{-9} fatal accidents per flight hour from the last pre-implementation CRA 3. This increase is a direct consequence of the increase in the numbers of WO, WS, and WC events, viz. from 1 WO report in CRA 3 to 5 WO reports, 3 WS reports, and 3 WC reports in the current CRA and the corresponding increase in the amount of time spent at a wrong flight level. CRA 3 had 10 minutes spent at a wrong opposite-direction flight level whereas the current CRA has a total of 138.4 minutes spent at a wrong opposite-direction flight level plus 145.4 minutes spent at a wrong same-direction flight level. The increases in the times spent at a wrong level translate directly in increases in the probabilities of vertical overlap $P_z(S_z)_{opp}^{wl}$ and $P_z(S_z)_{same}^{wl}$ as well as $P_z(S_z)_{same,\theta i}^{wl}$, $i = 1,\ldots 3$, in table 3.12 and subsequently into the estimate of the vertical collision risk N_{az}^{wl} due to aircraft having levelled off at a wrong flight level.

Eq. (3.22) indicates that this individual component of the total vertical collision risk alone does not meet the total vertical TLS of 5 × 10^{-9} fatal accidents per flight hour. Though it is probably correct to believe that, in the absence of precise data, the times spent at a wrong level have been estimated somewhat conservatively, it is on the other hand necessary to be aware of the sensitivity of the different probabilities of vertical overlap to the annual number of flight hours T which was shown in section 3.4 to be dominated by the flight hours in the Cape Town and Johannesburg FIRs.

AIRPROX report 1188

The event described in this AIAG report has been classified as a 400 ft LHD. Unfortunately, the report did not provide any information about the duration of this LHD. As a result, it is necessary to calculate the vertical collision risk due to this type of event by means of the model in eqs. (3.1) and (3.5) with t_{400} as a free parameter. In principle, it is then possible to determine a maximum value for t_{400} such that the corresponding risk is not larger than some appropriate proportion of the total vertical TLS of 5×10^{-9} fatal accidents per flight hour. This approach was also followed in the last pre-implementation CRA 3, see reference 6.

Thus, $P_z(S_z)^{non-whl}$ of eq. (3.5) is expressed as

$$P_z(S_z)^{non-whl} = \frac{t_{400}}{T} P_z(S_z)_{400} \qquad (3.23)$$

and the collision risk model for the non-whole numbers of flight level errors becomes

$$N_{az}^{non-whl} = 2\left(\frac{t_{400}}{T} P_z(1000)_{400}\right) P_y(0) n_x(equiv) \left\{1 + \frac{|\bar{\dot{y}}|}{2\bar{V}} + \frac{\lambda_{xy}}{\lambda_z}\frac{|\bar{\dot{z}}|}{2\bar{V}}\right\} \qquad (3.24)$$

Table 3.13 summarises the parameter values for this collision risk model.

Parameter	Estimated value	Parameter	Estimated value
T (hrs)	852706	$P_y(0)$	0.109
$P_z(1000)_{400}$	0.0003300	$n_x(equiv)$	0.1022
t_{400} (hrs)	?	$\left\{1 + \frac{\lvert\bar{\dot{y}}\rvert}{2\bar{V}} + \frac{\lambda_{xy}}{\lambda_z}\frac{\lvert\bar{\dot{z}}\rvert}{2\bar{V}}\right\}$	1.0271

Table 3.12 Summary of parameter estimates for collision risk model of eq. (3.24)

Substitution of the various parameter values into the model gives for the risk due to large height deviations of the non-whole numbers of flight levels type

$$N_{az}^{non-whl} = 2\left(\frac{t_{400}}{852706} \times 0.0003300\right) \times 0.109 \times 0.1022 \times 1.0271 \qquad (3.25)$$

or

$$N_{az}^{non-whl} = (0.0003300 \times t_{400}) \times 1.1727 \times 10^{-6} \times 0.02288 \qquad (3.26)$$

i.e.

$$N_{az}^{non-whl} = t_{400} \times 8.86 \times 10^{-12} \qquad (3.27)$$

Clearly, this component of the total vertical collision risk now depends on the duration t_{400} of the pertinent large height deviation.

To get some feel for this particular risk component, three values have been assumed for the duration t_{400} of the deviation, i.e. 15 minutes, 30 minutes and 60 minutes. The results are shown in table 3.14.

t_{400} (hrs)	$N_{az}^{non-whl}$
0.25	2.21×10^{-12}
0.5	4.43×10^{-12}
1.0	8.86×10^{-12}

Table 3.14 Estimates of the vertical collision risk due to large height deviations of the non-whole numbers of flight levels type as a function of an assumed duration of the 400 ft large height deviation

Table (3.14) shows that this individual component of the total vertical risk is well below the total vertical TLS of 5×10^{-9} fatal accidents per flight hour for a duration of up to one hour or even (much) longer. The main reasons for the low risk values in table 3.14 are that there was only a single LHD and that the magnitude of the LHD was relatively small compared to the upper bound of 300 ft for typical height-keeping performance of RVSM approved aircraft. (Cf. the 500 ft and 600 ft LHDs included in the last pre-implementation CRA 3 (Ref. 6)). It should be kept in mind, however, that this individual risk component needs to be added to the other components to assess whether the sum of the risks due to all components meets the total vertical TLS. This is examined below where $t_{400} = 1$ hr is taken as a fair estimate with $N_{az}^{non-whl} = 8.9 \times 10^{-12}$ fatal accidents per flight hour.

