THE IMPACT OF TURNS ON HOST RADAR TRACKING

Mike Paglione, Confesor Santiago, Federal Aviation Administration, Atlantic City, NJ
Hollis Ryan, Gregg Gramatges, General Dynamic Corporation, Mays Landing, NJ

Abstract

The Federal Aviation Administration (FAA) is upgrading its Air Traffic Control (ATC) system and plans to replace the existing en route automation system. The Host Computer System (HCS) is the main frame computer operating in all twenty en route Air Route Traffic Control Centers (ARTCCs) in the continental United States. This paper extends a previous study analyzing how the HCS's tracking of radar surveillance data was compared to time coincident Global Positioning Satellite System (GPS) aircraft positions. Using several hundred flights collected from all twenty ARTCCs, this paper compares how the HCS's radar tracking function performs during horizontal turns versus the same flight's straight portion of flight. The paper presents an analysis methodology and reports on a modest effect of turns on the HCS's radar tracking.

Background

In the United States, the current surveillance data processing in the en route air traffic automation uses selected radars based on the geographic position to the aircraft in a mosaic or grid like map across the continental United States. Next, it applies a simple alpha-beta tracker to smooth the radar position reports. These smoothed position reports are referred to as track reports. This processing resides in the Host Computer System (HCS) located at each Air Route Traffic Control Center (ARTCC). There are 20 of these ARTCCs that divide the continental United States en route airspace. The operational HCS software was developed back in the 1970's even though the hardware was upgraded in the 1990's.

In the 2008 time frame, the entire HCS software and hardware will be replaced by the Federal Aviation Administration's (FAA) En Route Automation Modernization (ERAM) Program. The 1970's en route tracker will be replaced with a new state-of-the-art Kalman Filter tracker. The tactical aircraft-to-aircraft conflict alert algorithms are also undergoing a major upgrade to work in conjunction with the new tracker. The new computer system will be a distributed network based computer system with IBM 72 bit processors.

To support the testing of the ERAM Program, the FAA's Simulation and Analysis Group has lead several studies on the surveillance data processing in the en route environment. In the report [1] published in early August 2005, an analysis was conducted comparing a large sample of differential Global Positioning Satellite (GPS) aircraft positions to time coincident HCS track reports. This analysis was also presented in October 2005 in [2]. The study reported a cross track error of 0.1 nautical miles (i.e. side-to-side lateral error) and a much larger along track error of 0.7 nautical miles (i.e. lengthwise or longitudinal error), indicating the major source of error is a lag, possibly due to the HCS tracks smoothing or more likely the time stamping of the messages themselves.

Shortly afterwards, in August 2005, a simulation was conducted in the FAA's Integration and Interoperability Laboratory. It utilized a four-hour field recording of air traffic data from Washington ARTCC collected in March 2005. The sample contained roughly 1500 aircraft flight segments and about 350,000 track report messages. The overall tracking accuracy was consistent with the previous GPS based study documented in [1,2], but included an analysis evaluating the accuracy of the HCS tracking during horizontal turns of the aircraft. From previous studies [3], the maneuver state of the aircraft had been shown to significantly influence the accuracy of the tracking algorithm. The HCS simulation in [4] developed a methodology of comparing the turn and straight portion of the flights and reported a modest impact of a turn on the tracking accuracy. However, it also reported inadequacies in the methods used to determine the turns and recommended improvements for future investigation.

This paper builds on these previous studies, applying the lessons learned from the HCS simulation study in [4], and has used the high quality GPS data from the earlier tracking study in [1]. The objective of this paper is to re-examine the impact of turns on the radar tracking accuracy of the HCS. The paper provides the tools, methodology, and baseline of performance of the legacy HCS tracker's accuracy partitioned for turns and straight portions of flight. This baseline will be used to evaluate the tracking performance of the future ERAM replacement system.

Analysis Methodology

In [4] the turn status of each track report was determined by comparing the course heading change between adjacent HCS track reports after modest smoothing was applied; details are provided in [5]. Next, turning and not turning track reports were compared by their horizontal, cross track, and along track errors. Measurements were taken in [4] that represents the deviation between the HCS track reported positions and the input simulated positions. However, in [6] a more accurate method was developed to determine the turn status of these position reports. This newer turn detection method will be utilized in this paper.

To improve sensitivity further, the ground truth GPS positions from [1] and [2] can be used to determine the turn state as opposed to the noisy HCS track reports. For this paper, the analysis was repeated using this improved data and a very effective statistical technique described in the next section.

Statistical Analysis

Inferential statistics are methods that go beyond summarizing a sample data set but attempt to draw conclusions about the population based on the sample information [8]. 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, and along tracking errors and the independent variables include the turn status (i.e. the track is within a turn or not). For most parametric inferential tests, it is assumed that the sample data approximates a Normal Distribution, and therefore it is important to test for normality when applying these tests.

