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Analysis of Area Navigation (RNAV-2) En Route Separation with Conventional Routes Without Radar Surveillance Including Impromptu Routes

Flight Systems Laboratory
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Flight Systems Laboratory
Flight Technologies and Procedures Division
Flight Standards Service

Analysis of Area Navigation (RNAV-2) En Route Separation with Conventional Routes Without Radar Surveillance Including Impromptu Routes

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12. Abstract

The purpose of this study is to provide a collision risk assessment of centerline-to-centerline en route separation between Area Navigation (RNAV-2) routes with separation for both opposite and same direction traffic and conventional VOR routes under scenarios without radar surveillance and to provide a route boundary risk assessment for straight, impromptu RNAV routes which are not under radar surveillance as long as the routes are point-to-point routes between published waypoints.

The analysis is based on previous studies, [1] and [2], and on the Terminal Instrument Procedures standard [3], Chapter 17 material on conventional route construction criteria.
The study uses statistical distributions similar to those developed in [1] and [2] to model the likelihood of adjacent aircraft intersecting laterally. Using those models, it estimates the probability of collision.

The study develops a general risk model that can be used to determine the probability of collision between aircraft on conventional VOR routes and suitably equipped RNAV FMS aircraft on parallel routes laterally separated by any centerline-to-centerline distance, longitudinally separated by any distance, flying opposite or same directions, with straight segments and without radar surveillance.

This study develops risk estimates for scenarios in which the target aircraft's navigation is assumed to comply with the AC 90-100A RNAV standard only and for aircraft using GPS navigation specifically.

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Executive Summary

The purpose of this study[1] is to provide a collision risk assessment of centerline-to-centerline en route separation between Area Navigation (RNAV-2) routes with separation for both opposite and same direction traffic and conventional VOR routes under scenarios without radar surveillance. It also provides a route boundary risk assessment for straight, impromptu RNAV routes which are not under radar surveillance as long as the routes are point-to-point routes between published waypoints.

The analysis is based on previous studies, [1] and [2], and on the Terminal Instrument Procedures standard [3], Chapter 17 material on conventional route construction criteria. This study uses statistical distributions similar to those developed in [1] and [2] to model the likelihood of adjacent aircraft intersecting laterally. Using those models, it estimates the probability of collision.

General risk model was developed that can be used to determine the probability of collision between aircraft on conventional VOR routes and suitably equipped RNAV FMS aircraft on parallel routes laterally separated by any centerline-to-centerline distance, longitudinally separated by any distance, flying opposite or same directions, with straight segments and without radar surveillance.

Risk estimates for scenarios were developed in which the target aircraft's navigation is assumed to comply with the AC 90-100A RNAV standard only and for aircraft using GPS navigation specifically.

Tables in Section 2.0, specify estimated collision rates for RNAV aircraft on routes adjacent to conventional routes based on various centerline-to-centerline separation distances, two route configurations, whether the RNAV aircraft navigation is assumed to be RNAV-2 only or specifically GPS, and whether the aircraft are flying same direction routes or opposite direction routes. Additionally, tables that specify estimated route boundary penetration rates for RNAV, straight, impromptu routes based on navigation type (RNAV-2 or GPS) are contained in this section.

[1] This study is a follow-on to the two studies "Analysis of Area Navigation (RNAV/RNP-1 and RNP-2) En Route Separation along Adjacent Straight Segments without Radar Surveillance Including Impromptu Routes (Phase IV)" and "Analysis of Area Navigation (RNAV) En Route Separation with Conventional Routes including Turns and Special Use Airspace" and utilizes their results.

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1.0 Introduction

1.1 Purpose and Structure of This Document

The purpose of this study is to provide a risk assessment of lateral en route separation between conventional VOR routes and parallel Area Navigation (RNAV-2) routes with both opposite and same direction traffic without radar surveillance and to assess lateral route width risk for impromptu RNAV/RNP-2 routes operating without radar surveillance.

This document is divided into three sections in addition to an appendix and list of references:
1. This introduction which set out the questions to be addressed.
2. A results section which answers these questions.
3. A methodology section which explains how the questions were answered.

1.2 Background to the Questions

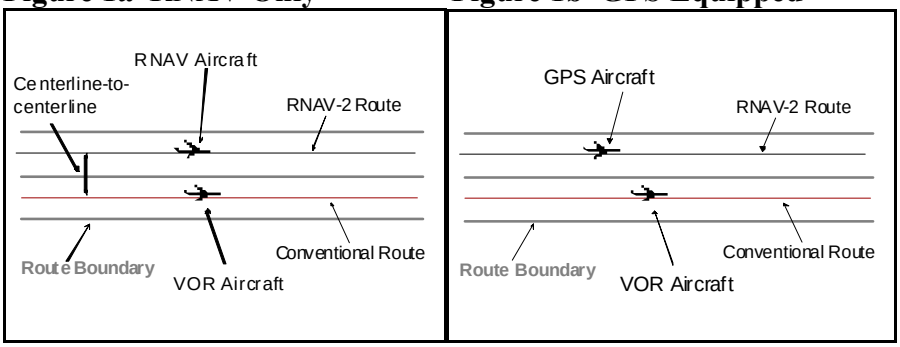
There are two types of questions addressed in this document. The first is about separation for straight[2], adjacent, non-radar VOR and RNAV-2 routes. The second type is about route width for single, non-radar RNAV-2 impromptu routes.

Adjacent VOR / RNAV-2 Route Separation

We analyze the collision risk for route separation based on two different assumptions about the RNAV aircraft lateral deviation from centerline. In the first case we assume only that the aircraft are suitably equipped RNAV aircraft, as referenced in AC 90-100A [5], flying RNAV routes (Figure 1a). In the second case we assume that the aircraft are GPS equipped[3] and flying the RNAV route based on GPS navigation (Figure 1b). We assume that, in either case, the adjacent aircraft are flying the conventional route using VOR navigation. Specifically, that conventional aircraft will follow routes whose boundaries are described in the TERPS standard [3].

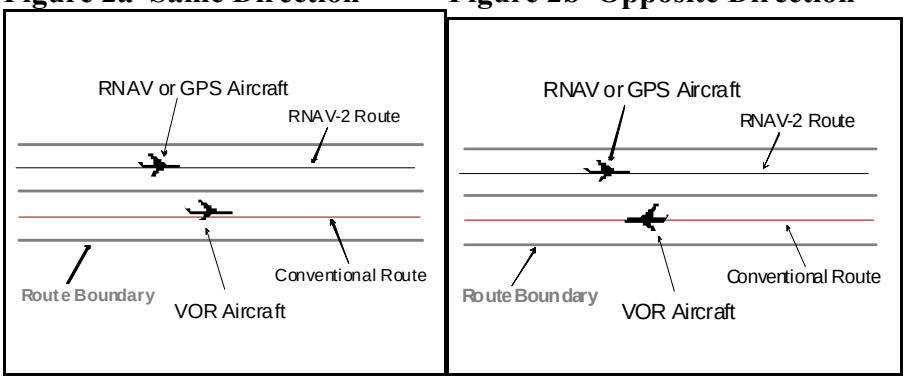
[2] With turns less than 15º.
[3] Of course RNAV aircraft may be GPS equipped. The distinction here is between RNAV aircraft meeting only the AC 90-100A equipage standard and aircraft equipped and navigating with GPS.

