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Comparison of Host Radar Tracks to Aircraft Positions from the Global Positioning Satellite System

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16. Abstract

The Federal Aviation Administration (FAA) air traffic control system relies directly on aircraft locations provided by the long range en route surveillance radars. The accuracy of the radars is an important factor in determining the overall performance of the system. To support the planned modernization of the air traffic control system a study was conducted to measure the accuracy of the radar tracking function of the system. This was done by comparing aircraft radar tracks produced by the existing system with the tracks for the same aircraft produced by the Global Positioning Satellite System (GPS) position reports. It was assumed that the GPS data was the ground truth. The GPS data was available from the FAA's Reduced Vertical Separation Minimum (RVSM) Certification Program. The Host Air Traffic Management Data Distribution System (HADDS) at each Air Route Traffic Control Center (ARTCC) captures the radar track data. This data is then archived at the William J. Hughes Technical Center (WJHTC) for a period of time. The radar tracks for 265 flights were compared to their GPS "tracks". Three distance metrics were used: horizontal track error and its two components cross track error and along track error. A total of 54170 pairs of position reports were compared. The distributions of the errors were plotted and basic descriptive statistics were determined. It was found that the average horizontal error was 0.69 nautical miles (nm), the root mean square value of the horizontal error was 0.78 nm, the average cross track error was 0.12, and the average along track error was 0.67 nm.

17. Key Word

Aircraft flight paths

HCS, Host Computer System

Lateral Trajectory Error / Cross Track Error

Longitudinal Trajectory Error / Along Track Error

Radar data processing

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We would like to acknowledge David Zhou of General Dynamics and summer intern, Dimitar Kolev of Titan Corporation, who both performed a considerable amount of the processing steps required in the study. Finally, we would like to thank the FAA's ERAM Program Office for funding this study via the ERAM Test Group at the William J. Hughes Technical Center.

Executive Summary

The FAA's ERAM Test Group (ACB-550) formed the Automation Metrics Test Working Group (AMTWG) in 2004. The team's charter is to support the developmental and operational testing of ERAM by developing a set of metrics that quantify the effectiveness of key system functions in ERAM. The targeted system functions are Surveillance Data Processing (SDP), Flight Data Processing (FDP), Conflict Probe Tool (CPT), and the Display System (DS) modules. The metrics are designed to measure the performance of ERAM. They also are designed to measure the performance of the legacy En Route automation systems in operation today. When appropriate, they will allow comparison of similar functionality in ERAM to legacy systems.

The project is divided into key phases: first a metrics identification process was performed. A list of approximately one hundred metrics was generated by the AMTWG and mapped to the Air Traffic services and capabilities found in the Blueprint for the National Airspace System Modernization 2002 Update. This took place most of fiscal year 2004 and initial metrics results were published in June 2004 in the document titled, "ERAM Automation Metrics Progress Report of the Automation Metrics Test Working Group". Next, an implementation-planning phase was performed. In this step, the identified metrics were prioritized for more detailed refinement during 2005. The plan "ERAM Automation Metrics and Preliminary Test Implementation Plan," documents the implementation-planning phase. It lists these metrics, gives the rational for selecting them, and provides a high level description on how the highest priority metrics will be measured.

The final project phase is the data collection and analysis phase. In this step, AMTWG will document the further refinement and application of these metrics on the current legacy systems in a series of Metric Reports. AMTWG is planning the delivery of four Metric Reports for fiscal year 2005 covering several of the ERAM subsystems. This technical note documents the first of these reports implementing metrics to support testing of ERAM's Surveillance Data Processing's (SDP) tracking algorithms. It documents the radar tracking positional accuracy of the legacy Host Computer System by comparison to Global Positioning Satellite System (GPS) calculated aircraft positions.

A sample of GPS data from 265 flights from January through February of 2005 was processed from the over 10,000 flights collected by the Reduced Vertical Separation Minimum (RVSM) Certification Program. A total of 54,170 measurements were calculated comparing the GPS positions to time coincident Host radar track positions from all 20 Centers in the continental United States. This representative sample of operational data allowed the AMTWG to estimate the performance of the existing ATC tracking function.

Three basic metrics were employed. They include: horizontal error that is the unsigned straight line distance between the time coincident radar track and GPS position, along track error that is the longitudinal orthogonal component (ahead and behind) of the horizontal error, and cross track error that is the lateral orthogonal component (side to side) of the horizontal error. For this study, the average horizontal error was 0.69 nautical miles or 4200 feet. As shown in Figure ES- 1, the cross track error distribution is symmetrical about zero; however, the along track error distribution is strongly skewed in the negative direction with an average error of -0.67 nautical miles. The radar position is consistently lagging in time. This bias in the data suggests that the Host radar data has an uncompensated delay.

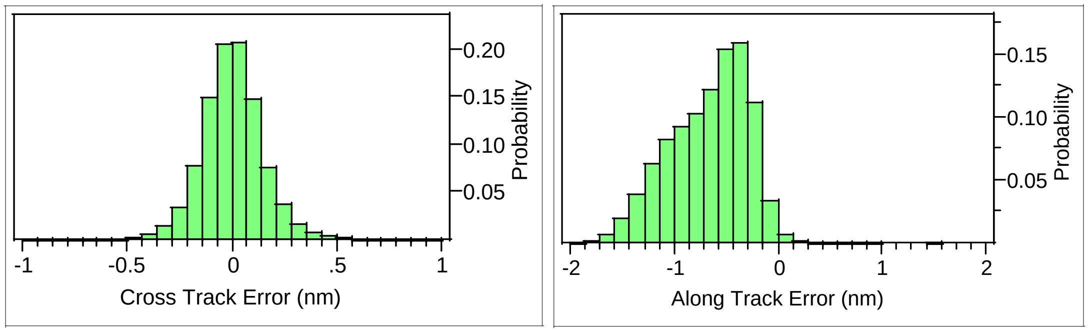


Figure ES- 1: Cross and Along Track Error Histograms

The overall horizontal Root Mean Square (RMS) statistic is 0.78 nm, which is the square root of the average of the squared error measurements. Previous studies used simulation methods to produce similar results. Most noteworthy is that produced by Trios Incorporated in November 2003. The report titled, "Host Tracker Performance Assessment," documented a steady state (no turns) RMS value of 0.2 – 0.5 nm, for the two fixed speeds of 250 and 600 knots. The results were very comparable to this study, since the Trios analysis also reported larger errors for turning tracks, while this study included about 13% of its samples as turns and a range of speeds with a median around 350 knots.

Inferential statistics were performed to test the impact of source Air Route Traffic Control Center (or Center), altitude, and track turning status on the HCS's track error measurements. Both the Center and turn status resulted in statistically significant differences, but had no practical difference, ranging from 0 to 0.23 nautical miles for the Center analysis and turn status had even smaller values. Lastly, the study did provide evidence to support that altitude does have a modest impact on the tracker's performance with about a 0.35 nautical mile increase in comparing measurements taken below 10,000 feet to 45,000 feet and beyond. AMTWG cautions however that the altitude could be a composite indicator for other more influential factors such as aircraft speed and aircraft type not studied in the report.

Finally, the study ended with detailed reviews of selected flights that complement the overall statistics for all the flights, illustrating the processing steps. The results of the examples are consistent with the overall statistics listed above. For the cross track errors, the signed errors tend to cancel resulting in a sample mean close to zero. They also exhibit a negative bias in the along track error providing yet more evidence of an uncompensated longitudinal error.

Therefore, the statistics provide a baseline of performance for the legacy Host surveillance tracking algorithm that can later be referred to in the ERAM Testing Program for similar SDP functionality. The AMTWG Implementation Plan, discussed above, also presents a companion metric study for SDP tracking that utilizes simulation methods. The resulting simulation runs on the legacy Host Computer System and can be later adapted to run through ERAM. These two studies combined provide a strong foundation to address the critical operational issue (COI 1.0), as documented in the FAA's *Test Evaluation Master Plan* for ERAM. COI 1.0 requires the ERAM Test Program to verify that ERAM supports air traffic control operations with at least the same effectiveness as the current system. Furthermore, this technical note based on a relatively large sample of operational and GPS data can also serve as validation of these simulations.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Purpose

The Federal Aviation Administration (FAA) began development of a new Air Traffic Control (ATC) system to replace the existing Host Computer System (HCS) in the en route domain. The Host system is used by all twenty en route ATC Centers in the continental United States. The new system, called ERAM (for En Route Automation Modernization), is being developed by the Lockheed Martin Corporation. As documented in the FAA's *Test Evaluation Master Plan*, the ERAM Test Program is required to ensure key operational issues are verified (WJHTC/ACB-500 2003). These issues are organized as critical operational issues. The first critical operational issue (COI 1.0) requires that ERAM supports ATC operations with at least the same effectiveness as the current system. Therefore, the performance of the radar track subsystem in ERAM must be as good as the performance of the existing Host radar tracking. To determine this, a baseline performance of the Host is required to provide performance standards to later compare to ERAM.

This technical note documents the results of comparing the HCS aircraft tracks with tracks obtained from the Global Positioning Satellite System (GPSS or GPS). This study is one of several proposed and planned by the Automation Metrics Test Working Group (AMTWG) in the "ERAM Automation Metrics and Preliminary Test Implementation Plan," published in June 2005 (WJHTC/ACB-330 2005).

1.2 Background

The FAA's ERAM Test Group (ACB-550) formed the Automation Metrics Test Working Group (AMTWG) in 2004. The team's charter is to support the developmental and operational testing of ERAM by developing a set of metrics that quantify the effectiveness of key system functions in ERAM. The targeted system functions are Surveillance Data Processing (SDP), Flight Data Processing (FDP), Conflict Probe Tool (CPT), and the Display System (DS) modules. The metrics are designed to measure the performance of ERAM. They also are designed to measure the performance of the legacy En Route automation systems in operation today. When appropriate, they will allow comparison of similar functionality in ERAM to legacy systems (e.g. HCS).

The project was divided into key phases: first a metrics identification process was performed. A list of approximately one hundred metrics was generated by the AMTWG and mapped to the Air Traffic services and capabilities found in the Blueprint for the National Airspace System Modernization 2002 Update (FAA 2002). This took place most of fiscal year 2004 and initial metrics results were published in June 2004 in the document, "ERAM Automation Metrics Progress Report of the Automation Metrics Test Working Group" (WJHTC/ACB-550 2004). Next, an implementation-planning phase was performed. In this step, the identified metrics were prioritized for more detailed refinement during 2005. The plan "ERAM Automation Metrics and Preliminary Test Implementation Plan," documents the implementation-planning phase. It lists these metrics, gives the rational for selecting them, and provides a high level description on how the highest priority metrics will be measured. The Implementation Plan provides the metric's traceability to the basic controller decisions, ERAM Critical Operational Issues (COIs), and the development contractor's technical performance measurements (TPMs). The categories of high priority metrics are: (1) SDP radar tracking, (2) SDP tactical alert processing, (3) FDP flight plan route expansion, (4) FDP aircraft trajectory generation, (5) CPT strategic aircraft-to-aircraft conflict prediction, (6) CPT aircraft-to-airspace conflict prediction, (7) additional system level metrics, and (8) DS human factor and performance metrics.

The final project phase is the data collection and analysis phase. In this step, AMTWG will document the further refinement and application of these metrics on the current legacy systems in a series of Metric Reports. AMTWG is planning the delivery of four Metric Reports for fiscal year 2005 with one covering each of the ERAM modules discussed above, SDP, FDP, CPT, and DS respectively. These reports will be published in multiple drops to provide the ERAM Test Team on-time information. The drops will coincide with the approaches used to implement the metrics. This technical note documents the first of these reports implementing metrics on SDP's surveillance tracking algorithms. It documents the radar tracking positional accuracy of the Host as compared to GPS calculated aircraft positions.

Previous studies have mainly used simulation methods to ascertain metrics on Host radar tracking accuracy, most notably is the study completed by Trios Corporation in November 2003 (Trios Inc., 2003). The study developed a wide array of metrics related to radar tracking defined as quantifiable measurements of performance (MOPs). The most relevant MOPs to this study directly evaluated the Host radar tracker's positional accuracy using a series of simulation runs using the FAA's Interfacility and Radar System (FIRS) simulation tool. The study examined two target motion states: steady state, and maneuver state. Steady state referred to level and straight flight and maneuver state was applied to a time period that the target undergoes heading or speed change, or the time period in which the tracker statistical behavior is not in steady state (context dependent).

Table 1-1: Trios Radar Track Position Accuracy Metrics[1]

Host Measure of Performance	Description	Host Assessment Results	
		250 knots	600 knots
Track Accuracy, Steady State Position	Difference Between True Target Position and Tracker Predicted Position During Steady State	0.2-0.3 nm RMS	0.2-0.5 nm RMS
Track Accuracy, Maneuver State Position	Difference Between True Target Position and Tracker Predicted Position During a Maneuver	1.2-1.3 nm peak RMS during turn maneuver 0.7-0.9 nm peak RMS during speed Maneuver	1.6-1.7 nm peak RMS during turn maneuver 0.7-1.0 nm peak RMS during speed maneuver

The AMTWG study documented in this report is a representative sample of operational radar track and GPS positions collected from the field. The Trios Study, described above, based on simulation required specific choices for the parameters of the aircraft being modeled. For example, aircraft were modeled at two typical speeds 250 knots and 600 knots. Turn maneuvers used were three degrees per second for 250 knot velocities and one degree per second for 600 knot velocities. Linear acceleration maneuvers were designed for 0.05g linear acceleration-deceleration, approximately 0.94 knots per second. The positional accuracy results of the Trios study have being extracted into Table 1-1. The results are partitioned by the two fixed speed

[1] Table 1-1 was extracted from Table ES-1 in the Trios Study (Trios Inc., 2003). The RMS or Root Mean Square metric is the mean of the squared distance between true simulated position and radar tracked position. It is proportional to this study's average horizontal error described later in Section 3.3.2 and presented in Section 4.1.1.1.

profiles and steady and maneuver state. Despite the differences in design, both are valid approaches and comparable. The Trios error statistics will be later compared to the AMTWG results presented in the Data Analysis Section 4 and concluded in Section 5.

1.3 Scope

Initially, approximately 400 aircraft flights from all 20 United State's Air Route Traffic Control Centers (ARTCCs or Centers) were selected for the tracking comparison. The differential GPS data for these flights was available by the Reduced Vertical Separation Minimum (RVSM) Certification Group within the Separation Standards (ACB-310) at the FAA's William J. Hughes Technical Center, WJHTC, (WJHTC/ACB-310, 2004). The recorded radar track data was obtained from the FAA server which archives the recordings of the radar tracks for all of the Centers for the last several months. The comparison has been done in the horizontal plane only; the differences in reported altitudes have not been addressed in this study.

The GPS data is accurate to within a few meters, while the radar data is accurate to within a fraction of a nautical mile. For this study the GPS data is considered to be ground truth and a difference between the GPS data and the radar data is considered to be an error. In comparing the radar track to the GPS three distance metrics have been employed: (1) horizontal error, (2) longitudinal or along track error, and (3) lateral or cross track error. These are the measurements that have been previously used (Paglione, et al., 1999) and (Cale, et al. 2001). Descriptive statistics have been calculated for these metrics, such as sample mean and standard deviation. Inferential statistical tests have been performed to determine whether or not the accuracy is influenced by factors such as ARTCC (or Center), altitude, and whether the aircraft was turning.

1.4 Document organization

This technical note is organized into the following primary sections. Sections 2 and 3 describe the data collection and data reduction processes, Section 4 defines the analysis with statistical measures and their application. Conclusions are provided in Section 5. Additional details of the study are given in the Appendices.

2 Data Collection

Aircraft track data was collected from the Host radar processing subsystem and GPS positions from RVSM certification recordings. This section provides an overview of the collection of both these data sets.

2.1 Collection of Host Radar Track Data

As illustrated in Figure 2-1, the radar track data from each of the Host Computer Systems is recorded by Host Air Traffic Management (ATM) Data Distribution System (HADDS) and archived to a network server at the WJHTC. This data was then made accessible via secure link to the AMTWG (authors of this paper) by AOS-330 who maintains the system. The HADDS Server has search capabilities utilizing the Structured Query Language (SQL), allowing acquisition of traffic data for specific flights and days. The process includes: (1) selection of the specific flights to request, (2) acquisition of the data by utilizing the HADDS Server and querying for the identified flights, and finally (3) processing the flight data into the form required by legacy data analysis tools.

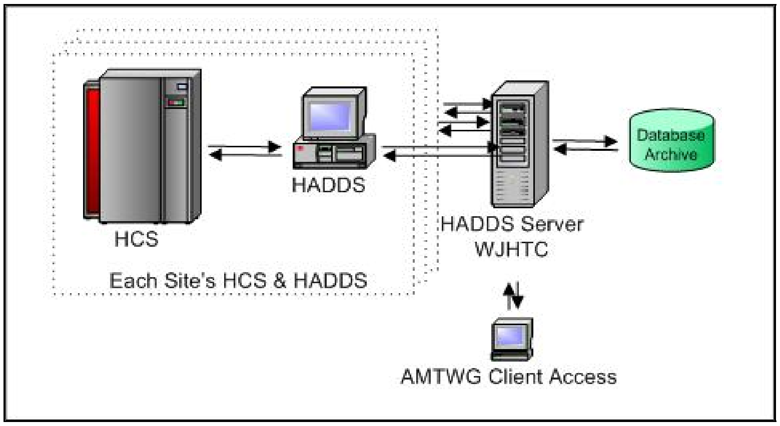


Figure 2-1: Host Track Data Collection

2.1.1 Flight Selection

The Separation Standards Group (ACB-310) at the WJHTC has certified approximately 10,000 aircraft to fly in RVSM airspace. The certification process entails recording GPS position reports for the subject aircraft for about forty minutes while it is in straight and level cruise. For this study, AMTWG selected approximately 400 flights which were flown from January 3, 2005 through February 25, 2005. Relatively recent flights were chosen to ensure that their radar tracking data would be available on the HADDS Server. The flight identification information was obtained from a RVSM database. The flights are identified by a sequence number, aircraft call sign, and a date (date that they were flown).

2.1.2 Data Acquisition and Processing

The Host's radar track data is recorded by the HADDS as a sequence of messages using the format of the Common Message Set (CMS) (FAA, 2001). As illustrated in Figure 2-1, the radar track data was queried for the selected aircraft and date and downloaded manually, one day at a time. Thus, all of the CMS messages for the selected flights and all of the Centers on a specific day were downloaded into a single file. A given flight might fly through, for example seven Centers, and the GPS recorded portion of the flight may go through three Centers. Furthermore, the AMTWG legacy tools from ACB-330 required processing on individual centers. Therefore, AMTWG developed a process that grouped flight segments in common Centers from all the days and flights downloaded. The process also discarded flight segments[2] that did not have matching GPS data. For the example above, only the flight segments in the three Centers common to both GPS and Host would be retained for further analysis.

The flights varied in length, but due to the source all had a minimum duration of about 40 minutes. Some of the flights were made specifically for RVSM certification. For other flights the GPS and altimeter recording were incidental.

2.2 Collection of GPS Data

GPS data for each flight after processing by the RVSM Group is recorded to flat files, labeled with a DFA file extension (differential GPS ASCII file format). Each flight is identified by a sequence number. There are two different data formats depending on whether the field data was

[2] There is a distinction between flight and flight segments. A flight may travel through many Center's airspace, but a flight segment is just the portion of the flight within a Center.

collected by the Computer Services Support Inc. or by the Aeronautical Radio Inc. All of the DFA files for the period of January 3 through February 25, 2005 were downloaded for processing by AMTWG. The GPS reports were normally at one second time stamps but occasionally had time gaps or other anomalies, such as stationary, duplicate, and positions beyond the operating conditions of commercial aircraft.

3 Data Reduction

A number of computer processing steps were necessary to prepare the data for the comparison. Most of the software tools were developed for previous studies to examine the trajectory accuracy of decision support tools (Paglione, et al., 1999) and adapted here for this study as described in more detail in (Ryan, 2005). Since the legacy tools were designed to process only one Center's flight segments at a time by comparing radar track and trajectory predictions, AMTWG needed to alter the format of the GPS data to match the legacy trajectory formats. Before the comparison of the radar track and GPS could be performed, several preprocess steps included: (1) filtering the radar track data to match the available duration of GPS data, (2) segregating the data by Center, and (3) converting the data from longitudes and latitudes to the Center specific stereographic coordinate frame. The subsequent subsections will describe the details of these processing steps. The overall process is further illustrated in Figure 3-1.

3.1 Radar Data Reduction

As stated above, analysis tools to compare the radar data to the GPS data were available from previous work comparing radar data to trajectories (predicted flight paths). These tools require the data to be in specific formats. The radar data was run through a scenario parsing program which converted the CMS formatted messages downloaded from HADDS into an internal message format. An important part of the processing was the conversion of the latitude and longitude aircraft positions into stereographic XY positions. Each Center has its own unique stereographic coordinate system and therefore it was essential to know the Center identification for every track report. The distance metrics used for the comparison are defined in terms of the stereographic coordinates.

As illustrated in Figure 3-1 in the data process flow stream of the Host radar track, the data is first extracted and downloaded from the HADDS website, then parsed and converted to the XY coordinate frame. Since the flights are extracted for all Centers they fly through, the flights are segregated by Center into flight segments. Next, these flight segments of track are compared to the GPS data and filtered for time overlap accordingly. This step may eliminate flight segments in which GPS was not available. Unlike the GPS data, which is fairly smooth and clean, Host track data may contain gross errors due to lags in the recording process or other anomalous reasons. Thus, AMTWG runs the track data through a post-processing tool that checks for reasonableness. This is documented in detail in reference (Ryan and Paglione, 2004). Finally, the track reports are interpolated and synchronized to 10 second intervals timed to the hour of the day. This step is in preparation for later comparison to its companion GPS data.

3.2 Preprocessing the GPS Data

For the first step as listed in Figure 3-1, the GPS DFA files were downloaded and positional data extracted. The latitude and longitude positions were converted to stereographic XY coordinates, analogous to the radar data. The GPS data was nominally sampled at a one second sampling rate. However, many flights contained time gaps of much larger durations. For each GPS flight, the longest contiguous segment of track data was identified and saved; the rest of the data was discarded. A contiguous track segment was defined to be one in which there were no gaps longer than ten seconds. The longest track segment for each GPS flight was written to a relational database table along with its identifying information. Approximately 15% of the data was discarded to obtain contiguous GPS track data.