In this study, the analysis is a comparison of two populations, the track reports in a turn and those flying straight. Thus, the null hypothesis assumes the difference between the mean of each of these populations is zero, meaning there is no expected difference between these two populations. If a difference was present, it could be considered the effect of turning. If the difference is zero, then the effect of turning is negligible.

The test statistic seeks to say with confidence that the null hypothesis is true or not true. The null hypothesis is illustrated in Equation 1 below. The typical Two-Sample *t* Test estimates the individual sample means and the difference between the means is calculated. An alternative Paired *t* Test approach suggested in [4] requires taking the individual differences of the turning and non-turning track reports for each flight studied.

In both the Two-Sample and Paired tests, the null hypothesis is essentially the same, namely that the differences between the two runs under study are zero. In the Two-Sample *t* Test, the individual sample means are estimated and their difference calculated, while in the Paired *t* Test, the individual differences are calculated and the mean of these differences is estimated.

$$H_o : \mu_1 - \mu_2 = \mu_D = 0 \qquad \textbf{Equation 1}$$

where μ_1 is the population mean of the treatment run one, μ_2 is the population mean of the treatment run two, and μ_D is the difference of the means

However, for the tests above, the test statistic and resulting sample size are very different. The test statistic for the Two-Sample *t* Test is presented in Equation 2. As shown, the denominator is a function of the individual treatment sample variances and their respective sample sizes.

$$\text{Test statistic}: \; t = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{s_1^2}{m} - \frac{s_2^2}{n}}} \qquad \textbf{Equation 2}$$

where $\bar{x}$ is the sample mean of the first treatment run and $\bar{y}$ is the sample mean of the second treatment run, s_1^2 is the sample variance of the first treatment run and m is the sample size of this run, and s_2^2 and n are the same for the second run.

The rejection region of the Two-Sample *t* Test is expressed in the following Equation 3.

$$\text{Reject null hypothesis}: \text{ if } t \geq t_{\alpha/2,\upsilon} \text{ or } t \leq -t_{\alpha/2,\upsilon} \qquad \textbf{Equation 3}$$

where $t_{\alpha/2,\upsilon}$ or $-t_{\alpha/2,\upsilon}$ are parameters taken from the Student-*t* distribution, α is the significance level of the test, and υ is the degrees of freedom for this test[1].

For the Paired *t* Test, the test statistic is illustrated in Equation 4.

$$t = \frac{\bar{d}}{s_D / \sqrt{n}} \qquad \textbf{Equation 4}$$

where the s_D is the sample standard deviation of the differences (i.e. the $D_i = x_i - y_i$ with *i* as the index for each flight), $\bar{d}$ is the average of the differences, and the n is the sample size of these differences.

The rejection region of the Paired *t* Test is expressed in the following Equation 5.

$$\text{Reject null hypothesis}: \text{ if } t \geq t_{\alpha/2,n-1} \text{ or } t \leq -t_{\alpha/2,n-1} \qquad \textbf{Equation 5}$$

These two test statistics defined in Equation 2 and Equation 4 differ in their denominators. For the Two-Sample *t* Test, the denominator is the difference of the individual run standard deviations divided by each run's sample size, while for the Paired *t* Test the denominator is the standard deviation of the individual differences within the runs divided by the sample size of differences. The relationship of these variances (square of the standard deviation) is illustrated in Equation 6 adapted from [8] and [9].

$$\mathrm{V}(\overline{\mathrm{X}} - \overline{\mathrm{Y}}) = \mathrm{V}(\overline{\mathrm{D}}) = \mathrm{V}\left(\frac{1}{v}\sum D_i\right) = \frac{\mathrm{V}(D_i)}{v} = \frac{\sigma_1^2 + \sigma_2^2 - 2\rho\sigma_1\sigma_2}{v} \qquad \textbf{Equation 6}$$

where $\mathrm{V}(\overline{\mathrm{X}} - \overline{\mathrm{Y}})$ is the variance of the difference of the average for each treatment $\overline{\mathrm{X}}$ and $\overline{\mathrm{Y}}$ respectively, $\mathrm{V}(\overline{\mathrm{D}})$ is the variance of the average difference $\overline{\mathrm{D}}$, v is the sample size of the treatments, σ_i^2 is the variance of the sample where *i* is the index of each sample, and ρ is the correlation coefficient for the two treatments