Figure 1a RNAV Only **Figure 1b GPS Equipped**



For each of those two cases we first analyze the collision risk assuming the aircraft are flying the adjacent routes in the same direction (Figure 2a) and then assuming the aircraft are flying the adjacent routes in the opposite direction (Figure 2b).

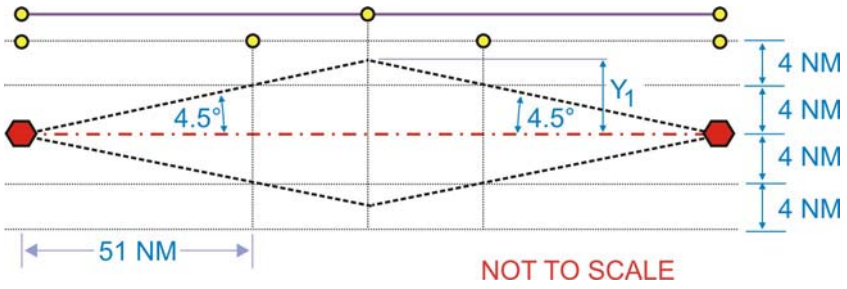
Figure 2a Same Direction **Figure 2b Opposite Direction**



Finally, we analyze the collision risk with two different configurations for the RNAV route when the conventional route splays out (i.e., diverges and then converges) for crossover point (COP) distances greater than 51 NM. The first configuration assumes that the RNAV route splays out along with the conventional route (see Figure 3a – RNAV route is green and VOR route is red). The second configuration assumes that the RNAV route remains straight but is set at a distance away from the conventional route so that the routes will never overlap (see Figure 3b – RNAV route is purple).

Figure 3a Splayed Configuration

Figure 3b Straight Configuration



Impromptu Route Width

We assume that the impromptu routes analyzed for lateral route containment are single, straight routes not under radar surveillance and are point-to-point routes between published waypoints.

As with the RNAV-2 adjacent to conventional routes above, we analyze two cases based on navigation. In the first case we assume only that the aircraft are suitably equipped RNAV aircraft, as referenced in AC 90-100A, flying RNAV routes. In the second case we assume that the aircraft are GPS equipped and flying the RNAV route based on GPS navigation.

1.3 Specific Questions Addressed

We ask six specific questions.

Question 1 What is the collision risk with 8 NM centerline-to-centerline lateral separation for an RNAV-2 route adjacent to a conventional VOR route assuming (i) no surveillance (ii) splayed configuration and (iii) RNAV-2 navigation on the RNAV route? (See Figure 3a – the centerline-to-centerline distance will be 8 NM except over the splayed section.)

We also analyze other centerline-to-centerline separation distances for comparison to the 8 NM separation. And we analyze risk for both the same direction and opposite direction adjacent routes and for various traffic density assumptions. The collision risks are typically different for same and opposite direction adjacent routes and for different traffic densities because the rate of exposure (i.e., the number of times per hour an aircraft on one route is adjacent to one on the other route) is much greater for opposite direction than for same direction aircraft.

Question 2 What is the collision risk with 8 NM centerline-to-centerline lateral separation for an RNAV-2 route adjacent to a conventional VOR route assuming (i) no surveillance (ii) straight configuration and (iii) RNAV-2 navigation on the RNAV route? (See Figure 3b – the centerline-to-centerline distance may be greater than 8 NM depending on the amount of splay.)

Again, we also analyze other centerline-to-centerline separation distances for comparison to the 8 NM separation. And we analyze risk for both the same direction and opposite direction adjacent routes and traffic densities.

Question 3 What is the collision risk with 8 NM centerline-to-centerline lateral separation for an RNAV-2 route adjacent to a conventional VOR route assuming (i) no surveillance (ii) splayed configuration and (iii) GPS navigation on the RNAV route? (See Figure 3a.)

Once again, we also analyze other centerline-to-centerline separation distances. And we analyze risk for both the same direction and opposite direction adjacent routes and traffic densities.

Question 4 What is the collision risk with 8 NM centerline-to-centerline lateral separation for an RNAV-2 route adjacent to a conventional VOR route assuming (i) no surveillance (ii) straight configuration and (iii) GPS navigation on the RNAV route? (See Figure 3b.)

Once again, we also analyze other centerline-to-centerline separation distances. And we analyze risk for both the same direction and opposite direction adjacent routes and traffic densities.

Question 5 What is the risk of an aircraft exiting a single, straight, RNAV impromptu route boundary assuming (i) no surveillance and (ii) RNAV-2 navigation? (See Figure 4a.)

We analyze the risk for various centerline-to-centerline separation distances.

Question 6 What is the risk of an aircraft exiting a single, straight, RNAV impromptu route boundary assuming (i) no surveillance and (ii) GPS navigation? (See Figure 4b.)

Again, we analyze the risk for various centerline-to-centerline separation distances.

Figure 4a RNAV Impromptu

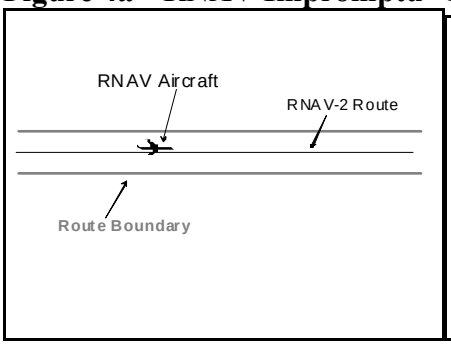
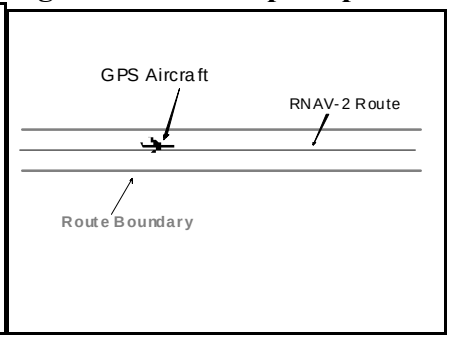


Figure 4b GPS Impromptu



2.0 Results

We present the answers for each of the six questions here.

Question 1 What is the collision risk with 8 NM centerline-to-centerline lateral separation for an RNAV-2 route adjacent to a conventional VOR route assuming (i) no surveillance (ii) splayed configuration and (iii) RNAV-2 navigation on the RNAV route?