Once all of the GPS data for all the selected flights was stored to the database, another software program extracted the data at 10 second intervals and was written to flat files, one for each Center, consistent in format with legacy software tools. Now segregated by Center, each of these GPS data files provides the input for the comparison processing to the radar tracks.

3.3 Comparison Processing

After the collection and preprocessing of the radar and GPS data, the two input sources for each Center are ready for processing using the existing track accuracy computer software tools. The radar track data, which are now coordinate-converted, checked for reasonableness, interpolated, and time synchronized to 10 second intervals, reside in a set of relational database tables. The GPS positions, which are now parsed, coordinate-converted, and formatted into trajectory files sampled at 10 second intervals, are awaiting comparison in flat files.

3.3.1 Application of Interpolation for Time Coincidence

To calculate the time coincident spatial metrics defined in the subsequent Section 3.3.2, both the radar track data and GPS positions must not only be in the same coordinate frame, but synchronized to the same time positions as well. The radar track data was already time synchronized to 10 second intervals on the hour. However, the GPS trajectory positions were sampled at 10 second intervals but not synchronized to the hour. The software tool responsible for the comparison processing first linearly interpolates the GPS positions to synchronize them to same 10 second intervals as the radar. Next, each aircraft's particular flight segment within the Center and coincident GPS positions are matched by time and sent for processing the spatial metrics.

Note, the GPS positions as originally supplied at 1 second time intervals, technically speaking, should not require any interpolation. However, due to compatibility issues with legacy software tools, it was necessary to sample at 10 second intervals and then later use interpolation to time synchronize to the track data. AMTWG determined that the impact of these steps to be negligible.

3.3.2 Spatial Metrics

Matched and synchronized in the previous step, a radar track position of an aircraft is compared to the time coincident GPS position of the aircraft. Three metrics have been calculated for each pair of reports: (1) horizontal error, (2) along track or longitudinal error, and (3) cross track or lateral error. The details of the computation have been given in references (Paglione, et al., 1999) and (Ryan and Paglione, 2004) and partially repeated in APPENDIX A – Metrics. In summary, horizontal error is the unsigned straight line distance between the time coincident radar track and GPS position. Along and cross track errors are the signed orthogonal components of the horizontal error. Along track is the longitudinal component. A positive value indicates the track is ahead of the GPS position and negative is behind the time coincident GPS report. The cross track error is the lateral or side to side error component of the horizontal error. A positive cross track error indicates the track is to the right of the GPS position and negative is to the left.

A data processing run was made for each of the 20 Centers. Each run produced position errors for all of the matched tracks for all the flight segments within the Center. A GPS flight which flies through more than one Center's airspace will have part of its error data assigned to each of the airspaces that it traverses. The results for all Centers will be summarized in Section 4.

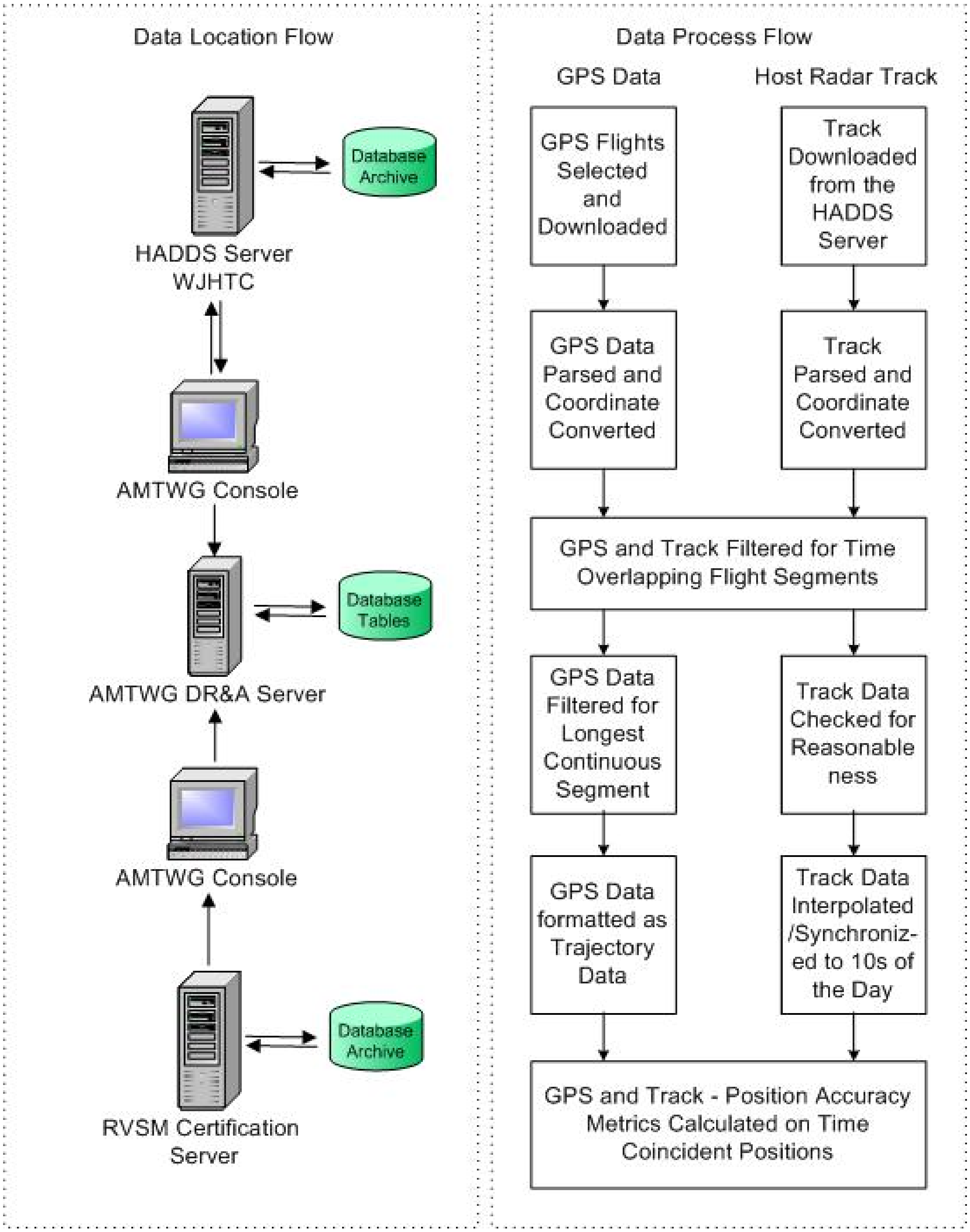


Figure 3-1: Data Reduction Process Flow

4 Data Analysis

The analysis presents the results of calculating the three error metrics described in Section 3.3.2 and APPENDIX A – Metrics. Each GPS track report was matched with a radar track report having the same time stamp. The three error metrics were calculated for every time matched pair of track reports. The error values were grouped by flight segment and by Center. Stored in a large relational database table as defined in Section 3.3.2, the original 400 flights resulted in 54,170 pairs of measurements from 265 flights. Partitioning the flights by Center into flight segments produces a total of 391 flight segments.

A small number of outliers have been excluded from this data. The outliers do not represent the basic accuracy of the Host radar tracking capabilities and represent artifacts produced from the data collection process. Flight segments that have a maximum horizontal error of greater than 2 nautical miles were categorized as outliers. This threshold was chosen after careful inspection of the data and review of several individual flights. Twenty three of the 414 flight segments have been excluded in this way (414-23=391), representing 5.8 % of the measurements.

There are three subsections that follow: Section 4.1 includes all the descriptive statistics that describe the entire set of flight segments or categories of flight segments, next Section 4.2 presents statistical analyses that answer specific questions (for example are each Center's trackers performing the same, is the tracker performing the same during turns or at different altitude bands), and finally in Section 4.3 two sample flights are presented in detail to illustrate how the errors were calculated and what they really mean.

4.1 Descriptive Statistics

For this study, the descriptive statistics summarize and quantify the accuracy data collected for the horizontal and along and cross track error metrics. The statistics typically used in this study are the sample mean, the median, the standard deviation, and the maximum and minimum values taken from our sample of flight segments. The statistics are illustrated by graphical methods such as histograms in the subsequent sub-sections. These statistics are calculated either for all flight segments, by flight segment, or other factors of consideration like Center or turn status.

4.1.1 Overall Error Rates

The overall error rates for all flight segments and all measurements are listed in the following Table 4-1. The signed error values tend to cancel out in some statistics like sample mean. Therefore, Table 4-1 provides both the signed and unsigned values for cross and along track statistics. The average signed cross track error is very small (100 feet) while the average unsigned (magnitude) cross track error is significantly larger (700 feet). However, the signed and unsigned averages for the along track error are similar in magnitude, since along track errors are consistently negative. A large along track error represents a time error. This data therefore indicates that the HCS track report time stamping has an uncompensated error. At a speed of 420 knots, an error distance of 0.67 nautical miles corresponds to time error of about 6 seconds.

The RMS or Root Mean Square is the square root of the sample mean of squared errors. It is proportional to the sample mean of the unsigned metrics but tends to weight more heavily the upper and lower tails of the distribution. In Table 4-1, the RMS statistic for horizontal error was about 0.1 nautical mile higher than the sample mean with similar results for the other metrics as well. Since RMS squares the error measurements, it is the same for signed and unsigned errors.

Table 4-1: Sample Mean and RMS Statistics for All Flight Segments

		Horizontal Error		Cross Track Error		Along Track Error	
Type	Sample Size	Mean	RMS	Mean	RMS	Mean	RMS
Signed	54170	0.69	0.78	0.00	0.16	-0.67	0.77
Unsigned				0.12		0.67	

4.1.1.1 Overall Horizontal Error Distribution

The horizontal error distribution as presented in Figure 4-1 is skewed with a peak around 0.4, sample mean 0.69, and median 0.63 nautical miles. Horizontal error is an unsigned metric by definition, so the skew is a result of the combination of its two orthogonal components along and cross track errors. The standard deviation of the horizontal error is 0.36 nautical miles. The 75th and 25th quantiles are 0.95 and 0.40, respectively.

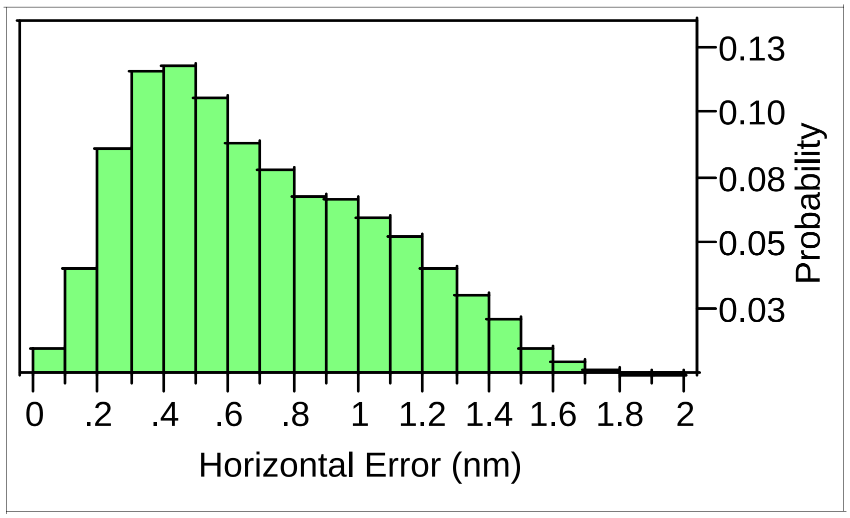


Figure 4-1: Histogram of Horizontal Error

4.1.1.2 Overall Cross Track Error

The cross track error is a signed metric that is symmetric around a population mean of zero. The sample mean is for all practical purposes zero at 0.00 nautical miles (0.002 resulted and is beyond the precision of the data source) and sample standard deviation of 0.16 nautical miles. The sample median is also 0.00 nautical miles and the 75th and 25th quantiles are 0.09 and -0.09, respectively. All indicate a very symmetric distribution around zero nautical miles error.

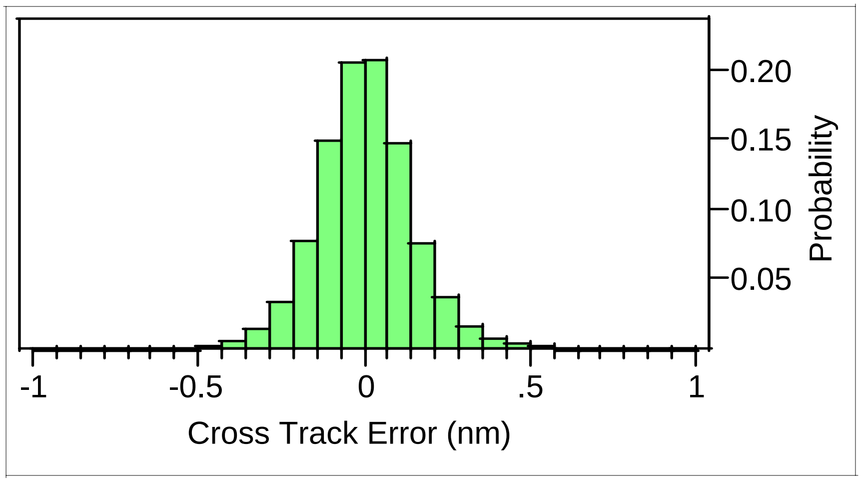


Figure 4-2: Histogram of Cross Track Error

4.1.1.3 Overall Along Track Error

The along track error is another signed metric like the previous cross track error, but unlike the very symmetric cross track error the along track distribution is significantly negatively skewed. It has a sample mean -0.67 nautical miles and median of -0.61 nautical miles. The standard deviation is 0.38 nautical miles and the 75th and 25th quantiles are -0.37 and -0.94 nautical miles, respectively. Thus, the along track error not only provides the magnitude of the error but illustrates the inherent lag in the HCS tracker algorithm's smoothing of the aircraft position.

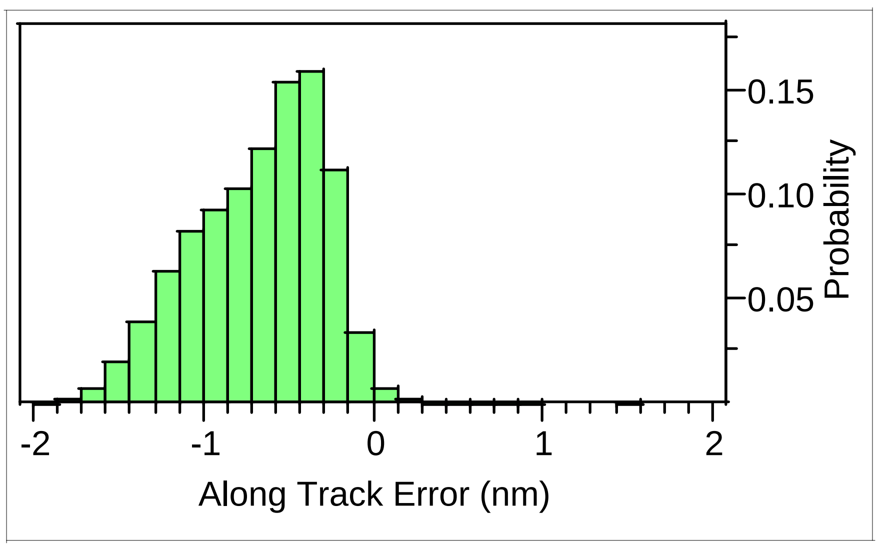


Figure 4-3: Histogram of Along Track Error

4.1.2 Worse Cases by Center

In this section, each Center's flight segment with the largest average horizontal error has been listed in Table 4-2. The unsigned cross and along track errors are also provided. The list represents the most poorly performing flight segments in the entire sample. The range of horizontal errors is from 0.66 to 1.6 nautical miles. This list provides a view of the maximum magnitude of a flight's tracker errors across all twenty centers. In subsequent Section 4.2, we shall explore the complete distributions for each center.

Table 4-2: Error Statistics by Center for Flights with Maximum Average Horizontal Error

CENTER		AVERAGE HORIZONTAL ERROR	AVERAGE UNSIGNED CROSS TRACK ERROR	AVERAGE UNSIGNED ALONG TRACK ERROR
Albuquerque	ZAB	1.12	0.07	1.11
Chicago	ZAU	1.36	0.13	1.34
Boston	ZBW	1.03	0.12	1.02
Washington	ZDC	1.61	0.37	1.54
Denver	ZDV	0.94	0.36	0.84
Fort Worth	ZFW	1.37	0.13	1.36
Houston	ZHU	1.02	0.10	1.01
Indianapolis	ZID	1.20	0.13	1.19
Jacksonville	ZJX	1.31	0.08	1.30
Kansas City	ZKC	1.03	0.14	1.01
Los Angeles	ZLA	1.55	0.23	1.52
Salt Lake City	ZLC	0.84	0.06	0.83
Miami	ZMA	1.11	0.11	1.10
Memphis	ZME	1.08	0.19	1.01
Minneapolis	ZMP	1.06	0.13	1.05
New York	ZNY	0.69	0.10	0.67
Oakland	ZOA	1.02	0.12	1.01
Cleveland	ZOB	1.21	0.26	1.17
Seattle	ZSE	0.66	0.11	0.65
Atlanta	ZTL	1.28	0.12	1.26

The flight segments having the largest average cross track error in each Center and the flight segments having the largest average along track error in each Center are listed in APPENDIX B – Aggregate Statistics by Center.

Statistics for the three error metrics for all of the individual flight segments are given in APPENDIX C – Flight Segment Error Data.

4.2 Inferential Statistics

Inferential statistics are methods that go beyond summarizing the sample with an objective to draw conclusions about the population based on the sample information (Devore, 2000). They are used to test for a specific question or series of questions by determining if a given independent variable influences the dependent variable. In this study, the dependent variables include the horizontal, cross track, or along track errors and the independent variables include the Center, turn status (i.e. the track is within a turn or not), vertical transition status (i.e. track is climbing, descending or level), or altitude interval. Therefore, this section will provide evidence or illustrate the lack of statistical evidence whether a variable influences the HCS tracker's performance.

4.2.1 Tracker Error by Center

For the 54,170 measurements between HCS track and GPS aircraft positions, data was sampled from all twenty NAS Centers in the United States. The samples ranged from 10,721 samples in ZKC (Kansas City Center) to only 172 in ZSE (Seattle Center). The following Figure 4-4 illustrates the statistical box plot diagram for each Center's distribution of horizontal tracker errors. The box plot diagram presents several quantile statistics and the range of data as a vertical box. This vertical box contains the 25^{th} quantile at the bottom, median as the center line, and 75^{th} quantile as the top line. The difference between the 75^{th} and 25^{th} quantiles is referred to as the interquartile range. The vertical line extending above and below the box provides an indication of the upper and lower values of the sample. There distances are calculated by the following equations:

upper line = 75^{th} quantile + 1.5 (interquartile range) **Equation 4-1**

lower line = 25^{th} quantile - 1.5 (interquartile range) **Equation 4-2**

In Figure 4-4, y-axis is horizontal error in units of nautical miles and x-axis is each Center in the NAS. The box plots are presented in red while the actual sample means and standard deviations are presented as blue lines. The center blue line is the sample mean and is surrounded by plus or minus the standard error mean[3]. The farther out blue lines above and below the mean represent one standard deviation above and below the mean. The grand mean (sample mean of entire data set) is presented as the solid gray horizontal line across the entire axis in Figure 4-4.

[3] Standard error mean is the standard deviation divided by the square root of the sample size.

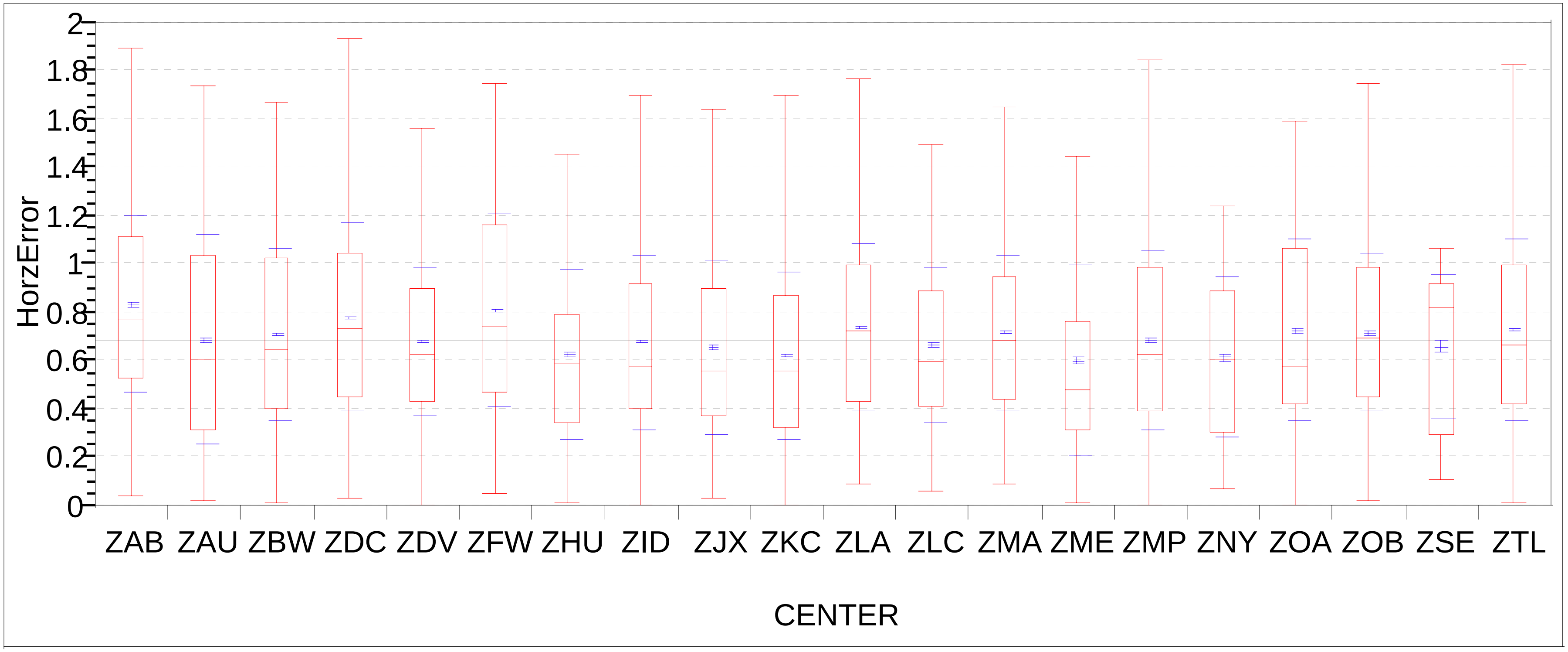


Figure 4-4: Horizontal Track Error Box Plots Per Center[4]

[4] See Table 4-2 for full listing of Center names and respective codes (e.g. Albuquerque for ZAB).