From Equation 6, the mean of the differences fore each treatment are equal, defined as $\overline{\mathrm{D}} = \overline{\mathrm{X}} - \overline{\mathrm{Y}}$. This variance is represented in the denominator of both statistical tests. However, the correlation coefficient, ρ, is assumed zero in the Two-Sample *t* Test, representing independence of the treatment runs. However, for the Paired *t* Test it is assumed at or close to one, representing a positive dependence between treatment runs. The other difference is the *v* sample size. For the Two-Sample *t* Test, the *v* is approximately equal to *m+n-2* (*m* and *n* are the sample sizes per treatment run, 1 and 2, respectively). The Paired *t* Test's *v* is equal to *k*-1, where *k* is the number of differences. The number of differences *k* is equal to the smaller *m* or *n* if they are not equal. Since *m* and *n* are equal in

[1] This degrees of freedom parameter is a function of the number of samples taken for the test and approximately equal to *m+n-2*. The actual formula is defined in Section 9.2 of [8].

this paper, the Paired test's k is about half the sample size of the Two-Sample test.

In summary, if the two populations being evaluated are highly correlated, Equation 6 shows that the precision of the Pair t Test improves significantly and would more than compensate for the loss in degrees of freedom as compared to the Two-Sample t Test. However, if the two sample populations are independent, the gain in degrees of freedom suggests using the Two-Sample t Test.

Tracker Error by Turn Status

From the statistical analysis above, to successfully block out the variability between flights and focus the analysis on the turn status, the tracker error needs to be correlated within a flight. In other words, if a flight had a large tracker error, both its track positions in turn and not in turn should be greater than a typical flight and vice versa. This was expressed in Equation 6, where a ρ value close to 1 indicates a strong correlation. To apply the Paired statistical test, the differences between these paired sample means within a flight are calculated. Furthermore, these differences need to be normally distributed.

In the subsections that follow, two data sets will be tested using the Paired test. For each data set, the average tracker error for horizontal, cross track, and along track are calculated for each flight's turn and non-turn events. Next, the difference between these sample means are calculated, which is consistent with the hypothesis test in Equation 1 and test statistic in Equation 4. The correlation and normality of these paired sample means are evaluated as well. Finally, the Paired t Test will either reject or affirm the hypothesis that the difference in tracker error for turning or straight portions of flight is statistically significant. If significant, the difference calculated provides an estimate of the magnitude of the effect of a turning maneuver on the tracker's accuracy.

Analysis of Data Set One

The first data set includes a subset of 118 flights from a sample 265 flight segments collected in January and February 2005 from all 20 ARTCCs. A flight segment is a portion of an aircraft flight, usually about 30 to 60 minutes in duration. For this data set, these flight segments were originally collected for use in the aircraft certification for the RVSM (Reduced Vertical Separation Minimum) Program. The subset was formed by including flights that had a minimum of 30 track reports in turns and not in turns. Using the FAA's Simulation and Analysis Group's latest methods, turn status is calculated using a combination of linear and quadratic models, described in detail in [6]. For the 118 flights, seven were determined to be outliers and omitted from this analysis because they exhibited a systematic error (e.g. recording error) not within the scope of this paper.

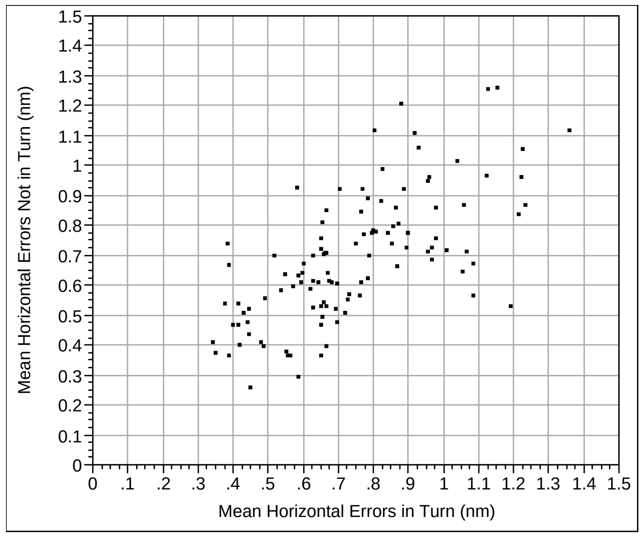

Figure 1: Paired Mean Horizontal Errors

For the remaining 111 flights segments, each flight's sample mean of horizontal track error for in turn and not in turn were plotted in Figure 1. The plot illustrates a positive-linear trend between the within flight turning and not turning errors. This is repeated for cross and along track errors with consistent results but not shown in the paper. The graphical result is verified by a linear correlation coefficient close to one, which is a statistic that quantifies the linear relationship between two variables. In Table 1, the correlation coefficient for the horizontal error is reported at 0.7 and the cross and along track errors are 0.6 and 0.7, respectively. Thus, the flight segments demonstrate a moderate positive-linear trend providing sufficient justification on using the Paired t Test.

