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Analysis of Lateral Track Deviation along Two Q-Routes

Dr. Richard Greenhaw, AFS-440
Dr. Sherri Avery, CRC & Associates
Gerry McCartor, AFS-440

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Flight Operations Simulation
and Analysis Branch, AFS-440
6425 S. Denning, Room 104
Oklahoma City, Oklahoma 73169
Phone: (405) 954-8191

Flight Systems Laboratory

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Federal Aviation Administration
Flight Operations Simulation and Analysis Branch
Mike Monroney Aeronautical Center
Oklahoma City, OK 73125

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Reviewed by:

10/26/05

Stephen W. Barnes — Date
Manager, Flight Operations Simulation and
Analysis Branch

Released by:

11/16/05

John W. McGraw — Date
Manager, Flight Technologies and
Procedures Division

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Technical Report

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12. Abstract

The purpose of this study is to provide a preliminary risk assessment of RNAV en route separation using radar track data available from two Q-Routes. The study estimates the risk of RNAV aircraft deviating from the defined Q-Route laterally by more than 1, 2, 3, or 4 nautical miles.

The analysis is based on actual long-range radar track data collected by the Jacksonville Air Route Traffic Control Center (ARTCC) for all potential Q-Route 100 and 102 flights between February 19 and March 3, 2003.

The study applies extreme value analysis, a type of statistical analysis, to determine the probability of RNAV aircraft deviating from the defined Q-Route laterally by more than 1, 2, 3, or 4 nautical miles. The study estimates these probabilities for all aircraft and for GPS-equipped aircraft versus non-GPS aircraft.

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Executive Summary

The purpose of this study is to provide a preliminary risk assessment of Area Navigation (RNAV) enroute separation using radar track data available from two Q-Routes. The study will estimate the risk of RNAV aircraft deviating from the defined Q-Route laterally by more than 1, 2, 3, or 4 nautical miles (NM).

The analysis is based on actual long-range radar track data collected by the Jacksonville Air Route Traffic Control Center (ARTCC) for all potential Q-Route 100 and 102 flights during the period from February 19 through March 3, 2003. The study analyzed two straight-track segments of the routes: 189 NM on the Q100 segment and 147 NM on the Q102 segment.

The study applies extreme value analysis, a type of statistical analysis, to determine the probability of RNAV aircraft deviating from the defined Q-Route laterally by more than 1, 2, 3, or 4 NM. The study estimates these probabilities for all aircraft and for Global Positioning System (GPS)-equipped aircraft versus non-GPS aircraft.

The results of this analysis show that the probability of deviation from a straight Q-Route path by more than 4 NM during one hour of flight is less than 1.0 E-10 (1 in 10,000,000,000). And the probability of deviation from a straight Q-Route path by more than 3 NM during one hour of flight is less than 1.0 E-08 (1 in 100,000,000). For the GPS versus non-GPS cases, the limits that would provide a risk protection of 1.0 E-07 (a probability of exceeding the limit of 1 in 10,000,000) are about plus or minus 1.3 NM for GPS aircraft and about plus or minus 1.5 NM for non-GPS aircraft.

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1.0. Introduction

1.1. Purpose and Structure of this Document

The purpose of this study is to provide a preliminary risk assessment of Area Navigation (RNAV) en route separation using radar track data available from two Q-Routes. The study will estimate the risk of RNAV aircraft deviating from the defined Q-Route laterally by more than 1, 2, 3, or 4 nautical mile (NM).

1.2. Statement of the Problem

Specifically, this study seeks to quantify the lateral track deviation of typical RNAV aircraft flying a designated Q-Route. This lateral track deviation will be used to determine the probability that a typical RNAV aircraft deviates laterally from the track by more than certain given distances (each of 1, 2, 3, and 4 NM).

The study examined four operational scenarios (see Figures 1 and 2):

1. Aircraft on route Q-100 from west to east between waypoints REDFN and REMIS (189 NM)
2. Aircraft on route Q-100 from east to west between waypoints REMIS and REDFN (189 NM)
3. Aircraft on route Q-102 from west to east between waypoints BLVNS and BACCA (147 NM)
4. Aircraft on route Q-102 from east to west between waypoints BACCA and BLVNS (147 NM)

RNAV aircraft on these routes were tracked between February 19 and March 6, 2003, by Jacksonville long-range radar (ATCBI-6).