Collision risk is given in the units of expected frequency of collisions per hour of flight of the aircraft under consideration[4]. Because of the angular behavior of the VOR lateral deviation from centerline, the risk is highly dependent on COP distance from the VOR.

Table 1 gives the estimated hourly collision frequency for various centerline-to-centerline separation values and COP distances for the splayed configuration with RNAV-2 navigation, same direction routes, and 20 NM in trail (longitudinal) traffic density.

Table 1 Estimated Hourly Collision Frequency: Splayed Configuration, RNAV-2 Navigation, Same Direction, 20 NM In Trail Traffic Density

	COP Distance							
Separation	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
8	9.5E-13	2.6E-12	1.4E-11	7.7E-09	3.6E-07	2.3E-06	4.3E-06	5.2E-06
10	1.2E-15	3.3E-15	1.5E-14	7.1E-13	6.7E-10	1.9E-08	7.0E-08	1.6E-07
12	1.5E-18	4.2E-18	1.9E-17	3.2E-16	2.3E-13	5.0E-11	5.2E-10	2.7E-09
14	2.0E-21	5.3E-21	2.5E-20	4.0E-19	3.3E-17	4.3E-14	1.8E-12	2.5E-11
16	2.5E-24	6.8E-24	3.1E-23	5.1E-22	2.9E-20	1.2E-17	2.8E-15	1.2E-13
18	3.2E-27	8.6E-27	4.0E-26	6.5E-25	3.6E-23	3.2E-21	1.8E-18	3.3E-16
20	4.0E-30	1.1E-29	5.1E-29	8.3E-28	4.6E-26	3.1E-24	5.7E-22	4.7E-19

	COP Distance				
Separation	**90**	**100**	**110**	**120**	**130**
8	5.9E-06	6.4E-06	6.8E-06	7.1E-06	7.3E-06
10	3.0E-07	4.8E-07	6.8E-07	9.0E-07	1.1E-06
12	9.1E-09	2.3E-08	4.8E-08	8.5E-08	1.4E-07
14	1.7E-10	7.5E-10	2.4E-09	6.0E-09	1.3E-08
16	2.0E-12	1.6E-11	8.6E-11	3.2E-10	9.4E-10
18	1.4E-14	2.5E-13	2.2E-12	1.3E-11	5.4E-11
20	6.3E-17	2.5E-15	4.2E-14	4.0E-13	2.5E-12

For other in trail traffic density assumptions (i.e., density = 5 NM or 40 NM[5]) multiply the frequency values in Table 1 by 20 and divide by the density. For example to modify

[4] Expected frequency of collisions per flight hour will be a very, very small number. For example, the value 5.2E-06 means 5.2 times 10^{-6} or 5.2 times one one-millionth collisions per hour. That would be equivalent to an expected 5.2 collisions in one million hours of flight.
[5] Note that larger in-trail distance assumptions may be more realistic, since even 20 NM longitudinal separation may rarely be the case in the scenarios modeled here.

the 8 NM separation at 10 NM COP distance value of 9.5 E-13 to assume a 40 NM density, multiply 9.5 E-13 by 20 and divide by 40 giving 4.75 E-13. For opposite direction routes, multiply [6] the frequency values in Table 1 by 10.

Question 2 What is the collision risk with 8 NM centerline-to-centerline lateral separation for an RNAV-2 route adjacent to a conventional VOR route assuming (i) no surveillance (ii) straight configuration and (iii) RNAV-2 navigation on the RNAV route?

Table 2 gives the estimated hourly collision frequency for various centerline-to-centerline separation values and COP distances for the straight configuration with RNAV-2 navigation, same direction routes, and 20 NM in trail (longitudinal) traffic density.

The dashes in the table for COP distances between 90 and 130 reflect the fact that for those COP distances with smaller separation values (such as 8 through 16 NM) there would be an overlap of the routes[7], which is not allowed.

Table 2 Estimated Hourly Collision Frequency: Straight Configuration, RNAV-2 Navigation, Same Direction, 20 NM In Trail Traffic Density

	COP Distance							
Separation	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
8	9.5E-13	2.6E-12	1.4E-11	7.7E-09	3.6E-07	3.3E-06	6.7E-06	8.1E-06
10	1.2E-15	3.3E-15	1.5E-14	7.1E-13	6.7E-10	3.5E-08	4.3E-07	1.0E-06
12	1.5E-18	4.2E-18	1.9E-17	3.2E-16	2.3E-13	1.3E-10	6.1E-09	8.1E-08
14	2.0E-21	5.3E-21	2.5E-20	4.0E-19	3.3E-17	1.4E-13	3.8E-11	1.5E-09
16	2.5E-24	6.8E-24	3.1E-23	5.1E-22	2.9E-20	4.8E-17	1.0E-13	1.6E-11
18	3.2E-27	8.6E-27	4.0E-26	6.5E-25	3.6E-23	1.0E-20	1.1E-16	8.3E-14
20	4.0E-30	1.1E-29	5.1E-29	8.3E-28	4.6E-26	8.4E-24	5.4E-20	2.3E-16

	COP Distance				
Separation	**90**	**100**	**110**	**120**	**130**
8	--	--	--	--	--
10	5.7E-07	--	--	--	--
12	2.0E-07	1.2E-07	--	--	--
14	2.0E-08	5.2E-08	3.2E-08	--	--
16	5.1E-10	6.4E-09	1.7E-08	1.0E-08	--
18	7.8E-12	2.1E-10	2.4E-09	6.3E-09	3.9E-09
20	7.2E-14	4.5E-12	9.9E-11	1.1E-09	2.7E-09

Question 3 What is the collision risk with 8 NM centerline-to-centerline lateral separation for an RNAV-2 route adjacent to a conventional VOR route assuming (i) no surveillance (ii) splayed configuration and (iii) GPS navigation on the RNAV route?

[6] The same operation can be performed for the other tables below. If modifying for both traffic density and direction, perform both operations, one after the other.
[7] Actually, even at smaller COP distances such as 80 NM, the route widths could overlap. However, those values have been included for comparison purposes, since this is an analysis document, and not a set of criteria.

Table 3 gives the estimated hourly collision frequency for various centerline-to-centerline separation values and COP distances for the splayed configuration with GPS navigation, same direction routes, and 20 NM in trail (longitudinal) traffic density.

