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Transition to the CNS/ATM Systems in the CAR and SAM Regions

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(Lima, Peru, 10 to 14 May 2005)

Agenda Item: 3: Review of RVSM issues in the CARSAM Regions

c) Safety and Airspace Monitoring Working Group

An Update to the Summary of the Reduced Vertical Separation Minimum (RVSM) Safety Assessment to Reflect the Operations Safety after the RVSM Implementation in CAR/SAM airspace in January 20th.

(Paper presented by the CARSAMMA)

Summary

This working paper presents an update to the summary of the results of applying the internationally accepted safety assessment process to introduction of the Reduced Vertical Separation Minimum (RVSM) into the airspace over the Caribbean and South American Regions. The paper provides the values of all collision risk model parameters, including those associated with application of the model to the case of intersecting traffic. The paper also presents risk estimates arising from large height deviations which Air Traffic Service providers in the Region have reported to the CARSAMMA. The paper also shows that the total risk estimate associated with the RVSM operation is still heavily influenced by the level of operational risk

References:

1. Manual on Implementation of a 300 m (1,000 ft) Vertical Separation Minimum Between FL 290 and FL 410 Inclusive, International Civil Aviation Organization, Doc 9574, Montreal, March 1992.
2. Review of the General Concept of Separation Panel, Sixth Meeting, Montreal, 28 November – 15 December 1988, ICAO Doc 9536, RGCSP/6, Volumes 1 and 2.
3. Review of the General Concept of Separation Panel, Seventh Meeting, Montreal, 30 October - 20 November 1990, ICAO Doc 9572, RGCSP/7.
4. WP/26 of the APATM/9, Lima, 15-19 November 2004

1. Introduction

1.1 At its Ninth Meeting the CAR/SAM RVSM Implementation Task Force considered the safety assessment associated with planned January 2005 implementation of the Reduced Vertical Separation Minimum (RVSM) in CAR/SAM airspace. This safety assessment was provided jointly by the CARSAMMA, the RVSM regional monitoring agency designated by the CAR/SAM Air Navigation Planning and Implementation Regional Group, and by the Task Force's Safety and Airspace Monitoring Working Group. After some adjusts and discussion the Task Force agreed that the safety assessment supported implementation of the RVSM in CAR/SAM airspace.

1.2 The safety assessment presented at RVSM/TF/9 indicated that the level of risk attributable to all causes for the planned implementation did not exceed the amount that can be tolerated in light of the agreed safety goal, the Target Level of Safety (TLS), considering the hypotheses adopted. In order to update this safety assessment, the CARSAMMA requested some States/International Organizations to collect traffic samples that would reflect the operations after the implementation.

1.3 The purpose of this paper is to provide a comprehensive update to the CAR/SAM safety assessment for consideration by the Task Force, addressing the implementation.

2. Background

2.1 This section of the paper provides summary information on the internationally accepted collision risk methodology applied in assessing the safety of RVSM operation. Included in this summary are discussions of the TLS and of the collision risk model, including sources of data from the CAR/SAM Regions used to estimate its parameters.

2.2 The TLS and RVSM Safety Assessment

2.2.1 The International Civil Aviation Organization's Review of the General Concept of Separation Panel (RGCSP) carried out the work leading to the guidance material of reference 1. At its Sixth Meeting (reference 2), the Panel adopted a TLS value of 2.5 fatal accidents per 10^9 flying hours as the safety goal to accompany RVSM introduction on a worldwide basis. This RGCSP Meeting marked the culmination of roughly five year's data collection and analysis work by several States, as well as substantial review and assessment of these results within the body. The focus of these efforts had been determination of the feasibility of implementing RVSM, with principal emphasis on assessing the ability of aircraft height-keeping systems to perform to a sufficiently high standard. At this Meeting, the Panel adopted requirements for an aircraft's height-keeping system – composed of an altimetry and an altitude-keeping system – which it judged both feasible and capable of satisfying the TLS.

2.2.2 At its Seventh Meeting (reference 3), the Panel examined new information indicating that large height deviations, arising principally from errors in granting or following ATC clearances, were occurring in portions of worldwide airspace where RVSM implementation was being contemplated. The Panel recognized that the risk associated with these events should also be taken into account when considering introduction of RVSM. Accordingly, the Panel agreed to change the overall TLS value to 5 fatal accidents per 10^9 flying hours and to recommend that this value be the upper bound on the risk of midair collision due to all causes in connection with the 1000-ft vertical separation standard above FL290. The Panel further agreed that the safety goal for aircraft height-keeping performance should remain at the previously established value of 2.5 fatal accidents per 10^9 flying hours. Finally, the Panel decided that, in assessing whether RVSM implementation would be safe, both the safety goal for aircraft height-keeping performance and the overall TLS value should be satisfied simultaneously.

2.2.3 Thus, as envisioned by the RGCSP, introduction of RVSM would be safe if:

a) collision risk due to all causes does not exceed 5 fatal accidents per 10^9 flying hours, and, at the same time,

b) collision risk due to aircraft height-keeping systems does not exceed 2.5 fatal accidents per 10^9 flying hours.

2.2.4 The Panel made clear that risk assessment in regard to aircraft height-keeping systems should take into account the effects of turbulence, loss of altitude hold and crew response to airborne collision-avoidance system alerts as well as errors arising from aircraft altimetry and altitude-keeping system performance. During safety assessment leading to successful 1997 North Atlantic (NAT) RVSM implementation, the ensemble of risk attributable to all of these causes came to be called "technical risk."

2.2.5 The Panel also made clear that risk assessment in regard to human error should take into account errors in which:

a) aircraft fail to climb or descend as required,

b) aircraft climb or descend without ATC clearance,

c) ATC clearances result in losses in specified aircraft separation standards,

d) entries into airspace at an incorrect flight level, and

e) any other error attributable to human oversight.

2.2.6 In the safety assessment process, the summation of risk attributable to all these causes above is termed "operational risk".