Figure 1

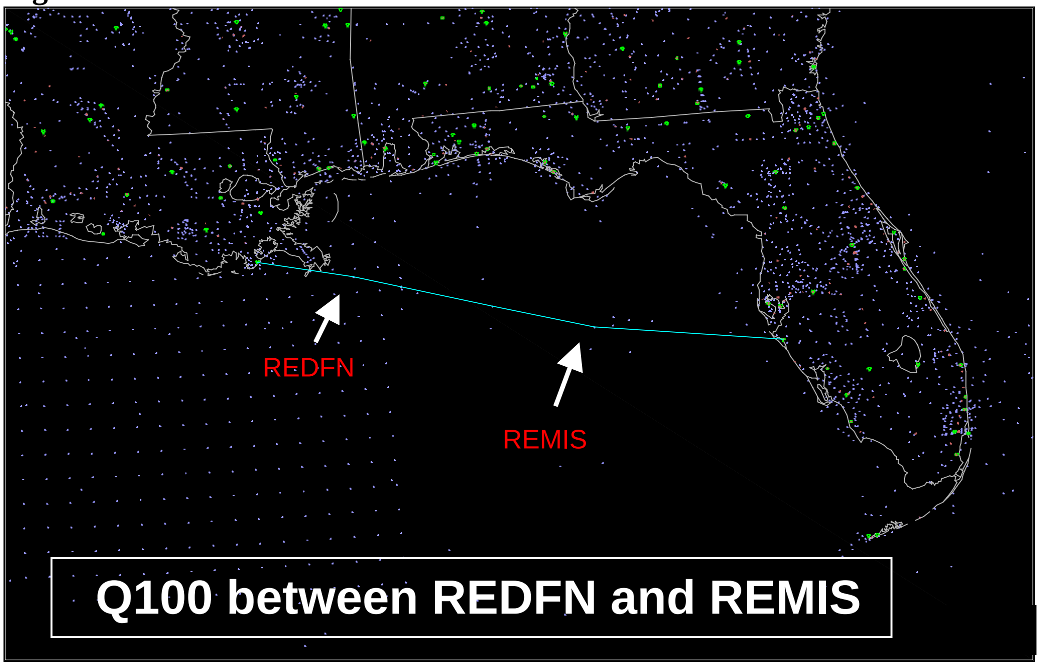
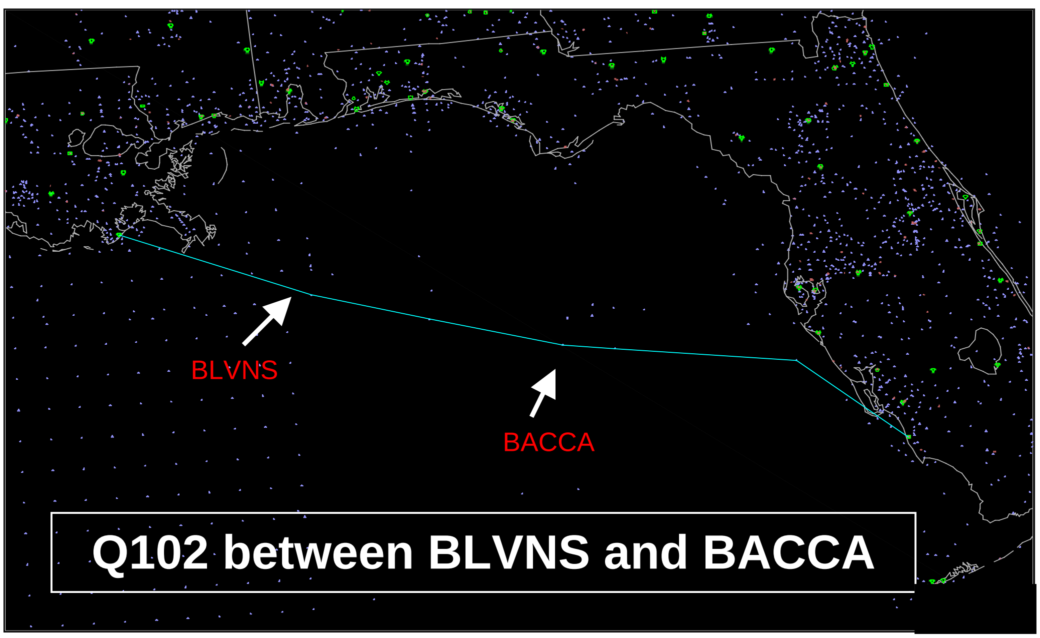


Figure 2



2.0. Study Methodology

2.1. Data Collection

We collected Performance Data Analysis and Reporting System (PDARS) long-range radar data and flight information from the Jacksonville Air Route Traffic Control Center (ARTCC) for all potential Q-Route 100 and 102 flights during the dates and times listed in Table 1. There were 1,127 flights tracked. During these times, operators logged anomalous flights (such as aircraft vectored off the route or aircraft not authorized for RNAV operations). We removed 262 of these anomalous flights from the data set leaving 865 flights.

Table 1

Date	Start Time (UTC)	End Time (UTC)
19-Feb	1230	2130
20-Feb	1700	2130
21-Feb	1330	2230
24-Feb	1230	2130
25-Feb	1230	2130
26-Feb	1230	2130
27-Feb	1230	2050
3-Mar	1700	2230
4-Mar	1245	2230
5-Mar	1700	2230
6-Mar	1230	2230

We examined these 865 flight tracks and eliminated 111 of them due to the following reasons:

Aircraft left route before reaching last waypoint (65)
Aircraft entered route after first waypoint (17)
Aircraft never entered route or route could not be determined (21)
Aircraft intentionally left route and returned -- apparently vectored (4)
Too few data points (4)

The 754 remaining tracks then represented all aircraft tracks recorded that attempted the complete route (between REDFN and REMIS for Q100 or between BLVNS and BACCA for Q102) during the study period. See Appendix A for details of the outlier detection methodology and examples of discarded tracks.