Total vertical collision risk

The total vertical collision risk due to all causes under AFI RVSM is the sum of the three risk components $N_{az}^{cl/d}$, N_{az}^{wl}, and $N_{az}^{non-whl}$ and the technical vertical collision risk N_{az} given by eq. (2.25), i.e.

$$N_{az}^{total} = N_{az}^{cl/d} + N_{az}^{wl} + N_{az}^{non-whl} + N_{az} \tag{3.28}$$

Substitution of the risk estimates given by eqs. (3.21), (3.22), (3.27), and (2.25) into eq. (3.28) gives the following estimate for the total vertical risk in fatal accidents per flight hour:

$$N_{az}^{total} = 1.9\times10^{-9} + 2.9\times10^{-8} + 8.86\times10^{-12} + 2.7\times10^{-10} = 31.2\times10^{-9} \tag{3.29}$$

Eq. (3.29) shows that the total vertical TLS of 5×10^{-9} is exceeded by a factor of approximately 6. (The third term in the middle part of eq. (3.29) represents the risk due to LHDs not involving whole number of flight levels and does not in any way affect the estimate of the total vertical collision risk.) It should be remarked that, intentionally, the risk estimate of eq. (3.29) does not include the risk mitigating effect of ACAS.

The post-implementation risk estimate of $N_{az}^{total} = 31.2\times10^{-9}$ fatal accidents per flight hour may be compared with the last pre-implementation estimate, which, dependent on the assumed durations of the non-whole numbers of flight levels events, ranged from 6.9×10^{-9} to 11.2×10^{-9} fatal accidents per flight hour.

The most critical component appears to be the vertical collision risk due to aircraft levelling off at a wrong flight level. This component has increased by almost an order of magnitude from 3.4×10^{-9} in CRA 3 to 2.9×10^{-8}. As was mentioned before, this is caused by increases in the number of events and the amount of time spent at a wrong flight level. The latter increased from 10 minutes spent at a wrong opposite-direction flight level in CRA 3 to 138.4 minutes spent at a wrong opposite-direction flight level and 145.4 minutes spent at a wrong same-direction flight level in the current CRA. Although the time estimates are likely to be conservative, the increase in the number of events from 1 to 11 definitely signals a problem.

The component of the total vertical collision risk due to improper flight level crossings is of the same order of magnitude as in the last pre-implementation CRA 3. The technical vertical risk component has increased by nearly an order of magnitude compared to its CRA 3 value, but is one to two orders of magnitude smaller than the improper flight level crossings and wrong flight level risk components. Finally, one component of the total vertical collision risk has decreased, viz. the risk due to large height deviations of the non-whole numbers of flight levels type. This component changed from a value of the order of 10^{-9} to a negligible value.

It should be clear that the above result is conditional on many factors, the most important one being the completeness and representation of the data available to the assessment. As mentioned at several places, there is a need for considerable caution in this respect.

One specific factor that has been mentioned before concerns the sensitivity of the estimate of the total number of flight hours to the value of the annual flying time in the Cape Town and Johannesburg FIRs. Another specific factor concerns the effect of increased lateral navigation accuracy, i.e. the proportion of aircraft using GNSS-based navigation.

As follows from the various collision risk models, the risk increases essentially proportionally to $P_y(0)$, the probability of horizontal overlap for aircraft on the same route. Table 2.5 showed $P_y(0)$ as a function of the proportion α of aircraft using GNSS (based on $\lambda_y = 158.71$ ft). The current assessment assumed that 50% of the AFI RVSM aircraft population would be using GNSS with a corresponding value of $P_y(0) = 0.109$ (based on $\lambda_y = 163.81$ ft). If the proportion of GNSS users would increase to 75%, the value of $P_y(0)$ would increase to 0.167. Consequently, the risk estimates would increase by a factor of approximately 1.5.

4 CONCLUSIONS

4.1 OVERALL

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 pertinent 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. Based on the data available to the assessments, the technical vertical TLS was found to be met, but the total vertical TLS was found not to be met. The estimate of the total vertical collision risk was 31.2×10^{-9} fatal accidents per flight hour, i.e. approximately 6 times the total vertical TLS.

The total vertical risk is made up of four components and was dominated by the risk due to aircraft having levelled off at a wrong flight level. Although, in the absence of precise data, the times spent at wrong opposite- and same-direction flight levels had to be estimated conservatively, the number of events of this type definitely signals a problem. The next important component was the risk due to improper flight level crossings. This component made up approximately 40% of the total vertical TLS and was approximately 12% larger than in the last pre-implementation CRA.

The most important parameter of the vertical collision risk models is the probability of vertical overlap due to large height deviations. Two data sources have been used for the estimation of this parameter, namely, firstly, AFI ATS Incident Analysis Working Group (AIAG) 2008 and 2009 AIRPROX reports and, secondly, ARMA Form 1 data. Compared with the last pre-implementation CRA, the number of vertical AIAG AIRPROX reports for the AFI RVSM airspace increased from 13 to 50, 41 of which have been included in the post-implementation CRA. In addition, the number of FIR/UIRs actually reporting one or more large height deviations in ARMA Form 1 increased from 4 to 11, and the number of reported events increased approximately in proportion from 13 to 36, 7 of which have been included in the CRA. Although some of the reported events have not explicitly been included in the CRA, their occurrence cannot be ignored and should be duly evaluated in order to prevent the recurrence of similar events in the future.

Although both the AIAG and ARMA Form 1 data have been very useful for the assessment of the total vertical collision risk in AFI RVSM airspace, there remains considerable concern as to whether a complete and fully representative sample of incident data has been obtained. All the stakeholders involved with AFI RVSM must continue to make every effort to ensure that sufficient and reliable data on large height deviations are made available for the benefit of AFI RVSM collision risk assessment.