2.3 Collision Risk Modeling and RVSM Safety Assessment

2.3.1 Collision risk model for technical risk

2.3.1.1 References 2 and 3 contain detailed developments of the basic collision risk model (CRM) used in conjunction with RVSM implementation.

2.3.1.2 Reference 2 provides the model for the total technical risk, expressed as the sum of three basic types of collision risk, as:

$$N_{az} = N_{az}\,(\text{same}) + N_{az}\,(\text{opposite}) + N_{az}\,(\text{cross}) \qquad (1)$$

where the terms in (1) are defined in Table 1.

Parameter	Description
N_{az}	Expected number of accidents per aircraft flight hour resulting from collisions due to the loss of vertical separation between aircraft pairs at adjacent flight levels
N_{az}(same)	Expected number of accidents per aircraft flight hour between aircraft pairs flying on the same route in the same direction at adjacent flight levels
N_{az}(opposite)	Expected number of accidents per aircraft flight hour between aircraft pairs flying on the same route in opposite directions at adjacent flight levels
N_{az}(cross)	Expected number of accidents per aircraft flight hour between aircraft pairs flying on crossing routes at adjacent flight levels

Table 1. Technical Risk Model Parameter Definitions

2.3.1.3 The model form appropriate for the estimation of same-route "technical" risk reflecting the contributions of pairs of aircraft at adjacent flight levels where the members of pair are flying the same or in opposite directions, N_{az}(same) and N_{az}(opposite), is:

$$N_{az}(same) + N_{az}(opp) = P_z(S_z)P_y(0)\frac{\lambda_x}{S_x}\left\{\begin{array}{l} E_z(same)\left[\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{\dot{y}}|}{2\lambda_y} + \frac{|\overline{\dot{z}}|}{2\lambda_z}\right] + \\ E_z(opp)\left[\frac{2|\overline{V}|}{2\lambda_x} + \frac{|\overline{\dot{y}}|}{2\lambda_y} + \frac{|\overline{\dot{z}}|}{2\lambda_z}\right] \end{array}\right\} \quad (2)$$

where the parameters of the model presented in (2) are defined in Table 2, below.

CRM Parameter	Description
S_z	Vertical separation minimum.
$P_z(S_z)$	Probability that two aircraft nominally separated by the vertical separation minimum S_z are in vertical overlap.
$P_y(0)$	Probability that two aircraft on the same track are in lateral overlap.
λ_x	Average aircraft length.
λ_y	Average aircraft wingspan.
λ_z	Average aircraft height with undercarriage retracted.
S_x	Length of longitudinal window used to calculate occupancy.
$E_z(same)$	Same-direction vertical occupancy for a pair of aircraft at adjacent flight levels on same route.
$E_z(opp)$	Opposite-direction vertical occupancy for a pair of aircraft at adjacent flight levels on same route.
$\overline{\lvert\Delta V\rvert}$	Average relative along-track speed between aircraft on same direction routes.
$\overline{\lvert V\rvert}$	Average absolute aircraft ground speed.
$\overline{\lvert\dot{y}\rvert}$	Average absolute relative cross track speed for an aircraft pair nominally on the same track.
$\overline{\lvert\dot{z}\rvert}$	Average absolute relative vertical speed of an aircraft pair that have lost all vertical separation

Table 2. Same-Route Technical Risk Model Parameter Definitions

2.3.1.4 The term "occupancy" as used in table 2 refers to aircraft pairs which are "proximate" in the sense that they are within some arbitrary distance or time - for example, 80 nm or 10 minutes – of each other on the route at adjacent flight levels. This proximity is used as a measure of the relative density of aircraft pairs in airspace, with a higher relative density leading to a higher estimate of risk. The term "overlap" refers to the event that the centers of mass of two aircraft in a given – along-track, cross-track or vertical - are closer together than twice the size of an aircraft – length, wingspan or height – in that dimension.

2.3.1.5 Same and opposite direction passing frequencies, $N_x(same)$ and $N_x(opp)$, are related to the same and opposite direction vertical occupancies through the following relations:

$$N_x(same) = \frac{\lambda_x}{\hat{S}_x} E_z(same) \frac{\overline{|\Delta V|}}{2\lambda_x}$$

and

$$N_x(opp) = \frac{\lambda_x}{\hat{S}_x} E_z(opp) \frac{\overline{|V|}}{\lambda_x}$$

where the parameters are identical to those described in the previous table.

2.3.1.6 The CARSAM airspace requires estimation of technical risk at route intersections, N_{az}(cross). The following CRM form is appropriate for this estimation:

$$N_{az}(cross) = \begin{cases} \sum_{i=1}^{n} P_h(\theta_i) P_z(S_z) \dfrac{\pi S_h}{2\left|\overline{\dot{h}(\theta_i)}\right|} \dfrac{1}{t_F} \dfrac{2K(\theta_i)}{N} \left[\dfrac{2\left|\overline{\dot{h}(\theta_i)}\right|}{\pi \lambda_h} + \dfrac{\left|\overline{\dot{z}}\right|}{2\lambda_z} \right] & for \dfrac{\pi S_h}{2\left|\overline{\dot{h}(\theta_i)}\right|} < t_F \\ \sum_{i=1}^{n} P_h(\theta_i) P_z(S_z) \dfrac{2K(\theta_i)}{N} \left[\dfrac{2\left|\overline{\dot{h}(\theta_i)}\right|}{\pi \lambda_h} + \dfrac{\left|\overline{\dot{z}}\right|}{2\lambda_z} \right] & for \dfrac{\pi S_h}{2\left|\overline{\dot{h}(\theta_i)}\right|} \geq t_F \end{cases} \quad (3)$$

where the parameters of the model presented in (3) are defined in Table 3, below.