2.2. Data Conversion and Organization

The PDARS data included radar tracks by latitude and longitude in addition to aircraft identification, type, and navigation capability. We converted the track latitudes and longitudes into along track distances and cross track deviations.

Then we organized the 754 converted data tracks into a database by track ID, route, aircraft type, and navigational capability. Table 2 lists the number of tracks by route. Table 3 lists the percent of aircraft by navigational aid.

Table 2

Route	Direction	Tracks
Q100	East	261
Q100	West	320
Q102	East	158
Q102	West	15
Total		754

Table 3

NAV	Percent
GPS	53%
FMC	96%
IRU	68%

3.0. Summary of Data Analysis and Risk Evaluation

3.1. Organization of the Analysis

In order to quantify the later dispersion of the Q-Route tracks, this study will focus on the distribution of lateral track deviation. In the remainder of this report, when a distribution is referred to, it will mean a distribution of lateral track deviations. The routes Q100 and Q102 both display distributions that center essentially about zero, but have variance and kurtosis values which indicate they should be analyzed separately. However, it appears reasonable to analyze the east and west directions for each route together.

Figure 3 is a histogram for the Q100 distribution (east and west combined) and Figure 4 is a histogram for Q102 (east and west combined). The results of Kolmogorov-Smirnov tests for each distribution are consistent with the assumption that the distributions are normal. The smooth curve plotted with each histogram represents a normal fit. Table 4 gives the means and standard deviations for the two routes.

Table 4

Route	SD	Mean
Q100	0.172	-0.007
Q102	0.159	0.002

Figure 3 **Q100 Lateral Deviation Distribution**

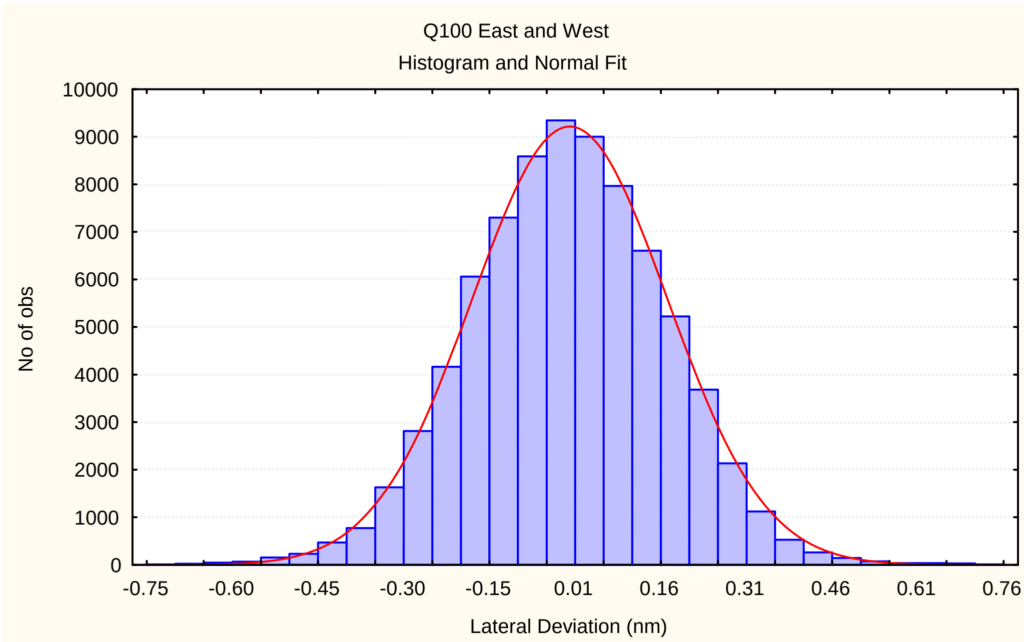
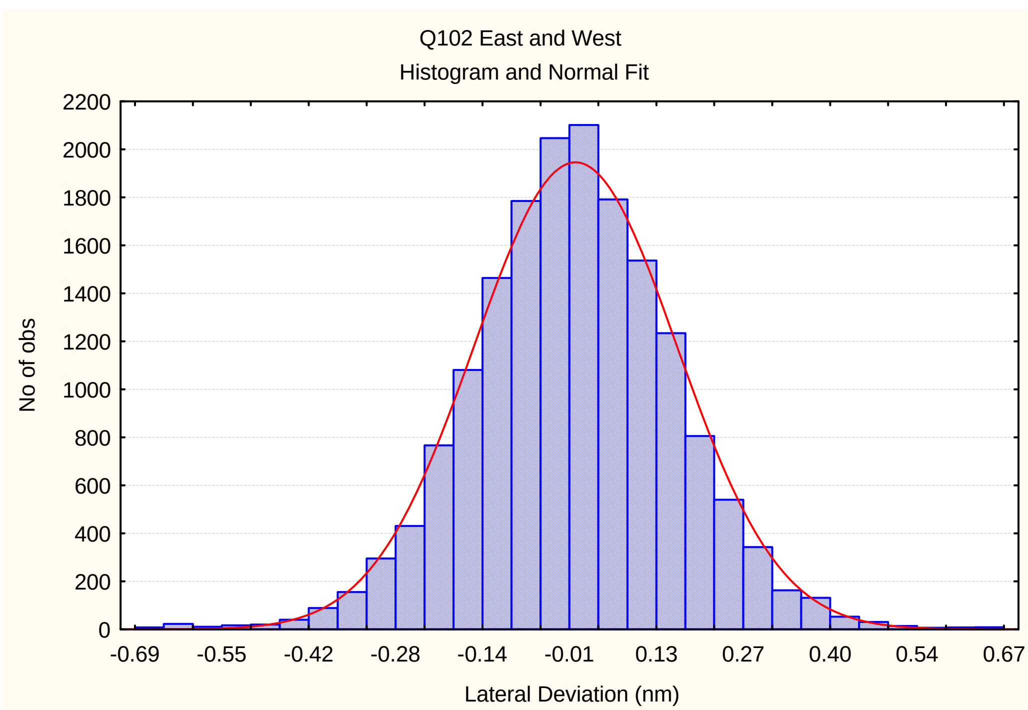