The reporting of large height deviations in ARMA Form 1 does not appear to be consistent with that in the AIAG AIRPROX reports. This inconsistency needs to be resolved in order to obtain sufficient credibility for the assessment process.

The next important parameter of the vertical collision risk models is passing frequency. This is estimated from traffic flow data collected by ARMA from the African States in ARMA Form 4 on a monthly basis. A considerable amount of data limitations have been identified. These limitations must be eliminated in order to make the passing frequency estimation process more precise and reliable.

The limitations in the ARMA Form 4 and Form 2 data do not only affect the passing frequency estimation, but also that of the annual flying time in AFI RVSM airspace. This in turn affects the estimation of the rate of large height deviations and, consequently, that of the total vertical collision risk under AFI RVSM.

In the case of vertical collision risk, passing frequency primarily refers to aircraft at adjacent flight levels passing one another in the horizontal plane. Given the semi-circular flight level system, aircraft at adjacent flight levels of the same route should be flying in opposite directions and an aircraft at the next adjacent flight level should again be flying in the same direction as at the first flight level. However, the flight directions that can be inferred from the traffic flow data in ARMA Form 4, suggest for a non-negligible number of cases that an aircraft flying at the next adjacent flight level is flying in the opposite direction with respect to the first flight level. Similarly, based on the flight directions inferred from the ARMA Form 4 traffic flow data, opposite direction passings between aircraft at the same flight level have been identified for a non-negligible number of cases. The cause(s) of these apparent inconsistencies need to be investigated.

4.2 TECHNICAL VERTICAL COLLISION RISK

Based on current traffic levels, the technical vertical collision risk was estimated as 2.7×10^{-10} fatal accidents per flight hour, i.e. approximately an order of magnitude below the technical vertical TLS of 2.5×10^{-9} fatal accidents per flight hour. This risk is essentially due to the loss of vertical separation between opposite direction traffic at adjacent flight levels of a route. The precision of lateral navigation is an important factor with regard to vertical collision risk. It has been assumed that 50% of the flying time in AFI RVSM airspace would be made with GNSS navigation and the remaining 50% with VOR/DME navigation.

The risk increasing effect of an extended use of GNSS navigation has not been taken into account in the current risk estimate. An increase of the GNSS flight time proportion to 75%, for example, would cause the estimate of the technical vertical risk to increase by a factor of approximately 1.5. On the other hand, the risk mitigating effect of strategic lateral offsets has not been incorporated either.

The estimate for the technical vertical collision risk is considered to be non-conservative with regard to the data limitations affecting the passing frequency estimation. In addition, the risk increasing effect of future traffic growth has not been considered. The margin between the technical TLS and the estimate of the technical vertical collision risk is believed to be sufficient to cope with these factors.

4.3 TOTAL VERTICAL COLLISION RISK

Total vertical collision risk is the risk due to all causes including normal, or typical, height deviations of RVSM approved aircraft. Causes of vertical collision risk other than normal height deviations generally lead to large, atypical height deviations. These large height deviations have been classified into large height deviations involving whole numbers of flight levels and those not involving whole numbers of flight levels. Appropriate models for the collision risk due to such deviations developed for the pre-implementation CRAs have been re-used, but with their parameters updated on the basis of the data available for the first year of RVSM operations in the AFI Region.

The AIAG 2008 - 2009 data for the current post-implementation CRA comprised 41 vertical events compared with 13 vertical events in the AIAG 2007 data set for the last pre-implementation CRA. Forty out of the 41 events concerned large height deviations of the whole numbers of flight levels type and the remaining event concerned a large height deviation of the non-whole numbers of flight levels type. The AIAG data have been supplemented with 7 large height deviations, all of the whole numbers of flight levels type, reported in ARMA Form 1. Only two events were jointly included in both data sets.

Total vertical collision risk is made up of four components. The total risk was found to be dominated by the risk due to aircraft levelling off at a wrong flight level. Using a conservative approach to account for the lack of precise data on the duration of the pertinent events, the risk component due to aircraft having levelled off at a wrong flight level was estimated to be 29.1×10^{-9} fatal accidents per flight hour. The risk due to improper flight level crossings was found to be the next important component, with an estimate of 1.9×10^{-9} fatal accidents per flight hour. The technical vertical collision risk component was approximately one order of magnitude smaller, viz. 2.7×10^{-10} fatal accidents per flight hour and the risk due to large height deviations of the non-whole numbers of flight levels type was found to be negligible. All these component risk estimates are based on current traffic levels and 50% GNSS flying time. The total vertical collision risk, including the technical vertical collision risk, was thus estimated as 31.2×10^{-9} fatal accidents per flight hour, i.e. approximately 6 times the total vertical TLS. The current, post-implementation, estimate is significantly larger than the last pre-implementation estimate, which was in the range of 6.6×10^{-9} – 11.2×10^{-9} fatal accidents per flight hour. The increase is caused by the risk due to aircraft having levelled off at a wrong flight level.

The estimates of the three components of the vertical collision risk due to large height deviations are very sensitive to the annual flight hour estimate for the Cape Town and Johannesburg FIRs since this makes up nearly 43% of the total number of flight hours used for the three risk components.

Given the limited distribution of the AIAG AIRPROX reports over the FIR/UIRs in the AFI Region and across the airline population, there is considerable concern as regards the completeness and representation of the AIAG data set. This concern is even greater with regard to the reporting of large height deviations in ARMA Form 1. Thus, there continues to be a need for improvements in incident reporting.

The effect of data limitations, traffic growth, extended use of GNSS navigation, and the potential use of lateral offsets on the estimate of the total vertical collision risk is essentially similar to that on the technical vertical collision risk.