Table 3 Estimated Hourly Collision Frequency: Splayed Configuration, GPS Navigation, Same Direction, 20 NM In Trail Traffic Density

	COP Distance							
Separation	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
8	1.1E-245	7.8E-57	1.0E-23	1.1E-13	1.8E-09	1.2E-07	6.0E-07	1.7E-06
10	0.0E+00	7.7E-88	7.0E-36	4.9E-20	2.3E-13	1.9E-10	3.4E-09	2.4E-08
12	0.0E+00	9.9E-126	9.6E-51	8.2E-28	4.0E-18	9.0E-14	8.5E-12	1.8E-10
14	0.0E+00	1.6E-170	2.6E-68	5.3E-37	9.7E-24	1.2E-17	8.8E-15	7.2E-13
16	0.0E+00	3.5E-222	1.4E-88	1.3E-47	3.2E-30	4.1E-22	3.7E-18	1.5E-15
18	0.0E+00	9.6E-281	1.5E-111	1.3E-59	1.4E-37	3.7E-27	6.0E-22	1.5E-18
20	0.0E+00	0.0E+00	3.2E-137	4.8E-73	8.9E-46	8.9E-33	3.8E-26	7.7E-22

	COP Distance				
Separation	**90**	**100**	**110**	**120**	**130**
8	3.4E-06	5.7E-06	6.8E-06	7.1E-06	7.3E-06
10	9.5E-08	2.6E-07	5.7E-07	9.0E-07	1.1E-06
12	1.6E-09	8.0E-09	2.7E-08	7.1E-08	1.4E-07
14	1.6E-11	1.6E-10	9.4E-10	3.7E-09	1.1E-08
16	9.9E-14	2.2E-12	2.3E-11	1.4E-10	6.3E-10
18	3.6E-16	1.9E-14	4.0E-13	1.3E-12	8.9E-13
20	7.5E-19	1.1E-16	4.9E-15	9.3E-14	3.0E-13

Question 4 What is the collision risk with 8 NM centerline-to-centerline lateral separation for an RNAV-2 route adjacent to a conventional VOR route assuming (i) no surveillance (ii) straight configuration and (iii) GPS navigation on the RNAV route?

Table 4 gives the estimated hourly collision frequency for various distances.

Table 4 Estimated Hourly Collision Frequency: Straight Configuration, GPS Navigation, Same Direction, 20 NM In Trail Traffic Density

	COP Distance							
Separation	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
8	1.1E-245	7.8E-57	1.0E-23	1.1E-13	1.8E-09	2.5E-07	1.1E-06	2.1E-06
10	0.0E+00	7.7E-88	7.0E-36	4.9E-20	2.3E-13	5.5E-10	4.9E-08	2.2E-07
12	0.0E+00	9.9E-126	9.6E-51	8.2E-28	4.0E-18	3.4E-13	2.3E-10	1.4E-08
14	0.0E+00	1.6E-170	2.6E-68	5.3E-37	9.7E-24	5.6E-17	4.3E-13	1.2E-10
16	0.0E+00	3.5E-222	1.4E-88	1.3E-47	3.2E-30	2.4E-21	3.1E-16	4.9E-13
18	0.0E+00	9.6E-281	1.5E-111	1.3E-59	1.4E-37	2.7E-26	8.7E-20	1.0E-15
20	0.0E+00	0.0E+00	3.2E-137	4.8E-73	8.9E-46	8.2E-32	9.3E-24	1.0E-18

(Table 4 continued next page)

Table 4 (Continued)

	COP Distance				
Separation	**90**	**100**	**110**	**120**	**130**
8	--	--	--	--	--
10	1.6E-07	--	--	--	--
12	6.0E-08	4.3E-08	--	--	--
14	5.1E-09	2.0E-08	1.4E-08	--	--
16	6.8E-11	2.2E-09	8.3E-09	5.8E-09	--
18	5.4E-13	4.4E-11	1.1E-09	3.8E-09	2.6E-09
20	2.4E-15	5.7E-13	3.0E-11	6.1E-10	2.0E-09

Question 5 What is the risk of an aircraft laterally[8] penetrating a single, straight, RNAV impromptu route boundary assuming (i) no surveillance and (ii) RNAV-2 navigation?

The relationship to the route under consideration to existing terrain or fixed obstacles is not specified. Therefore, only route boundary penetration is analyzed. Route boundary penetration risk is given in the units of expected frequency of penetrations per hour of flight of the aircraft under consideration.

Table 5 gives the estimated hourly penetration frequency for RNAV-2 navigation for various route widths and speeds. (For example, a width of 8 NM would mean centerline ± 4 NM.) . Penetration is not typically considered to be a catastrophic event.

Table 5 Estimated Hourly Penetration Frequency: RNAV Navigation

Route	Aircraft Speed			
Width	**200 kts**	**300 kts**	**400 kts**	**500 kts**
6	1.0E-04	1.6E-04	2.1E-04	2.6E-04
8	7.1E-07	1.1E-06	1.4E-06	1.8E-06
10	4.8E-09	7.1E-09	9.5E-09	1.2E-08
12	3.2E-11	4.8E-11	6.4E-11	8.0E-11
14	2.2E-13	3.2E-13	4.3E-13	5.4E-13
16	1.5E-15	2.2E-15	2.9E-15	3.6E-15

Question 6 What is the risk of an aircraft exiting a single, straight, RNAV impromptu route boundary assuming (i) no surveillance and (ii) GPS navigation?

Table 6 gives the estimated hourly penetration frequency for GPS navigation for various route widths and speeds. The zeros indicate, not that the frequency would be exactly zero, but that the calculated value could not be distinguished from zero to within the precision of the software tools used.

[8] We make no assumptions about altitude. The penetration frequency includes penetration on either side of the route boundary. These values would be the same for a published RNAV-2 or GPS route.

Table 6 Estimated Hourly Penetration Frequency: GPS Navigation

Route Width	Aircraft Speed 200 kts	300 kts	400 kts	500 kts
6	3.3E-15	5.0E-15	6.7E-15	8.3E-15
8	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00

3.0 Methodology

3.1 Model Description

We will describe the risk model in terms of a scenario with straight en route track segments with turns of no more than 15°. These can be parallel, adjacent straight tracks with aircraft on those tracks flying either opposite or same direction routes. The aircraft at risk can be on either the conventional route or the RNAV route. The aircraft are assumed not to be under radar surveillance. The calculations for this scenario are based on various Changeover Point[9] (COP) distances from the VOR. (See Figures 5a and 5b.)

We do not include the hazard of wake encounter in the risk calculation. We do not include RNP integrity, RNP continuity, or TCAS alert mitigation in the risk calculation. The lateral deviation model *does* account for both normal lateral deviation and anomalous deviation such as those that are sometimes called blunders.

The specific Test Criterion Violation (TCV) for this scenario is the combined lateral, longitudinal, and vertical conjunction of the two aircraft. This conjunction is modeled by centers of gravity of the aircraft converging to within their mean wingspan laterally, within their mean lengths longitudinally, and within their mean heights vertically.