Figure 4 **Q102 Lateral Deviation Distribution**

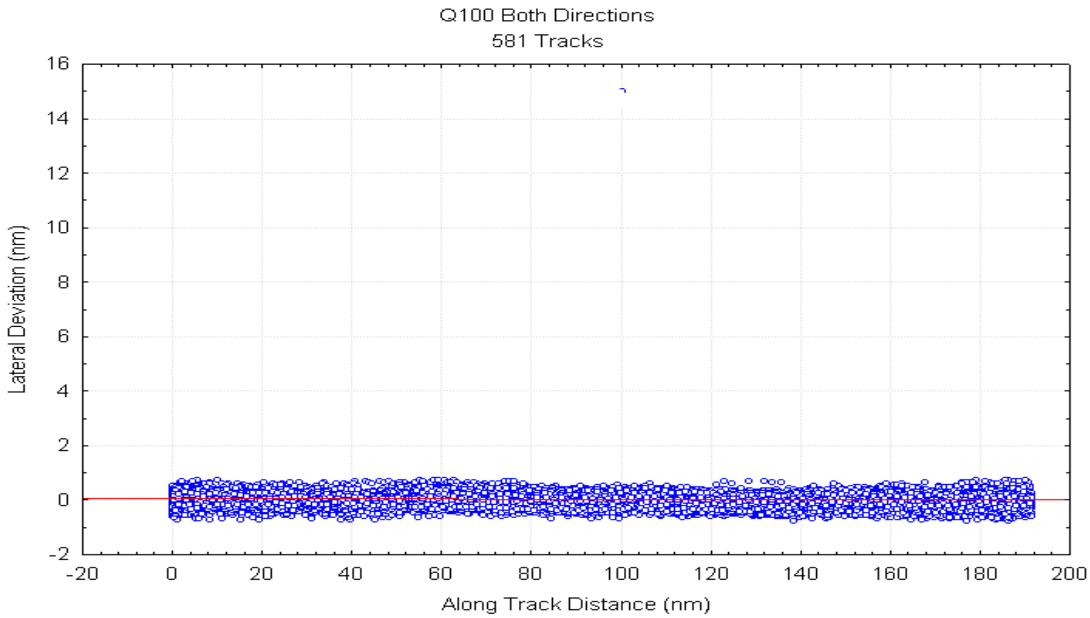


We will first analyze each route (Q100 then Q102) separately. Then we will analyze the tracks for the Q100 route by navigational capability.

3.2. Q100 Risk Analysis

Figure 5 shows plots of the lateral deviations by along track distance for the 581 Q100 tracks. Table 4 shows the mean and standard deviation for these tracks.

Figure 5 **Q100 Tracks**



To analyze the risk of an RNAV aircraft deviating laterally from route Q100 by 1, 2, 3, or 4 NM, we use classical Extreme Value Theory to develop a distribution for the maximum lateral deviation values. This theory provides two things. First, it provides a family of distributions called General Extreme Value (GEV) distributions that model block maximums such as those of the deviations. Second, it provides the justification for using a GEV distribution to extrapolate beyond the range of the maximum deviation values found in the sample data.

The family of GEV distributions is described by the distribution function:

$$\text{GEV}(x) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$, where μ is the location parameter, σ is the scale parameter, and ξ is the shape parameter. Changing the value of any one of the parameters provides a different member of the family of GEV distributions.

We use the sample data and a standard extreme value technique (extreme value maximum likelihood estimation) to estimate the three parameter values, and thus the specific distribution that fits our data.