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Appendix A AIRCRAFT POPULATION

A.1 INTRODUCTION

Flight time proportions are needed with respect to three parameters of the vertical collision risk model, namely the overall ASE probability distribution on the one hand and average aircraft dimensions and speed on the other.

A.2 AIRCRAFT POPULATION DATA

All participating FIR/UIRs (30) are required to submit traffic flow information (Form 4) for the flight level band FL290 – FL410 to ARMA on a monthly basis. For 16 FIR/UIRs, the traffic flow information for one or more months has been able to be processed. In total, 121 months have been processed with a total flight time of 221517.3 hrs. Only 31.6% of the 348 months that should have been submitted by the 29 FIR/UIRs could be processed.

Using the available data, an estimate of the total flight time for the period of time from 25 September 2008 – 30 September 2009 was calculated in two steps. Firstly, an estimate was calculated for the period of time from 1 October 2008 – 30 September 2009. All (usable) data for this period of time was available for Mauritius only. For the remaining FIR/UIRs, the flight hour estimates for the 12 month period were obtained by taking the available months and scaling these up with the appropriate factors. Secondly, a minor correction of 1.64% was applied to account for the period of time from 25 September – 30 September 2008. The result is shown in table A.1, with a total of 318809 flight hours. Compared with the last pre-implementation CRA, CRA 3, no Form 4 data was received from Antananarivo and Kinshasa anymore whereas (usable) Form 4 data was received from Addis Ababa, Entebbe, Gaborone, Lilongwe, Nairobi and Windhoek for the first time.

FIR/UIR	No of months processed	Flight time estimate for period of time 25 September 2008 – 30 September 2009 (hrs)
Addis Ababa	9	17697
Algiers	11	100170
Asmara	9	1814
Beira	3	22303
Dakar	6	6871
Dar Es Salaam	5	26914
Entebbe	1	4876
Gaborone	10	19398
Kano	6	11013
Lilongwe	7	2003
Lusaka	6	10702
Mauritius	12	11653
Mogadishu	11	21332
Nairobi	7	46424
Roberts	7	8229
Windhoek	11	7410
Total	121	318809

Table A.1 Flight time estimate by FIR/UIR for the first year of RVSM operations in the AFI Region, 25 September 2008 – 30 September 2009

A.3 FLIGHT TIME PROPORTIONS FOR THE OVERALL ASE DISTRIBUTION

The flight time proportions β_i, $i = 1,\ldots,n_{MG}$, in the overall ASE probability density model of eq. (2.17) of the main text are needed by monitoring group.

The traffic flow data collection form (Form 4) includes for each flight the aircraft type in column C. The flight time by aircraft type can thus 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 aircraft type for the AFI Region. The flight time by aircraft type then needs to be translated into flight time proportion by monitoring group. This is done on the assumption that the aircraft type in column C of Form 4 is given in the form of the ICAO aircraft type designator[6]. In practice, this is not always the case and,

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[6] To determine the ICAO aircraft designators, ICAO Doc 8643 has been used (Available via internet: http://www.icao.int/anb/ais/8643/). This document was last updated on 8 October 2009.

apart from invalid designators, the actual aircraft type and or series may be given. Hence, some pre-processing of the "aircraft type field" has had to be performed. Firstly, flights were deleted[7] for which either this field was empty or the field contained one of the following designators:

155, 830, 1246, A, A300, A134, A311, A312, A313, A10A, A322, A324, A329, A32A, A330, A331, A336, A33L, A340, A344, A347, A349, A350, A351, A353, AFR 959, AFR 976, B702, B707, B723, B727, B728, B745, B746, B747, B730, B754, B756, B757, B758, B767, B769, B76F, B76X, B77, B771, B774, B776, B777, B7777, B78, B783, B786, B787, B7W, B7Y38, BA42, BA46, BEL 352, BG73, BG77, BGB, BJ20, BB72, BN74, BV74, BV76, BD700, C604, C656, C9, CIRT, CL01, CL10, CR60, CRJ4, CRJ797, CS10, D20, D238, D25B, D338, DA90, DBBB, DC8, DC9, DC9 , DC97, DC9L, DHC8, DKAM, EC07, EI35, ERKE, ETH, F29TH, F500, F50H, F15, F18, GL51, GL5T, GLF1, GLF8, GMFF, H125, H25, H250, H253, H25D, H25P, H325, H762, HA4T, HLLT, HS12, HS125, HS25, HS253, HS35, HS70, FA40, FA60, FAJS, FAX7, G100, G135, G150, G151, G159, G50, G900, GCIV, GILX, GIOX, J32W, JET, JETF, JS35, K135, K35R, K36R, KAME, KLM591, KQA, L298, L29B, L329, L35, L382, L39, LC60, LFOK, LFPG, LIGU, LJ50, LJ65, LPPT, LSGG, MD85, MD86, MOGI, MORJ, N276, OM11, P180, P2, PC12, QA32, QTR, RJ4R, SAA, SAA048, SAA049, SADA, SEY, SJ2, SL30, T202, TB7F, TBM700, TERA, UB532, WW24, XXX, ZAWA.