In the previous studies ([1] and [2]) we made several assumptions about the RNAV aircraft:

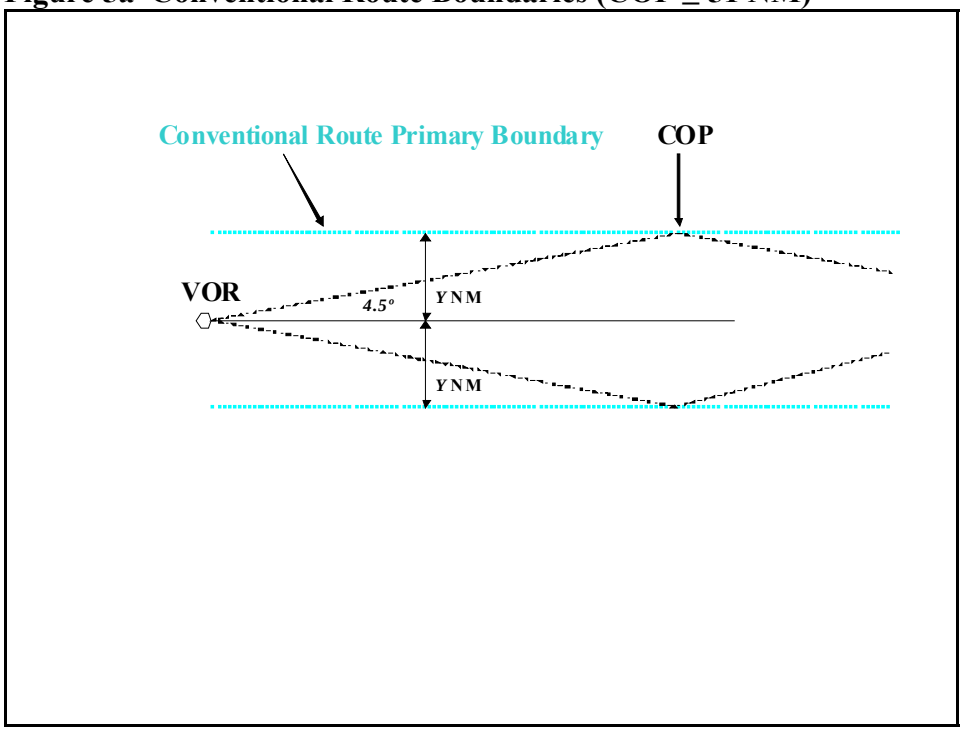
- The aircraft lateral, longitudinal, and vertical deviations are independent.
- The aircraft length and width are both approximately 0.03 NM (182 feet).
- The probability of aircraft on adjacent tracks being at the same altitude is 1.
- The aircraft is contained laterally within 2 NM of the straight track 95% of the time.

This last assumption is based on the AC 90-100A en route requirement for RNP-2 aircraft. We used a statistical distribution to model the lateral track deviation that would provide 95% containment. The specific distribution used is a mixed Johnson S_B / Double-Exponential distribution. This distribution satisfies both theoretical and empirical reasonableness tests. Theoretically, the distribution models a combination of core (typical) lateral deviation behavior and tail (atypical) lateral deviation behavior. Empirically, the distribution is conservative as compared to the results of the three empirical studies ([6], [7], and [8]).

[9] A Changeover Point is a point between navigation facilities along en route segments at which the pilot using the route should "change over" the navigation equipment to receive course guidance from the facility ahead instead of the one behind. See Figures 5a and 5b.

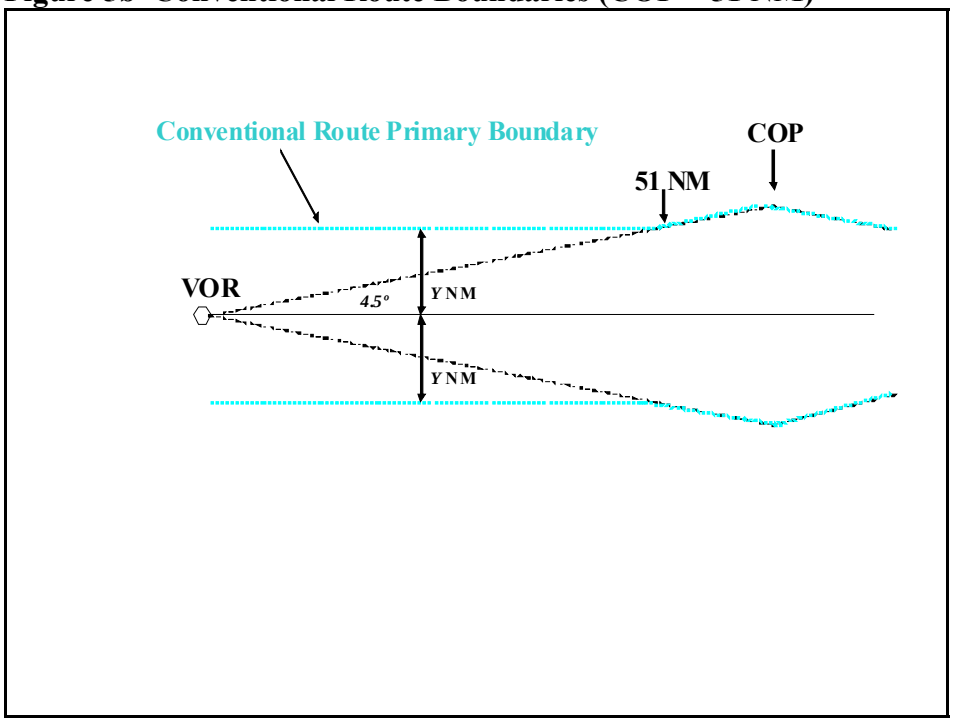
The probability of a TCV for this scenario is the sum of the probabilities of three mutually exclusive events: side-to-side (C_s), top-to-bottom (C_t), or nose-to-nose[10] (C_n) collision between aircraft on adjacent tracks.

Figure 5a Conventional Route Boundaries (COP ≤ 51 NM)[11]



[10] Or nose-to-tail for same-direction adjacent aircraft.
[11] Figure 5a shows the COP at exactly 51 NM. For COP values less than 51 nm, the apex of the splay would fall below the upper route boundary.

Figure 5b Conventional Route Boundaries (COP > 51 NM)



That is,

$$P(TCV) = P(C_s) + P(C_t) + P(C_n). \quad (1)$$

In the previous study [1] this TCV probability was shown to have a value given by the equation,

$$P(TCV) = P_y(S_y)\left[\frac{1}{\sqrt{2}} + 1\right], \quad (2)$$

where $P_y(S_y)$ is the probability of a lateral overlap of the two aircraft on the two routes, and S_y is the track-to-track distance assumed.

To find $P_y(S_y)$, let the lateral positions of the aircraft be given by the variables y_1 and y_2 respectively. The aircraft will be assumed to be in lateral overlap when their centers of gravity are within λ. That is, when $|y_2 - y_1| < \lambda$. And therefore, the probability of lateral overlap,

$$P_y(S_y) = P(|y_2 - y_1| < \lambda). \quad (3)$$

But, $P(|y_2 - y_1| < \lambda) = P(-\lambda < y_2 - y_1 < \lambda)$. And this probability can be found by integrating the PDF describing $(y_2 - y_1)$ between $-\lambda$ and λ.