Table 1: Data Set One Paired Statistical Test Results

		Horizontal Error (nm)		Cross Track Error (nm)		Along Track Error (nm)	
	Sample Size	**Mean Diff.**	**P-value**	**Mean Diff.**	**P-value**	**Mean Diff.**	**P-value**
Metrics	111	0.06	0.0004	0.03	0.0001	0.05	0.0018
Correlations		0.67		0.55		0.67	

The pairing of the error metrics produces an additional benefit by normally distributing the error differences. For the Paired statistical test, the test statistic requires the sampled differences to be normally distributed. As illustrated in Figure 2, the horizontal error differences model a Normal Distribution quite well. Figure 2 presents a Normal Quantile Plot. It visualizes the extent to which a variable is normally distributed. If a variable is normal, the data will approximate a diagonal straight line in the plot. This kind of plot is also called a Quantile-Quantile Plot, or Q-Q Plot.

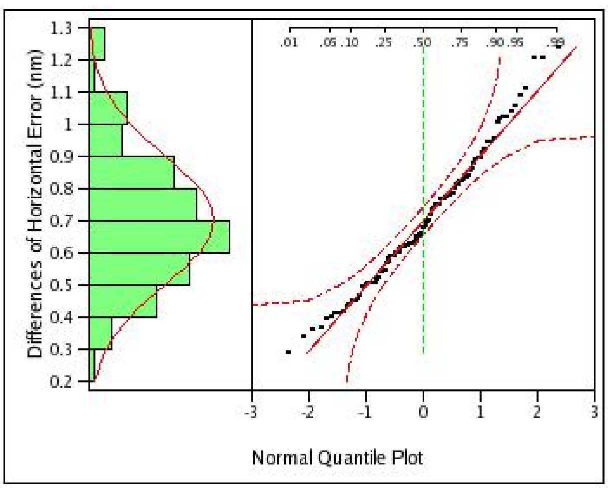

Figure 2: Horizontal Error Q-Q Plot

The Normal Quantile Plot also shows Lilliefors confidence bounds, reference lines, and a probability scale [11]. On the left of Figure 2 the histogram is overlaid with the Normal Distribution curve and the Q-Q Plot is to the right. The dark data points represent the mean sample differences and the closer they fall on the diagonal line the closer the data fits a Normal Distribution. The dotted curved lines represent the Lilliefors confidence bounds. If the data points fall within these bounds, it can be concluded that the data is normally distributed.

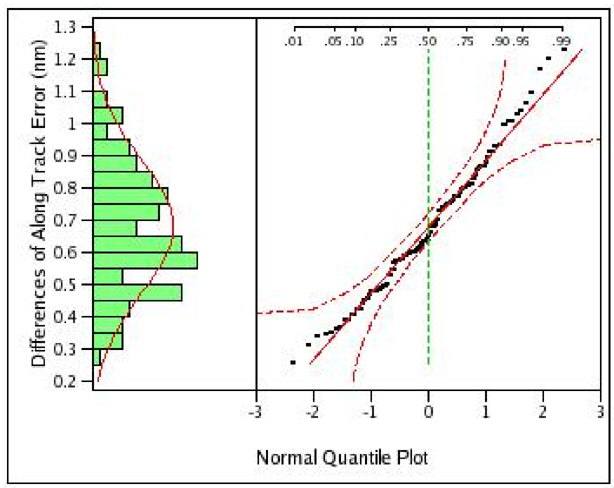

Figure 3: Along-Track Error Q-Q Plot

As indicated earlier, Figure 2 provides evidence that the horizontal error differences do follow a Normal Distribution. The same can be concluded for the along track error differences, as illustrated in Figure 3. For the cross track error differences in Figure 4, the errors are slightly skewed with a larger than expected upper tail. However, for purposes of this study, it can be assumed approximately normal.

In summary, the results presented Table 1 provide the average difference of the means for turning versus straight tracker error for horizontal, cross track, and along track, respectively. It represents the overall effect of turning on the tracker accuracy. Table 1 also reports the Paired statistical test results. From [12], the p-value in the table indicates the "probability that you would obtain the present results if the null hypothesis were true." As a result, a small p-value (say less than 0.05) allows you to safely reject the null hypothesis. For all three metrics, it indicates that the difference is statistically significant. However, the differences are fairly small (e.g. 0.06 nm ~ 400 feet), indicating the calculated effect of turning is minimal yet larger for the along track error versus cross track.