Secondly, after the removal of spaces and other invalid characters, the following substitutions have been made:

319 → A319, 320 → A320, 332 → A332, 343 → A343, 346 → A346, 350 → A350, 742 → B742, 763 → B763, 1343 → A343, 4343 → A343, 1C76 → IL76, 1L76 → IL76, 3B77W → B77W, A036 → A306, A139 → A319, A219 → A319, A230 → A320, A308 → A30B, A33 → A333, A33- → A333, A332 → A332, A332A → A332, A3332 → A332, A3333 → A333, A334 → A343, A3343 → A343, A3436 → A346, A3453 → A343, A3463 → A346, A3465 → A345, A380 → A388, A39 → A319, A42 → A342, A43 → A343, A432 → A342, A434 → A343, A46 → A346, A737 → B737, A738 → B738, A752 → B752, A772 → B772, A773 → B773, AA319 → A319, AM 135 → E135, AN12 → AN12, AN124 → A124, AT24 → AT43, B11 → BA11, B1-1 → BA11, B1-11 → BA11, B144 → B744, B180 → C180, B319 → A319, B332 → A332, B333 → A333, B346 → A346, B37 → B737, B373 → B737, B378 → B738, B38 → B738, B575 → B757, B63 → B763, B67 → B767, B673 → B763, B6763 → B763, B72 → B720, B72S → B732, B73 → B737, B7333 → B733, B73G → B736, B73W → B77W, B74 → B744, B7422 → B742, B742F → B742, B7444 → B744, B74S → B74S, B7562 → B752, B762 → B762, B7672 →

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[7] This applies only to the flight time proportions, not to the passing frequency calculations.

B762, B76B7632 → B762, B7772 → B772, B77L → B77L, B77W → B77W, B7O3 → B703, B833 → B733, B838 → B738, B882 → B772, BA111 → BA11, BAC11 → BA11, BAC1-11 → BA11, BB763 → B763, BB773 → B773, BB77W → B77W, BD 70 → BE70, BD70 → BE70, BY38 → B738, BY73 → B773, C-17 → C17, C55 → C550, C-550 → C550, C552 → C550, C560E → C56X, C600 → C500, C601 → C501, C625 → C525, CALX → GALX, CARJ → CRJ1, CJR1 → CRJ1, CJR2 → CRJ2, CL130 → C130, CL160 → C160, CL56X → C56X, CL61 → CL60, CL64 → CL60, CL65 → CL60, CL6O → CL60, CL6ø → CL60, CLEX → GLEX, CLF4 → GLF4, CLJ1 → CRJ1, CLJ2 → CRJ2, CN35 → CN35, CR12 → CRJ2, CR17 → CRJ7, CR2 → CRJ2, CR7 → CRJ7, CRJ → CRJ1, CRJ10 → CRJ1, CRJ-100 → CRJ1, CRJ200 → CRJ2, CRJJ → CRJ1, D764 → B764, DA10 → FA10, DA20 → FA20, DA50 → FA50, DC1ø → DC10, DCI0 → DC10, DO328 → D328, DRJ2 → CRJ2, E1170 → E170, E125 → E135, E133 → E135, E315 → E135, E342 → A342, E710 → E170, EA30 → A306, EA31 → A310, EA319 → A319, EA32 → A320, EA33 → A332, EA332 → A332, EA34 → A342, EA343 → A343, EA45 → A345, F10 → FA10, F135 → E135, F190 → E190, F200 → FA20, F2000 → F2TH, F2000EX → F2TH, F25H → F2TH, F90 → F900, F9000 → F900, F902 → F900, FA7 → F70, FA7X → F70, FA90 → F900, FA900 → F900, FGLF4 → GLF4, FK10 → F100, FK28 → F28, FK50 → F50, FK70 → F70, FLF3 → GLF3, FLF4 → GLF4, FLF5 → GLF5, FZTH → F2TH, G 200 → GALX, G 3 → GLF3, G 4 → GLF4, G 5 → GLF5, G2 → GLF2, G200 → GLF2, G3 → GLF3, G4 → GLF4, G5 → GLF5, GELX → GLEX, GFL2 → GLF2, GIII → GLF3, GIV → GLF4, GL4 → GLF4, GLAX → GALX, GLE5 → GLF5, GLFX → GLEX, GLG5 → GLF5, GLT5 → GLF5, GLX → GLEX, GLX4 → GLF4, GLXX → GLEX, GMEX → GLEX, GV → GLF5, HS25A → H25A, HS25B → H25B, IL78 → IL76, JE135 → E135, L1010 → L101, L1011 → L101, L135 → E135, LD11 → MD11, LI011 → L101, LJ36 → LJ35, LR31 → LJ31, LR35 → LJ35, LR45 → LJ45, LR55 → LJ55, LR60 → LJ60, M080 → MD80, M082 → MD82, M083 → MD83, M084 → MD84, M087 → MD87, M090 → MD90, M87M → MD87, MA11 → MD11, MB82 → MD82, MC82 → MD82, MD-11 → MD11, MO87 → MD87, MS11 → MD11, N733 → B733, N742 → B742, N763 → B763, PMR1 → PRM1, PRIM → PRM1, PRMI → PRM1, Q343 → A343, Q345 → A345, R135 → E135, R190 → E190, R722 → B722, RJ85 → RJ85, RJHI → RJ1H, TU154 → T154, V744 → B744, VRJ2 → CRJ2.

For the remaining flights, the flight time proportions by ICAO aircraft type designator were mapped onto the monitoring groups, using the relationship between ICAO aircraft type designators and monitoring groups. It should be remarked that this relationship is not unique, i.e. a single monitoring group may cover more than one ICAO aircraft type designator and a single ICAO aircraft designator may belong to more than one monitoring group (dependent on the actual aircraft type and/or series). In the former case, the pertinent flight time proportions are simply summed for the single monitoring group whereas in the latter case the flight time proportion is equally distributed over the pertinent monitoring groups. It should also be noted that an implicit assumption underlying the flight-time-proportions calculations is that all flights between FL290 and FL410 inclusive have been included in the Forms 4. Table A.2 shows the resulting flight time proportions by monitoring group.