The PDF describing (y_2 - y_1) is the convolution of the two PDFs of the two variables, y_2 and -y_1. The PDF for the variable y_1 is that of the criterion-based distribution for RNAV route lateral deviation developed in [1]. The PDF for the variable y_2 is that of the conventional route lateral deviation and is developed in Appendix B. Appendix A gives the details for the convolution of these two PDFs and of the integration that yields the PDF for the lateral overlap probability, $P_y(S_y)$, (see Equation A4)[12]. This lateral overlap probability will vary for RNAV-2 versus GPS navigation and for splayed versus straight configurations.

Table 7 gives the lateral overlap probability for the case of RNAV-2 navigation and splayed configuration, $P_y(S_y)$, for various values of track-to-track separation and COP distances based on this distribution.

[12] $P_y(S_y)$ is actually determined by averaging the values obtained from Equation A4 for each member of the family of distributions corresponding to distances from the VOR that are multiples of 5 NM: 0, 5, 10, … .

Table 7 Overlap Probabilities, $P_y(S_y)$, by Track-to-Track Distance and COP for Splayed Configuration, RNAV-2 Navigation

	COP Distance							
Separation	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
8	1.1E-13	3.0E-13	1.6E-12	9.0E-10	4.2E-08	2.7E-07	5.1E-07	6.1E-07
10	1.4E-16	3.9E-16	1.8E-15	8.3E-14	7.8E-11	2.2E-09	8.3E-09	1.9E-08
12	1.8E-19	4.9E-19	2.3E-18	3.7E-17	2.7E-14	5.9E-12	6.1E-11	3.2E-10
14	2.3E-22	6.2E-22	2.9E-21	4.7E-20	3.9E-18	5.0E-15	2.1E-13	2.9E-12
16	2.9E-25	7.9E-25	3.7E-24	6.0E-23	3.4E-21	1.4E-18	3.2E-16	1.5E-14
18	3.7E-28	1.0E-27	4.7E-27	7.6E-26	4.3E-24	3.7E-22	2.1E-19	3.9E-17
20	4.7E-31	1.3E-30	6.0E-30	9.7E-29	5.4E-27	3.7E-25	6.7E-23	5.5E-20

	COP Distance				
Separation	**90**	**100**	**110**	**120**	**130**
8	6.9E-07	7.5E-07	7.9E-07	8.3E-07	8.5E-07
10	3.5E-08	5.6E-08	8.0E-08	1.1E-07	1.3E-07
12	1.1E-09	2.7E-09	5.6E-09	1.0E-08	1.6E-08
14	2.0E-11	8.8E-11	2.8E-10	7.1E-10	1.5E-09
16	2.3E-13	1.9E-12	1.0E-11	3.8E-11	1.1E-10
18	1.7E-15	2.9E-14	2.6E-13	1.5E-12	6.3E-12
20	7.4E-18	2.9E-16	4.9E-15	4.7E-14	2.9E-13

Table 8 gives the lateral overlap probability for the case of RNAV-2 navigation and straight configuration, $P_y(S_y)$. In some cases an overlap probability is not given for a particular separation and COP distance due to the fact that for that separation, the COP distance would cause the conventional and RNAV boundaries to overlap as in Figure 5b.

Table 8 Overlap Probabilities, $P_y(S_y)$, by Track-to-Track Distance and COP for Straight Configuration, RNAV-2 Navigation

	COP Distance							
Separation	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
8	1.1E-13	3.0E-13	1.6E-12	9.0E-10	4.2E-08	3.9E-07	7.8E-07	4.2E-06
10	1.4E-16	3.9E-16	1.8E-15	8.3E-14	7.8E-11	4.1E-09	5.0E-08	1.2E-07
12	1.8E-19	4.9E-19	2.3E-18	3.7E-17	2.7E-14	1.5E-11	7.1E-10	9.5E-09
14	2.3E-22	6.2E-22	2.9E-21	4.7E-20	3.9E-18	1.6E-14	4.5E-12	1.8E-10
16	2.9E-25	7.9E-25	3.7E-24	6.0E-23	3.4E-21	5.6E-18	1.2E-14	1.8E-12
18	3.7E-28	1.0E-27	4.7E-27	7.6E-26	4.3E-24	1.2E-21	1.3E-17	9.8E-15
20	4.7E-31	1.3E-30	6.0E-30	9.7E-29	5.4E-27	9.9E-25	6.3E-21	2.7E-17

	COP Distance				
Separation	**90**	**100**	**110**	**120**	**130**
8	--	--	--	--	--
10	6.7E-08	--	--	--	--
12	2.4E-08	1.4E-08	--	--	--
14	2.4E-09	6.1E-09	3.8E-09	--	--
16	6.0E-11	7.5E-10	2.0E-09	1.2E-09	--
18	9.1E-13	2.4E-11	2.9E-10	7.4E-10	4.6E-10
20	8.5E-15	5.3E-13	1.2E-11	1.2E-10	3.2E-10

Table 9 gives the lateral overlap probability for the case of GPS navigation and splayed configuration, $P_y(S_y)$, for each of the values of track-to-track separation, S_y: 8, 10, 12, 14, 16, 18, and 20 NM and COP distances (10 to 130 NM) based on this distribution.

Table 9 Overlap Probabilities, $P_y(S_y)$, by Track-to-Track Distance and COP for Splayed Configuration, GPS Navigation

	COP Distance							
Separation	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
8	1.3E-246	9.1E-58	1.2E-24	1.3E-14	2.1E-10	1.4E-08	7.0E-08	2.0E-07
10	0.0E+00	9.1E-89	8.2E-37	5.8E-21	2.7E-14	2.2E-11	4.0E-10	2.8E-09
12	0.0E+00	1.2E-126	1.1E-51	9.6E-29	4.7E-19	1.1E-14	1.0E-12	2.1E-11
14	0.0E+00	1.9E-171	3.1E-69	6.2E-38	1.1E-24	1.4E-18	1.0E-15	8.4E-14
16	0.0E+00	4.1E-223	1.7E-89	1.6E-48	3.7E-31	4.8E-23	4.3E-19	1.7E-16
18	0.0E+00	1.1E-281	1.8E-112	1.5E-60	1.7E-38	4.4E-28	7.0E-23	1.8E-19
20	0.0E+00	0.0E+00	3.7E-138	5.6E-74	1.0E-46	1.0E-33	4.4E-27	9.1E-23

	COP Distance				
Separation	**90**	**100**	**110**	**120**	**130**
8	4.0E-07	6.7E-07	7.9E-07	8.3E-07	8.5E-07
10	1.1E-08	3.1E-08	6.7E-08	1.1E-07	1.3E-07
12	1.9E-10	9.4E-10	3.2E-09	8.4E-09	1.6E-08
14	1.9E-12	1.9E-11	1.1E-10	4.3E-10	1.3E-09
16	1.2E-14	2.5E-13	2.7E-12	1.7E-11	7.4E-11
18	4.2E-17	2.3E-15	4.7E-14	1.5E-13	1.0E-13
20	8.8E-20	1.3E-17	5.8E-16	1.1E-14	3.6E-14

Table 10 gives the lateral overlap probability for the case of GPS navigation and straight configuration, $P_y(S_y)$, for each of the values of track-to-track separation, S_y: 8, 10, 12, 14, 16, 18, and 20 NM and COP distances (10 to 130 NM) based on this distribution.