Table 4-3 summarizes the same statistics presented in Figure 4-4 graphically. The results show that the horizontal error per Center is not that different in magnitude. In Appendix D – Comparison of Horizontal Error Means by Center, the means were statistically compared using a Tukey-Kramer statistical test[5]. The results showed that several of the pairwise differences (Center against Center) was indeed statistically significant, but as illustrated in the box plot and Table 4-3 the differences are not large ranging from 0.00 to 0.23 nautical miles.

Table 4-3: Horizontal Track Error Statistics by Center[6]

Center	Sample Size	Mean	Std Dev	Std Err Mean
ZAB	1840	0.83	0.36	0.01
ZAU	1791	0.69	0.43	0.01
ZBW	1946	0.71	0.36	0.01
ZDC	3106	0.78	0.39	0.01
ZDV	3411	0.68	0.31	0.01
ZFW	2227	0.81	0.40	0.01
ZHU	4567	0.63	0.35	0.01
ZID	4351	0.68	0.36	0.01
ZJX	1879	0.66	0.36	0.01
ZKC	10721	0.62	0.35	0.00
ZLA	2784	0.74	0.35	0.01
ZLC	1101	0.67	0.32	0.01
ZMA	3057	0.72	0.32	0.01
ZME	1253	0.60	0.40	0.01
ZMP	2859	0.69	0.37	0.01
ZNY	593	0.62	0.33	0.01
ZOA	1276	0.73	0.38	0.01
ZOB	1651	0.72	0.33	0.01
ZSE	172	0.66	0.30	0.02
ZTL	3585	0.73	0.38	0.01

The box plots for the two orthogonal components cross and along track errors are presented in the following two figures, Figure 4-5 and Figure 4-6, respectively. The cross track error shows that while both the mean and spread of a couple of the Center's measurements were large, most were close about the grand mean.

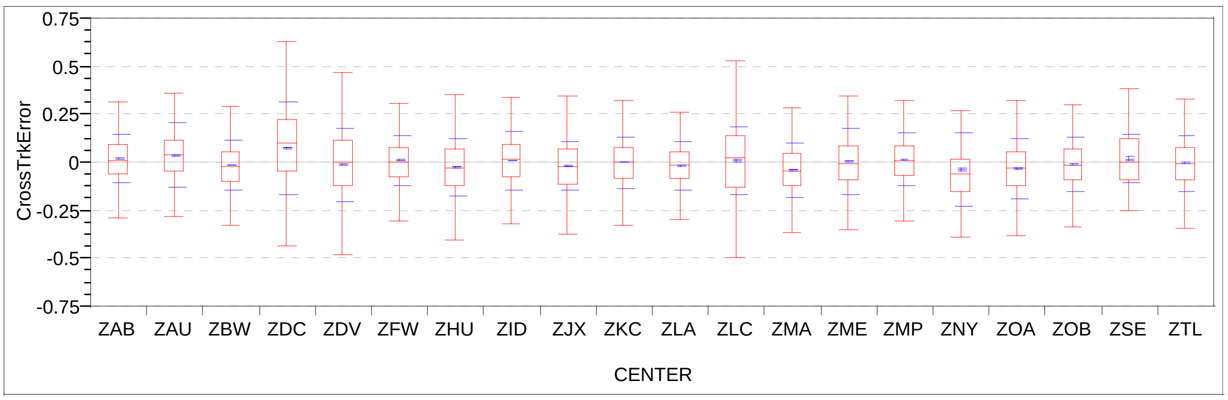


Figure 4-5: Cross Track Error Box Plots Per Center

[5] Tukey-Kramer is a standard statistical test for comparing multiple sample means. It is provided within the SAS Institute's JMP statistical application; see www.jmp.com for details, (SAS Institute Inc., 2003).
[6] All error statistics such as horizontal, cross and along track metrics are presented in units of nautical miles. Units of nautical miles will continue to be used throughout this report for these same metrics.

The along track errors illustrated in Figure 4-6 are more variable than the cross track errors, yet the along track differences between means are still low between the Centers, ranging from 0.26 to 0.00 nautical miles.

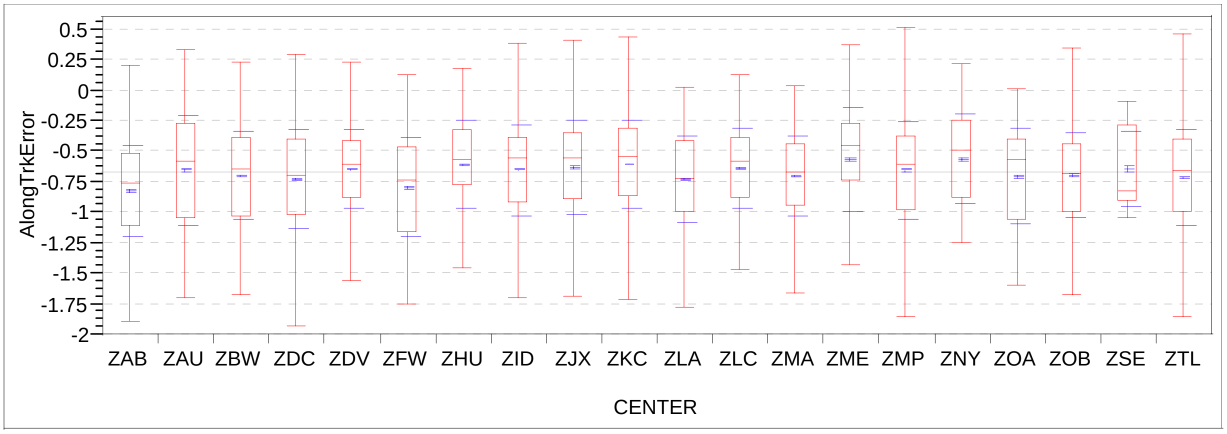


Figure 4-6: Along Track Error Box Plots Per Center

4.2.2 Tracker Error by Turn Status

It has been proposed that the accuracy of the tracking algorithm is influenced by whether the aircraft is within a turn. In this section, turn status is determined by comparing the course heading change between adjacent HCS track reports after modest smoothing is applied; details provided in (Paglione, et al., 1999). Next, turning and not turning track reports are compared by their horizontal, cross track, and along track errors (same errors calculated in Section 4.1). The following Figure 4-7 illustrates the box plots of these two sample populations. Zero refers to no turns, and one refers to measurements with track data determined to be turning. From Figure 4-7 and Table 4-4, the difference between the two sample means is 0.01 nautical miles, indicating that the turn status does not appear to influence the accuracy by much if at all.

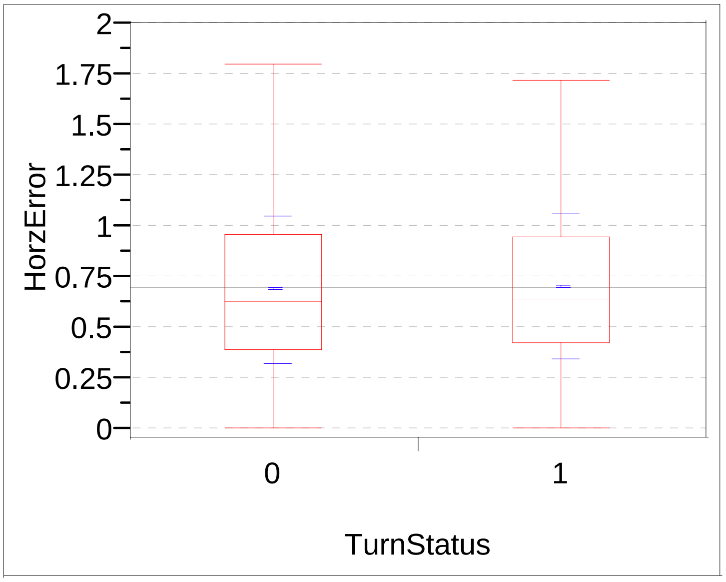


Figure 4-7: Horizontal Track Error Box Plots by Turn Status

Table 4-4: Turn Status Error Statistics

		Horizontal Error		Cross Track Error		Along Track Error	
Turn Status	**Sample Size**	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
No turn	47327	0.69	0.36	0.00	0.15	-0.67	0.38
Turn	6843	0.70	0.36	0.00	0.20	-0.66	0.38

The subsequent Figure 4-8 and Figure 4-9 provides comparison of the two samples for the cross and along track errors. Like the Center factor in Section 4.2.1, a Tukey-Kramer test was performed comparing the two sample means. The test indicated that there is a statistically significant effect between the sample means with the horizontal and cross track error measurements but not along track error. This is clearly illustrated in the Table 4-4 where the along track error means are within 0.01 nautical miles and standard deviation even closer. The cross track error has greater differences with a standard deviation 0.05 nautical miles larger for turning measurements.

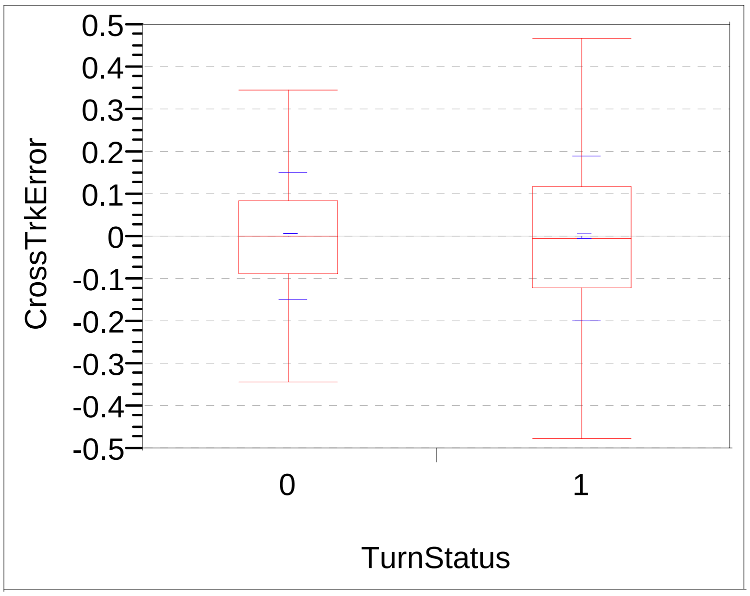


Figure 4-8: Cross Track Error Box Plot by Turn Status

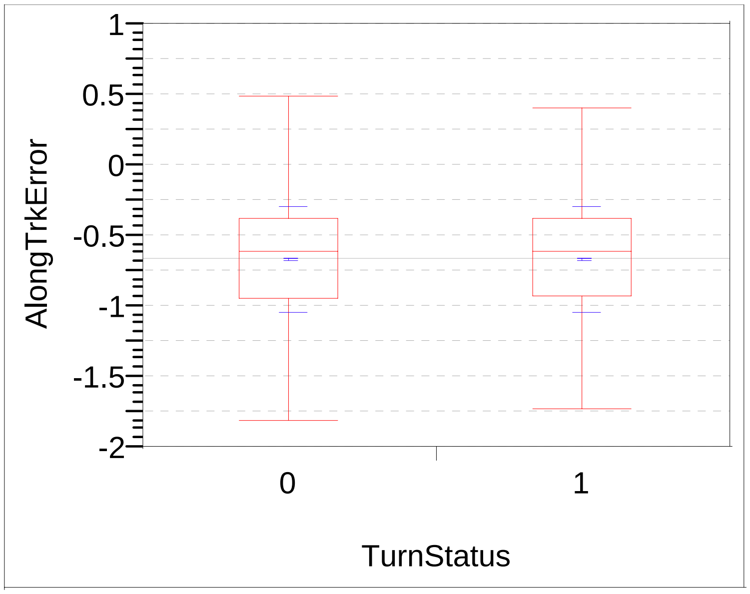


Figure 4-9: Along Track Error Box Plots by Turn Status

In summary, the horizontal and cross track errors did exhibit a statistically significant effect for turning measurements, but not by much. After careful review of the processing in this study, turn status, which as indicated above is currently based on the HCS track reports, should be based on the less noisy GPS positions. In a subsequent analysis, this data will be revisited using the GPS positions to calculate the turns and perhaps the effect of turning status will be greater.

4.2.3 Tracker Error by Altitude Interval

Different aircraft frames and categories operate at different altitudes with different speed profiles and weather influence. Due to this, it was speculated that altitude may indirectly influence the tracker's performance. For this section, the data sets were categorized into the following altitude bands: 0 to 10,000 feet, 10,000 to 18,000 feet, 18,000 to 29,000 feet, 29,000 to 40,000 feet, and above 40,000 feet. As listed in Table 4-5, the data set is somewhat biased with 88 percent of the measurements being sampled from the altitude band 29,000 to 40,000 feet. However, the data still exhibits clear patterns of performance. This is presented in Table 4-5 where each error metric's sample mean and standard deviation is listed. This is also illustrated in Figure 4-10 where each altitude band's box plot is presented. Consistent with the statistics from Table 4-5, the box plots show the steady rise in both sample mean and standard deviation, despite very large disparity between altitude band sample sizes.

Table 4-5: Altitude Band Error Statistics

		Horizontal Error		Cross Track Error		Along Track Error	
Altitude Band	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
0-100	202	0.39	0.22	0.03	0.13	-0.35	0.24
100-180	461	0.64	0.35	-0.03	0.14	-0.62	0.36
180-290	3657	0.67	0.35	0.00	0.16	-0.65	0.36
290-400	47710	0.69	0.36	0.00	0.15	-0.67	0.38
400-	2140	0.74	0.38	0.00	0.17	-0.71	0.40

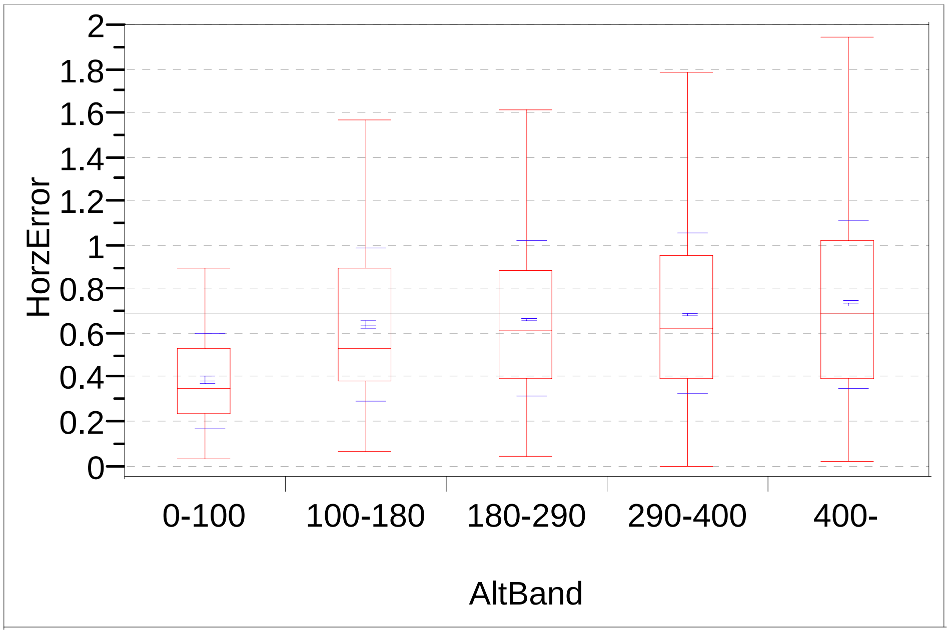


Figure 4-10: Horizontal Track Error Box Plots by Altitude Band

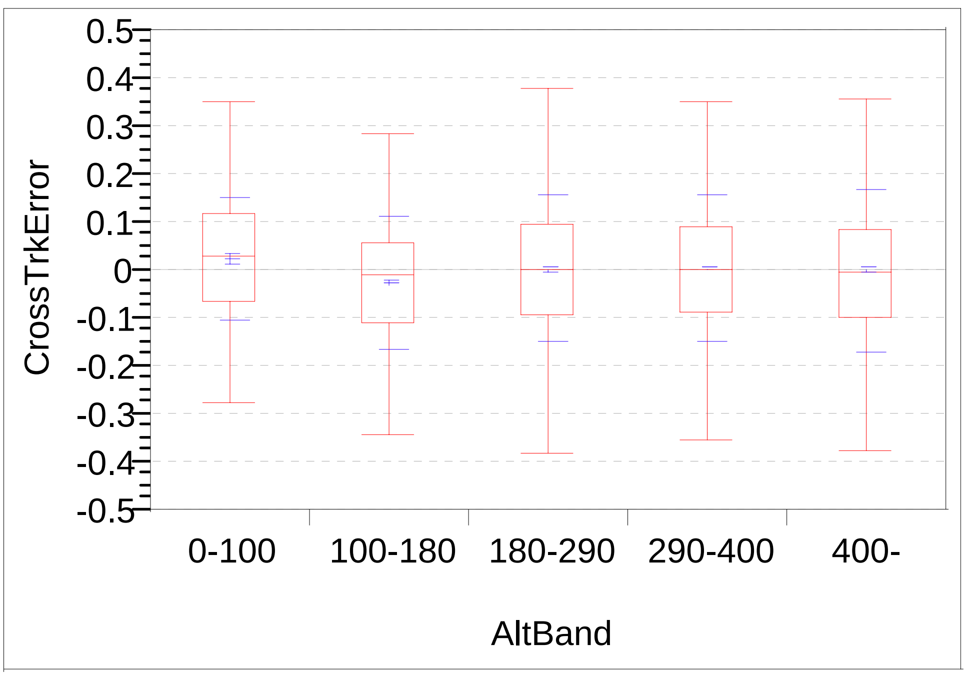


Figure 4-11: Cross Track Error Box Plots by Altitude Band

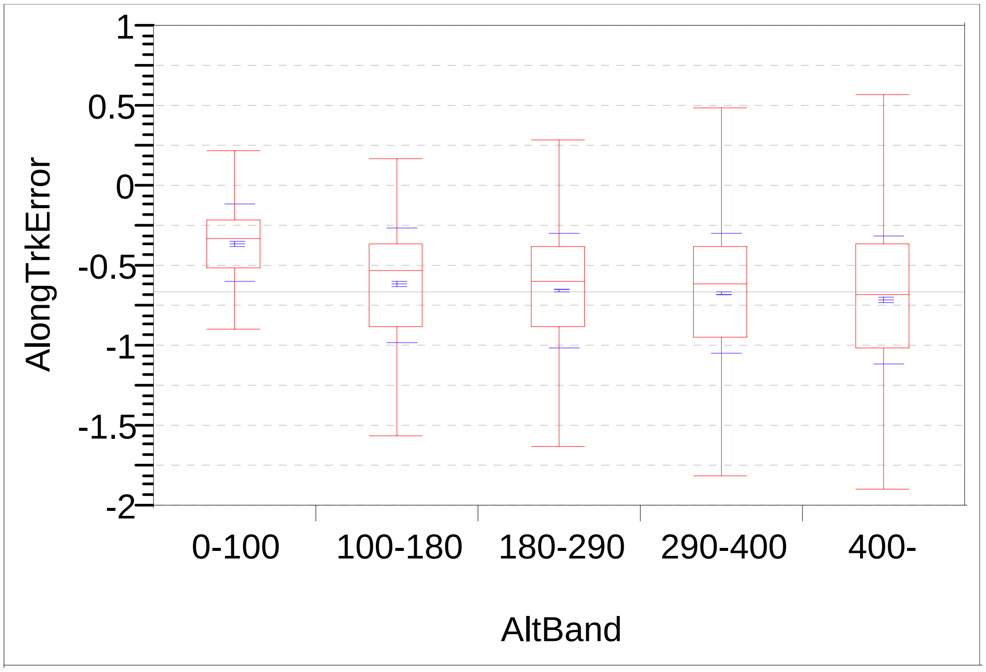


Figure 4-12: Along Track Error Box Plots by Altitude Band

Figure 4-10, Figure 4-11 and Figure 4-12 all illustrate a rise in the variability of the data as the altitude band is increased. The figures also show a steady increase in the sample mean for the horizontal and along track errors as the altitude band increases and rather flat difference between sample means for the cross track error. This result was further confirmed by applying the Tukey-Kramer statistical test for differences between means. The test confirmed that the mean cross track error did not significantly change as a function of altitude band. However, the horizontal and along track errors did produce a statistically significant effect. For both these metrics, the two altitude bands spanning 10,000 to 29,000 feet did not have a significant difference between each other but were both different from the other bands. Thus, the study does provide evidence to support that altitude does have an impact on the tracker's performance. However, AMTWG cautions that altitude could also be a composite indicator for other more influential factors such as aircraft speed and aircraft type.

4.3 Illustrative Flights

To complement the previous Sections 4.1and 4.2 that presented statistics on all the flights, this section presents a detailed overview of two flights within the study. The first flight has a substantial quantity of calculated metrics with errors representative of the typical flight. It has a long flight segment flying through ZKC (Kansas City Center) with overlapping GPS data. The second flight sample has less calculated metrics but relatively large cross track errors.

4.3.1 Sample Flight One

For the first sample, a flight segment having typical horizontal error was selected. It illustrates the process of comparing the radar track to the GPS positions. The aircraft is a business jet, a Falcon Mystere 900. The flight is flying from Springfield Illinois to Kansas City Missouri, to Wichita Kansas, to a Fayetteville Arkansas radial, and back to St. Louis Missouri. The segment analyzed is in ZKC. In fact, the entire flight captured in the recorded data is in ZKC.

4.3.1.1 Data Collection

4.3.1.1.1 Radar

The radar track data for this flight was downloaded from the HADDS server, along with four other flights with GPS data for January 20, 2005. The data was first sorted by Center and track reports converted from longitude and latitude to stereographic coordinates. Next, radar track for each flight segment are filtered for overlapping GPS data. As stated above, Sample Flight One had only one flight segment entirely in the Kansas City Center.