Monitoring Group	Flight time proportion	Monitoring Group	Flight time proportion
A124	0.0007786	CL604	0.00095891
A300	0.00174724	CL605	0.00095891
A306	0.00495064	CRJ-700	0.00382482
A310-GE	0.00417261	CRJ-900	0.00030183
A310-PW	0.00417261	D328	0.00049311
A318	1.7887E-05	DC10	0.00339168
A320	0.09915932	DC86-7	7.0246E-05
A330	0.10430652	DC86-7-1	7.0246E-05
A340	0.11041919	DC86-7NG	7.0246E-05
A345	0.00523442	DC95	6.4795E-05
A346	0.04544687	E135-145	0.00242958
A380	3.7206E-05	E170	0.01059358
ASTR	3.5265E-05	F100	0.0001263
ASTR-1	3.5265E-05	F2TH	0.00102094
ASTR-SPX	3.5265E-05	F70	0.00044729
AVRO	0.0031174	F900	0.00727306
B701	0.00014937	FA10	0.00033713
B703	0.00013696	FA10NG	0.00033713
B703NG	0.00013696	FA20	0.00027297
B712	2.3633E-05	FA50	0.00343656
B727	0.00150315	GALX	0.00036266
B732	0.00753262	GLEX	0.00170933
B737C	0.02333145	GLF2	0.00017299
B737CL	0.03974891	GLF2-3	0.00041086
B737NX	0.08401357	GLF2B	0.00017299
B744-10	0.03823512	GLF2B-G	0.00017299
B744-5	0.03823512	GLF2-G	0.00017299
B747CL	0.01103896	GLF3	0.00023788
B74S	0.00011128	GLF4	0.00226892
B752	0.02108632	GLF5	0.00179263

B753	0.00090312		H25A-400	0.00011951
B764	0.00296475		H25B-700	0.00031462
B767	0.09246707		H25B-700-A	0.00031462
B772	0.09680711		H25B-700NG	0.00031462
B773	0.05494728		H25B-750	0.00031462
BA11	0.00083583		H25B-800	0.00031462
BD100	0.00035704		H25B-800NG	0.00031462
BE20	0.00039426		H25C	4.2456E-06
BE40	3.5182E-05		H25CNG	4.2456E-06
BE40-BEECH	3.5182E-05		HERCULES	7.7751E-05
C17	0.00129956		IL62	0.00015533
C5	0.0001874		IL76	0.00533974
C500	0.0001255		IL86	4.8097E-06
C500-1	8.9325E-05		IL96	4.1104E-05
C510	0.00017802		KC135	0.00013696
C525	0.00019248		L101	0.00082502
C525-II	7.0068E-06		LJ31	3.2237E-05
C550-B	0.0006158		LJ31NG	3.2237E-05
C550-II	0.00061766		LJ35/6	0.00166437
C550-IING	0.0006158		LJ45	0.00048826
C550-SII	0.0006158		LJ55	0.00027837
C560	0.00037511		LJ60	0.00031932
C56X	0.00010546		MD11	0.02048931
C650	8.2723E-05		MD80	0.00656648
C680	0.00062503		MD90	0.00041757
C750	5.0442E-05		PRM1	0.0001042
CARJ	0.00961566		T154	2.3548E-05
CL600	0.00095891		T204	7.4897E-06
CL600-1	0.00095891		VC10	5.1702E-05
CL600NG	0.00095891		YK42	2.9096E-06

Table A.2 Population of RVSM approved aircraft

A.4 OVERALL ASE DISTRIBUTION

This part of Appendix A summarizes the modelling of the overall ASE distribution for the RVSM approved aircraft population expected to be operating in AFI RVSM airspace.

Assume that n_{MG} aircraft monitoring groups 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. 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.

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

where the weighting factors β_i, $i = 1,\ldots,n_{MG}$, are the proportions of flight time contributed by monitoring group i. Both the weighting factors and the monitoring groups' ASE probability densities need to be inferred from monitoring data pertaining to the AFI RVSM airspace. (See Appendix A.3 for a discussion on the estimation of the weighting factors.)

The monitoring groups' probability densities $f_i^{ASE}(a)$, $i = 1,\ldots,n_{MG}$ 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 <u>not</u> 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. (A.1) 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.

For the current post-implementation CRA, ASE probability densities $f_i^{ASE}(a)$, $i = 1,\ldots,n_{MG}$, from the latest RVSM safety assessment for the EUR region have been used, based on height monitoring data for the period 1 January 2007 – 31 December 2008.

Figures A.1 and A.2 show the resulting overall ASE probability density $f^{ASE}(a)$ given by eq. (A.1), based on the above mentioned height monitoring data. The logarithmic scale of figure A.2 provides a better indication of the tail of the overall ASE probability density for the RVSM approved aircraft population operating in AFI RVSM airspace.

Figure A.1 Overall ASE probability density for the AFI RVSM POSC CRA aircaft population