Table 10 Overlap Probabilities, $P_y(S_y)$, by Track-to-Track Distance and COP for Straight Configuration, GPS Navigation

	COP Distance							
Separation	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
8	1.3E-246	9.1E-58	1.2E-24	1.3E-14	2.1E-10	2.9E-08	1.3E-07	9.6E-07
10	0.0E+00	9.1E-89	8.2E-37	5.8E-21	2.7E-14	6.4E-11	5.8E-09	2.6E-08
12	0.0E+00	1.2E-126	1.1E-51	9.6E-29	4.7E-19	3.9E-14	2.7E-11	1.6E-09
14	0.0E+00	1.9E-171	3.1E-69	6.2E-38	1.1E-24	6.5E-18	5.0E-14	1.4E-11
16	0.0E+00	4.1E-223	1.7E-89	1.6E-48	3.7E-31	2.8E-22	3.6E-17	5.8E-14
18	0.0E+00	1.1E-281	1.8E-112	1.5E-60	1.7E-38	3.2E-27	1.0E-20	1.2E-16
20	0.0E+00	0.0E+00	3.7E-138	5.6E-74	1.0E-46	9.6E-33	1.1E-24	1.2E-19

(Table 10 continued next page)

Table 10 (Continued)

	COP Distance				
Separation	**90**	**100**	**110**	**120**	**130**
8	--	--	--	--	--
10	1.9E-08	--	--	--	--
12	7.0E-09	5.0E-09	--	--	--
14	6.0E-10	2.4E-09	1.7E-09	--	--
16	8.0E-12	2.6E-10	9.7E-10	6.8E-10	--
18	6.3E-14	5.1E-12	1.3E-10	4.5E-10	3.1E-10
20	2.9E-16	6.6E-14	3.5E-12	7.1E-11	2.3E-10

Since the acceptable level of safety for these en route operations is specified in terms of the number of collisions per hour of flight, the TCV rate must be converted to the units of collisions per hour of flight. To accomplish this we multiply the TCV rate by the expected number of encounters of adjacent aircraft per hour of flight. If we assume an mean ground speed of V knots (for opposite-direction aircraft), a mean passing speed of ΔV knots (for same-direction aircraft), and a mean traffic separation of d NM then in one hour an aircraft will encounter 2V/d other aircraft on an opposite direction track and ΔV /d aircraft on a same-direction track.

Therefore, the hourly collision rate, C, for this scenario can be determined from the single equation,

$$C(S_y, V, \Delta V, d, n_0, n_s) = \left(\frac{2V}{d} n_o + \frac{\Delta V}{d} n_s\right)\left[\frac{1}{\sqrt{2}} + 1\right] P_y(S_y) \quad (4)$$

Where n_0 is the number of opposite direction tracks adjacent to the target aircraft track (the values of n_0 can be 0, 1, or 2), and n_s is the number of same direction tracks adjacent to the target aircraft track (the values of n_s can also be 0, 1, or 2, but subject to $1 \leq n_0 + n_s \leq 2$, since the target track cannot be adjacent to more than 2 other tracks).

A mean longitudinal traffic separation, *d*, of 5 NM was used in the case of radar surveillance in previous studies. However, since radar surveillance is not assumed in this study, we analyze collision risk primarily using a longitudinal separation value 20 NM with instructions on how to modify this longitudinal assumption to other distances (e.g., 5, 10, 40, etc.). The tabular values above are calculated assuming $V = 500$ knots, $\Delta V =$ 100 knots, and $d = 20$ NM.

Tables 1 through 4 in the Results Section (Section 2) give these hourly collision rates (or frequencies) for various assumptions.

The penetration frequencies in tables 5 and 6 were calculated based on the Q-Route GPS distribution results in [8].

2.2 Summary of Data Used

Data on RNAV Route Aircraft

The RNAV route aircraft data for this study are used to validate the risk models, but the models themselves are based on values specified in AC 90-100A.

AC 90-100A specifies a value for track-keeping accuracy for RNAV aircraft approved for Q-Route operations. These criteria are the bases for this study's turn path definition model.

We used three empirical studies, [6], [7], and [8], to validate the RNAV aircraft track-keeping accuracy distributions developed.

Data on Conventional Route Aircraft

We based the distributions for conventional aircraft track-keeping accuracy on two studies:

- [9] a study that quantified conventional FTE (flight technical error) using a family of Johnson S_U distributions (for lateral deviations at various distances from the VOR facility)
- [10] a study that quantified conventional NSE (navigational system error using VOR facilities and aircraft sensors) using normal distributions.

We combined the distributions from these two studies to arrive at a total system error for lateral deviation of conventional en route aircraft. This provided a family of distributions, one member for each of several distances from the VOR facility.

These combined conventional lateral error distributions were used together with the RNAV lateral error distribution to arrive at a probability of lateral overlap between an aircraft on a conventional route and an aircraft on an adjacent RNAV route.

Appendix A

Statistical Distributions Used in the Study

RNAV Route Lateral Deviation Distribution

(The Mixed Johnson S_B and Double Exponential Distribution PDF, from [1])

$$f_1(x) = \begin{cases} \frac{\alpha}{2\delta}\exp\left[-\frac{|x|}{\lambda}\right] + (1-\alpha)\frac{\eta\lambda}{\sqrt{2\pi}}\frac{1}{(x-\varepsilon)(-x+\varepsilon+\lambda)}\exp\left[-\frac{1}{2}\left(\eta^2\ln\left\{\left(\frac{x-\varepsilon}{-x+\varepsilon+\lambda}\right)^2\right\}\right)\right], \varepsilon < x < \varepsilon+\lambda \\ \frac{\alpha}{2\delta}\exp\left[-\frac{|x|}{\lambda}\right], x \le \varepsilon . or . x \ge \varepsilon+\lambda \end{cases} \quad \text{(A1)}$$

The Convolution of Variables y_2 and y_1 and the Probability of $|y_2 - y_1| < W$

The PDF describing (y_2 - y_1) is the convolution of the two PDFs of the two variables, y_2 and -y_1. The convolution of two variables y_2 and +y_1 is defined as the integral

$$f(u) = \int_{-\infty}^{\infty} f_1(y_1) f_2(u - y_1) dy_1 \quad \text{(A2)}$$

where $u = y_1 + y_2$. If f_1 and f_2 are PDFs of y_1 and y_2, then f is the PDF of $u = y_1 + y_2$.