CRM Parameter	Description
S_z	Vertical separation minimum.
$P_z(S_Z)$	Probability that two aircraft at adjacent flight levels nominally separated by the vertical separation minimum S_Z are in vertical overlap.
θ	Angle formed at the intersection of two crossing-routes
N	The number of groups made from crossing routes with similar angles of intersection
$P_h(\theta)$	Probability of horizontal overlap for two aircraft at adjacent flight levels on routes crossing at angle θ
S_h	Planned horizontal separation
λ_h	Larger of the average aircraft wingspan or fuselage length
λ_z	Average aircraft height with undercarriage retracted
S_x	Length of longitudinal window used to calculate occupancy.
$K(\theta)$	Number of proximate aircraft pairs on routes that cross at angle θ.
T_F	Average duration of flights on the crossing routes
N	Number of flights on the crossing route during the time period for which $T_h(\theta)$ hours of proximity were estimated
$T_h(\theta)$	Total time that aircraft pairs on routes that cross at angle θ are horizontally proximate.
$\left|\overline{\dot{h}(\theta)}\right|$	Average relative horizontal speed during overlap for aircraft pairs on routes with crossing angle θ.
$\left|\dot{z}\right|$	Average absolute relative vertical speed of an aircraft pair that have lost all vertical separation

Table 3. Crossing-Route Technical Risk Model Parameter Definitions

2.3.2 Collision risk model for operational risk

2.3.2.1 The CRM appropriate for estimation of risk due to large height deviations (LHD) resulting in errors which are whole multiples of the vertical separation standard is a variation of equation (2). The proportion of the total flying time spent at incorrect levels, P_i, may be interpreted as the probability that an aircraft is flying at an incorrect level. The proportion of the total flying time spent at incorrect levels, P_i, is determined by summing the individual times for each LHD and dividing the total system flight time over the calendar interval during which LHDs were tallied. For this CAR/SAM post implementation safety assessment, the total system flight time is estimated as the total system flight time computed from the 14 days sample of traffic movements received from the CAR/SAM flight information regions (FIRs) multiplied by twelve.

2.3.2.2 To determine the probability of vertical overlap, $P_z(1000)$, it is necessary to multiply P_i by the probability that two aircraft nominally flying at the same level are in vertical overlap, $P_z(0)$. The vertical overlap probability arising from errors resulting in deviations of integral multiples of the vertical separation standard is, therefore, given by:

$$P_z\,(n \times S_z) = P_z\,(0)\,P_i \qquad (5)$$

Having determined the vertical overlap, $P_z(S_z)$, the collision risk for such deviations can be estimated using equation (2).

2.4 Traffic Movement Data and the RVSM Safety Assessment

2.4.1 At RVSM/TF/9, the Task Force recognized that with the change in the airspace structure from a vertical separation standard of 2000ft to a 1000ft separation standard the safety of the operations should be reassessed. Accordingly, the Task Force agreed that a further sample of traffic from the FIRs representing the biggest passing frequencies where RVSM would be implemented should be collected for the period 13-26 February 2005. The CARSAMMA received traffic samples from 7 FIRs.

2.5 Height-Keeping Performance Monitoring and the RVSM Safety Assessment

2.5.1 Estimation of technical risk requires the availability of information describing errors in aircraft altimetry and altitude-keeping systems. The CARSAMMA used the same source material for this information as was employed in the monitoring of safety used in the NAT Region by the Central Monitoring Agency (CMA) added with the LHD reported to CARSAMMA by the CAR/SAM ATS providers.

3. Discussion

3.1 This section of the working paper describes the process and source material for estimating values for each of the parameters in tables 1 and 2, and provides those values. Where appropriate, this section also references Task Force decisions or precedent from the CAR/SAM RVSM implementation safety assessment which influenced a choice of a value.

3.2 Aircraft size

3.2.1 The aircraft length, wingspan and height shown in table 4, was used in estimating risk for the CAR/SAM RVSM safety assessment. These values were estimated from the traffic sample.

Aircraft	**λ_z = Height (nm)**	**λ_x = Length (nm)**	**λ_y = Wingspan (nm)**
Average Aircraft	0,0064265	0,0211091	0,0188960

Table 4. Aircraft Size Used in CAR/SAM RVSM Safety Assessment

3.2.2 Estimation of the risk for proximate aircraft pairs at adjacent flight levels on crossing routes requires the diameter of the disk representing the shape of an aircraft in the horizontal plane, $\lambda_{h.}$ This value has been taken as 0,0211091nm for average aircraft in the CAR/SAM airspace.

3.3 Relative aircraft speeds

3.3.1 Table 7 presents the values and sources for estimation of relative aircraft speeds used in the CAR/SAM safety assessment. The values of average relative along-track speed and average absolute aircraft ground speed are those obtained from the analysis of the traffic sample. The CARSAMMA used the value of relative cross-track speed already used in the safety assessment of other Regions. The value so obtained is, 20 knots.

3.3.2 The value for the relative horizontal-plane speed of a pair of aircraft on crossing routes as they are in horizontal overlap was determined from the angle of route intersections in the route system analyzed assuming that the speed of an individual aircraft is 443.78 knots.

3.3.3 The value for relative vertical speed shown in table 5, 1.5 knots, is that used in both the NAT and Pacific RVSM safety assessments.

Parameter Symbol	Parameter Definition	Parameter Value	Source for Value
$\overline{\|\Delta V\|}$	Average relative along-track speed between aircraft on same direction routes	26.31 knots	Estimated from CAR/SAM sample
$\overline{\|V\|}$	Average absolute aircraft ground speed	443.78 knots	Estimated from CAR/SAM sample
$\overline{\|\dot{y}\|}$	Average absolute relative cross track speed for an aircraft pair nominally on the same track	20 knots	Value used in NAT RVSM safety assessment
$\overline{\|\dot{h}(\theta)\|}$	Average relative horizontal speed during overlap for aircraft pairs on routes with crossing angle varying from 5 to 175 degrees	Depends on the angle of intersection	Corresponds to average aircraft speed of 443.78 knots
$\overline{\|\dot{z}\|}$	Average absolute relative vertical speed of an aircraft pair that have lost all vertical separation	1.5 knots (all traffic flows)	Value used in NAT and Pacific RVSM safety assessments

Table 5. Relative Aircraft Speeds Used in CAR/SAM RVSM Safety Assessment

3.4 Probability of Lateral Overlap

3.4.1 The CARSAMMA used the 0.3 NM as a s.d. of lateral keeping to estimate a value for $P_y(0)$. The result of this estimation is a value of 0.0445.