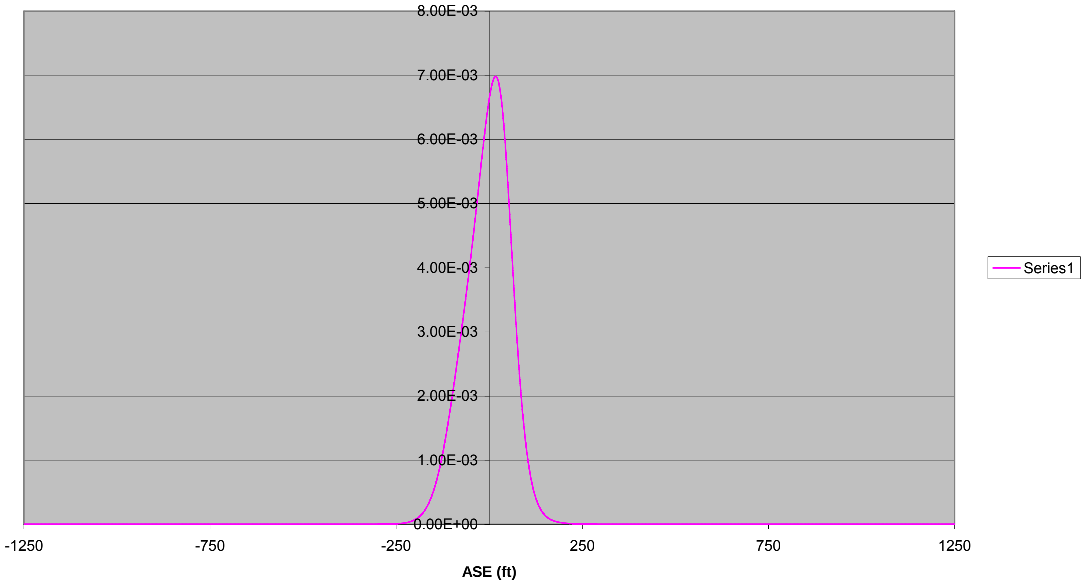
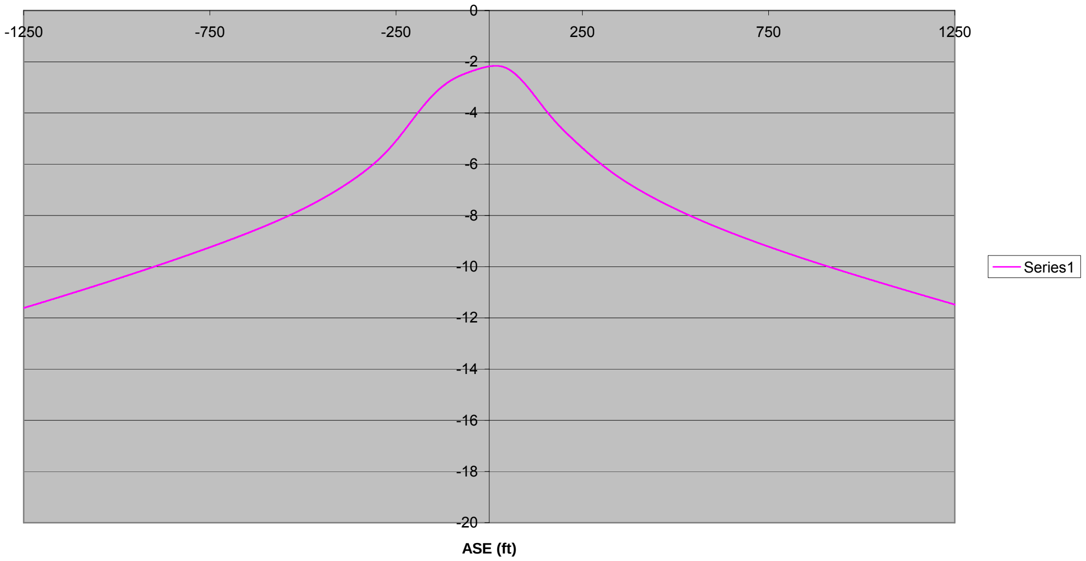


Figure A.2 Logarithm (base 10) of overall ASE probability density for the AFI RVSM POSC CRA aircaft population



A.5 FLIGHT TIME PROPORTIONS FOR AVERAGE AIRCRAFT DIMENSIONS AND CRUISING SPEED

Each ICAO 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 aircraft designator, 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 aircraft designator have been used as weighting factors for the calculation of average aircraft dimensions. The resulting weighted average dimensions are given in Table A.4.

An average cruising speed of 463.4 kts has been calculated.

Aircraft Dimension	Value (ft)
Length	171.49
Width	163.81
Height	50.29

Table A.4 Average aircraft dimensions for AFI RVSM POSC CRA aircraft population

Appendix B PROCESSING OF ARMA FORM 4 TRAFFIC FLOW DATA

B.1 INTRODUCTION

In order to estimate the passing frequency, States have been requested by the ARMA to submit monthly flight progress information (Form 4) for all aircraft in the flight level band FL290 – FL410 for the period September 2008 to September 2009 (13 months). Form 4 contains for each flight besides the aircraft type, operator, origin and destination, for all waypoints that flight passes the name of the waypoint, the time at which the aircraft passes and the flight level. Besides the traffic flow data, monthly movements for each FIR/UIR should have been provided through Form 2.

In the analysis only complete months after the introduction of RVSM have been included, i.e. October 2008 to September 2009 (12 months). In total, 121 months of Form 4 data have been processed. This corresponds to 34% of all months for which data should have been provided.

Before the passing frequency was computed some pre-processing was preformed on the information that has been received electronically. The following steps were performed:

1. The information for a flight was brought in a format which has all the information on one line. Based on the submitted forms, the conversions varied between FIR/UIRs. Some conversions were done using scripts while others were performed manually. The specifics for each FIR/UIR are given in Section B.2 below.
2. Only flights have been included that had flight progress complete information respect to waypoint name, time and flight level[8].
3. Only segments of the flights in the FL290-FL410 flight level band have been taken into account.
4. Segments with an unrealistic flight time (i.e. more than 4 hours) have been removed manually.

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[8] For some FIR/UIR only one flight level was given. It was assumed that this flight level holds for all waypoints. It is indicated in section B.2 if this has been the case.