Also, if the PDF of y_1 is symmetric about zero, then the convolution of y_2 and y_1 is equivalent to the convolution of y_2 and $-y_1$. Therefore, f is also the PDF of $u = y_2 - y_1$.

This means that the probability of $|y_2 - y_1| < W$ is the integral of f between $-W$ and W. That is,

$$P(|y_2 - y_1| < W) = \int_{-W}^{W} f(x) dx . \quad \text{(A3)}$$

But $f(x)$ is defined in (2) where f_1 is the Mixed Johnson S_B and Double Exponential distribution PDF defined in (A1), that is, the PDF for the RNAV en route lateral deviations from [1] and f_2 is the PDF for the conventional route lateral deviations derived in Appendix B. Therefore,

$$P(|y_2 - y_1| < W) = \int_{-W}^{W}\int_{-\infty}^{\infty} f_1(y_1) f_2(x - y_1) dy_1 dx \quad \text{(A4)}$$

where f_1 and f_2 are defined in above.

Appendix B

Conventional Route Lateral Deviation Distribution

The random variable y_2 that represents the conventional route lateral deviation is itself the sum of two random variables: the lateral error due to FTE, y_{2F},and the lateral error due to NSE, $y_{2N.}$

The distribution PDF for the random variable, y_{2F}, the conventional lateral FTE, is taken from the study [X]. In that paper the PDF was found to be from a Johnson SU distribution:

$$f_{2F}(x) = \frac{\eta}{\sqrt{2\pi}} \frac{1}{\sqrt{(x-\varepsilon)^2 + \lambda^2}} \exp\left[-\frac{1}{2}\left(\gamma + \eta \ln\left\{ \left(\frac{x-\varepsilon}{\lambda}\right) + \left[\left(\frac{x-\varepsilon}{\lambda}\right)^2 + 1 \right]^{\frac{1}{2}} \right\} \right)^2 \right] \quad \text{(B1)}$$

where $-\infty < x < \infty$, $-\infty < \gamma < \infty$, $-\infty < \varepsilon < \infty$, $\eta > 0$, $\lambda > 0$. The location parameter is ε. The scale parameter is λ. The shape (including skewness) parameters are γ and η. Since the FTE is angular, the parameter values change as you move away from the VOR. At 40 NM the values (for lateral distances in meters) are: $\gamma = -0.28539$, $\eta = 1.6796$, $\varepsilon = -300.094$, and $\lambda = 1893.1183$.

The distribution PDF for the random variable, y_{2N}, the conventional lateral NSE, is taken from the study [10]. In that paper the PDF was found to be from a Normal distribution:

$$f_{2\mathrm{N}}(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma} \right)^2 \right] \tag{B2}$$

At 40 NM the values (for lateral distances in meters) are: $\mu = 0$ and $\sigma = 1939.8$.

Therefore, the PDF for the total lateral deviation is the convolution of these two PDFs. That is,

$$f_2(u) = \int_{-\infty}^{\infty} f_{2F}(y) f_{2N}(u-y)\,dy \tag{B3}$$

This function, f2(u), is actually a family of distributions whose members are found by evaluating the parameters at appropriate distances from the VOR.

References

[1] "Analysis of Area Navigation (RNAV/RNP-1 and RNP-2) En Route Separation along Adjacent Straight Segments without Radar Surveillance Including Impromptu Routes (Phase IV)"

AFS-400 Safety Study Report number DOT-FAA-AFS-450-51

This paper by the FAA's Flight Technologies and Procedures Division (AFS-400) was published in December, 2008. The paper's analysis was confined to RNAV en route segments with no turns greater than 15 degrees (and therefore assumed to be straight).

[2] "Analysis of Area Navigation (RNAV) En Route Separation with Conventional Routes including Turns and Special Use Airspace"

AFS-400 Safety Study Report number DOT-FAA-AFS-440-26

This paper by the FAA's Flight Technologies and Procedures Division (AFS-400) was published in January, 2007. The paper's analysis includes both RNAV en route straight segments and those with turns greater than 15 degrees.

[3] United States Standard for Terminal Instrument Procedures (TERPS), 3rd Ed.

Change 19, June 2002

Chapter 17, especially pages 173 through 180 on en route spacing.

[4] RTCA DO-236

[5] FAA AC 90-100A

[6] "Preliminary Re-evaluation of the Probability of Lateral Overlap, Py(0), based on non-GPS and GPS Equipped Aircraft Performance at Entry into North Atlantic Reduced Vertical Separation Minimum Airspace"

North Atlantic Mathematicians' Implementation Group
NAT MIG/5-WP/18
Atlantic City, April 1999

This paper was published by the North Atlantic Mathematicians' Implementation Group as NAT MIG/5-WP/18 in April 1999. The paper's analysis was based on data collected in 1995 from 11 aircraft flights by 5 operators with 3 aircraft types (B747-200, B747-400, A340). Each aircraft was using GPS navigation on an oceanic route -- 5 flights were North Atlantic routes, 5 were Pacific Oceanic Airspace, and one was a South Atlantic route.

[7] "Estimating the Well-Fit Model for the Distribution of Cross Track Deviations of GPS Equipped Aircraft on a North Pacific Route"

Separation and Airspace Safety Panel (SASP)
SASP-WG/WHL/4-WP/23
Honolulu, United States, 10-21 November 2003

This paper was published by the Separation and Airspace Safety Panel (SASP) as SASP-WG/WHL/4-WP/23 in November 2003. The paper's analysis was based on data collected between December 2001 and 23 May 2002, from 3,150 flights on the North Pacific route R220. Each aircraft, types B747-400, B777, A340, was using GPS navigation on the route.

[8] "Analysis of Lateral Track Deviation along Two Q-Routes"

AFS-400 Safety Study Report number DOT-FAA-AFS-440-14

This paper was published by the FAA's Flight Technologies and Procedure s Division (AFS-400) in October 2005. The paper's analysis was based on data collected between February 19 and March 6, 2003, from 865 flights on Q-Routes 100 and 102 in the Gulf of Mexico. Each aircraft was using some type of RNAV navigation, typically GPS or DME/DME on the route.

[9] "Analysis of VOR En Route Flight Technical Error (FTE) based on Data Collected by FAA Flight Inspection Aircraft", Don P. Pate, FAA Flight Inspection National Field Office, Operations Research Staff, AFS-512, December, 1975.

[10] "An Analysis of Radio Navigation Sensor Accuracies Associated with Area Navigation (RNAV)", Thomas V. Logue, FAA Systems Research and Development Service, August 1978.

Report Number FAA-RD-78-85.

[11] "FAA Order 7110.65, Section 3 Special Use and ATC Assigned Airspace"

Paragraph 9-3-2. Separation Minima (b).