3.5 Vertical Occupancies

3.5.1 It should be recalled that two aircraft are said to be proximate vertically, as this term relates to collision risk, if the aircraft are assigned to adjacent flight levels. Based on the operational use of the routes in CAR/SAM Regions, it is clear that aircraft pairs may be flight-planned within 1000 ft vertically on the same route or crossing route when the RVSM is applied. The CARSAMMA processed the traffic movement data in order to determine the number of proximate pairs of aircraft seen from 13-26 February 2005 in the 7 FIR analyzed. The same-direction and opposite-direction passing frequencies for aircraft operating on adjacent flight levels and the same route or the vertical occupancy for aircraft operating on crossing routes were estimated using this sample of traffic movements.

3.5.2 The estimate for the vertical occupancy for the RVSM was derived from the traffic samples received from the 7 CAR/SAM FIR. The vertical occupancy is estimated to be 0.5721.

3.5.3 The estimates for the same-direction and opposite-direction passing frequencies were derived from the traffic samples received from the 7 CAR/SAM FIR. The same-direction and opposite-direction passing frequencies are estimated to be 0.1167 and 0.2509 respectively.

3.5.4 An approximation of $P_h(\theta)$, the probability of horizontal overlap for aircraft-pairs at adjacent flight levels on routes crossing at angle θ, was determined. For the safety assessment on crossing routes it was used the value of $P_h(\theta)$ combined of all crossings with different angles from 5 to 175 degrees with a 5° interval.

3.6 Probability of Vertical Overlap Attributable to Technical Height-Keeping Performance

3.6.1 As noted previously, technical risk is considered to arise from the effects of turbulence, loss of altitude hold and crew response to airborne collision avoidance system alerts - as well as from errors in aircraft altimetry and altitude-keeping system performance. Hence, estimation of the probability of vertical overlap must account for contributions to vertical error arising from all of these sources.

3.6.2 CARSAMMA compared the results of monitoring aircraft height-keeping performance in the NAT and in the CARSAM Region and found them to be similar. As a result, the CARSAMMA has used the estimates of ASE from the NAT in the CARSAM RVSM safety assessment.

3.6.3 LHD attributable to turbulence, emergency descent through flight levels on route centerline without clearance and response to collision avoidance system advisories have the potential to adversely influence the probability of vertical overlap due to technical height-keeping performance. For the CARSAM RVSM implementation safety assessments, these types of errors, in contrast to errors associated with the height-keeping systems of aircraft with State RVSM approval, were found to lead to larger values of this important model parameter.

3.6.4 The Task Force has consistently called on ATS providers, airspace users and others to forward monthly reports of these sorts of LHD to the CARSAMMA. While not all ATS units have provided these monthly reports, those received by the CARSAMMA for the time period February 2004 through January 2005 have highlighted just a few significant instances of LHD attributable to turbulence, emergency descents without ATC clearance or responses to collision avoidance system advisories. Because of the important effect of this parameter on vertical collision risk, the CARSAMMA has taken a cautious approach to specifying its value. This approach considered the LHD from the NAT Region added to the ones from the 7 CAR/SAM FIR as shown in the table 6 below.

$P_Z(1000)$	$P_Z(0)$	$P_y(0)$
5.6811×10^{-9}	0.4070	0.0445

Table 6. Results of the vertical overlap probability

3.7 Probability of Vertical Overlap Attributable to Instances of Mistakes in Granting or Following an ATC Clearance

3.7.1 It will be recalled that estimation of P_z (1000) due to large height deviations requires determination of two quantities: (1) the proportion of total flying time spent at incorrect levels, P_i, and (2) the probability that two aircraft nominally flying at the same level are in vertical overlap, P_z (0).

3.7.2 System risk is directly proportional to the amount of total flight time spent at the wrong flight levels. Estimation of this time is a key determinant of whether or not the estimated system risk will meet the TLS.

3.7.3 Operational errors are likely to result in aircraft operating at whole number multiples of the vertical separation standard from their assigned flight level. Sometimes the aircraft levels in wrong flight level in the same direction of the flow and sometimes in the opposite direction of the flow. That fact is taken into account in the collision risk analysis. The proportion of flying time spent at incorrect levels, P_i, is determined as the ratio of the amount of time spent at incorrect levels to the total amount of flying time in CARSAM airspace during the period when the wrong-flight-level events occurred. As was the case in identifying large vertical errors associated with technical height-keeping performance, the CARSAMMA used the 12-month interval February 2004 through January 2005 as the period for analysis.

3.8 Technical Risk

3.8.1 The goal is to verify if the TLS of 2.5×10^{-9} fatal accidents per aircraft flying hours is satisfied according to a significant level of confidence**.** The technical risk that represents the CARSAM Region was evaluated considering the movement of three different adjacent FIR from the CAR Region and four from the SAM Region as it was done in the pre-implementation safety analysis. FIR Havana, Central America and Panama and Curitiba, Brasília, Recife and sector Manaus from Amazônica FIR. In the table below it is shown the parameters of the Technical Collision Risk Model for the pre-implementation (FV) and post-implementation (FIO) phases for reference.