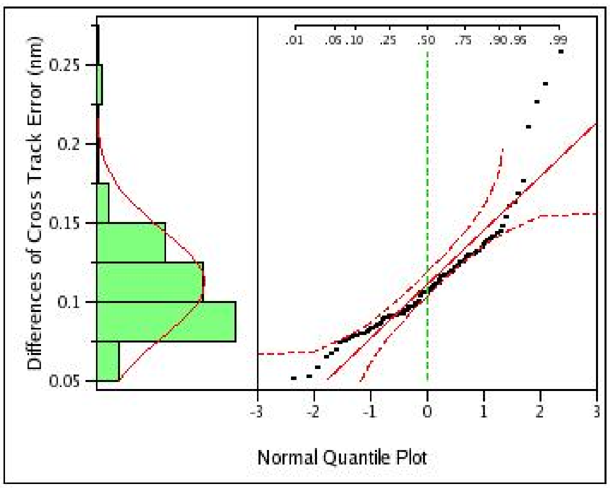

Figure 4: Cross Track Error Q-Q Plot

Analysis of Data Set Two

The second data set includes 27 flights selected from the Kansas City ARTCC, which is a subset of Data Set One's 111 flights. However, the main difference between the two data sets is the calculation of turn status. Each turning point, for all 27 flight segments, was verified manually against the very precise differential GPS positions. This analysis verifies if the precision of the turn status calculation affects the Paired *t* Test's statistical results.

For Data Set Two, the effect of turning on horizontal error is 0.07 nm, with correlation of 0.65, which is 0.01 nm greater than reported for Data Set One. The cross track error difference is 0.02 nm and along track error had an overall difference of 0.07. The correlations and p-values of the Paired statistical tests are consistent with what was reported in Data Set One. Overall, Data Set Two's precision calculation of turn status revealed only minor deviations from the previous results and serves as further verification of the conclusions from Data Set One's analysis.

Tracker Error by Turn Characteristics

It has just been shown that the HCS tracker accuracy is slightly degraded when the aircraft is turning. All turns are not equivalent however. The focus of this section is to explore whether the accuracy of the tracker depends on the nature of the turn. To answer this question three turn characteristics were chosen for examination that attempt to capture the basic nature of a turn. The characteristics selected were (1) average ground speed, (2) time duration, and (3) maximum heading difference. They are defined as:

- *Average ground speed*: the average of all ground speed measurements during the turn at 10-second intervals (knots or nautical miles per hour).
- *Time duration*: the difference between the end time and the start time of the turn (seconds).
- *Maximum heading difference*: the maximum of all differences between the heading at the start of the turn and every position point until the end of the turn at 10-second intervals (degrees).

The maximum heading difference is determined by checking all of the position points during a turn. This metric reports the maximum heading during the turn rather than the final net difference of the turn. For example the maximum heading difference for a 360 degree circle is 180 degrees whereas the net heading difference is zero.

Data Set for Turn Characteristics

This analysis used the 27 flights with the precisely defined turns from Data Set Two. The first step was to remove turns with durations that are less than 20 seconds. Next, any turns separated by 30 seconds or less were merged. Thus, extremely close pairs of discrete turns were analyzed as if they were a single, continuous turn. For 9 of the original 57 flights, the turn culling and merging eliminated all turn data. The flights with no turn data remaining were dropped, trimming the data set to 48 flights. Next, the flights with less than 30 tracker measurements in turn or less than 30 tracker measurements not in turn were culled. From [8], 30 samples are a suitable minimum for the Central Limit Theorem to apply. The final data set consisted of 27 flights providing 91 turn events.

Error Measurements and Correlations

Error measurements were calculated for each turn. The average horizontal error, the average cross track error, and the average along track error were calculated for each turn. The root mean squared error (RMS) was used for each metric. Using the RMS eliminates the canceling out of the positive values by the negative values and more heavily weights the larger errors.

To see if the three turn characteristics described above affected the tracking accuracy, the linear correlation coefficients between the errors and the characteristics were calculated. The results are given in Table 2.

Table 2: Correlations of Turn Characteristics

Correlation Coefficient	RMS Horizontal Error (nm)	RMS Cross Track Error (nm)	RMS Along Track Error (nm)
Average Ground Speed	0.310	0.092	0.307
Time Duration	0.212	0.392	0.225
Maximum Heading Difference	0.185	0.405	0.200

The correlations are all positive but are small, providing little evidence that the tracker accuracy is influenced by these selected turn characteristics. It may be that other turn characteristics not studied are more strongly correlated to tracking accuracy. Perhaps the noise in the tracking data masks the true correlations between the factors selected and the tracking accuracy.

Linear Regression

Linear regression was also applied to examine the effects of the turn characteristics on the tracking accuracy. All combinations of error measurements versus turn characteristics were calculated. The most significant result (best fit) is represented in Figure 5. Although the plot of maximum heading difference versus RMS of cross track error represents the best model available among all of the data, it cannot be trusted as an accurate predictor. Due to high randomness in the distribution, excessive residual errors prevent any accurate prediction of RMS cross track error within a reasonable range.