The radar track is shown in Figure 4-13. The X and Y coordinates in units of nautical miles are the stereographic coordinates of the local Center, ZKC in this case. The numbered vertical lines in the plot give the times in Coordinated Universal Time (UTC) seconds of the nodes in the plot. The nodes are at ten second intervals. Flight Sample One has one major and three minor turns.

The first track report is at 01:02:00 UTC (3720 seconds) at an altitude of 34500 feet where the aircraft is climbing at 380 knots. The last track report is at 02:24:20 UTC (8660 seconds) at an altitude of 25800 feet, while the aircraft is descending at 436 knots. The flight duration is 01:22:20 (4940 seconds). The aircraft climbs to a cruising altitude of Flight Level (FL) 350 and later on climbs to and cruises at Fl 370. It makes a wide 180 degree turn and returns to near where the flight started. It then descends as it is approaching the end of the flight at St. Louis.

4.3.1.1.2 GPS

The GPS track data for this flight was file transferred from the RVSM certification repository in the DFA ASCII format. The GPS track is shown in Figure 4-14. The GPS portion of the flight is in level cruise, first at Flight Level 350 and then at Flight Level 370. The GPS flight segment starts at 00:58:26 (3506 seconds) UTC at a GPS altitude of 27600 feet. The GPS coordinate system is similar to the Host coordinate system but it is not quite the same, namely in the altitude dimension. Thus, the altitude values cannot be directly compared. The GPS flight segment ends at 02:24:25 (8665) UTC at a GPS altitude of 26000 feet.

The data of interest in the DFA file are the time stamped latitudes and longitudes of the aircraft positions which have been recorded every second.

4.3.1.2 Data Reduction

It is necessary to reduce both the radar track data from HADDS and the positions from GPS to a form that can be directly compared and into formats compatible with the existing computer software tools. Particularly the metrics defined in APPENDIX A – Metrics are calculated within the stereographic coordinate frame (using a planar XY coordinate frame).

4.3.1.2.1 Radar

The radar track data has samples nominally every 12 seconds. However, sometimes the portions of a flights track data are missing and sometimes it contains positional errors as well. Therefore, it is necessary first to determine when these errors occur (checking for reasonableness) and then repair the data when possible. These heuristic methods are first described in reference (Paglione, et al., 1999) and later in detail in reference (Ryan and Paglione, 2003). The resulting flight data may retain gaps where the data could not be repaired. In some cases, flights are discarded because the software cannot accurately make these repairs and gaps were too large. No comparisons can be made when the data is missing. For Flight Sample One, the processing required repairs to seven isolated track reports. To facilitate the comparison operation, the radar data is re-sampled to 10 second intervals and synchronized to the hour.

4.3.1.2.2 GPS

The GPS data requires three processing steps. The first step is the conversion of the latitudes and longitudes into XYs for the local Center. The second step is a data extraction step. Although the GPS data is nominally sampled every second there are many data dropouts, some are quite long. It was desired to use a contiguous GPS track segment for the comparison. Therefore the longest contiguous segment of GPS track data was extracted for this flight (and for all of the flights). A contiguous segment was defined as one in which there are no gaps longer than 10 seconds. For Flight Sample One, the longest contiguous segment starts at 01:12:03 (4323 seconds) UTC and ends at 02:24:25 (8665 seconds) UTC. The first part of the GPS track has been discarded because of gaps in the data. The total duration of this GPS flight is 01:25:59 (5159 seconds) and the duration of the longest continuous segment is 01:12:22 (4342 seconds). The third step was to re-sample the position reports to every 10th point. This was done simply for compatibility issues with legacy software tools as discussed in previously in Section 3.3.1.

4.3.1.2.3 Comparison

After the processing is complete as described in Section 4.3.1.2.2 above, the radar track data and the GPS track data are ready for comparison. The horizontal, along and cross track error metrics are calculated for every radar position report for which there is a time matched GPS position. The mechanics of the sampling have been described In Reference [5]. For this sample flight, there are 374 position error measurements.

4.3.1.3 Data Analysis

At the resolution in Figure 4-13 and Figure 4-14 the two tracks lie on top of each other. An expanded plot is shown in Figure 4-15 for the turn at the western end of the track. At this expanded scale the differences between the tracks can be seen. The radar track lags the GPS track in the turn and is about ten seconds late. In the turn the horizontal error is about 1.4 nm. The radar track swings wide in the turn and is off laterally by about 0.33 nm. Later on in the flight the aircraft is flying straight and level the radar track wanders from side to side. This behavior is illustrated in Figure 4-16. The radar track wanders up to 0.18 nm away from the GPS track.

The distributions of the horizontal track errors the cross track errors, and the along track errors for this flight segment are given in Figure 4-17, Figure 4-18, and Figure 4-19 respectively. The along track error distribution and the horizontal error distribution are bimodal. When the flight enters the turn at the western end of the track, the along track errors increase to over 1 nautical mile and stay above 1 nautical mile for some time after the turn is completed.

The descriptive statistics for both signed and unsigned errors for this flight segment are given in the following Table 4-6. In addition, Flight One's RMS of the horizontal error is 0.89 nm.

Table 4-6: Radar Track Errors for Sample Flight One in Nautical Miles

		Horizontal Error		Cross Track Error		Along Track Error	
Type	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Signed	374	0.80	0.39	-0.04	0.12	-0.79	0.39
Unsigned				0.10	0.07	0.79	0.39

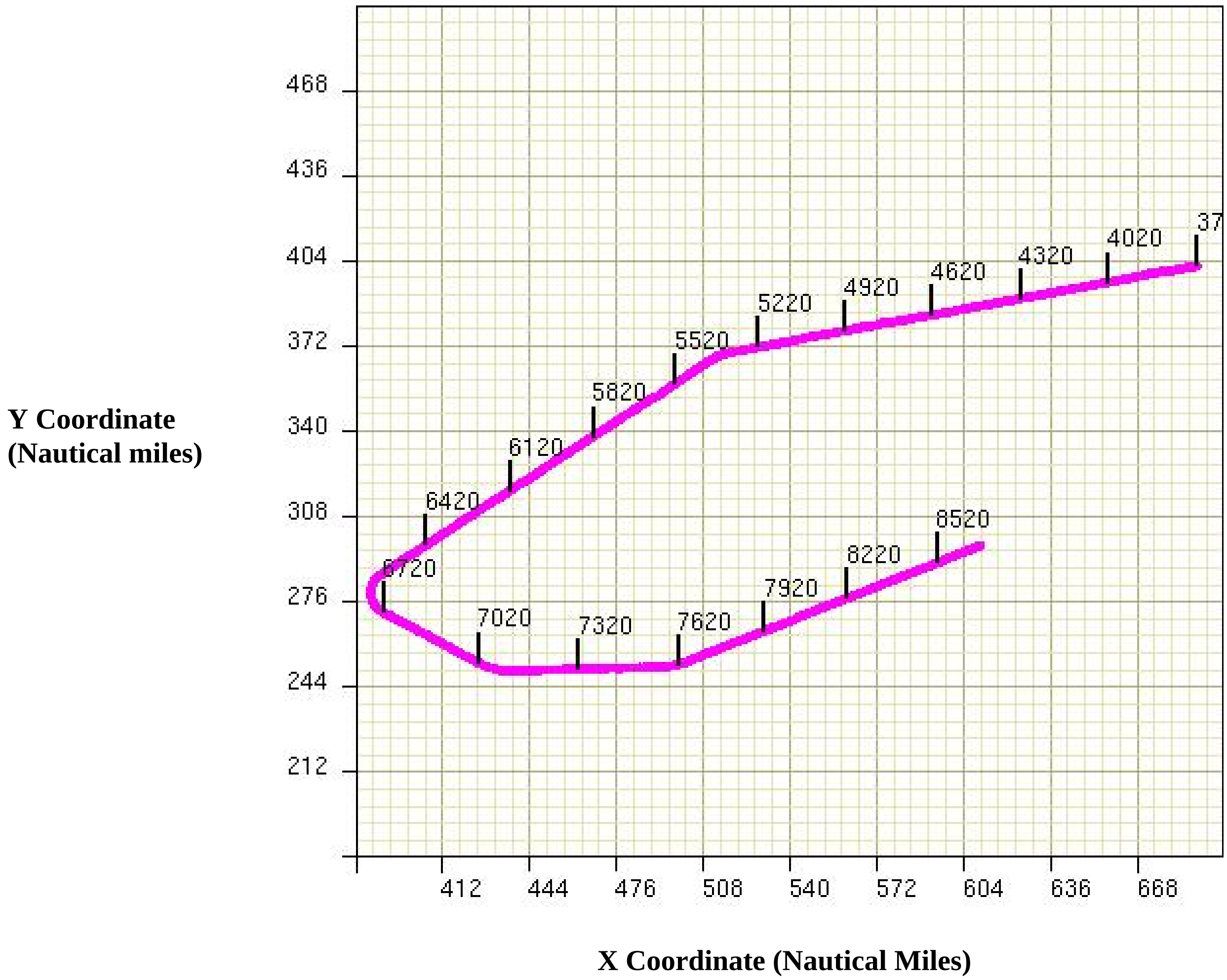
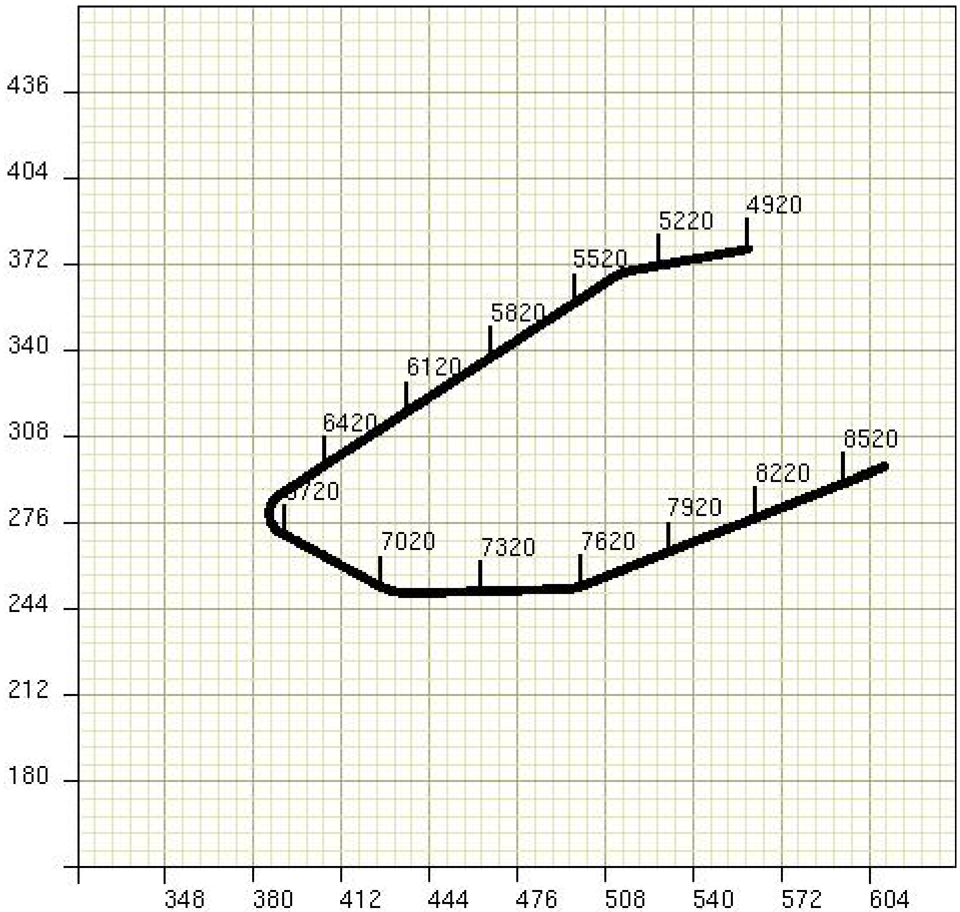


Figure 4-13: Radar Horizontal Flight Path of Sample Flight #1 – ZKC Stereographic Coordinates – Time Tags in Seconds UTC



Y Coordinate (Nautical Miles)

X Coordinate (Nautical Miles)

Figure 4-14: GPS Horizontal Flight Path of Sample Flight #1 – ZKC Stereographic Coordinates

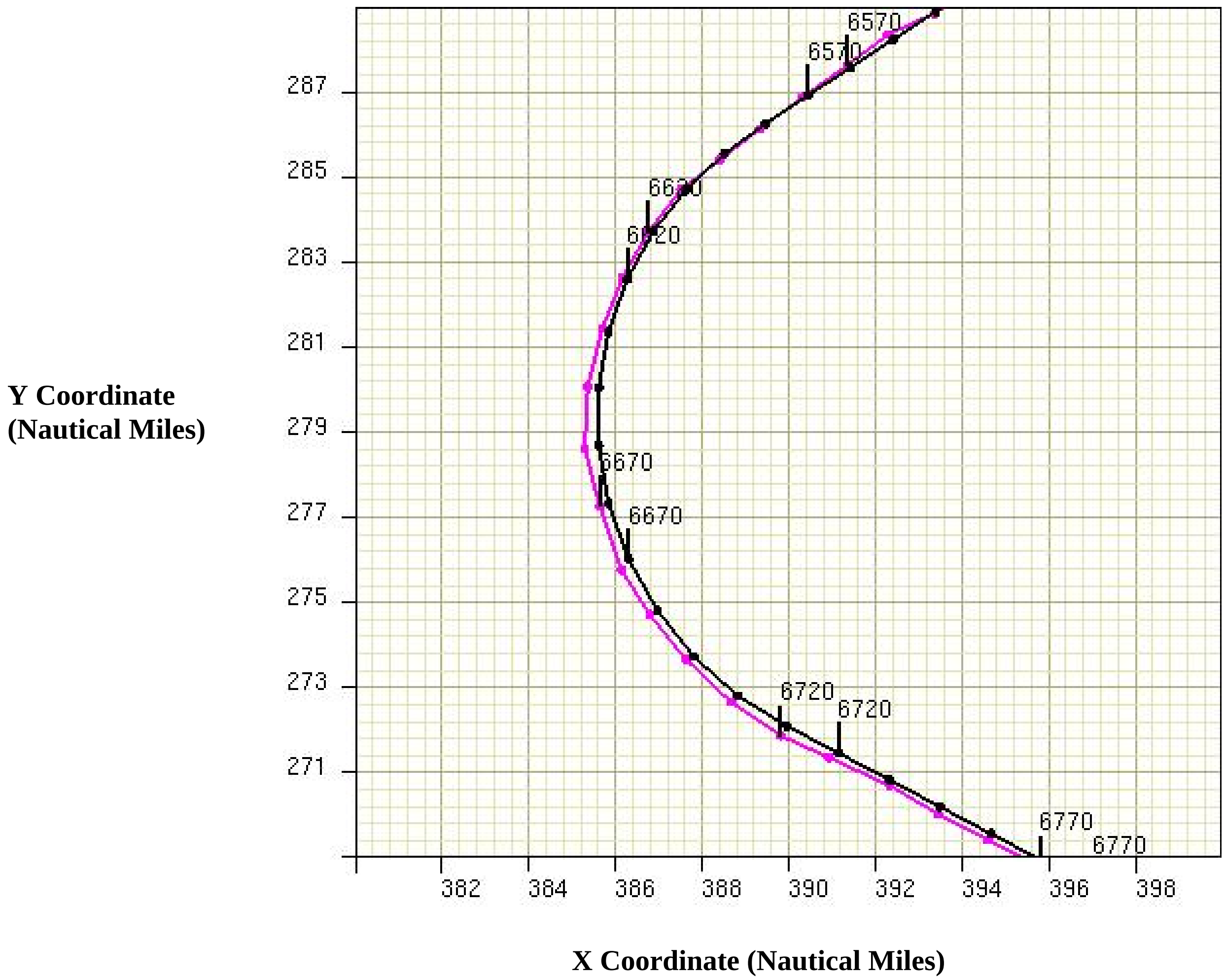
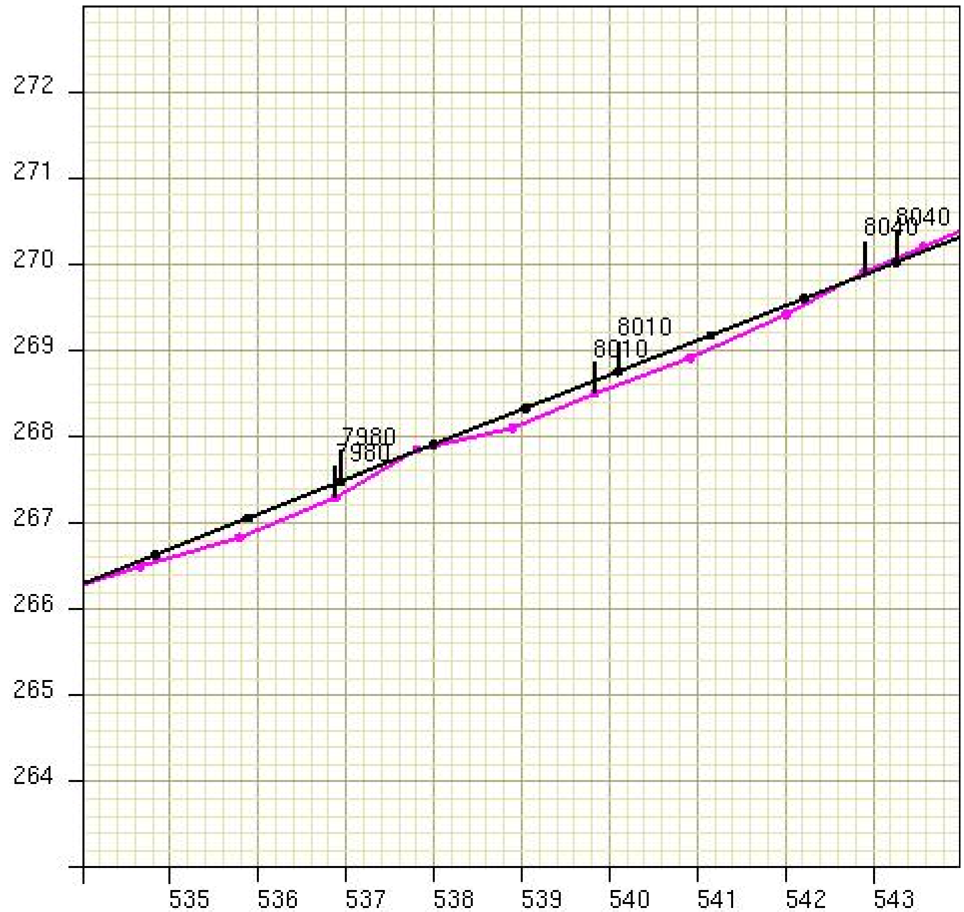


Figure 4-15: Expanded Radar (Left) and GPS (Right) Horizontal Tracks – Sample Flight One

Y Coordinate
(Nautical Miles)



X Coordinate (Nautical Miles)

Figure 4-16: Radar (Right) and GPS (Left) Tracks - Straight and level Cruise – Sample Flight One

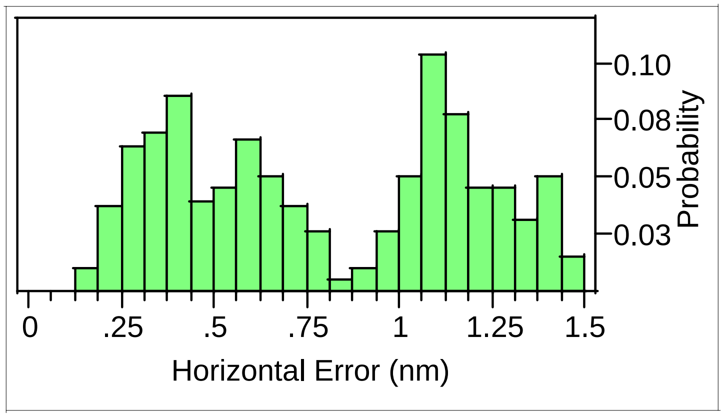


Figure 4-17: Horizontal Track Error for Sample Flight One

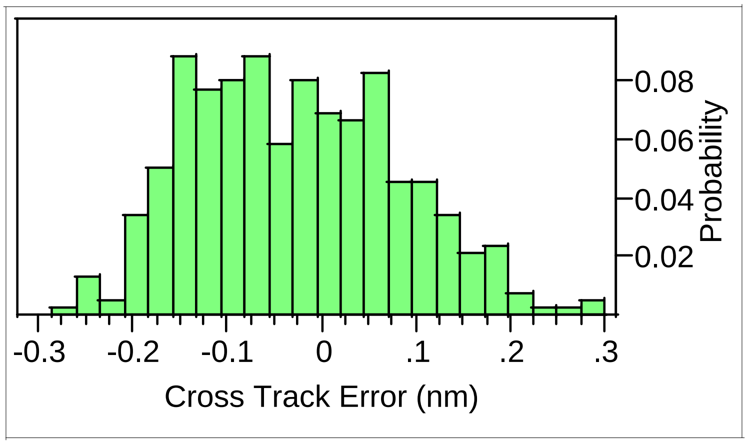


Figure 4-18: Cross Track Error for Sample Flight One

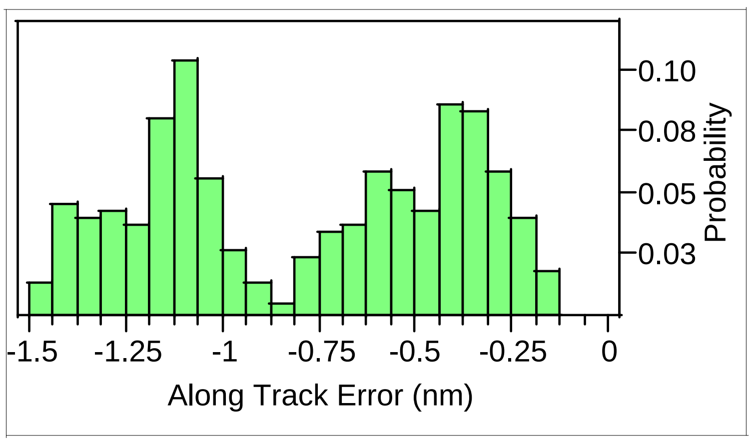


Figure 4-19: Along Track Error for Sample Flight One

4.3.2 Sample Flight Two

A second flight segment having a large lateral error has been selected to further illustrate the comparison of the radar track to the GPS track. The aircraft is a business jet, a Falcon Mystere 10. The flight is from Knoxville Tennessee to Beckley West Virginia and back to Knoxville. The segment is in ZID (Indianapolis Center). It is a RVSM certification flight with a 180 degree turn.