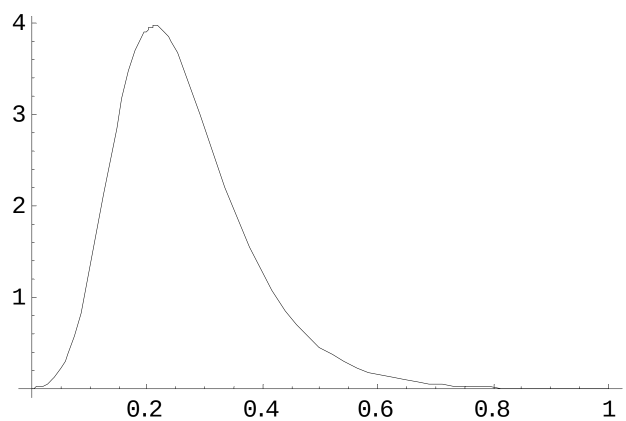
We get the sample data from the 581 Q100 tracks by segmenting the 189 NM tracks into nine 20 NM blocks and one 9 NM block.

Autocorrelation analysis shows that the track deviations become uncorrelated at 20 NM, so we can assume that each block is independent. For each of the 581 tracks we find the maximum absolute value deviation per block, yielding 5810 maxima, or extreme values.

Based on these maxima, the parameter values the estimation technique yields are:
μ = 0.2125, σ = 0.0927, and ξ = -0.0098 with standard errors 0.0014, 0.0010, and 0.0104, respectively.

The density function corresponding to GEV(x) with these parameters is plotted in Figure 6. The horizontal axis units in Figure 6 are NM.

Figure 6 **Q100 GEV Density Function**



Based on this GEV density function, we estimate the probability of an aircraft deviation exceeding a given value within a 20 NM segment. These probabilities are listed in Table 5. The standard error associated with these probability estimates, computed by the delta method, is on the order of 1.66 E-18. Note that the probability of a deviation exceeding 4 NM was calculated to be zero to the precision of the software used.

Table 5 also lists the probabilities of a deviation exceeding the given limits in a 200 NM segment and in one hour of flight (assuming an average speed of 500 knots).

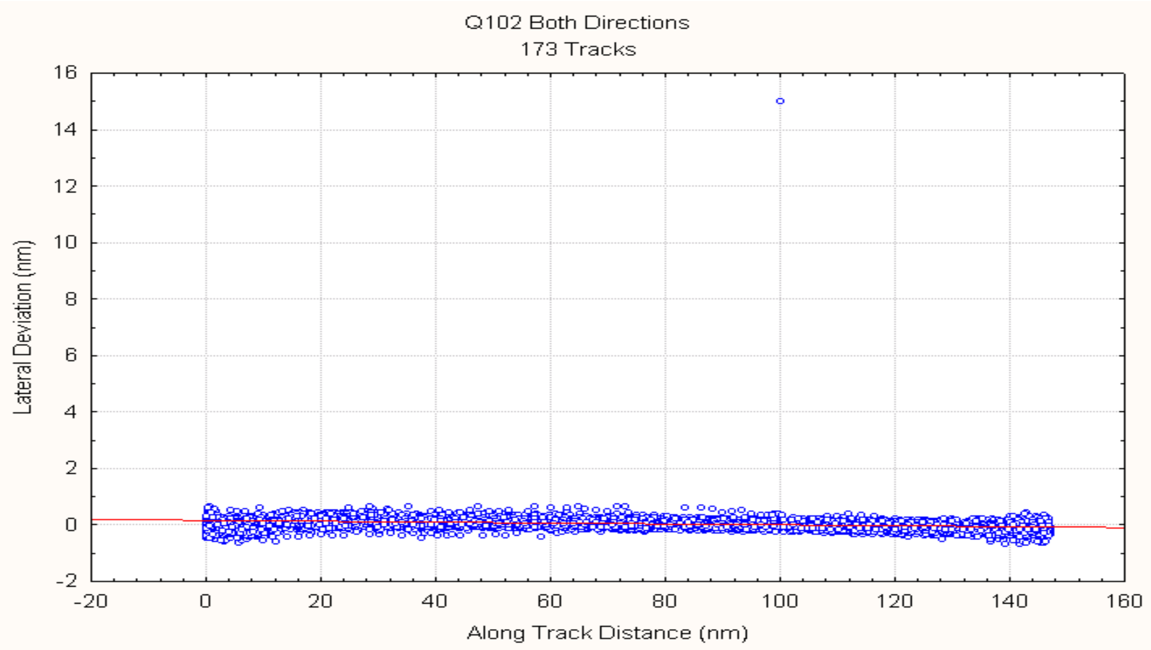
Table 5

Limit (NM)	Probability of Exceeding Limit in 20 NM	Probability of Exceeding Limit in 200 NM	Probability of Exceeding Limit in 1 Hour
1.0	1.40 E-04	1.40 E-03	3.50 E-03
2.0	5.16 E-10	5.16 E-09	1.29 E-08
3.0	3.33 E-16	3.33 E-15	8.33 E-15
4.0	0.00 E-18	0.00 E-18	0.00 E-18

3.3. Q102 Risk Analysis

Figure 7 shows plots of the lateral deviations by along track distance for the 173 Q102 tracks. Table 4 shows the mean and standard deviation for these tracks.