Parameters	AIRSPACE					
	CARIBBEAN		SOUTH AMERICA		CAR/SAM	
	IOP	VP	IOP	VP	IOP	VP
$P_y(0)$	0,0456	0,0455	0,0440	0,0462	0,0445	0,0459
$P_z(0)$	0,4240	0,4193	0,3987	0,4084	0,4070	0,4078
$P_z(1000)$	$8{,}0640\times10^{-9}$	$9{,}7798\times10^{-9}$	$4{,}5292\times10^{-9}$	$3{,}3289\times10^{-9}$	$5{,}6811\times10^{-9}$	$5{,}2744\times10^{-9}$
$\lambda_x\ (MN)$	0,0217718	0,0217696	0,0208002	0,0217465	0,0211091	0,0217555
$\lambda_y\ (MN)$	0,0193459	0,019318	0,0186863	0,019698	0,0188960	0,0194945
$\lambda_z\ (MN)$	0,0066127	0,0065586	0,0063397	0,0066540	0,0064265	0,0066167
$\lambda_h\ (MN)$	0,0217718	0,0217696	0,0208002	0,0217465	0,0211091	0,0217555
$\left\|\overline{V}\right\|\ (MN/h)$	467,62	469,93	432,67	442,33	443,78	453,87
$\left\|\overline{\Delta V}\right\|\ (MN/h)$	0,0	20	26,31	31,32	26,31	31,31
$\left\|\overline{\dot{y}}\right\|\ (MN/h)$	20	20	20	20	20	20
$\left\|\overline{\dot{z}}\right\|\ (MN/h)$	1,5	1,5	1,5	1,5	1,5	1,5
N_x*(oposto)*	0,2751	0,6049	0,2228	0,3098	0,2509	0,4810
N_x*(mesmo)*	0,0	0,0	0,0117	0,02534	0,1167	0,02528
E_z*(cruzamento)*	0,2353	0,1038	0,7807	0,3902	0,5721	0,2877
S_x *(MN)*	80	80	80	80	80	80

Table 7. Summary of the technical vertical collision risk parameters

3.8.2 The collision risk was evaluated separately to the CAR and SAM Regions and for the total CARSAM airspace, as it is shown in table 8 below.

Caribbean		**South America**		**CAR/SAM**	
IOP	**VP**	**IOP**	**VP**	**IOP**	**VP**
$0{,}112\times10^{-9}$	$0{,}282\times10^{-9}$	$0{,}081\times10^{-9}$	$0{,}069\times10^{-9}$	$0{,}098\times10^{-9}$	$0{,}145\times10^{-9}$

Table 8. Technical collision Risk

3.8.3 Effect of the traffic growing

3.8.3.1 The evolution of collision risk in the period 2004 to 2015 was estimated to traffic growing annual rate of 8 % that direct affects the passing frequency value. The forecasts were shown in the fig. 1, 2 e 3, below. Note that the technical risk, until 2015, will be below the limit of 2.5×10^{-9}.

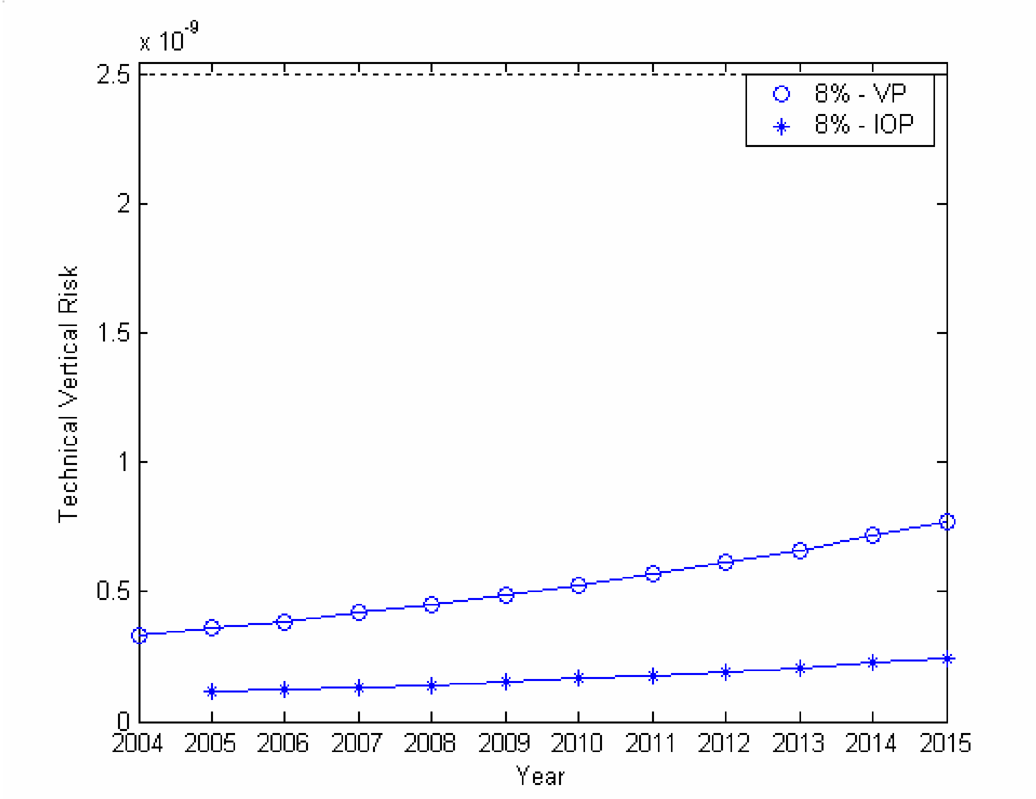

Fig 1 Technical Collision Risk forecast

(Havana, Central American and Panama)