4.3.2.1 Data Collection

4.3.2.1.1 Radar

The radar track data for this flight was downloaded from the HADDS server for January 13, 2005. The selected aircraft on this date had two flights (and several flight segments) present for both ZTL (Atlanta Center) and ZID (Indianapolis Center). The flights cross back and forth between the ZTL and ZID airspaces. The GPS flight has four flight segments in ZTL and three flight segments in ZID. Each flight segment has a different Computer Identification (CID) number assigned by the HCS. The GPS part of the flight is from Knoxville Tennessee to Beckley West Virginia and back. The sample of radar track in ZID examined for this study with time coincident GPS position reports is presented in Figure 4-20.

4.3.2.1.2 GPS

The GPS position reports are shown in Figure 4-21. The GPS portion of the flight is at level cruise at a GPS altitude of first at 29800 feet and then at 31800 feet. The GPS data starts at 18:23:08 (66188 seconds) UTC and ends at 18:55:02 (68102 seconds) UTC.

4.3.2.2 Data Reduction

4.3.2.2.1 Radar

As for all the flights selected, the radar track data for Sample Flight Two was downloaded from the HADDS server, segregated by Center, and latitudes and longitudes converted to local Center XY coordinates. The post processing of the radar track segment required fixing two isolated single track positions and one sequence of three track positions. The data was re-sampled, using linear interpolation, to 10 second intervals and synchronized to the hour.

4.3.2.2.2 GPS

The longest contiguous GPS flight segment starts at 18:23:08 (66188 seconds) UTC at a GPS altitude of 27600 feet. The GPS flight segment ends at 18:51:55 (67915 seconds) UTC at a GPS altitude of 31800 feet. Data at the end of the track has been discarded because of gaps in the data. The duration of the original GPS track is 00:31:54 (1914 seconds) and the duration of the longest contiguous segment is 00:28:47 (1727 seconds). The GPS latitudes and longitudes were converted to XYs, the longest contiguous segment extracted and re-sampled to 10 second intervals. The start time of the GPS segment is 18:26:30 (66390 seconds) UTC at a GPS altitude of 27800 feet, and the end time of the GPS segment is 18:51:53 (67913 seconds) UTC at a GPS altitude of 31800 feet.

4.3.2.2.3 Comparison

The pairing of time matched GPS track positions with radar track positions for this sample flight resulted in 153 error measurements.

4.3.2.3 Data Analysis

The radar track has noticeable cross track error. A portion of the flight segment was plotted in Figure 4-22 showing the cross track error. The cross track error before and after the turn ranges from 0.3 to 0.6 nautical miles. Figure 4-23 illustrates the deviations approaching the turn. The maximum cross track error on this portion of the flight segment is 0.79 nm.

The distributions of the horizontal track errors, the cross track errors, and the along track errors for this flight segment are given in Figure 4-24, Figure 4-25, and Figure 4-26 respectively. The descriptive statistics for both signed and unsigned errors for this flight segment are given in the following Table 4-7. In addition, Flight Two's RMS of the horizontal error is 0.88 nm.

Table 4-7: Radar Track Errors for Sample Flight Two in Nautical Miles

		Horizontal Error		Cross Track Error		Along Track Error	
Type	**Sample Size**	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Signed	153	0.82	0.34	-0.08	0.40	-0.70	0.35
Unsigned				0.32	0.25	0.70	0.35

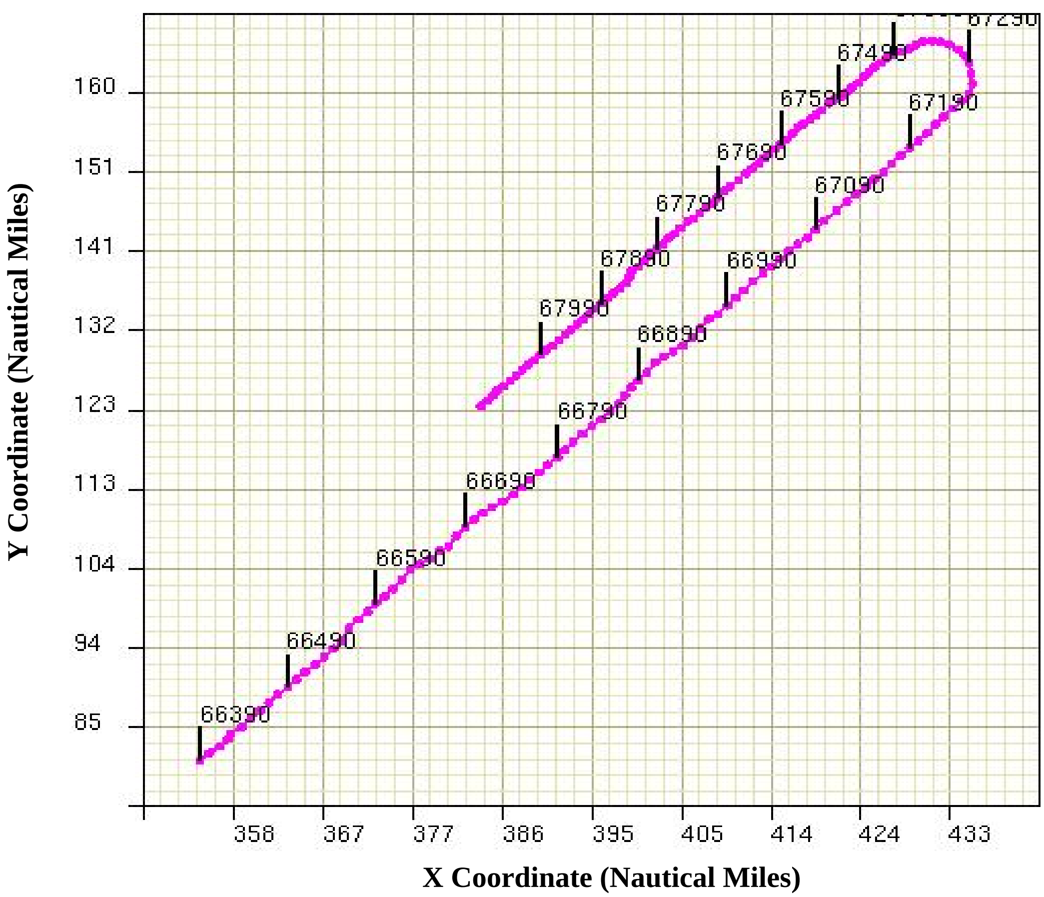
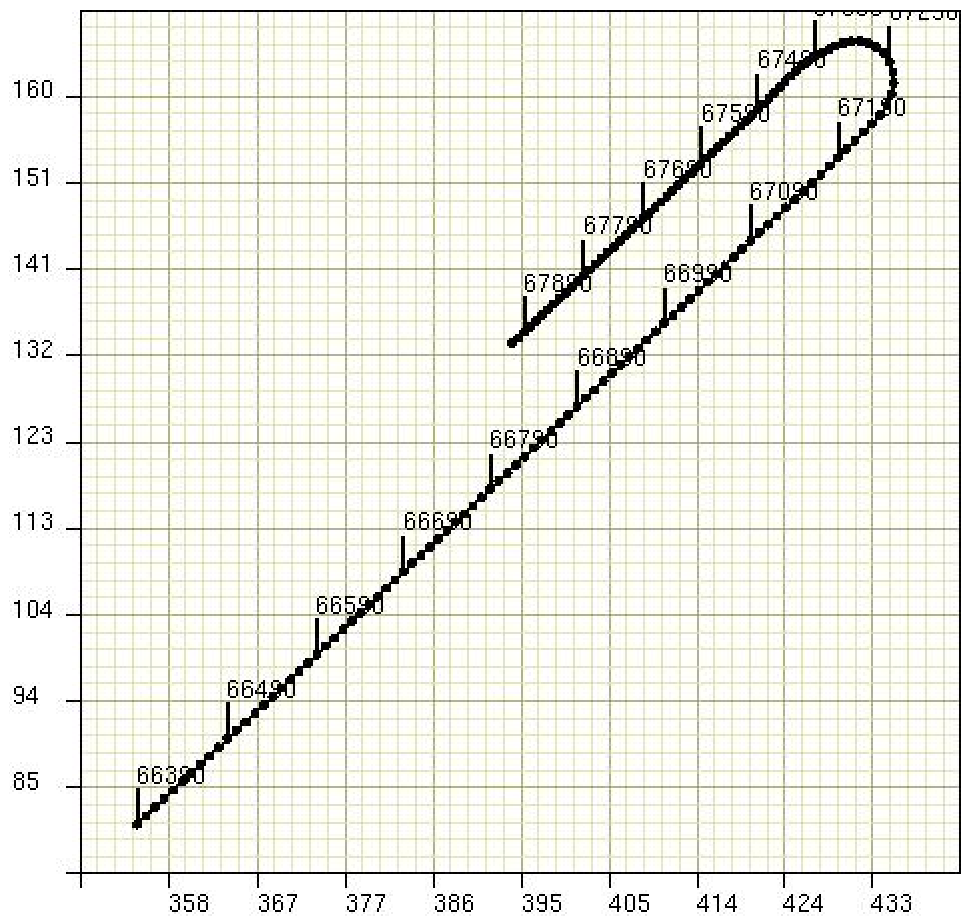


Figure 4-20: Radar Horizontal Flight Path of Sample Flight #2 – ZID Stereographic Coordinates – Time Tags in Seconds UTC



Y Coordinate (Nautical Miles)

X Coordinate (Nautical Miles)

Figure 4-21: GPS Horizontal Flight Path of Sample Flight #2 – ZID Stereographic Coordinates

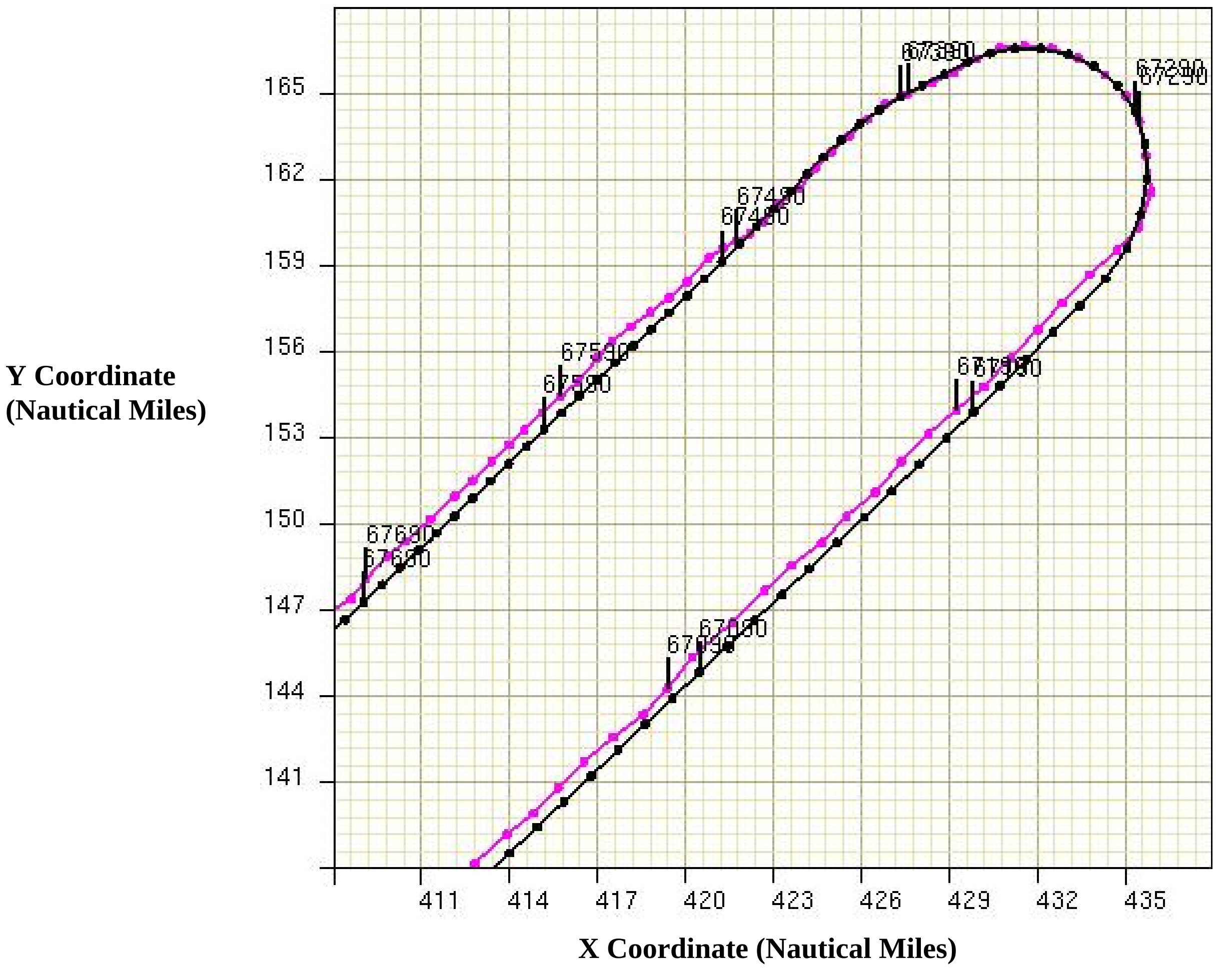


Figure 4-22: Expanded Radar (Left) and GPS (Right) Horizontal Tracks – Sample Flight Two

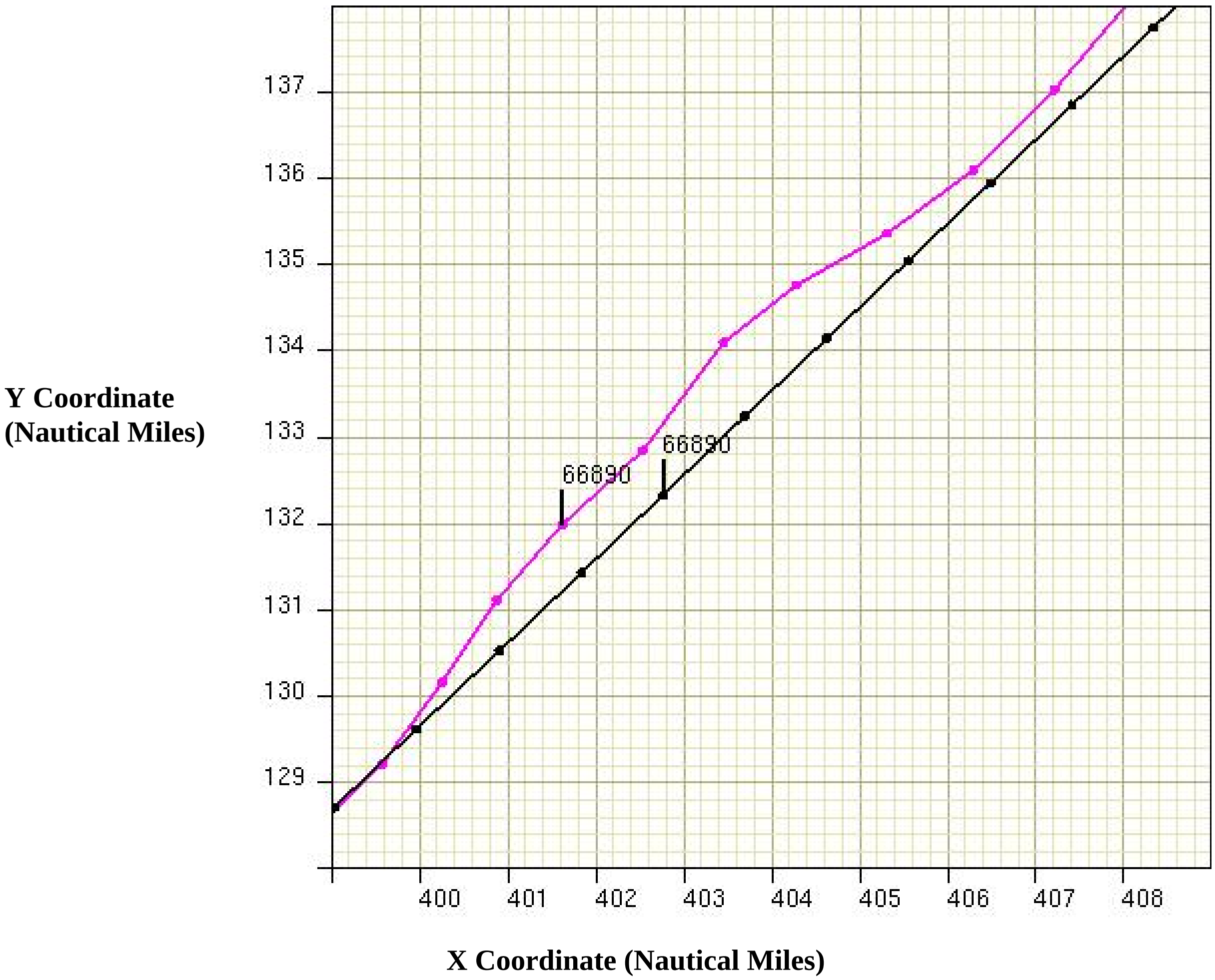


Figure 4-23: Radar (Left) and GPS (Right) Tracks – Straight and Level Cruise

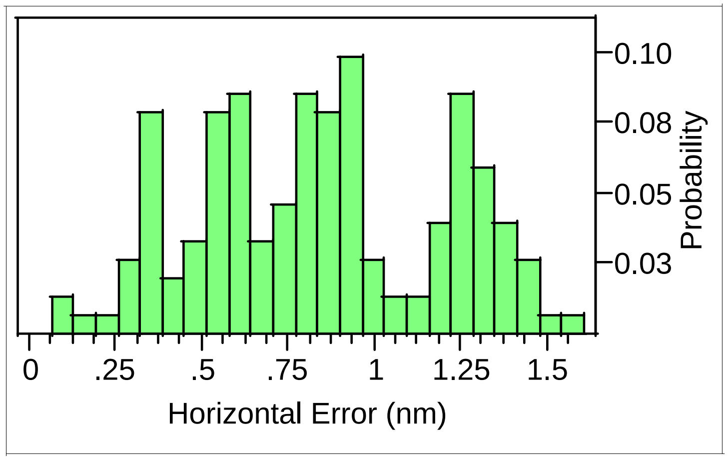


Figure 4-24: Horizontal Track Error for Sample Flight Two

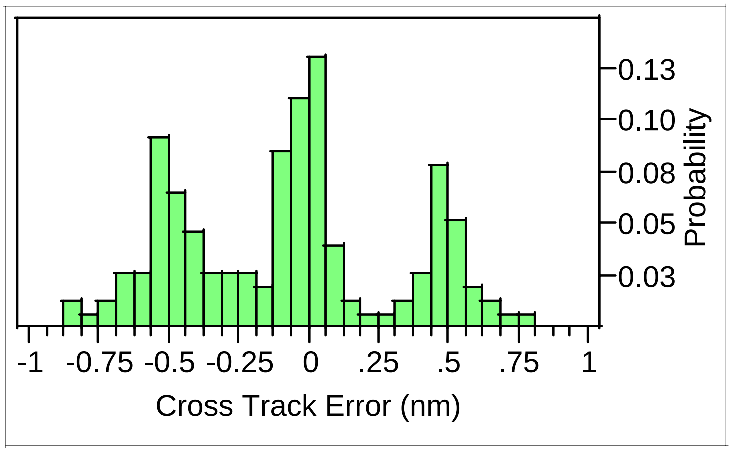


Figure 4-25: Cross Track Error for Sample Flight Two

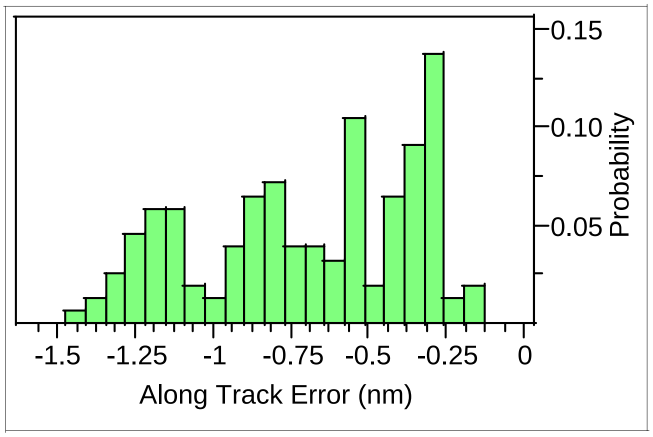


Figure 4-26: Along Track Error for Sample Flight Two

5 Conclusion

A sample of GPS data from 265 flights from January through February of 2005 was processed from the over 10,000 flights collected by the RVSM Certification Program. A total of 54,170 measurements were calculated comparing the GPS positions to time coincident Host radar track positions from all 20 Centers in the continental United States. This representative sample of operational data allowed the AMTWG to estimate the performance of the existing ATC tracking function. As presented in Section 1.2, the motivation was to support the ERAM Test Program to address COI 1.0 that requires that ERAM perform with at least the same effectiveness as the current system. This analysis supports this testing by providing a baseline of the current ATC automation's performance. It also advances the ERAM metrics development documented in AMTWG Implementation Plan (WJHTC/ACB-330, 2005).

Three basic metrics were employed in this study as presented in Section 3.3.2 and later in detail in APPENDIX A – Metrics. In summary, they include: horizontal error that is the unsigned straight line distance between the time coincident radar track and GPS position, along track error that is the longitudinal orthogonal component (ahead and behind) of the horizontal error, and cross track error that is the lateral orthogonal component (side to side) of the horizontal error.

5.1 Descriptive Statistics

The overall descriptive statistics for these error metrics are presented in Table 4-1 and distributions (histograms) are presented in Figure 4-1, Figure 4-2, and Figure 4-3. The average horizontal error was 0.690 nautical miles or 4200 feet. The cross track error distribution is symmetrical about zero; however, the along track error distribution is strongly skewed in the negative direction. The radar position is consistently lagging in time. This bias in the data suggests that the Host radar data has an uncompensated delay.