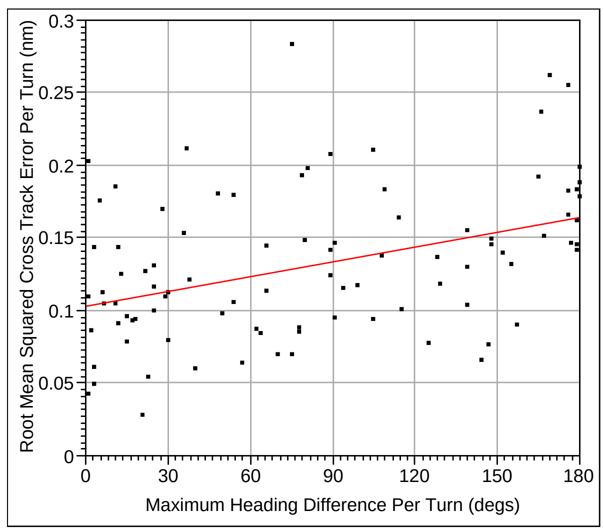

Figure 5: Maximum Heading Difference vs Root Mean Squared Cross Track Error

For future analysis, more turn characteristics can be examined, since by no means has all the number and variety of turn characteristics been exhausted for this study.

Sample Flight Analysis

In this section, a sample flight from Data Set 2 is illustrated graphically, and its tracker error measurements are described in detail. The aircraft for this selected flight sample is a Falcon 10 business jet, traveling at about 26,000 to 30,000 feet at ground speeds ranging from 220 to 470 knots. The flight had started in St. Louis Missouri's Spirit of St. Louis Airport and returned to the same location. As indicated earlier, the flight was used for domestic RVSM certification. For this particular flight, the aircraft probably had no passengers. The measurements for the sample are taken from before, during, and after a selected turn.

The plots were generated using a graphical tool called Trajectory Graphical User Interface (TrajectoryGUI), documented in [13]. TrajectoryGUI is designed to aid an analyst in studying an aircraft's radar track data versus its predicted trajectory, but can be applied to any plot of an aircraft's path. The trajectory data was replaced by the GPS position reports. The plots of data from before, during, and after the turn appear in Figure 6, Figure 7, and Figure 8 respectively. This sample flight supports the previously described results which reported slightly larger horizontal, cross track, and along track errors during a turn.

The track data for the sample flight begins at time 71036 seconds (19:43:56 UTC), ends at time 72830 (20:13:50 UTC), lasting 29 minutes 54 seconds. The flight includes 3 turns. The first turn occurs at 71480 seconds, ends at time 71670 seconds, lasting 3 minutes 10 seconds. The second turn occurs 6 minutes 40 seconds later; starting at time 72070, ending at time 72300, and lasting 3 minutes 50 seconds. A short time after the second turn ends; the aircraft begins its third and final turn. This last turn starts at 72540 seconds, ends at time 72780 seconds, lasting 5 minutes 40 seconds.

In Figure 6, a plot of the radar track versus the GPS ground truth data is shown. The radar track is the darker plot (or red in color) and the lighter gray (or green in color) is the GPS ground truth plot. The plots are located within a stereographic scaled coordinate system in units of nautical miles. All three figures depict 15 by 15 nautical miles (nm) of airspace. The plots have time-tagged points in seconds, which allow for the visualization of the radar track versus GPS ground truth measurement.