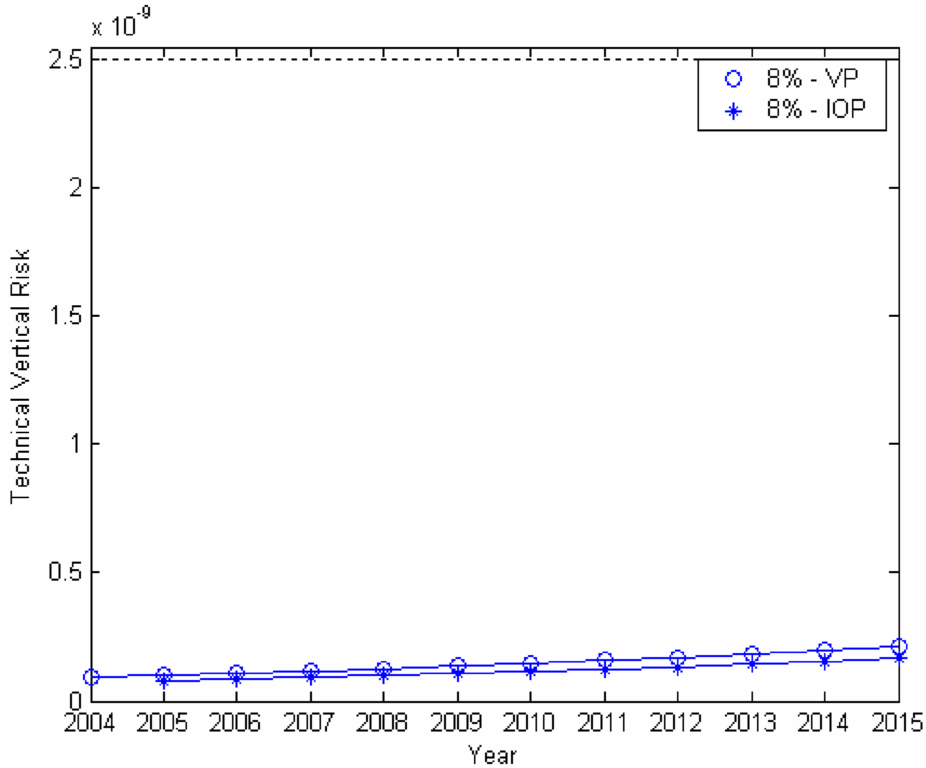

Fig 2 Technical Collision Risk forecast

(Curitiba, Brasília, Recife and Sector Manaus (FIR Amazônica))

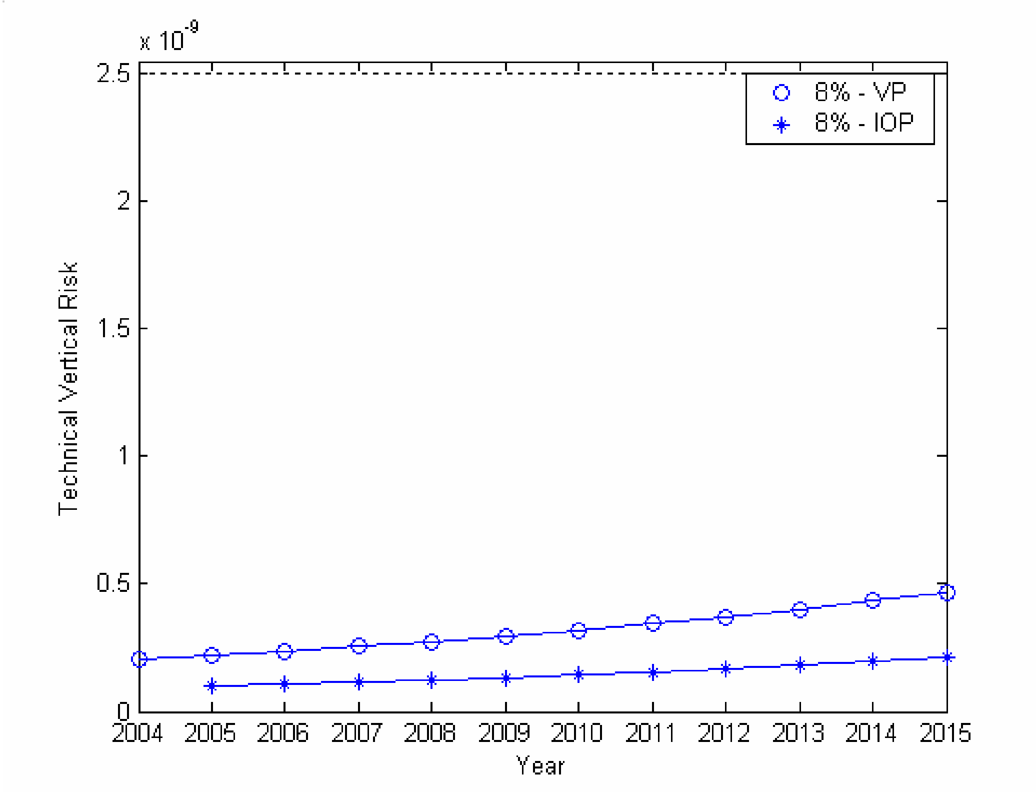

Fig 3 Technical Collision Risk forecast

(CARSAM)

3.9 Operational Risk

3.9.1 The CRM for operational risk was developed in connection with the CARSAM RVSM implementation. As such, it reflects certain operational characteristics of the CARSAM that are not common to other airspaces.

3.9.2 The LHD identified through the reports received by CARSAMMA may be due to operational procedures, adverse meteorological conditions or emergency procedures due to equipment failures or pressurization and can be divided in four main group types:

a) ATC-pilot loop errors and incorrect clearances;
b) aircraft contingency events;
c) deviations due to meteorological effects; and
d) deviations due to ACAS.

3.9.3 The errors definition according to the causes was based on the CMA classification and presented on the paper related to LHD on this meeting. The table 9 below shows the 7 large deviations (equal to or larger than 1000ft) for the region analyzed, considered operational and received by CARSAMMA, which types and causes are described in the table 10. In the table 9, the last four columns are referred to the numbers of crossed flight levels, n^{nc}, and the number of aircrafts leveling in wrong flight levels, n^{ne} in the same (S) and opposite (Op) direction of flow.

date	time	Acft type	AWY	Fix of LHD	FL	LHD	time (sec)		Error type	info	FIR	State	n^{ne}		n^{nc}	
							S	Op					S	Op	S	Op
03/02/04	21:30	-	UW5	-	-	-1000		20	**H**	nil	SBCW	SB	0	1	0	0
08/05/04	04:50	-	UW10	RESUS	350	1100		300	**B**	Mode C	SBRE	SB	0	1	0	0
13/05/04	23:30	B737	UZ5	NELSO	310	-1000		90	**E**	Mode C	SBRE	SB	0	1	0	0
16/06/04	18:32	-	UM788/UM792	CGR	370	-2000	90		**M**	Mode C	SBCW	SB	1	0	0	0
23/06/04	10:44	-	UM540	OSAMU	330	4000	180		**A**	Mode C	SBCW	SB	1	0	1	2
12/07/04	16:37	-	UA314	ETANO	310	4000	300		**M**	Mode C	SBCW	SB	1	0	0	0
22/07/04	05:53	-	UA308	MLO	330	-4000	90		**M**	Mode C	SBCW	SB	1	0	0	0
Total							**660**	**410**					**4**	**3**	**1**	**2**

Table 9. Operational LHD (equal to or more than 1000ft) received by CARSAMMA.