After the pre-processing, the number of opposite passings and crossings on adjacent flight levels (1000 ft) were counted. The analysis showed that some of the opposite passings occurred with 2000 ft and even with 0 ft. Both situations should in practise not occur. A possible explanation is that for some FIR/UIRs only one flight level has been specified for the entire flight. Additionally, the flight levels have only been specified at the waypoints and a flight could have changed its flight level between two consecutive waypoints. Therefore, it is assumed that the opposite passings on 2000 ft, 1000 ft and 0 ft occurred at 1000 ft and are taken into account.

B.2 FIR/UIR SPECIFIC ASPECTS

Algiers

For 11 months, complete Form 4 and Form 2 data has been received. Compared to the number of flights reported in Form 2, Form 4 contains 64% of the flights. About 2% of the flights have been removed due to the pre-processing. Hence, the passing frequency was based on 63% of the flights.

The traffic flow data contains for each flight several waypoints. A closer analysis showed, however, that not all waypoints have been reported. This could result in an incorrect number of opposite passings and crossings. The artefacts of this problem were observed served in the analysis of the Algiers traffic flow data, but may exist for other FIR/UIRs as well.

Mauritius

For all 12 months, Form 2 and Form 4 information has been received. 100% of the flights reported in Form 2 were also present in Form 4. After pre-processing Form 4, 76% of the flights have been taken into account. Form 4 contains only one flight level for a specific aircraft. It was assumed that this flight level holds for all waypoints of that flight.

Roberts

For Roberts FIR, Form 2 and Form 4 information has been received for 7 months. 99% of the flights have been processed. After processing, 96% of the flights remained. Form 4 contains only one flight level for a specific aircraft. It was assumed that this flight level holds for all waypoints of that flight.

Luanda

For Luanda FIR no information was received.

Antananarivo

For Antananarivo FIR no information was received.

Harare

For all 12 months, Form 2 and Form 4 have been received. However, Form 4 was submitted in hardcopy and not electronically. Hence, no progress information was processed.

Accra

For Accra FIR no information was received.

Lusaka

Form 4 was received for 6 months. Form 2 data have not been received. The data contained two waypoints per flight (FIR entry and exit waypoint) and sometimes only one. Only one flight level has been given. It was assumed that this flight level holds for all waypoints of that flight. After pre-processing 99% of the flights remained.

Cairo

For Cairo FIR no information was received.

Gaborone

For 10 months both Form 2 and Form 4 has been received. Form 4 contained the same number of flights as provided in Form 2. The progress data contained at most 3 waypoints per flight with one flight level. After pre-processing, 94% of the flights remained.

Nairobi

For 7 months Form 2 and Form 4 has been received, but the forms contain only one or two waypoint per flight. The data from Form 2 and Form 4 matched and after pre-processing the flight progress data 99.7% of the flights remained.

Brazzaville

For Brazzaville FIR no information was received.

N'Djamena

For N’Djamena FIR only one Form 4 has been received in a pdf-format. The information in this form was insufficient to obtain progress information.

Kinsasha

For Kinsasha FIR no information was received.

Addis Ababba

For 9 months Form 4 has been submitted. No Forms 2 have been received. The traffic flow data contained only two waypoints (FIR entry and exit waypoint) and only one flight level has been specified. It was assumed that this flight level holds for both waypoints. After pre-processing, 86% of the flights remained.

Tripoli

No information has been received for the Tripoli FIR.

Lilongwe

Form 4 was received for the Lilongwe FIR for 7 months. No Form 2 was received. The flight progress data contained only one waypoint or two waypoints. After pre-processing 53% of the flight remained.

Dakar

Form 4 was received for 6 months and for 4 of these months also Form 2 was available. However, only one month (January 2009) contained 2 waypoints. After pre-processing 85% of the flights remained.

Beira

For 3 months Form 4 has been submitted. No Forms 2 have been received. After pre-processing 99.9% of the flights remained.

Windhoek

For 11 months, complete Form 4 information has been received. No Form 2 data has been received. Form 4 contained per flight two waypoints (FIR entry and exit waypoint) with one flight level. It was assumed that this flight level was valid for both waypoints. After pre-processing, 99.7% of the flights remain.

Niamey

No information has been received for the Niamey FIR.

Mogadishu

Form 4 and Form 2 have been received for 11 complete months. For all of the flights reported in Form 2 progress information in Form 4 is obtained. After pre-processing 99.3% of the flights remain.

Seychelles

No information has been received for the Seychelles FIR

Entebbe

For 1 month, Form 4 and Form 2 have been received (October 2009). However, many flights only contain waypoint. After pre-processing 43% of the flights remain.

Khartoum

No information has been received for the Khartoum FIR.

Dar Es Salaam

For the Dar Es Salaam FIR 5 months of flight progress information (Form 4) has been received. However, Form 2 was only provided for 2 months. After pre-processing 99.6% of the flights remained. Form 4 contains only one flight level for a specific aircraft. It was assumed that this flight level holds for all waypoints of that flight.

Asmara

For 9 months Form 4 information has been received. For 6 months Form 2 data has been received. However, the Form 2 data was identical for all 6 months. Therefore, it has been assumed that the data was incorrect. Each flight contained 2 waypoints only. Of the submitted Forms 4, 99.7% of the flights remained after pre-processing. Furthermore, the flight level was given in a XXX/YYY format. It is assumed that this flight level XXX holds for the first waypoint and YYY for the second waypoint.

Kano

Form 2 and Form 4 has been received for 6 months. 94% of the flight reported in Form 2 reports appear in Form 4. After pre-processing 99.9% of the flights remain. Form 4 contains only one flight level for each flight. Sometimes the flight level is given in an XXX/YYY format. If that was the case, XXX has been taken.

Johannesburg

No information has been received for the Johannesburg FIR.

Cape Town

No information has been received for the Cape Town FIR.