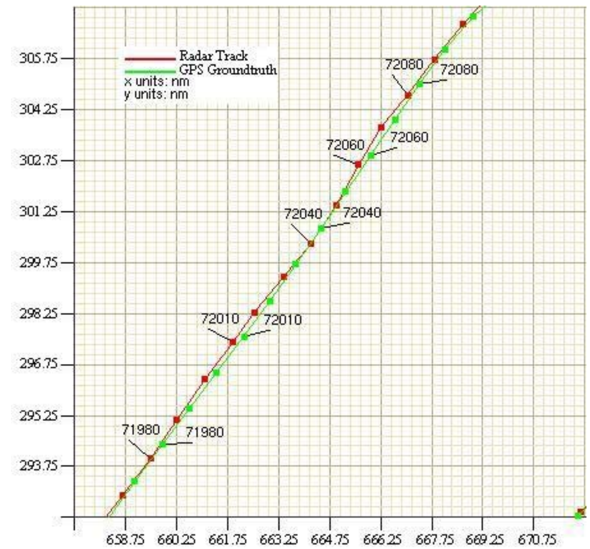

Figure 6: Radar track vs GPS Ground Truth Before Turn

The plot in Figure 6 captures 100 seconds of data prior to the aircraft beginning its second turn. The aircraft transitions from traveling straight to turning at time 72070 seconds. The mean horizontal error for this aircraft while traveling straight and turning is 0.71 nm and 1.08 nm, respectively. In this example, the aircraft is traveling straight leading up to its turn, with a mean horizontal error of 0.47 nm, which is comparable to the overall mean. The horizontal error is simply the distance between two time coincident (time tagged) points. When referring to the plots in Figure 6, one can notice the horizontal errors are in the range of the overall mean of 0.47 nm, with horizontal error at time 72010 being 0.34 nm, at time 72040 being 0.52 nm, and at time 72070 being 0.45 nm. Consistent with the previous results, cross track errors displayed in the plots demonstrate very little error. The along track errors remain approximately constant, with a maximum value of -0.54 nm.

Figure 7 illustrates the aircraft's second turn. The turn occurred after flying in a straight pattern for a total of 6 minutes 40 seconds. In the beginning of the turn, at times 72080 and 72110 seconds, the measurement errors of the radar track versus the GPS ground truth do not resemble the deviations expected when an aircraft is turning.

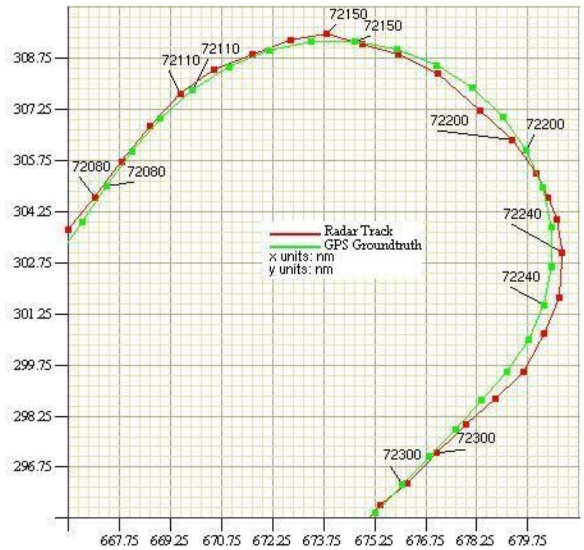

Figure 7: Radar Track vs GPS Ground Truth During Turn

For example, the horizontal error at time 72110 is 0.36 nm is significantly better than the mean horizontal error usually found during turns. At time 72150, where approximately 35% of this turn is completed, this contradiction ends and the errors start to increase as expected within a turn. At the stated 35% point, the horizontal error is 0.82 nm. The horizontal error achieves its maximum measurement of 1.55 nm at time 72240 seconds. Furthermore, the cross track error at 72240 seconds is similar to this flight's mean cross track error found when not in turn. On the other hand, along track error for this turn becomes visibly worse, demonstrating an approximately 100% increase.

The data during the 2-minute 50-second time period after the previous turn is presented in Figure 8. This figure illustrates how the measurement errors of an aircraft, coming out of a turn, do not instantaneously return to the smaller error found in straight paths. For example, at the end of this turn, the horizontal error is 1.38 nm. At the time 72330 seconds, which is 30 seconds after this turn, the horizontal error decreases to 1.06 nm. In addition, at the time 72370 seconds, the horizontal becomes even worse, measuring 1.24 nm. Although the horizontal error at these two times does not represent the mean horizontal error for this flight not in turn (0.67 nm), the error eventually returns to this value. The horizontal error returns to results that resemble what overall study demonstrated at time of 72430 seconds, which was 2 minutes 10 seconds after the completion of this turn. Based on this example flight and supported by the earlier statistics, it can be concluded that the straight path immediately after a turn are not representative of a typical straight path. Therefore, the fidelity of the error measurements to their respective means depends on the time after the turn.