Figure 7 **Q102 Tracks**



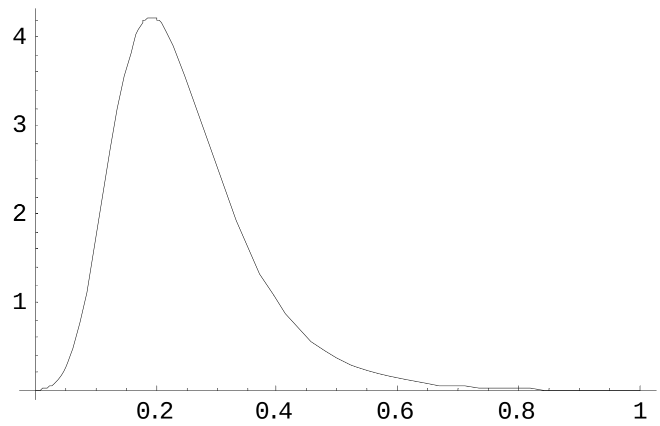
As with the Q100 analysis, to analyze the risk of an RNAV aircraft deviating laterally from route Q102 by 1, 2, 3, or 4 NM, we use classical Extreme Value Theory to develop a distribution for the maximum lateral deviation values.

We get the sample data from the 173 Q102 tracks by segmenting the 147 NM tracks into seven 20 NM blocks and one 7 NM block. Autocorrelation analysis shows that the track deviations become uncorrelated at 20 NM, so we can assume that each block is independent. For each of the 173 tracks we find the maximum absolute value deviation per block, yielding 1,384 maxima, or extreme values.

Based on these maxima, the parameter values the estimation technique yields are: μ = 0.1959, σ = 0.0870, and ξ = 0.0338 with standard errors 0.0027, 0.0020, and 0.0240, respectively.

The density function corresponding to GEV(x) with these parameters is plotted in Figure 8. The horizontal axis units in Figure 8 are NM.

Figure 8 Q102 GEV Density Function



Based on this GEV density function, we estimate the probability of an aircraft deviation exceeding a given value within a 20 NM segment. These probabilities are listed in Table 6. The standard error associated with these probability estimates, computed by the delta method, is on the order of 1.30 E-13.

Table 6 also lists the probabilities of a deviation exceeding the given limits in a 200 NM segment and in one hour of flight (assuming an average speed of 500 knots).

Table 6

Limit (NM)	Probability of Exceeding Limit in 20 NM	Probability of Exceeding Limit in 200 NM	Probability of Exceeding Limit in 1 Hour
1.0	3.21 E-04	3.21 E-03	8.03 E-03
2.0	1.50 E-07	1.50 E-06	3.75 E-06
3.0	3.41 E-10	3.41 E-09	8.53 E-09
4.0	2.20 E-12	2.20 E-11	5.50 E-11

3.4. Q100 Risk Analysis by Navigational Capability

We analyzed the Q100 tracks by navigational capability. (There were too few Q102 tracks to analyze meaningfully by navigational category.) Tables 7 and 8 summarize the differences in lateral deviation mean and standard deviation (SD) by Global Positioning System (GPS), Flight Management Computer (FMC), and Internal Reference Unit, (IRU) navigational capability. Here the SDs are more useful than the means in estimating the size of the lateral deviation by category since the means are much closer to zero. Lower SDs mean less lateral dispersion. The smallest SD is that of the category of aircraft with all three capabilities (GPS, FMC, and IRU). The largest SDs are those of the categories with no GPS and no FMC.

Table 7

GPS	FMC	IRU	Mean	SD	Count
NO	NO	YES	-0.121	0.284	3
NO	YES	YES	0.001	0.178	236
YES	NO	NO	0.006	0.191	12
YES	YES	NO	-0.023	0.174	127
YES	YES	YES	0.003	0.146	135
Unknown			-0.014	0.183	68

Table 8

GPS	Mean	SD
NO	-0.003	0.180
YES	-0.009	0.162

We focused on the two categories that both had FMC and IRU, but differed in that one had GPS and one did not to estimate the difference in lateral deviation between a GPS aircraft and a non-GPS aircraft on this route. These categories have 135 and 236 tracks respectively. For each category, we plotted the tracks and performed an extreme value analysis of track lateral deviation.

As Figures 9 and 10 show, the GPS category tracks are tighter. We calculated the width of a 10^{-7} iso-probability limit for each category. That is, in the figure, a linear boundary above and below the track for which the probability of penetration is 10^{-7} over a 200 NM route. For the GPS category the width is plus or minus 1.29 NM. For the non-GPS category, the width is plus or minus 1.54 NM. It should be emphasized that these are all aircraft with FMC and IRU. Table 9 gives a list of several iso-probability limits for a 200 NM route.