For this study, the overall horizontal RMS is 0.78 nm. Previous studies used simulation methods to produce similar results. Trios Incorporated documented in reference (Trios Inc., 2003), with results summarized in Table 1-1, a steady state (no turns) RMS value of 0.2 – 0.5 nm depending on the speed. Trios reported the RMS values of 0.7 to 1.7 nm for turns depending on speed and maneuver details. Since the AMTWG produced errors for all measurements, turns and steady state, and a mix of operational speeds (median about 350 knots), the results are fairly consistent.

5.2 Inferential Statistics

Inferential statistics were performed to test the impact of Center, altitude, and track turning status on the HCS's track error measurements. First, in the analysis of a Center's influence on the tracker's performance, a set of box plot diagrams were generated by Center to visually review the differences between Centers in Figure 4-4. The statistical test performed did show a statistically significant difference between some Center's and not between others. Although statistically significant, the conclusion was the difference had no practical difference, ranging from 0.00 to 0.23 nautical miles.

The track turning status of every HCS track position was calculated using legacy tools, as defined in (Paglione, et al., 1999). This information was used to compare the difference between sample means from the distribution of tracking error that exhibited turning and the much larger sample without. Of the total 54,170 error measurements only 13 percent had exhibited turns, which is still a large enough sample statistically. Like the analysis of Center, a Tukey-Kramer inferential test was performed comparing the sample means. The test indicated that there is a statistically significant effect between the sample means with the horizontal and cross track error measurements but not along track error. This is clearly illustrated in the Table 4-4 where the along track error means are within 0.01 nautical miles and standard deviation even closer. The cross track error has greater differences with a standard deviation 0.05 nautical miles larger for turning measurements. Therefore, even if the results are statistically significant, the difference is so small in magnitude it has no practical difference. AMTWG believes that the small effect is mainly due to the use of the noisy HCS track as opposed to the smooth GPS data for calculating turns. AMTWG would apply an improved method of turn detection to provide more definitive results in the future.

The impact of altitude on the HCS tracker's performance is another factor examined in Section 4.2. The data sets were categorized into altitude bands: 0 to 10,000 feet, 10,000 to 18,000 feet, 18,000 to 29,000 feet, 29,000 to 40,000 feet, and above 40,000 feet, and compared statistically. Despite the fact that the altitude band 29,000 to 40,000 feet had 88 percent of the measurements, the sample mean and standard deviations exhibit a steady increase as altitude increases. The Figure 4-10, Figure 4-11 and Figure 4-12 all illustrate a rise in the variability of the data as they increase in altitude band. They also show the steady increase in the sample mean for the horizontal and along track errors as the altitude band increases and rather flat difference between sample means for the cross track error. This result was further confirmed by applying the Tukey-Kramer statistical test for differences between means. The test confirmed that the mean cross track error did not significantly change as a function of altitude band. However, the horizontal and along track errors did produce a statistically significant effect. For both these metrics, the two altitude bands spanning 10,000 to 29,000 feet did not have a significant different between each other but were both different to the other bands. Thus, the study does provide evidence to support that altitude does have an impact on the tracker's performance. Altitude could also be a composite indicator for other more influential factors such as aircraft speed and aircraft type.

5.3 Individual Sample Flights

To complement the Sections 4.1and 4.2 that presented statistics on all the flights, a detailed overview of two flights within the study were included in Section 4.3. The average horizontal radar error in the first example was 0.80 nm with a maximum of 1.5 nm. In the turn (Figure 4-15) the radar track swung wide of the GPS positions, being offset by 0.33 nm, and lagged the GPS positions by several seconds. On the straight part of the track (Figure 4-16) the radar track wanders back and forth but the lag as shown by the time tags is very small. In the second example, the average horizontal radar error is 0.82 nm and the maximum 1.5 nm. Figure 4-22 shows there are relatively large cross track errors and along track errors on the straight part of the track and little error in the turn. In the first example the errors in the turn are small; in the second example the errors in the turn are large. The differences in the errors between the two examples illustrate that the errors can vary from flight to flight but are also consistent with the general observation discussed previously that the negative bias provides evidence of an uncompensated longitudinal error. For the cross track errors, the signed errors tend to cancel resulting in a sample mean close to zero. Both sample flights produce this same result, but the later exhibits larger than normal cross track error. This larger error illustrates that flight variability can be quite large when reviewing specific flights.

6 List of Acronyms/Abbreviations

ACB-310	Separation Standards Analysis Group, WJHTC, FAA
ACB-330	Simulation and Analysis Group, WJHTC, FAA
ACB-550	ERAM & ECG Group, WJHTC, FAA
AMTWG	Automation Metrics Test Working Group
AOS-330	TMA Operational Support Group, WJHTC, FAA
ARINC	Aeronautical Radio, Inc.
ARTCC	Air Route Traffic Control Center
ASCII	American Standard Code for Information Exchange
ATC	Air Traffic Control
CID	Computer Identifier
CMS	Common Message Set
CPAT	Conflict Probe Assessment Team
CSSI	Computer Services Support, Inc.
DFA	Differential FAA GPS ASCII file format
ECG	En route Communications Gateway
ERAM	En Route Automation Modernization
FAA	Federal Aviation Administration
FL	Flight Level
GPS	Global Positioning Satellite System
GPSS	Global Positioning Satellite System
HADDS	Host Air Traffic Management Data Distribution System
HCS	Host Computer System
Host	ARTCC main frame computer
JSA	Joseph Sheairs Associates, Inc.
NAS	National Airspace System
nm	Nautical Miles
RMS	Root Mean Square
RVSM	Reduced Vertical Separation Minima
SCN	ASCII radar data file format
SQL	Structured Query Language
TMA	Traffic Manager Advisor
UTC	Coordinated Universal Time (see www.time.gov/about.html)
WJHTC	William J. Hughes Technical Center
ZAB	Albuquerque
ZAU	Chicago
ZBW	Boston
ZDC	Washington
ZDV	Denver
ZFW	Fort Worth
ZHU	Houston
ZID	Indianapolis
ZJX	Jacksonville
ZKC	Kansas City
ZLA	Los Angeles
ZLC	Salt Lake City
ZMA	Miami

ZME	Memphis
ZMP	Minneapolis
ZNY	New York
ZOA	Oakland
ZOB	Cleveland
ZSE	Seattle
ZTL	Atlanta

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[7] Any of the WJHTC references are internal FAA documents and are accessible but must be requested from the FAA author of this technical note at mike.paglione@faa.gov.

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APPENDIX A – Metrics

The horizontal error is the distance in the stereographic horizontal plane between the GPS track position and the radar track report having the same time. It is split into two orthogonal components, the along track error and the cross track error. This split is illustrated in the following Figure A-1. The description provided in this section is presented in more detail in reference (Ryan and Paglione, 2004) and originally in (Paglione, et al., 1999).

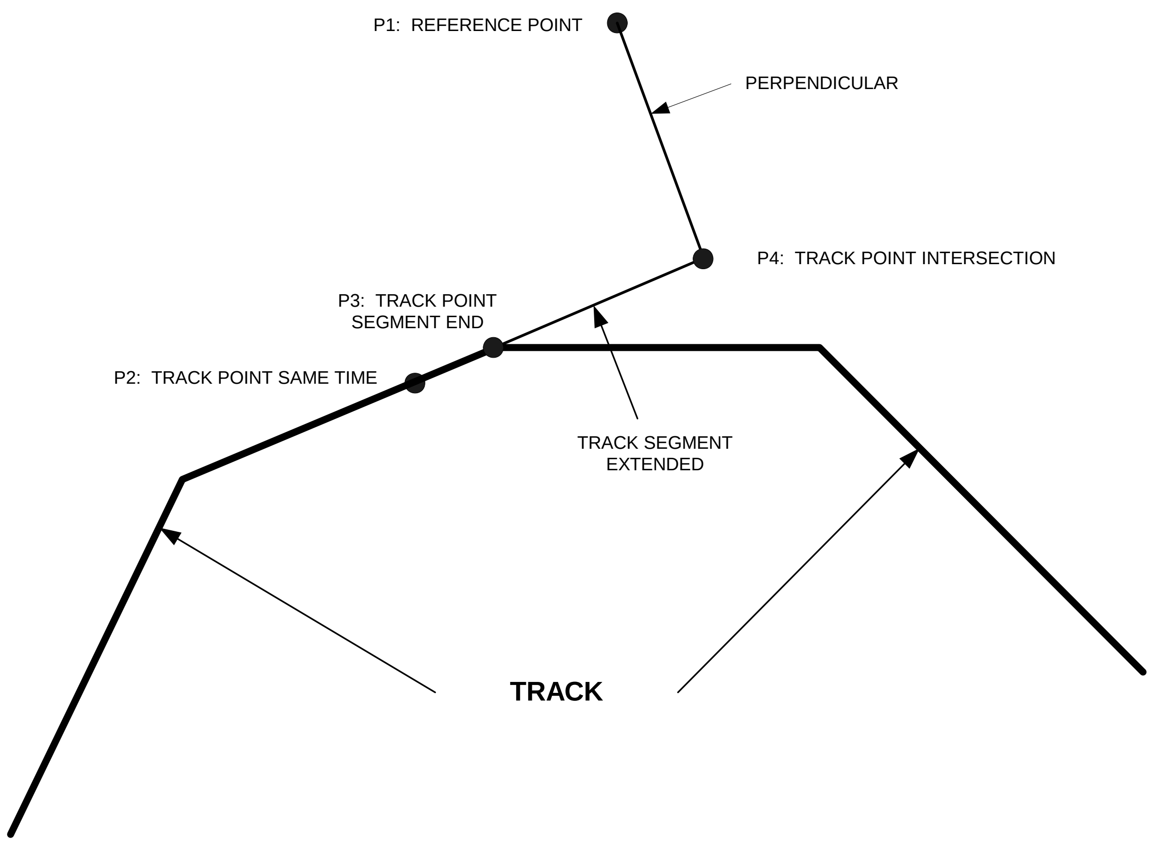

Figure A- 1: Aircraft Geometry for Measuring Along Track and Cross Track Errors

In the figure, the aircraft is flying from left to right. The GPS reference track location is designated as P1. The radar track is a set of straight-line segments defined by the individual radar track reports - four are shown in the figure. The first step is to use interpolation to find the location on the track that has the same time as the GPS reference point P1. This point is labeled P2. The horizontal error is defined as the straight-line distance between P1 and P2.

The next step in the calculation is to select the next track segment end point following P2, labeled as P3. A perpendicular is then drawn from the reference point P1 to the track segment P2-P3 or its line extension. In the figure, the perpendicular intersects the line P2-P3 extended to P4. The cross track or lateral error is defined as the length of the line P1-P4. The along track or longitudinal error is defined as the length of the line P2-P4.

If the reference point is to the right of the track, the cross track error is positive and otherwise is negative. If the reference point is ahead of the time synchronous track point, the along track error is positive and otherwise is negative. The sign (positive or negative) of the cross track error is the same as the sign of the vector cross product of the vectors from P2 to P1 and P2 to P3. The sign of the along track error is the same as the sign of the scalar product of the same vectors.

APPENDIX B – Aggregate Statistics by Center

The maximum error rates for each Center are shown in this appendix. In Table B-1, the flight segment having the largest average horizontal error is listed for each of the 20 Centers.
In Table B-2, the flight segment having the largest average cross track error is listed for each Center. In Table B-3, the flight segment having the largest average along track error is listed for each Center. The tables also give the maximum and minimum values of the errors for each flight segment. The averages and the maximum and minimum values shown here are for the magnitudes (unsigned values) of the errors.

Table B- 1 Maximum Horizontal Error Values by Center (Nautical Miles)

CENTER	AVERAGE HORIZONTAL ERROR	STDDEV HORIZONTAL ERROR	MAXIMUM HORIZONTAL ERROR	MINIMUM HORIZONTAL ERROR
ZAB	1.11769714	.367537811	1.826	.6634
ZAU	1.35556102	.369164251	1.7454	.52
ZBW	1.03410797	.259637619	1.5377	.2819
ZDC	1.60674444	.125965016	1.8877	1.4274
ZDV	.943407477	.274542717	1.4642	.4232
ZFW	1.36619091	.068154956	1.5098	1.2016
ZHU	1.02308345	.398882339	1.7088	.4538
ZID	1.19715588	.33594463	1.7016	.5159
ZJX	1.30519184	.342440926	1.6478	.7037
ZKC	1.02848503	.42687243	1.8331	.1656
ZLA	1.54844286	.130801057	1.7411	1.267
ZLC	.8352	.287513397	1.2349	.4926
ZMA	1.10914913	.296580277	1.5191	.4859
ZME	1.07716549	.350949129	1.9663	.3945
ZMP	1.06484923	.197658438	1.3862	.494
ZNY	.687397	.390236517	1.2468	.1813
ZOA	1.0205703	.343302332	1.5972	.2754
ZOB	1.20729385	.221298566	1.4032	.5184
ZSE	.663098837	.301949706	1.0646	.1138
ZTL	1.2789716	.427234551	1.9092	.4325

Table B- 2 Maximum Cross Track Error Values by Center (Nautical Miles)

CENTER	AVERAGE CROSS TRACK ERROR	STD DEV CROSS TRACK ERROR	MAXIMUM CROSS TRACK ERROR	MINIMUM CROSS TRACK ERROR
ZAB	.166488079	.080085555	.3278	.0007
ZAU	.325033113	.20815143	.7197	.0005
ZBW	.13093619	.115430406	.6865	.0014
ZDC	.634109524	.145176671	.8689	.4013

ZDV	.355453271	.184121297	.7759	.0194
ZFW	.134793594	.113590049	.6773	.0017
ZHU	.232597917	.092874599	.5155	.0345
ZID	.323648366	.247210539	1.1261	.0005
ZJX	.259636364	.067404989	.3718	.1456
ZKC	.230270297	.133692825	.4304	.0011
ZLA	.233407143	.178649883	.504	.0108
ZLC	.208905652	.121789137	.6166	.0002
ZMA	.236411111	.190157951	.8155	.0082
ZME	.2051075	.108833028	.4686	.0174
ZMP	.230690909	.178530397	.7783	.0033
ZNY	.215983333	.029427974	.2499	.1811
ZOA	.228385837	.115215312	.4937	.0031
ZOB	.262513846	.097543663	.4997	.0857
ZSE	.108749419	.073661351	.389	.0017
ZTL	.184711795	.154862179	.6564	.0018

Table B- 3 Maximum Along Track Error Values by Center (Nautical Values)

CENTER	AVERAGE ALONG TRACK ERROR	STD DEV ALONG TRACK ERROR	MAXIMUM ALONG TRACK ERROR	MINIMUM ALONG TRACK ERROR
ZAB	1.11433048	.368222258	1.8259	.6629
ZAU	1.34395593	.368493917	1.6941	.5257
ZBW	1.0213506	.262826786	1.5335	.2112
ZDC	1.5382	.073010068	1.642	1.4086
ZDV	.844257944	.3047288	1.3434	.0725
ZFW	1.35609091	.075475508	1.4878	1.1496
ZHU	1.01442872	.401912588	1.7046	.4537
ZID	1.18714608	.331534827	1.6824	.5085
ZJX	1.30041224	.346948743	1.6474	.692
ZKC	1.00957844	.431069384	1.832	.1554
ZLA	1.52240714	.112539439	1.6825	1.2621
ZLC	.830728571	.292179002	1.2347	.485
ZMA	1.09799711	.30428794	1.5083	.4557
ZME	1.00703451	.418319792	1.7733	.1928
ZMP	1.05410923	.198687328	1.3818	.4881
ZNY	.670725	.396587335	1.2454	.1246
ZOA	1.00520099	.356869864	1.5944	.2749
ZOB	1.16620308	.261768377	1.3647	.355
ZSE	.646309302	.309778232	1.0356	.086
ZTL	1.26230617	.447887493	1.8975	.2108

APPENDIX C – Flight Segment Error Data

This appendix presents statistics for all the flight segments within each Center. First, a summary table is listed that contains statistics for all flight segments per Center. Next, a larger table lists the flight segments per Center, where the cross and along track errors are signed measurements. For Table C-1, sample size is the total measurements for the entire Center and for Table C-2 sample size is the total measurements for the particular flight segment within the given Center.

Table C- 1 Summary of Radar Track Errors for all Centers

			Horizontal Error		Cross Track Error		Along Track Error	
Center		**Sample Size**	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Albuquerque	(ZAB)	1840	0.83	0.36	0.02	0.13	-0.82	0.37
Chicago	(ZAU)	1791	0.69	0.43	0.04	0.17	-0.66	0.45
Boston	(ZBW)	1946	0.71	0.36	-0.01	0.13	-0.70	0.36
Washington	(ZDC)	3106	0.78	0.39	0.08	0.24	-0.73	0.40
Denver	(ZDV)	3411	0.68	0.31	-0.01	0.19	-0.65	0.32
Fort Worth	(ZFW)	2227	0.81	0.40	0.01	0.13	-0.79	0.40
Houston	(ZHU)	4567	0.63	0.35	-0.02	0.15	-0.61	0.36
Indianapolis	(ZID)	4351	0.68	0.36	0.01	0.16	-0.66	0.37
Jacksonville	(ZJX)	1879	0.66	0.36	-0.02	0.13	-0.63	0.39
Kansas City	(ZKC)	10721	0.62	0.35	0.00	0.13	-0.60	0.36
Los Angeles	(ZLA)	2784	0.74	0.35	-0.01	0.12	-0.73	0.35
Salt Lake City	(ZLC)	1101	0.67	0.32	0.01	0.18	-0.64	0.33
Miami	(ZMA)	3057	0.72	0.32	-0.04	0.14	-0.70	0.33
Memphis	(ZME)	1253	0.60	0.40	0.01	0.17	-0.56	0.43
Minneapolis	(ZMP)	2859	0.69	0.37	0.02	0.14	-0.66	0.40
New York	(ZNY)	593	0.62	0.33	-0.03	0.19	-0.56	0.36
Oakland	(ZOA)	1276	0.73	0.38	-0.03	0.16	-0.70	0.39
Cleveland	(ZOB)	1651	0.72	0.33	-0.01	0.14	-0.69	0.35
Seattle	(ZSE)	172	0.66	0.30	0.02	0.13	-0.65	0.31
Atlanta	(ZTL)	3585	0.73	0.38	0.00	0.15	-0.71	0.39

Table C- 2 Error Statistics by Flight Segment and Center

			Horizontal Error		Cross Track Error		Along Track Error	
Flight Segment ID	Center	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
1-173	ZAB	229	0.93	0.34	0.08	0.12	-0.92	0.34
2-314	ZAB	11	0.70	0.13	-0.03	0.10	-0.69	0.13
3-556	ZAB	207	0.74	0.28	0.01	0.07	-0.74	0.28
4-438	ZAB	161	0.60	0.21	0.03	0.14	-0.58	0.22
5-041	ZAB	225	0.89	0.38	0.01	0.16	-0.87	0.40
6-759	ZAB	135	0.95	0.40	0.06	0.10	-0.94	0.40
7-745	ZAB	202	0.61	0.27	0.02	0.07	-0.60	0.27
8-658	ZAB	71	0.80	0.33	-0.01	0.07	-0.79	0.34
9-182	ZAB	151	0.80	0.38	0.06	0.17	-0.77	0.39
10-655	ZAB	105	1.12	0.37	-0.06	0.06	-1.11	0.37
11-197	ZAB	192	0.87	0.34	-0.03	0.10	-0.86	0.34
12-224	ZAB	78	0.89	0.37	0.01	0.18	-0.87	0.38
13-245	ZAB	73	1.11	0.35	0.03	0.13	-1.10	0.35
1-361	ZAU	49	0.61	0.32	-0.11	0.06	-0.57	0.38
2-679	ZAU	19	0.69	0.29	0.19	0.12	-0.62	0.37
3-955	ZAU	111	0.56	0.16	0.12	0.11	-0.53	0.17
4-053	ZAU	5	0.75	0.24	0.11	0.04	-0.74	0.24
5-910	ZAU	77	0.84	0.34	0.00	0.11	-0.83	0.34
6-397	ZAU	152	0.33	0.09	0.11	0.08	-0.29	0.09
7-976	ZAU	73	0.25	0.20	0.05	0.08	-0.21	0.23
8-985	ZAU	117	0.45	0.28	0.05	0.12	-0.42	0.30
9-299	ZAU	60	1.00	0.35	0.19	0.28	-0.95	0.31
10-238	ZAU	60	0.46	0.20	0.01	0.09	-0.44	0.22
11-740	ZAU	75	0.23	0.09	0.00	0.10	-0.20	0.11
12-001	ZAU	18	0.24	0.23	-0.01	0.09	-0.21	0.24
13-074	ZAU	59	1.36	0.37	-0.08	0.16	-1.34	0.37
14-081	ZAU	5	1.29	0.37	0.10	0.04	-1.29	0.38
15-839	ZAU	62	1.12	0.16	-0.14	0.08	-1.10	0.17
16-406	ZAU	36	0.29	0.19	0.12	0.06	-0.23	0.22
17-755	ZAU	35	1.11	0.08	-0.03	0.06	-1.11	0.08
18-862	ZAU	14	0.48	0.14	0.05	0.08	-0.46	0.17
19-042	ZAU	213	0.64	0.45	0.04	0.14	-0.61	0.47
20-077	ZAU	53	0.26	0.06	-0.01	0.07	-0.26	0.06
21-793	ZAU	151	0.77	0.35	0.06	0.38	-0.63	0.43
22-082	ZAU	181	1.02	0.37	0.05	0.07	-1.01	0.38
23-383	ZAU	94	1.09	0.37	0.05	0.09	-1.09	0.37
24-918	ZAU	72	0.93	0.33	0.04	0.09	-0.93	0.34
1-543	ZBW	61	0.85	0.40	0.01	0.06	-0.85	0.40
2-797	ZBW	307	0.74	0.27	0.00	0.14	-0.73	0.28
3-471	ZBW	149	0.51	0.21	-0.03	0.14	-0.49	0.22
4-467	ZBW	257	0.49	0.27	-0.04	0.08	-0.47	0.28
5-429	ZBW	81	0.81	0.32	0.02	0.15	-0.80	0.31
6-588	ZBW	58	0.27	0.11	-0.04	0.09	-0.25	0.11
7-948	ZBW	210	0.92	0.33	0.01	0.17	-0.91	0.33
8-873	ZBW	91	0.64	0.29	-0.05	0.11	-0.62	0.29