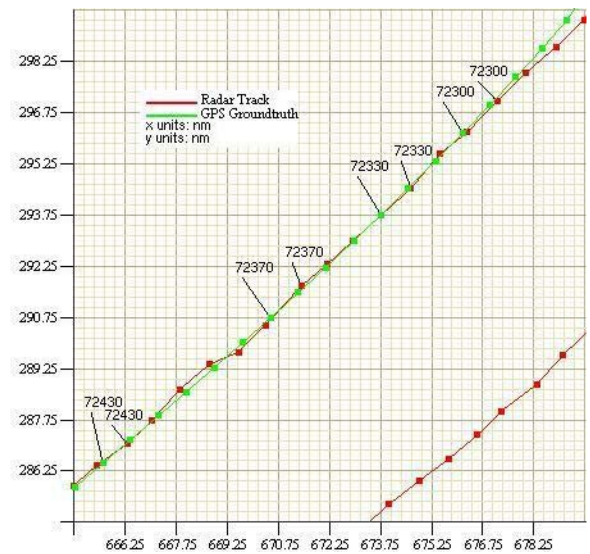

Figure 8: Radar Track vs GPS Ground Truth After Turn

Conclusion

Two data sets of HCS track reports, one of 111 flight segments and another of 27 flight segments, were evaluated against GPS position reports to identify the impact of turns on the HCS radar tracker. The data set contained flights from all 20 ARTCCs in the continental United States collected in January and February 2005. To block out the variability between flights, the average tracker error was calculated in turn and not in turn for each flight and applied to a Paired *t* Statistical Test. Due to the high correlation of tracking error within a flight and heterogeneity between flights, this Paired statistical test detected very small effects. The average impact of turn status on horizontal error, cross track error, and along track error was 0.06, 0.03, and 0.05 nm, respectively, when a flight was in turn. The Paired *t* test found all three errors to be statistically significant. The smaller data set of 27 flights had precisely defined turn events that were manually verified using GPS data. It produced a slightly larger effect. The effect was then further confirmed in the illustration of a detailed flight sample. The flight's HCS track positions were plotted before, during, and after a turn against its time coincident GPS position reports.

Several characteristics of the turns themselves were identified and evaluated. This included 91 turns extracted from Data Set Two. These turns were then analyzed to determine whether the individual characteristics of a turn play an explanatory or predictive role in relation to the tracker error measurements of each turn. The three factors explored included average ground speed, time duration, and maximum heading difference. For all three factors, the influence on the tracker error in turns was minimal.

This study found turns did have an effect on the HCS's tracker accuracy, albeit a small impact. Most importantly, the results and methods developed will be used to evaluate the tracking performance of the future ERAM replacement system. In future studies, a more thorough analysis of turn status could investigate the relationship between time after a turn status transition (straight to turn, or vice versa) and the HCS radar tracker error. The analysis could shed light on some time value before the true impact of the turn status is represented.

Reference

[1] Ryan, H. F. and M. M. Paglione, "Comparison of Host Radar Tracks to Aircraft Positions from the Global Positioning Satellite System", FAA Technical Note, DOT/FAA/CT-TN05/30, August 2005.

[2] Paglione, M. M. and H. F. Ryan, "Comparison of Host Radar Positions to Global Positioning Satellite Positions", Digital Avionics Systems Conference (DASC), Washington D.C., November 1-3, 2005.

[3] Trios Associates, Inc., November 2003, "Host Tracker Performance Assessment," FAA, Report, Washington, D.C.

[4] Paglione, M. M., W. C. Baldwin, and S. Putney, **"**Host Radar Tracking Simulation and Performance Analysis", FAA Technical Note, DOT/FAA/CT-TN05/31, August 2005.

[5] Paglione, M. M., H. F. Ryan, R. D. Oaks, J. S. Summerill, and M. L. Cale, "Trajectory Prediction Accuracy Report: User Request Evaluation Tool (URET)/Center-TRACON Automation System (CTAS)", FAA Technical Note, DOT/FAA/CT-TN99/10, May 1999.

[6] Paglione, M. M. and R. D. Oaks, "Determination of Horizontal and Vertical Phase of Flight in Recorded Air Traffic Data", American Institute of Aeronautics and Astronautics (AIAA) Guidance, Navigation, and Control Conference (GNC), Keystone, CO, August 2006.

[7] Paglione, M. M. and L. Charles, "Applying Pairwise Hypothesis Testing in Trajectory Accuracy Analysis, 48th Air Traffic Control Association (ATCA) Annual Conference Proceedings, October 2003.

[8] Devore, Jay L., *Probability and Statistics for Engineering and the Sciences*, Fifth Edition, Pacific Grove, CA, Duxbury, 2000.

[9] Montgomery, Douglas C., *Design and Analysis of Experiments*, Wiley 1997

[10] Cale, Mary Lee, Shurong Liu, Robert D. Oaks, Mike Paglione, Hollis F. Ryan, Scott Summerill, A Generic Sampling Technique For Measuring Aircraft Trajectory Prediction Accuracy, 4th USA/EUROPE Air Traffic Management R&D Seminar, December 3-7 2001.

[11] SAS Institute Inc., *JMP Statistics and Graphics Guide, Release 6,* SAS Institute Inc., August 2005.

[12] Lehman, A., N. O'Rourke, L. Hatcher, E. J. Stepanski, J*MP for Basic Univariate and Multivariate Statistics, A Step-by-Step Guide*, SAS Institute, Inc. February 2005.

[13] Santiago, C., R. D. Oaks, M. M. Paglione, A. Rusu, S. Putney, and S. Liu, "Using Graphical Software for Evaluating Aircraft Trajectory Predictions", 50th Air Traffic Control Association (ATCA) Annual Conference Proceedings, November 2005.