Table 9

Limit	GPS	non-GPS
10^{-6}	1.18 NM	1.41 NM
10^{-7}	1.29 NM	1.54 NM
10^{-8}	1.38 NM	1.65 NM

Figure 9 GPS E-07 Limits

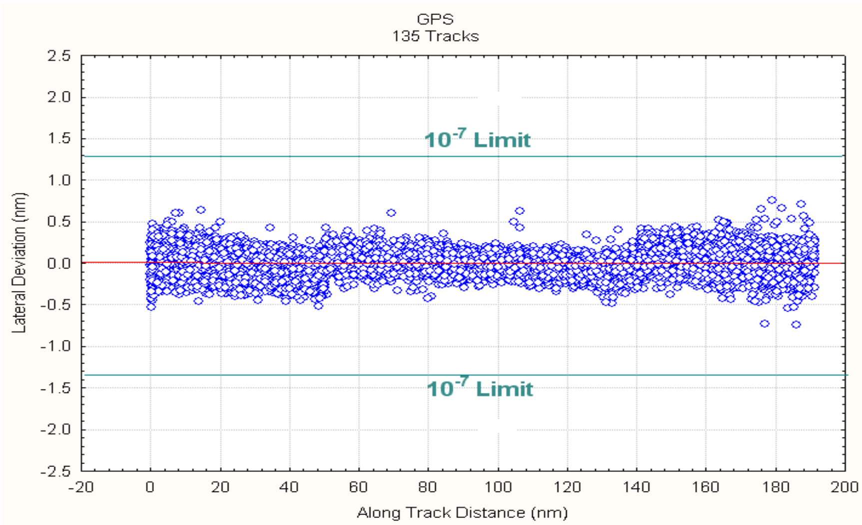
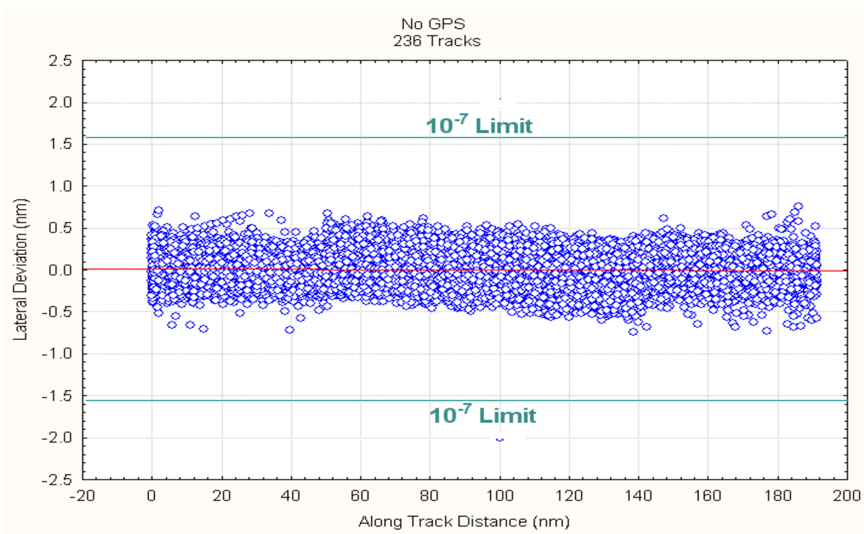


Figure 10 Non-GPS E-07 Limits



4.0. Results and Conclusions

4.1. Results

The primary result of this study is that, for a typical aircraft attempting to fly one of the two Q-Routes, Q100 or Q102, the probability of its lateral deviation exceeding 4 NM over a 200 NM distance is less than 1.0 E-10. That is, it is less than 1 in 10,000,000,000. This estimate is conservative since it uses the larger of the values from the separate analyses of Q100 and Q102. Table 10 summarizes the results for the two routes.

The difference in the results for the two routes is due to the difference in their sample sizes, a small difference in the mix of navigational capabilities of aircraft tracked on the two routes, and possibly radar tracking error variation between the two tracks.

Table 10

Limit (NM)	Q100 Probability of Exceeding Limit in 200 NM	Q102 Probability of Exceeding Limit in 200 NM	Rounded Upper Bound Probability of Exceeding Limit in 200 NM
1.0	1.40 E-03	3.21 E-03	1.0 E-02
2.0	5.16 E-09	1.50 E-06	1.0 E-05
3.0	3.33 E-15	3.41 E-09	1.0 E-08
4.0	0.00 E-18	2.20 E-11	1.0 E-10

Additional results show a real difference between aircraft similarly equipped (with FMC and IRU) but with or without GPS. See Table 9.

4.2. Caveats and Conclusions

A note about radar measurement error

The long-range radar tracks used were generated by an ATCBI-6 Secondary Radar at the Jacksonville ARTCC, approximately 230 NM from the midpoint of the routes. In this situation, the range error will be negligible compared to the azimuth error.