			Horizontal Error		Cross Track Error		Along Track Error	
Flight Segment ID	Center	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
9-269	ZBW	141	0.94	0.38	-0.07	0.09	-0.93	0.39
10-155	ZBW	251	1.03	0.26	0.03	0.15	-1.02	0.26
11-799	ZBW	183	0.61	0.36	0.00	0.13	-0.59	0.36
12-704	ZBW	157	0.43	0.11	0.00	0.10	-0.42	0.11
1-712	ZDC	76	0.55	0.19	0.26	0.13	-0.45	0.23
2-393	ZDC	106	0.34	0.19	0.01	0.09	-0.32	0.20
3-626	ZDC	134	0.81	0.37	0.05	0.19	-0.77	0.41
4-657	ZDC	6	0.60	0.23	0.11	0.05	-0.58	0.26
5-481	ZDC	137	0.59	0.27	-0.12	0.19	-0.52	0.31
6-845	ZDC	345	0.79	0.47	0.00	0.42	-0.71	0.42
7-328	ZDC	149	0.88	0.31	0.17	0.16	-0.85	0.31
8-235	ZDC	21	0.89	0.10	-0.63	0.15	-0.61	0.08
9-731	ZDC	100	1.10	0.31	0.16	0.16	-1.08	0.31
10-74F	ZDC	102	0.48	0.22	0.02	0.11	-0.47	0.22
11-352	ZDC	9	1.61	0.13	-0.37	0.31	-1.54	0.07
12-94N	ZDC	107	0.73	0.16	0.24	0.06	-0.69	0.16
13-110	ZDC	105	1.09	0.31	0.17	0.08	-1.08	0.31
14-883	ZDC	156	1.31	0.32	0.19	0.19	-1.28	0.35
15-201	ZDC	105	0.68	0.35	0.11	0.19	-0.65	0.36
16-317	ZDC	139	0.65	0.36	-0.17	0.17	-0.54	0.44
17-437	ZDC	188	0.58	0.25	0.05	0.17	-0.55	0.25
18-697	ZDC	159	0.87	0.21	0.15	0.10	-0.85	0.21
19-937	ZDC	169	0.76	0.27	0.16	0.16	-0.71	0.30
20-612	ZDC	61	0.82	0.27	0.35	0.15	-0.72	0.30
21-687	ZDC	95	0.97	0.43	0.05	0.10	-0.96	0.43
22-738	ZDC	180	0.72	0.37	-0.04	0.25	-0.65	0.41
23-108	ZDC	138	0.50	0.19	0.20	0.07	-0.42	0.25
24-648	ZDC	106	1.11	0.29	0.16	0.11	-1.09	0.29
25-684	ZDC	36	0.87	0.23	0.01	0.18	-0.86	0.22
26-545	ZDC	177	0.75	0.40	0.12	0.15	-0.72	0.42
1-403	ZDV	152	0.79	0.32	-0.06	0.18	-0.77	0.33
2-273	ZDV	141	0.78	0.34	-0.24	0.12	-0.72	0.37
3-583	ZDV	229	0.61	0.29	0.10	0.26	-0.53	0.32
4-279	ZDV	231	0.75	0.30	0.13	0.12	-0.72	0.30
5-322	ZDV	234	0.54	0.21	0.04	0.23	-0.48	0.23
6-384	ZDV	118	0.82	0.30	-0.25	0.21	-0.76	0.28
7-293	ZDV	53	0.71	0.34	-0.27	0.06	-0.55	0.49
8-706	ZDV	107	0.94	0.27	-0.36	0.18	-0.84	0.30
9-375	ZDV	254	0.70	0.32	0.00	0.14	-0.68	0.33
10-386	ZDV	202	0.72	0.28	-0.04	0.06	-0.71	0.28
11-258	ZDV	77	0.44	0.26	0.16	0.08	-0.39	0.28
12-780	ZDV	146	0.83	0.30	0.08	0.12	-0.82	0.30
13-858	ZDV	25	0.52	0.19	0.03	0.13	-0.50	0.19
14-199	ZDV	178	0.51	0.30	-0.06	0.18	-0.46	0.32
15-978	ZDV	236	0.79	0.30	0.02	0.19	-0.77	0.30
16-977	ZDV	12	0.40	0.13	0.17	0.09	-0.35	0.15
17-970	ZDV	221	0.64	0.28	0.00	0.13	-0.62	0.29
18-222	ZDV	192	0.65	0.32	0.05	0.09	-0.64	0.32

			Horizontal Error		Cross Track Error		Along Track Error	
Flight Segment ID	Center	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
19-818	ZDV	263	0.64	0.30	-0.02	0.13	-0.63	0.31
20-964	ZDV	34	0.58	0.22	-0.02	0.06	-0.57	0.25
21-952	ZDV	24	0.55	0.24	-0.01	0.06	-0.55	0.24
22-074	ZDV	266	0.63	0.25	0.05	0.09	-0.62	0.26
23-965	ZDV	16	0.73	0.26	-0.05	0.05	-0.73	0.26
1-317	ZFW	22	1.37	0.07	0.09	0.14	-1.36	0.08
2-454	ZFW	11	0.48	0.05	0.03	0.06	-0.48	0.05
3-316	ZFW	104	0.65	0.29	-0.09	0.08	-0.63	0.30
4-568	ZFW	56	0.54	0.16	0.01	0.16	-0.52	0.15
5-757	ZFW	122	0.41	0.24	0.02	0.07	-0.40	0.26
6-020	ZFW	190	0.75	0.31	-0.06	0.09	-0.74	0.32
7-071	ZFW	238	0.83	0.29	0.03	0.09	-0.83	0.30
8-564	ZFW	25	0.55	0.16	-0.08	0.09	-0.53	0.19
9-817	ZFW	127	1.02	0.35	0.10	0.11	-1.01	0.34
10-469	ZFW	140	0.86	0.37	0.11	0.11	-0.84	0.37
11-171	ZFW	113	1.02	0.38	-0.04	0.18	-1.00	0.39
12-344	ZFW	83	0.43	0.23	0.05	0.11	-0.40	0.24
13-526	ZFW	21	1.29	0.10	0.05	0.07	-1.29	0.11
14-945	ZFW	281	0.62	0.26	0.09	0.15	-0.59	0.28
15-119	ZFW	203	1.24	0.29	-0.05	0.08	-1.23	0.29
16-889	ZFW	146	0.55	0.25	0.05	0.15	-0.52	0.27
17-151	ZFW	142	1.20	0.38	-0.03	0.08	-1.19	0.38
18-238	ZFW	125	0.69	0.28	0.00	0.14	-0.67	0.28
19-715	ZFW	78	0.98	0.41	-0.06	0.09	-0.98	0.41
1-100	ZHU	158	0.57	0.40	-0.06	0.19	-0.52	0.43
2-745	ZHU	109	0.74	0.27	0.04	0.09	-0.74	0.27
3-074	ZHU	55	0.53	0.23	-0.08	0.10	-0.50	0.24
4-786	ZHU	296	1.02	0.40	0.04	0.12	-1.01	0.40
5-029	ZHU	25	0.67	0.17	0.06	0.10	-0.66	0.17
6-85V	ZHU	246	0.96	0.45	-0.08	0.18	-0.93	0.46
7-856	ZHU	124	0.84	0.11	0.08	0.13	-0.82	0.11
8-153	ZHU	205	1.02	0.40	0.00	0.12	-1.01	0.41
9-584	ZHU	160	0.44	0.19	-0.06	0.07	-0.43	0.19
10-635	ZHU	188	0.68	0.13	-0.05	0.12	-0.66	0.13
11-55A	ZHU	83	0.72	0.13	0.17	0.09	-0.69	0.14
12-08Y	ZHU	87	0.64	0.22	0.14	0.10	-0.62	0.21
13-522	ZHU	201	0.57	0.18	-0.05	0.12	-0.54	0.21
14-474	ZHU	128	0.47	0.23	-0.09	0.09	-0.45	0.23
15-874	ZHU	74	0.60	0.08	-0.12	0.08	-0.59	0.07
16-481	ZHU	198	0.52	0.29	-0.05	0.11	-0.51	0.29
17-639	ZHU	214	0.50	0.15	-0.17	0.10	-0.45	0.17
18-313	ZHU	179	0.62	0.30	-0.03	0.14	-0.60	0.31
19-857	ZHU	187	0.71	0.35	-0.03	0.11	-0.70	0.36
20-34A	ZHU	77	0.64	0.20	0.14	0.11	-0.61	0.21
21-344	ZHU	269	0.49	0.26	0.02	0.16	-0.45	0.27
22-51J	ZHU	281	0.62	0.31	0.03	0.15	-0.60	0.32
23-973	ZHU	96	0.85	0.29	-0.23	0.10	-0.81	0.30
24-701	ZHU	279	0.29	0.18	0.02	0.13	-0.26	0.18

			Horizontal Error		Cross Track Error		Along Track Error	
Flight Segment ID	Center	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
25-150	ZHU	314	0.51	0.33	-0.05	0.16	-0.48	0.32
26-952	ZHU	124	0.43	0.21	0.05	0.10	-0.41	0.21
27-30N	ZHU	210	0.42	0.21	-0.05	0.11	-0.40	0.20
1-198	ZID	277	0.89	0.36	-0.06	0.16	-0.85	0.40
2-922	ZID	27	0.37	0.05	-0.03	0.05	-0.37	0.05
3-889	ZID	81	0.91	0.31	0.04	0.06	-0.90	0.31
4-187	ZID	102	1.20	0.34	-0.13	0.10	-1.19	0.33
5-177	ZID	182	0.51	0.15	0.02	0.07	-0.50	0.16
6-650	ZID	223	0.63	0.24	-0.02	0.16	-0.61	0.25
7-226	ZID	96	0.67	0.24	0.15	0.18	-0.61	0.29
8-090	ZID	165	0.59	0.32	0.02	0.08	-0.58	0.32
9-685	ZID	165	0.76	0.32	0.03	0.06	-0.76	0.32
10-636	ZID	153	0.82	0.34	-0.08	0.40	-0.70	0.35
11-120	ZID	101	0.29	0.15	0.10	0.12	-0.25	0.15
12-222	ZID	206	0.59	0.36	-0.02	0.20	-0.55	0.36
13-134	ZID	145	0.93	0.29	0.02	0.20	-0.91	0.30
14-961	ZID	225	0.50	0.35	0.01	0.10	-0.49	0.36
15-070	ZID	150	1.06	0.48	-0.07	0.11	-1.05	0.49
16-916	ZID	114	0.81	0.39	0.00	0.11	-0.80	0.40
17-522	ZID	146	0.39	0.12	-0.01	0.15	-0.36	0.12
18-983	ZID	203	0.42	0.21	0.05	0.14	-0.32	0.30
19-500	ZID	146	0.59	0.27	0.05	0.10	-0.58	0.27
20-216	ZID	109	0.82	0.27	0.03	0.07	-0.81	0.27
21-470	ZID	228	0.78	0.30	-0.03	0.11	-0.77	0.30
22-083	ZID	249	0.42	0.18	0.06	0.08	-0.40	0.19
23-273	ZID	212	0.57	0.26	0.05	0.14	-0.55	0.26
24-887	ZID	264	0.76	0.32	0.07	0.09	-0.75	0.33
25-863	ZID	382	0.77	0.34	0.01	0.15	-0.75	0.35
1-536	ZJX	104	0.80	0.31	-0.05	0.08	-0.79	0.31
2-41D	ZJX	93	0.45	0.12	0.00	0.10	-0.44	0.12
3-70F	ZJX	214	0.63	0.26	-0.05	0.12	-0.61	0.29
4-275	ZJX	117	1.12	0.40	0.03	0.10	-1.11	0.40
5-951	ZJX	106	0.28	0.17	-0.02	0.10	-0.18	0.25
6-340	ZJX	81	1.03	0.08	-0.12	0.07	-1.03	0.08
7-817	ZJX	78	0.42	0.26	-0.10	0.17	-0.34	0.30
8-970	ZJX	186	0.44	0.21	0.04	0.14	-0.41	0.22
9-654	ZJX	156	0.71	0.35	-0.01	0.13	-0.67	0.40
10-803	ZJX	175	0.60	0.36	-0.05	0.14	-0.57	0.38
11-827	ZJX	68	0.45	0.26	-0.03	0.14	-0.42	0.27
12-126	ZJX	219	0.60	0.21	-0.02	0.11	-0.58	0.22
13-396	ZJX	11	0.42	0.07	-0.26	0.07	-0.33	0.05
14-416	ZJX	51	1.19	0.05	0.10	0.08	-1.18	0.05
15-672	ZJX	49	1.31	0.34	-0.05	0.08	-1.30	0.35
16-455	ZJX	171	0.63	0.29	0.06	0.09	-0.62	0.29
1-591	ZKC	304	0.78	0.29	-0.05	0.17	-0.76	0.30
2-191	ZKC	251	0.46	0.21	0.04	0.12	-0.44	0.22
3-961	ZKC	122	0.80	0.23	0.11	0.14	-0.77	0.25
4-888	ZKC	155	0.76	0.51	0.00	0.20	-0.73	0.52

			Horizontal Error		Cross Track Error		Along Track Error	
Flight Segment ID	**Center**	**Sample Size**	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
5-328	ZKC	264	0.66	0.41	-0.01	0.11	-0.65	0.42
6-778	ZKC	264	0.61	0.25	-0.03	0.10	-0.60	0.26
7-892	ZKC	219	0.51	0.25	-0.02	0.12	-0.49	0.27
8-989	ZKC	64	0.29	0.11	-0.06	0.06	-0.27	0.12
9-995	ZKC	215	0.61	0.36	0.00	0.12	-0.59	0.38
10-857	ZKC	164	0.65	0.21	0.03	0.15	-0.63	0.21
11-561	ZKC	207	0.51	0.17	0.02	0.08	-0.50	0.18
12-005	ZKC	206	0.34	0.35	-0.04	0.14	-0.26	0.39
13-443	ZKC	197	0.54	0.28	-0.03	0.12	-0.53	0.28
14-792	ZKC	221	0.63	0.36	0.02	0.14	-0.60	0.37
15-292	ZKC	285	0.74	0.24	0.06	0.10	-0.73	0.24
16-279	ZKC	240	0.94	0.35	0.04	0.16	-0.93	0.35
17-076	ZKC	240	0.63	0.22	0.00	0.07	-0.62	0.22
18-836	ZKC	140	0.66	0.41	-0.02	0.16	-0.63	0.42
19-687	ZKC	130	0.55	0.27	0.07	0.06	-0.54	0.27
20-075	ZKC	202	0.55	0.23	-0.02	0.13	-0.53	0.23
21-584	ZKC	202	0.40	0.23	0.01	0.10	-0.38	0.24
22-737	ZKC	188	0.47	0.26	0.00	0.10	-0.46	0.27
23-364	ZKC	197	0.91	0.35	-0.03	0.15	-0.90	0.35
24-729	ZKC	101	0.69	0.18	0.22	0.15	-0.63	0.21
25-021	ZKC	78	0.25	0.09	-0.03	0.07	-0.23	0.10
26-057	ZKC	265	0.54	0.26	0.00	0.11	-0.53	0.27
27-803	ZKC	213	0.47	0.27	-0.04	0.09	-0.46	0.27
28-429	ZKC	220	0.50	0.33	-0.01	0.14	-0.46	0.36
29-824	ZKC	167	1.03	0.43	-0.02	0.19	-1.01	0.43
30-230	ZKC	162	0.61	0.26	0.01	0.13	-0.59	0.26
31-668	ZKC	238	0.40	0.22	-0.03	0.11	-0.37	0.23
32-417	ZKC	214	0.88	0.34	-0.01	0.14	-0.86	0.35
33-259	ZKC	270	0.45	0.21	-0.03	0.10	-0.44	0.21
34-468	ZKC	216	0.78	0.25	-0.01	0.12	-0.77	0.25
35-616	ZKC	209	0.29	0.11	-0.04	0.15	-0.24	0.12
36-480	ZKC	52	0.67	0.10	0.09	0.10	-0.65	0.10
37-767	ZKC	90	0.72	0.29	0.04	0.20	-0.66	0.35
38-867	ZKC	197	0.77	0.34	0.00	0.14	-0.75	0.34
39-657	ZKC	153	0.51	0.37	0.00	0.13	-0.49	0.39
40-517	ZKC	240	0.84	0.34	0.05	0.13	-0.83	0.34
41-487	ZKC	160	0.93	0.28	-0.02	0.13	-0.91	0.31
42-973	ZKC	96	0.63	0.27	0.03	0.09	-0.59	0.33
43-553	ZKC	98	0.92	0.25	-0.08	0.14	-0.91	0.25
44-628	ZKC	144	0.33	0.27	0.03	0.08	-0.31	0.27
45-307	ZKC	94	0.39	0.09	0.04	0.16	-0.35	0.11
46-527	ZKC	374	0.80	0.39	-0.04	0.12	-0.79	0.39
47-205	ZKC	207	0.41	0.20	0.08	0.07	-0.39	0.21
48-012	ZKC	141	0.97	0.41	-0.05	0.15	-0.96	0.42
49-727	ZKC	218	0.79	0.37	0.02	0.10	-0.78	0.37
50-528	ZKC	138	0.48	0.21	-0.10	0.15	-0.44	0.24
51-061	ZKC	202	0.52	0.20	0.05	0.10	-0.50	0.20
52-710	ZKC	148	0.44	0.22	0.05	0.10	-0.43	0.23

			Horizontal Error		Cross Track Error		Along Track Error	
Flight Segment ID	Center	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
53-917	ZKC	289	0.70	0.42	0.00	0.15	-0.68	0.42
54-900	ZKC	65	0.61	0.31	-0.09	0.06	-0.60	0.31
55-913	ZKC	144	0.41	0.26	0.04	0.10	-0.39	0.26
56-504	ZKC	151	0.62	0.28	0.05	0.13	-0.60	0.29
57-340	ZKC	290	0.70	0.36	-0.01	0.11	-0.69	0.36
1-094	ZLA	158	0.89	0.23	-0.04	0.10	-0.89	0.23
2-856	ZLA	61	0.78	0.31	-0.03	0.06	-0.78	0.31
3-892	ZLA	22	0.78	0.30	0.03	0.08	-0.77	0.30
4-196	ZLA	75	1.03	0.06	0.02	0.10	-1.02	0.06
5-151	ZLA	117	0.68	0.21	-0.05	0.08	-0.67	0.21
6-979	ZLA	236	0.57	0.25	-0.02	0.13	-0.54	0.27
7-794	ZLA	118	0.86	0.30	-0.04	0.10	-0.85	0.31
8-478	ZLA	14	1.55	0.13	-0.16	0.25	-1.52	0.11
9-480	ZLA	70	1.35	0.20	0.00	0.11	-1.35	0.20
10-414	ZLA	122	0.54	0.26	-0.04	0.08	-0.53	0.27
11-350	ZLA	74	0.36	0.15	0.01	0.21	-0.31	0.11
12-384	ZLA	184	0.80	0.09	0.04	0.09	-0.79	0.09
13-636	ZLA	13	1.10	0.05	-0.10	0.07	-1.10	0.06
14-690	ZLA	179	0.83	0.33	-0.10	0.09	-0.82	0.33
15-090	ZLA	175	0.75	0.31	0.04	0.10	-0.74	0.31
16-67J	ZLA	3	0.55	0.02	-0.09	0.05	-0.54	0.03
17-585	ZLA	109	0.96	0.09	-0.02	0.09	-0.96	0.09
18-41N	ZLA	209	0.47	0.13	0.01	0.11	-0.45	0.14
19-18A	ZLA	72	0.89	0.30	0.07	0.22	-0.86	0.30
20-729	ZLA	254	0.82	0.38	-0.05	0.13	-0.81	0.38
21-11C	ZLA	117	0.38	0.20	-0.06	0.11	-0.35	0.21
22-786	ZLA	142	0.35	0.07	-0.07	0.07	-0.33	0.07
23-714	ZLA	68	1.04	0.37	0.05	0.10	-1.04	0.37
24-107	ZLA	112	1.02	0.41	0.06	0.09	-1.01	0.42
25-40T	ZLA	80	0.85	0.34	0.10	0.17	-0.81	0.37
1-810	ZLC	201	0.74	0.33	0.06	0.12	-0.72	0.33
2-055	ZLC	235	0.77	0.34	-0.04	0.16	-0.74	0.34
3-677	ZLC	246	0.53	0.21	0.01	0.18	-0.50	0.22
4-435	ZLC	230	0.63	0.36	0.00	0.24	-0.57	0.38
5-192	ZLC	182	0.69	0.28	0.05	0.12	-0.67	0.29
6-156	ZLC	7	0.84	0.29	-0.02	0.07	-0.83	0.29
1-16G	ZMA	153	0.77	0.25	-0.09	0.10	-0.76	0.25
2-869	ZMA	173	1.11	0.30	0.07	0.13	-1.10	0.30
3-352	ZMA	33	0.80	0.29	-0.09	0.05	-0.79	0.29
4-649	ZMA	125	0.68	0.38	0.06	0.15	-0.66	0.38
5-026	ZMA	206	1.04	0.35	-0.09	0.12	-1.02	0.36
6-077	ZMA	193	0.92	0.33	-0.06	0.14	-0.91	0.33
7-499	ZMA	29	0.34	0.06	0.10	0.08	-0.32	0.06
8-316	ZMA	161	1.03	0.22	-0.03	0.11	-1.02	0.22
9-369	ZMA	180	0.52	0.21	0.01	0.11	-0.50	0.22
10-957	ZMA	28	0.45	0.05	0.07	0.07	-0.44	0.05
11-654	ZMA	159	0.87	0.20	-0.13	0.19	-0.83	0.23
12-648	ZMA	142	0.61	0.12	-0.12	0.08	-0.59	0.13