Type of Error	Cause of the LHD
A	Failure to climb/descend as cleared
B	Climb/descend without ATC clearance
E	Deviation due to equipment failure
H	Aircraft not approved for operation in RVSM restricted airspace
M	Error in ATC-unit-to-ATC-unit transition message

Table 10. Classification of the received LHD

3.9.4 Classification of errors to the risk evaluation

The causes of the group errors "a" and "b" were classified and contribute to two different events:

- *Aircraft leveling in wrong flight level*;

  According to the table 9, 7 aircrafts had levelled in wrong flight level, reaching 1070 seconds with the average time spent in wrong flight level of 0.04246 hours and three of them in the opposite direction of the flow.

- *Aircraft climbing/descending through one or more flight levels*.

  According to the table 9, it has occurred only 3 crossings of flight levels without ATC clearance and two of them in the opposite direction of the flow.

All de deviation due to non severe meteorological effects (more than 300ft and less than 1000ft) were considered in the AAD distribution.

3.9.5 Determination of the appropriate parameter values to each group of errors classified

The calculations were done separately by Region (CAR and SAM) and to the whole CARSAM airspace. To both airspaces it were used the same data (Table 11) of aircrafts levelling in wrong flight level n^{ne}, number of flight levels crossed without clearance n^{nc} and average time spent in wrong flight level $\bar{t}_{ne}$. The climb/descend rate $|\bar{\dot{z}}_c|$, were assumed to be the 10 Kt.

parameter	CAR		SAM		CAR/SAM	
	IOP	VP	IOP	VP	IOP	VP
n^{ne}	0,0	4,29	7	6,71	7	11
n^{ne}_{same}	0,0	3,51	4	5,49	4	9
n^{ne}_{op}	0,0	0,78	3	1,22	3	2
n^{nc}_{same}	0,0	0,39	1	0,61	1	1
n^{nc}_{op}	0,0	0,78	2	1,22	2	2
n^{nc}	0,0	1,17	3	1,83	3	3
$\bar{t}^{ne}_t$	0,0	0,08535 *h*	0,04246 h	0,08535 *h*	0,04246 h	0,08535 *h*
$\bar{t}^{ne}_{same}$	0,0	0,0944 h	0,04583 h	0,0944 h	0,04583 h	0,0944 h
$\bar{t}^{ne}_{op}$	0,0	0,0444 h	0,037963 h	0,0444 h	0,03796 h	0,0444 h
t^{ne}_{same}	0,0	19,89 min	11 min	31,11 min	11 min	51,00 *min*
t^{ne}_{op}	0,0	2,08 min	6,83 min	3,25 min	6,83 min	5,33 *min*
t^{ne}_t	0,0	21,97 *min*	17,83 min	34,36 *min*	17,83 min	56,33 *min*
$\lvert\bar{\dot{z}}_c\rvert$	10 kt	10 kt	10 kt	10 kt	10 kt	10 kt

Table 11. Operational errors data

In the table 12 below it is shown the group errors parameters classified according to the application for the CAR/SAM Regions where: $P_z^{ne}(1000)$ is the vertical overlap probability due to an aircraft levelling in wrong flight level and $P_z^{nc}(1000)$ is vertical overlap probability due to an aircraft that cross one or more flight levels without ATC clearance. The parameters, α^{ne} and α^{nc}, are referred to the errors rate for aircraft levelling in wrong flight level and aircraft crossing a flight level without ATC clearance, respectively. The product $\alpha^{ne} \times \bar{t}^{ne}$ is the proportion of flying time spent in wrong flight level.

PARAMETER	CAR		SAM		CAR/SAM	
	IOP	VP	IOP	VP	IOP	VP
T (hours)	*200.520,0*	297.787,46	*442.054,3*	465.770,14	*642.574,3*	763.557,6
α^{ne}	0,0	$1{,}4406\times10^{-5}$	$1{,}5835\times10^{-5}$	$1{,}4406\times10^{-5}$	$1{,}0894\times10^{-5}$	$1{,}4406\times10^{-5}$
α^{nc}	0,0	$3{,}9290\times10^{-6}$	$6{,}7865\times10^{-6}$	$3{,}9290\times10^{-6}$	$4{,}6687\times10^{-6}$	$3{,}9290\times10^{-6}$
$Q = \alpha^{ne} \times \bar{t}^{ne}$	0,0	$3{,}9289\times10^{-6}$	$6{,}7237\times10^{-7}$	$3{,}9289\times10^{-6}$	$4{,}6255\times10^{-6}$	$3{,}9289\times10^{-6}$
$P_z(0)$	0,4232	0,4193	0,3987	0,4084	0,4070	0,4078
$P_z^{ne}(1000)$	0,0	$5{,}1595\times10^{-7}$	$2{,}6804\times10^{-}$	$5{,}0216\times10^{-7}$	$1{,}8825\times10^{-7}$	$5{,}0147\times10$
$P_z^{nc}(1000)$	0,0	$4{,}4049\times10^{-9}$	$8{,}6049\times10^{-9}$	$2{,}8572\times10^{-9}$	$6{,}0007\times10^{-9}$	$1{,}7331\times10^{-9}$

Table 12. Parameters of the operational errors group classified

3.10 Risk Assessment for Implementation of the RVSM in the CAR/SAM Regions

3.10.1 This section will provide an estimate of risk associated with all causes in connection with the RVSM implementation. The technical and operational risk values are combined to estimate the total risk attributable to all causes for the system.