The azimuth error for this radar system is specified to be ± 0.033 degrees. This translates into a lateral error measurement of up to 0.13 NM at 230 NM. Because of the consistency of the tracks and their tight centering about the route, we have reason to believe the radar accuracy performance was better than that specified. There are two types of error in any measurement: bias and random error. The fact that individual data tracks follow essentially smooth curves (with very little jitter), tends to support the assumption that there is very little significant random error in the radar measurement. Also, the fact that the mean of all tracks for each route is very close to zero, tends to support the assumption that either there is very little bias in the radar measurement or the radar bias cancels out the navigation bias for most of the aircraft (the latter being highly unlikely).

In any case, an error of plus or minus 0.13 NM in the track measurements would not affect the primary results significantly. For example, reducing the 4 NM limit by 0.13 NM on each side would result in changing the probability of exceeding the limit on Q102 from 2.20 E-11 to 4.05 E-11. This would not change the rounded upper bound probability of 1.0 E-10 reported in Table 10.

Blunders

The results assume no aircraft blunders or other failures attempt to follow the Q-Route. It could be that some of the late route entries, early departures, or failures to detect a route were due to blunders or other substantial navigational errors. Therefore, the results of this study should be interpreted as applying to estimates of flight technical error (FTE) and navigation system error (NSE) only.

Other Limitations

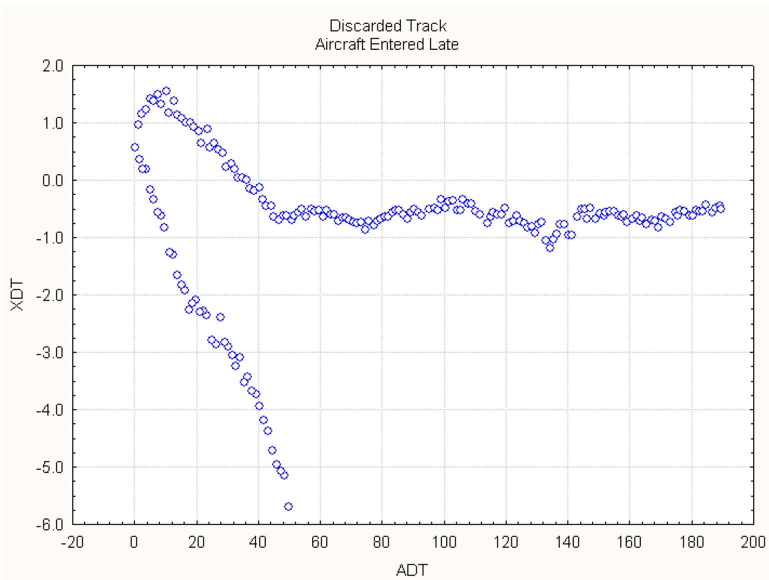
This study is obviously limited to the types of aircraft navigational capabilities available in the aircraft observed and to the weather conditions present on the dates of the observations. In addition, the tracks studied were straight segments of no more than 200 NM.

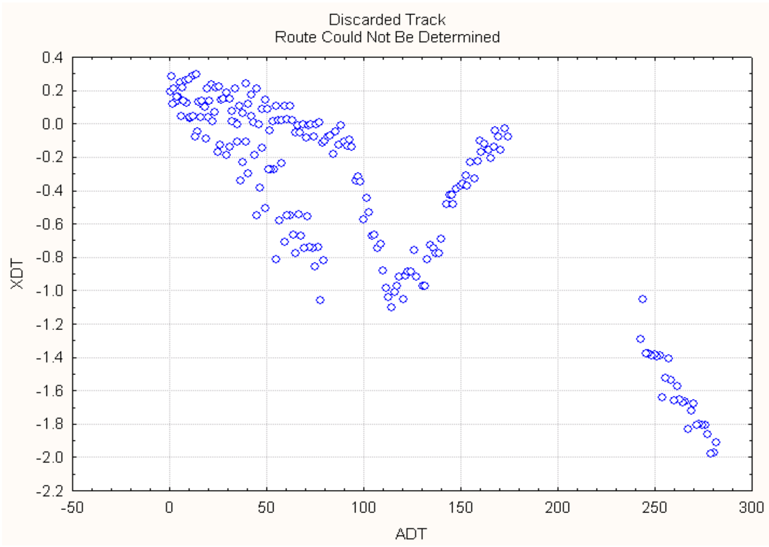
In the next phases of this study, we will incorporate a range of environmental conditions, navigational capabilities, and route geometry (including turns greater than 15 degrees).

Appendix A

Outlier Detection Criteria

1. Start with all tracks in the data set supplied.
2. Eliminate all tracks not flown during the hours when the air traffic operations staff monitored the flights.
3. Eliminate all tracks the air traffic operations staff detected as not valid Q100 or Q102 operations.
4. Examine graphs of the remaining tracks and determine if any were clearly the result of routes other than Q100 and Q102. That is, the tracks do not intermingle with, weave in and out of, or remain parallel but close to the Q100 and Q102 routes, but rather are clearly separate routes. Eliminate any such tracks.
5. Eliminate tracks that enter the route late or leave the route early.
6. Use only the remaining tracks for the lateral deviation analysis.




Discarded Track
Route Could Not Be Determined
XDT
ADT
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
-2.2
-50
0
50
100
150
200
250
300