			Horizontal Error		Cross Track Error		Along Track Error	
Flight Segment ID	Center	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
13-196	ZMA	216	0.80	0.20	-0.04	0.14	-0.78	0.22
14-785	ZMA	241	0.65	0.13	-0.06	0.15	-0.63	0.13
15-58B	ZMA	153	0.30	0.08	-0.01	0.06	-0.30	0.08
16-915	ZMA	63	0.63	0.24	-0.11	0.28	-0.56	0.21
17-658	ZMA	246	0.82	0.20	-0.03	0.11	-0.81	0.20
18-764	ZMA	138	0.37	0.13	-0.03	0.12	-0.35	0.13
19-725	ZMA	235	0.44	0.20	0.04	0.10	-0.42	0.20
20-181	ZMA	183	0.59	0.17	-0.09	0.11	-0.57	0.18
1-670	ZME	142	1.08	0.35	0.09	0.30	-1.00	0.44
2-597	ZME	40	0.36	0.08	0.20	0.11	-0.26	0.11
3-635	ZME	238	0.90	0.44	-0.02	0.15	-0.88	0.45
4-239	ZME	65	0.78	0.35	-0.06	0.12	-0.76	0.37
5-102	ZME	133	0.50	0.31	0.04	0.18	-0.45	0.32
6-142	ZME	70	0.39	0.23	0.10	0.11	-0.35	0.25
7-690	ZME	136	0.47	0.25	-0.02	0.14	-0.45	0.25
8-611	ZME	27	0.48	0.08	-0.16	0.05	-0.45	0.08
9-724	ZME	19	0.57	0.27	-0.08	0.07	-0.56	0.28
10-872	ZME	203	0.40	0.16	0.01	0.11	-0.38	0.18
11-254	ZME	180	0.34	0.26	-0.04	0.10	-0.25	0.33
1-611	ZMP	26	0.49	0.25	0.06	0.06	-0.42	0.35
2-063	ZMP	40	0.72	0.26	0.07	0.07	-0.71	0.26
3-831	ZMP	129	0.29	0.18	0.00	0.08	-0.27	0.18
4-420	ZMP	96	0.54	0.39	0.03	0.14	-0.51	0.39
5-981	ZMP	85	0.58	0.25	0.10	0.14	-0.55	0.26
6-847	ZMP	143	0.45	0.24	0.02	0.13	-0.43	0.24
7-252	ZMP	205	0.88	0.37	0.03	0.07	-0.88	0.38
8-132	ZMP	216	0.89	0.31	-0.07	0.09	-0.88	0.34
9-133	ZMP	187	0.59	0.26	-0.05	0.10	-0.58	0.26
10-313	ZMP	62	0.77	0.09	0.02	0.07	-0.76	0.10
11-025	ZMP	151	0.97	0.35	0.04	0.13	-0.96	0.35
12-232	ZMP	195	0.15	0.15	-0.03	0.09	0.03	0.19
13-651	ZMP	110	0.83	0.39	-0.12	0.14	-0.81	0.41
14-428	ZMP	5	0.20	0.10	0.07	0.07	-0.18	0.08
15-420	ZMP	227	0.54	0.24	0.08	0.22	-0.48	0.24
16-755	ZMP	38	0.49	0.08	0.00	0.05	-0.49	0.08
17-482	ZMP	130	1.06	0.20	0.08	0.13	-1.05	0.20
18-243	ZMP	55	0.76	0.19	0.06	0.13	-0.74	0.20
19-748	ZMP	142	0.77	0.31	0.06	0.12	-0.76	0.31
20-758	ZMP	111	0.57	0.28	-0.05	0.09	-0.56	0.28
21-898	ZMP	161	1.06	0.13	-0.01	0.17	-1.05	0.13
22-129	ZMP	82	0.88	0.44	0.04	0.11	-0.88	0.44
23-239	ZMP	22	0.59	0.21	0.21	0.20	-0.49	0.27
24-726	ZMP	130	0.73	0.34	0.07	0.10	-0.72	0.34
25-264	ZMP	111	0.66	0.26	0.09	0.10	-0.65	0.26
1-760	ZNY	200	0.69	0.39	-0.01	0.13	-0.67	0.40
2-585	ZNY	19	0.38	0.18	-0.01	0.09	-0.35	0.22
3-182	ZNY	112	0.65	0.25	-0.12	0.10	-0.64	0.25
4-824	ZNY	19	0.47	0.25	0.01	0.12	-0.43	0.28

			Horizontal Error		Cross Track Error		Along Track Error	
Flight Segment ID	Center	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
5-973	ZNY	115	0.54	0.25	0.10	0.31	-0.36	0.34
6-296	ZNY	6	0.42	0.10	0.15	0.17	-0.35	0.11
7-785	ZNY	122	0.61	0.33	-0.15	0.10	-0.56	0.36
1-844	ZOA	153	0.64	0.29	0.08	0.09	-0.62	0.29
2-000	ZOA	236	0.99	0.40	-0.05	0.08	-0.98	0.41
3-658	ZOA	202	1.02	0.34	-0.11	0.10	-1.01	0.36
4-738	ZOA	83	0.44	0.08	-0.08	0.05	-0.43	0.08
5-372	ZOA	233	0.44	0.17	-0.08	0.24	-0.35	0.18
6-294	ZOA	211	0.77	0.30	-0.03	0.15	-0.75	0.29
7-930	ZOA	25	0.10	0.04	0.00	0.04	-0.09	0.05
8-061	ZOA	5	0.35	0.09	-0.02	0.05	-0.34	0.10
9-860	ZOA	128	0.69	0.21	0.14	0.07	-0.67	0.21
1-410	ZOB	126	1.06	0.10	0.02	0.09	-1.05	0.10
2-019	ZOB	236	0.65	0.33	-0.02	0.10	-0.64	0.33
3-829	ZOB	124	0.37	0.20	-0.01	0.15	-0.29	0.27
4-871	ZOB	3	0.65	0.22	0.05	0.05	-0.64	0.21
5-429	ZOB	74	1.03	0.38	0.00	0.27	-0.98	0.40
6-854	ZOB	133	0.57	0.20	-0.06	0.11	-0.55	0.21
7-596	ZOB	68	0.68	0.08	0.05	0.11	-0.66	0.09
8-552	ZOB	98	0.46	0.27	0.06	0.10	-0.41	0.32
9-445	ZOB	11	0.62	0.25	0.01	0.09	-0.62	0.25
10-920	ZOB	93	0.71	0.30	0.01	0.07	-0.70	0.31
11-517	ZOB	29	1.14	0.16	-0.22	0.15	-1.11	0.19
12-556	ZOB	182	0.85	0.23	0.01	0.11	-0.84	0.24
13-330	ZOB	52	0.83	0.06	0.12	0.09	-0.82	0.06
14-140	ZOB	47	0.51	0.28	-0.06	0.07	-0.50	0.29
15-976	ZOB	154	0.77	0.23	0.01	0.14	-0.75	0.24
16-579	ZOB	30	0.48	0.16	0.06	0.09	-0.23	0.45
17-843	ZOB	126	0.59	0.26	-0.05	0.08	-0.58	0.26
18-035	ZOB	65	1.21	0.22	-0.08	0.27	-1.17	0.26
1-710	ZSE	172	0.66	0.30	0.02	0.13	-0.65	0.31
1-323	ZTL	64	0.89	0.30	0.05	0.11	-0.88	0.30
2-352	ZTL	120	0.90	0.36	-0.11	0.10	-0.89	0.36
3-165	ZTL	25	0.48	0.08	-0.06	0.05	-0.48	0.09
4-93A	ZTL	216	0.59	0.26	0.02	0.11	-0.58	0.27
5-266	ZTL	47	0.37	0.20	0.15	0.14	-0.10	0.35
6-513	ZTL	265	0.54	0.27	-0.10	0.15	-0.49	0.31
7-384	ZTL	81	1.28	0.43	-0.12	0.10	-1.26	0.45
8-01F	ZTL	163	0.92	0.39	-0.03	0.17	-0.89	0.42
9-835	ZTL	113	1.02	0.35	0.01	0.19	-0.99	0.40
10-153	ZTL	165	0.46	0.24	-0.06	0.07	-0.45	0.24
11-687	ZTL	110	0.86	0.28	0.07	0.09	-0.86	0.28
12-050	ZTL	55	0.17	0.05	-0.02	0.05	-0.16	0.05
13-881	ZTL	176	0.64	0.30	-0.04	0.11	-0.62	0.31
14-598	ZTL	64	0.96	0.33	0.03	0.09	-0.95	0.34
15-263	ZTL	66	0.83	0.20	-0.08	0.05	-0.82	0.20
16-79T	ZTL	283	0.65	0.29	-0.02	0.12	-0.64	0.29
17-260	ZTL	195	0.97	0.38	0.11	0.22	-0.94	0.38

			Horizontal Error		Cross Track Error		Along Track Error	
Flight Segment ID	Center	Sample Size	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
18-966	ZTL	185	0.59	0.27	-0.01	0.09	-0.59	0.28
19-645	ZTL	104	0.54	0.22	-0.07	0.14	-0.51	0.25
20-651	ZTL	291	0.72	0.42	0.00	0.11	-0.71	0.42
21-077	ZTL	103	0.71	0.26	0.16	0.15	-0.67	0.29
22-000	ZTL	147	0.94	0.37	0.02	0.15	-0.93	0.38
23-402	ZTL	83	0.41	0.19	-0.05	0.05	-0.41	0.19
24-928	ZTL	194	0.82	0.34	0.06	0.16	-0.80	0.35
25-13Y	ZTL	34	1.19	0.08	-0.16	0.06	-1.18	0.09
26-866	ZTL	127	0.94	0.37	0.07	0.08	-0.93	0.37
27-738	ZTL	109	0.71	0.27	0.12	0.12	-0.69	0.28

Appendix D – Comparison of Horizontal Error Means by Center

The following Table D- 1 lists the differences in the sample mean of horizontal error for all twenty Centers in the study in units of nautical miles.

Table D- 1 Differences of Center Sample Means

Dif=Mean[i]-Mean[j]	ZAB	ZFW	ZDC	ZLA	ZTL	ZOA	ZOB	ZMA	ZBW	ZAU	ZMP	ZDV	ZID	ZLC	ZSE	ZJX	ZHU	ZKC	ZNY	ZME
ZAB	0.00000	0.02427	0.05379	0.09024	0.09959	0.10660	0.11430	0.11460	0.12267	0.14424	0.14786	0.15269	0.15358	0.16648	0.17105	0.17709	0.20496	0.21071	0.21789	0.22940
ZFW	-0.02427	0.00000	0.02952	0.06597	0.07531	0.08233	0.09003	0.09033	0.09840	0.11997	0.12358	0.12841	0.12931	0.14221	0.14677	0.15282	0.18069	0.18644	0.19361	0.20512
ZDC	-0.05379	-0.02952	0.00000	0.03645	0.04579	0.05281	0.06050	0.06081	0.06887	0.09044	0.09406	0.09889	0.09978	0.11268	0.11725	0.12329	0.15117	0.15691	0.16409	0.17560
ZLA	-0.09024	-0.06597	-0.03645	0.00000	0.00934	0.01636	0.02405	0.02436	0.03242	0.05399	0.05761	0.06244	0.06333	0.07623	0.08080	0.08684	0.11472	0.12046	0.12764	0.13915
ZTL	-0.09959	-0.07531	-0.04579	-0.00934	0.00000	0.00701	0.01471	0.01501	0.02308	0.04465	0.04827	0.05310	0.05399	0.06689	0.07146	0.07750	0.10537	0.11112	0.11830	0.12981
ZOA	-0.10660	-0.08233	-0.05281	-0.01636	-0.00701	0.00000	0.00770	0.00800	0.01607	0.03764	0.04126	0.04609	0.04698	0.05988	0.06445	0.07049	0.09836	0.10411	0.11129	0.12280
ZOB	-0.11430	-0.09003	-0.06050	-0.02405	-0.01471	-0.00770	0.00000	0.00030	0.00837	0.02994	0.03356	0.03839	0.03928	0.05218	0.05675	0.06279	0.09066	0.09641	0.10359	0.11510
ZMA	-0.11460	-0.09033	-0.06081	-0.02436	-0.01501	-0.00800	-0.00030	0.00000	0.00807	0.02964	0.03325	0.03809	0.03898	0.05188	0.05645	0.06249	0.09036	0.09611	0.10329	0.11480
ZBW	-0.12267	-0.09840	-0.06887	-0.03242	-0.02308	-0.01607	-0.00837	-0.00807	0.00000	0.02157	0.02519	0.03002	0.03091	0.04381	0.04838	0.05442	0.08229	0.08804	0.09522	0.10673
ZAU	-0.14424	-0.11997	-0.09044	-0.05399	-0.04465	-0.03764	-0.02994	-0.02964	-0.02157	0.00000	0.00362	0.00845	0.00934	0.02224	0.02681	0.03285	0.06072	0.06647	0.07365	0.08516
ZMP	-0.14786	-0.12358	-0.09406	-0.05761	-0.04827	-0.04126	-0.03356	-0.03325	-0.02519	-0.00362	0.00000	0.00483	0.00572	0.01862	0.02319	0.02923	0.05710	0.06285	0.07003	0.08154
ZDV	-0.15269	-0.12841	-0.09889	-0.06244	-0.05310	-0.04609	-0.03839	-0.03809	-0.03002	-0.00845	-0.00483	0.00000	0.00089	0.01379	0.01836	0.02440	0.05227	0.05802	0.06520	0.07671
ZID	-0.15358	-0.12931	-0.09978	-0.06333	-0.05399	-0.04698	-0.03928	-0.03898	-0.03091	-0.00934	-0.00572	-0.00089	0.00000	0.01290	0.01747	0.02351	0.05138	0.05713	0.06431	0.07582
ZLC	-0.16648	-0.14221	-0.11268	-0.07623	-0.06689	-0.05988	-0.05218	-0.05188	-0.04381	-0.02224	-0.01862	-0.01379	-0.01290	0.00000	0.00457	0.01061	0.03848	0.04423	0.05141	0.06292
ZSE	-0.17105	-0.14677	-0.11725	-0.08080	-0.07146	-0.06445	-0.05675	-0.05645	-0.04838	-0.02681	-0.02319	-0.01836	-0.01747	-0.00457	0.00000	0.00604	0.03391	0.03966	0.04684	0.05835
ZJX	-0.17709	-0.15282	-0.12329	-0.08684	-0.07750	-0.07049	-0.06279	-0.06249	-0.05442	-0.03285	-0.02923	-0.02440	-0.02351	-0.01061	-0.00604	0.00000	0.02787	0.03362	0.04080	0.05231
ZHU	-0.20496	-0.18069	-0.15117	-0.11472	-0.10537	-0.09836	-0.09066	-0.09036	-0.08229	-0.06072	-0.05710	-0.05227	-0.05138	-0.03848	-0.03391	-0.02787	0.00000	0.00575	0.01293	0.02444

Dif=Mean[i]-Mean[j]	ZAB	ZFW	ZDC	ZLA	ZTL	ZOA	ZOB	ZMA	ZBW	ZAU	ZMP	ZDV	ZID	ZLC	ZSE	ZJX	ZHU	ZKC	ZNY	ZME
ZKC	-0.21071	-0.18644	-0.15691	-0.12046	-0.11112	-0.10411	-0.09641	-0.09611	-0.08804	-0.06647	-0.06285	-0.05802	-0.05713	-0.04423	-0.03966	-0.03362	-0.00575	0.00000	0.00718	0.01869
ZNY	-0.21789	-0.19361	-0.16409	-0.12764	-0.11830	-0.11129	-0.10359	-0.10329	-0.09522	-0.07365	-0.07003	-0.06520	-0.06431	-0.05141	-0.04684	-0.04080	-0.01293	-0.00718	0.00000	0.01151
ZME	-0.22940	-0.20512	-0.17560	-0.13915	-0.12981	-0.12280	-0.11510	-0.11480	-0.10673	-0.08516	-0.08154	-0.07671	-0.07582	-0.06292	-0.05835	-0.05231	-0.02444	-0.01869	-0.01151	0.00000

Using the JMP Software Package[8], a Tukey-Kramer test was performed that performs comparisons for all pairs of means. This statistical inference test determines if and what pairs of sample means are statistically different. This test is an exact alpha-level test if the sample sizes are the same and conservative if the sample sizes are different as in this study. The Tukey-Kramer test quantifies the Least Significant Distance (LSD), which is the difference that would be significant. By comparing it to the sample difference, pairs that are positive are therefore larger than the LSD and are significantly different. The Table D- 2 lists these comparisons for all the Center sample means for this study. There are many of the pairs that are significantly different and many more that are not. The key result is even if some of the pair wise means are significantly different statistically the amount that they are is rather small, ranging from 0.0003 to 0.23 nautical miles.

Table D- 2 Tukey-Kramer Horizontal Error Test by Center

Abs(Dif)-LSD	ZAB	ZFW	ZDC	ZLA	ZTL	ZOA	ZOB	ZMA	ZBW	ZAU	ZMP	ZDV	ZID	ZLC	ZSE	ZJX	ZHU	ZKC	ZNY	ZME
ZAB	-0.04187	-0.01574	0.01643	0.05208	0.06316	0.06033	0.07124	0.07713	0.08137	0.10208	0.10990	0.11595	0.11826	0.11809	0.06978	0.13543	0.16989	0.17866	0.15791	0.18288
ZFW	-0.01574	-0.03806	-0.00575	0.02986	0.04105	0.03773	0.04878	0.05494	0.05898	0.07965	0.08769	0.09381	0.09621	0.09541	0.04626	0.11303	0.14786	0.15686	0.13492	0.16027
ZDC	0.01643	-0.00575	-0.03223	0.00330	0.01466	0.01058	0.02182	0.02845	0.03216	0.05276	0.06115	0.06739	0.06995	0.06814	0.01777	0.08618	0.12163	0.13103	0.10718	0.13310
ZLA	0.05208	0.02986	0.00330	-0.03404	-0.02274	-0.02658	-0.01540	-0.00892	-0.00510	0.01552	0.02379	0.03001	0.03251	0.03102	-0.01899	0.04893	0.08418	0.09345	0.07020	0.09595
ZTL	0.06316	0.04105	0.01466	-0.02274	-0.03000	-0.03439	-0.02306	-0.01625	-0.01268	0.00790	0.01642	0.02272	0.02534	0.02313	-0.02768	0.04133	0.07703	0.08662	0.06200	0.08813
ZOA	0.06033	0.03773	0.01058	-0.02658	-0.03439	-0.05028	-0.03964	-0.03433	-0.02968	-0.00889	-0.00150	0.00441	0.00654	0.00764	-0.03872	0.02442	0.05814	0.06650	0.04817	0.07228
ZOB	0.07124	0.04878	0.02182	-0.01540	-0.02306	-0.03964	-0.04420	-0.03849	-0.03413	-0.01339	-0.00570	0.00031	0.00257	0.00276	-0.04501	0.01995	0.05419	0.06283	0.04278	0.06751
ZMA	0.07713	0.05494	0.02845	-0.00892	-0.01625	-0.03433	-0.03849	-0.03249	-0.02876	-0.00816	0.00021	0.00646	0.00900	0.00724	-0.04308	0.02526	0.06068	0.07007	0.04630	0.07219

[8] JMP is a statistical analysis package and product of the SAS Institute Incorporated; see www.jmp.com (SAS Institute, 2003).

Abs(Dif)-LSD	ZAB	ZFW	ZDC	ZLA	ZTL	ZOA	ZOB	ZMA	ZBW	ZAU	ZMP	ZDV	ZID	ZLC	ZSE	ZJX	ZHU	ZKC	ZNY	ZME
ZBW	0.08137	0.05898	0.03216	-0.00510	-0.01268	-0.02968	-0.03413	-0.02876	-0.04072	-0.02002	-0.01214	-0.00606	-0.00373	-0.00409	-0.05265	0.01334	0.04791	0.05675	0.03564	0.06073
ZAU	0.10208	0.07965	0.05276	0.01552	0.00790	-0.00889	-0.01339	-0.00816	-0.02002	-0.04244	-0.03466	-0.02861	-0.02632	-0.02640	-0.07458	-0.00909	0.02531	0.03405	0.01348	0.03838
ZMP	0.10990	0.08769	0.06115	0.02379	0.01642	-0.00150	-0.00570	0.00021	-0.01214	-0.03466	-0.03359	-0.02737	-0.02485	-0.02643	-0.07652	-0.00849	0.02681	0.03612	0.01272	0.03851
ZDV	0.11595	0.09381	0.06739	0.03001	0.02272	0.00441	0.00031	0.00646	-0.00606	-0.02861	-0.02737	-0.03075	-0.02815	-0.03023	-0.08089	-0.01209	0.02353	0.03305	0.00869	0.03475
ZID	0.11826	0.09621	0.06995	0.03251	0.02534	0.00654	0.00257	0.00900	-0.00373	-0.02632	-0.02485	-0.02815	-0.02723	-0.02995	-0.08127	-0.01155	0.02447	0.03430	0.00871	0.03510
ZLC	0.11809	0.09541	0.06814	0.03102	0.02313	0.00764	0.00276	0.00724	-0.00409	-0.02640	-0.02643	-0.03023	-0.02995	-0.05413	-0.09956	-0.03759	-0.00416	0.00404	-0.01328	0.01046
ZSE	0.06978	0.04626	0.01777	-0.01899	-0.02768	-0.03872	-0.04501	-0.04308	-0.05265	-0.07458	-0.07652	-0.08089	-0.08127	-0.09956	-0.13695	-0.09513	-0.06473	-0.05795	-0.06315	-0.04492
ZJX	0.13543	0.11303	0.08618	0.04893	0.04133	0.02442	0.01995	0.02526	0.01334	-0.00909	-0.00849	-0.01209	-0.01155	-0.03759	-0.09513	-0.04144	-0.00694	0.00186	-0.01902	0.00599
ZHU	0.16989	0.14786	0.12163	0.08418	0.07703	0.05814	0.05419	0.06068	0.04791	0.02531	0.02681	0.02353	0.02447	-0.00416	-0.06473	-0.00694	-0.02658	-0.01669	-0.04251	-0.01607
ZKC	0.17866	0.15686	0.13103	0.09345	0.08662	0.06650	0.06283	0.07007	0.05675	0.03405	0.03612	0.03305	0.03430	0.00404	-0.05795	0.00186	-0.01669	-0.01735	-0.04640	-0.01923
ZNY	0.15791	0.13492	0.10718	0.07020	0.06200	0.04817	0.04278	0.04630	0.03564	0.01348	0.01272	0.00869	0.00871	-0.01328	-0.06315	-0.01902	-0.04251	-0.04640	-0.07376	-0.05179
ZME	0.18288	0.16027	0.13310	0.09595	0.08813	0.07228	0.06751	0.07219	0.06073	0.03838	0.03851	0.03475	0.03510	0.01046	-0.04492	0.00599	-0.01607	-0.01923	-0.05179	-0.05074

Note: Positive values show pairs of means that are significantly different.