3.10.2 The vertical collision risk was calculated with the Reich Collision Risk Model associated to each group of LHD. In the table 13 it is presented the values of risk for the resulting models:

- N_{az}^{tec} is the technical vertical risk;
- N_{az}^{ne} is the vertical risk due to aircraft leveling in wrong flight level;
- N_{az}^{nc} is the vertical risk due to an aircraft crossing a flight level without ATC clearance;
- N_{az}^{ACAS} is the vertical risk due to ACAS advisories; and
- N_{az} is the vertical collision risk due to all causes or the total risk.

Risk	CAR		SAM		CAR/SAM		*TLS*
	IOP	VP	IOP	VP	IOP	VP	
N_{az}^{Tec}	$1{,}1\times10^{-10}$	$2{,}8\times10^{-10}$	$8{,}1\times10^{-11}$	$6{,}9\times10^{-11}$	$9{,}8\times10^{-11}$	$1{,}5\times10^{-10}$	$5{,}0\times10^{-9}$
N_{az}^{ACAS}	0	$1{,}8\times10^{-10}$	0	$5{,}2\times10^{-11}$	0	$1{,}1\times10^{-10}$	
N_{az}^{ne}	0,0	$1{,}7\times10^{-9}$	$3{,}0\times10^{-9}$	$3{,}6\times10^{-9}$	$1{,}8\times10^{-9}$	$3{,}4\times10^{-9}$	
N_{az}^{nc}	0,0	$1{,}0\times10^{-10}$	$1{,}2\times10^{-10}$	$7{,}5\times10^{-11}$	$7{,}6\times10^{-11}$	$9{,}6\times10^{-11}$	
N_{az}^{Total}	$1{,}1\times10^{-10}$	$2{,}2\times10^{-9}$	$3{,}2\times10^{-9}$	$3{,}8\times10^{-9}$	$2{,}0\times10^{-9}$	$3{,}7\times10^{-9}$	

Table 13 Collision Risks to the CARSAM Region

3.10.3 As can be seen the total risk for the CARSAM Region is approximately 2.5 times smaller than the agreed TLS.

3.10.4 It is necessary to remark that this total risk was strongly influenced by seven LHD. Most of them due to error in ATC-unit-to-ATC-unit transition message.

4. Results and Conclusions

4.1 This paper provides estimates of technical, operational, and total risk for the RVSM operation in the airspace of the CARSAM Regions in the post-implementation phase.

4.2 As can be seen from the values presented above, the technical risk estimated for the combined RVSM implementations is 0.098×10^{-9}. This estimate satisfy the agreed TLS value of no more than 2.5 x 10^{-9} fatal accidents per flight hour due to the loss of a correctly established vertical separation standard of 1000 ft.

4.3 The total risk estimated for the combined RVSM implementation for the CARSAM airspace is 2.0×10^{-9}. The total risk estimate associated with the combined RVSM implementation satisfies the agreed TLS value of no more than 5.0 x 10^{-9} fatal accidents per flight hour due to all causes.

4.4 The maximum passing frequency gives an indication of the location where potentially can happen the maximum risk. The pick for the region happened in Recife FIR (SBRE), in the route segment SAGAZ-LIBRA of the airway UW58, and its value was of 1.343. The second highest pick happened in Havana FIR, in the segment TANIA-UCA in the airway UG430 with the value of 1.226.

4.5 The total number of flown hours considered for the analyses of risk evaluation for the CAR/SAM Regions corresponds to the total of hours of flight of Havana, Central America and Panama FIR of the Caribbean Region, together with Curitiba, Brasília, Recife FIR and sector Manaus of Amazônica FIR of the South American Region.

4.6 The evaluation of the lateral overlap probability, $P_y(0) = 0.0445$, was done with a model based on an analytic distribution described by a double exponential function due to the lack of data on lateral deviations. In consequence, in the next evaluation of RVSM the supervision of this parameter should be made through the collection of the lateral deviations, in agreement with the monitoring program.

4.7 Although data of vertical deviations have not been integrally obtained of the CAR/SAM Regions to determine the probability distribution function for TVE, the cumulative considerations taking the obtained typical deviations of the NAT Region, more the typical deviations collected in the CAR/SAM Regions, constitute a conservative approach for the calculation of the vertical overlap probability. The obtained value is below the established limit, however, as necessary and pertinent measure, the verification of the probability should be made through programmed collections of the typical and atypical deviations happened in the CAR/SAM Regions.

4.8 The technical vertical collision risk was evaluated separately for the Caribbean, South American and for the whole airspace of the CAR/SAM Regions. All the considered cases are below the TLS.

4.9 The evaluation of the growth of the technical risk for the CAR/SAM Regions, due to the growth of the air traffic, was accomplished for annual growth rates of 8% a year, up to 2015. The forecast shows that the technical risk, up to 2015, will be below the TLS of 2.5×10^{-9}.

4.10 The main operational errors (LHD) collected in the CAR/SAM Regions in the period from February 2004 to January 2005 are related to transition messages between ATC Units.

4.11 The classification of the operational errors for evaluation purpose resulted in: 7 aircrafts leveling in wrong level, reaching 1070 seconds, with an average time spent in wrong level of approximately 0.04246 hours; three crossings of flight level without ATC clearance and no deviations due to ACAS. All the deviations due to not severe meteorological effects (above 300 feet and below 1000 feet) were considered in the atypical AAD values.

5. Recommendations

5.1 The recommendations described in this section have as objective help in the efforts that should be done in the next tasks associated with the collision risk evaluation after the RVSM implementation in the CAR/SAM Regions.

5.2 Data On the Traffic Flow - Received data from several States could not be treated due to different reasons, from the non understanding of how the data should be transcribed in the spreadsheets until inconsistency of data. It is advisable that before the collection of data States pay attention to the guidelines developed for this procedure and approved by the RVSM TF.

5.3 Data on the Vertical Deviations due to Operational Errors - Information on these types of events is obtained through ATC or pilot's reports. Unfortunately important data on these deviations like number of crossed flight levels, time spent in non authorized flight level are rarely informed. As these deviations are consequences of errors or contingency actions a work plan should be developed to obtain these data with a high level of confidence.

5.4 That States/International Organizations and airlines continue to do efforts in obtaining and informing the LHD to the CARSAMMA.