

TIME SHIFTING BEACON RADAR REPORTS IN RECORDED AIR TRAFFIC DATA

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Abstract

The Federal Aviation Administration's National Airspace System is a network of air navigation facilities, air traffic control facilities, and airports, along with the technologies and the rules and regulations to operate the system. One of these technologies is a conflict probe, which is used by air traffic controllers to predict aircraft-to-aircraft and aircraft-to-airspace conflicts. To be effective the conflict probe must predict potential conflicts accurately. Although functional testing can be performed to evaluate a conflict probe, it is essential that the probe also be tested using scenarios that preserve the real-world errors that affect the probe's accuracy. This requires that test scenarios be developed that are based on recorded air traffic data. However, recorded air traffic data generally does not contain actual conflicts. This requires that the flights be shifted in time so that aircraft-to-aircraft conflicts are created in the test scenarios. This paper describes a technique in which recorded beacon radar reports can be time shifted in order to create aircraft-to-aircraft conflicts for conflict probe testing.

Introduction

The Federal Aviation Administration (FAA) created the National Airspace System (NAS) to provide a safe and efficient airspace environment for civil, commercial, and military aviation. The NAS is composed of a network of air navigation facilities, air traffic control facilities, and airports, along with the technologies and the rules and regulations to operate the system. One of the technologies incorporated within the NAS is a conflict probe, which is an air traffic management decision support tool used by air traffic controllers to predict aircraft-to-aircraft and aircraft-to-airspace conflicts -- where a conflict is defined as a violation

of minimum legal separation standards as established by the NAS rules and regulations. To be effective the conflict probe must have the confidence of the air traffic controllers who use it, and therefore must predict potential conflicts accurately.

In 1996, the FAA established the Conflict Probe Assessment Team (CPAT) to evaluate the accuracy of conflict probes. Since that time, CPAT has measured the conflict prediction accuracy of the User Request Evaluation Tool (URET) [1], measured the trajectory modeling accuracy of both URET and the Center TRACON Automation System (CTAS) [2], and assisted in the accuracy testing of URET Current Capability Limited Deployment (CCLD) [3, 4], which was the operational implementation of URET. CPAT also developed the risk reduction test scenarios used during the deployment of URET CCLD into all of the Air Route Traffic Control Centers (ARTCCs). During these efforts, CPAT collaborated with other researchers to develop methodologies for generating test scenarios based on recorded air traffic data in order to preserve the real-world errors that affect a conflict probe's accuracy.

To generate the test scenarios used in these methodologies, CPAT time shifts recorded air traffic data to create aircraft-to-aircraft conflicts. This is necessary because the recorded air traffic data generally does not contain actual conflicts since the air traffic controllers, in the performance of their jobs, take actions to separate the aircraft.

In these test scenarios a series of 4-dimensional trajectory points model the flight path of each aircraft. The four dimensions consist of time as one dimension and the aircraft's position as the other three dimensions. The three positional components can be the aircraft's x-, y-, and z-coordinates in a Cartesian coordinate system or its latitude, longitude, and altitude in a spherical

coordinate system. For the test scenarios, each flight's trajectory point is time shifted by altering the time component by a flight-specific constant value, while retaining the values of each of the three positional components. This retains the time-sequenced positions associated with the aircraft's flight path, but causes the arrival at each position to occur at a different time in the scenario. Independently time shifting the trajectories of the individual flights within a scenario creates a test scenario containing aircraft-to-aircraft conflicts with characteristics (such as the angle between the flight paths of the two aircraft and the distance between the two aircraft at their closest approach) similar to those encountered in actual air traffic operations [5].

In their previous work, CPAT has used recorded track data from the En Route Host Computer System (HCS) tracker for scenario generation and were able to time shift the recorded air traffic data by simply adding or subtracting the desired amount of time shift to each of the track points. However, more recently, CPAT has been involved with providing the scenarios for testing the accuracy of the Surveillance Data Processing (SDP) and Flight Data Processing (FDP) functions in the En Route Automation Modernization (ERAM) system, which is replacing the HCS for en route air traffic control. For ERAM testing the FAA is using the ATCoach®¹ En Route Edition Simulation product as the primary simulation package for subsystem, system, and operational testing of ERAM in both the operational and non-operational environment [6]. For CPAT's support of ERAM's accuracy testing, CPAT provides two ASCII-formatted scenario files: the ATCCoach® Scenario File and the ATCoach® Radar Injection File².

ATCoach® Scenario File

In this test environment, this file is primarily used to define time-sequenced air traffic controller input commands.

ATCoach® Radar Injection File

This file contains time-sequenced beacon radar reports defined in a hexadecimal format. For the ERAM testing the generation of the Radar Injection File requires time shifting the recorded radar surveillance data, which is much more complex than time shifting track data. This paper will show why merely adding the desired amount of time shift to the times associated with each beacon radar report does not work because this puts the beacon radar reports at times that are not coincident with the radar site's scan. This paper will then present the beacon radar report time shifting algorithm developed by CPAT that time shifts the recorded beacon radar reports using an interpolation scheme that approximates the positional components for an aircraft when it would be illuminated by the radar. This paper will also identify problems that CPAT encountered when this beacon radar report time shifting algorithm was implemented using recorded field data and discuss how these problems were resolved.

Radar Reports

The en route air traffic control facilities within the NAS use a surveillance radar technology known as the Air Traffic Control Radar Beacon System (ATCRBS). This system detects and measures the position of aircraft using reflected radio signals emitted during a radar antenna's scan, which is nominally once every 12 seconds. When an aircraft is illuminated each scan, the system also requests additional information, such as an aircraft's flight identity and altitude, from the aircraft itself. Unlike primary radar systems, which measure only the range and azimuth of aircraft with respect to the radar antenna, ATCRBS relies on the aircraft being equipped with a radar transponder, which replies to each radar interrogation signal by transmitting encoded data back to the radar.

An ATCRBS radar site provides a total of eleven message types to an en route air traffic control facility; these are: primary search messages, beacon messages, beacon strobe messages, primary search strobe messages, status messages, fixed primary search messages, beacon test messages,

¹ ATCoach® is a registered trademark of UFA Inc., 18 Commerce Way, Suite 4000, Woburn, MA 01801.

² Reference 7 documents the format for each of these files.

primary test messages, and three types of weather map messages³.

The ATCoach® Radar Injection Files generated by CPAT for ERAM accuracy testing contain ASCII messages that map to a subset of these messages. These messages include beacon messages, reinforced messages, and search real time quality control messages.

Beacon Messages

The Beacon messages identify the aircraft by its Mode 3/A transponder code and provide position information for the aircraft. The Mode 3/A transponder code is 4-digit octal identification code assigned by the air traffic controller. The aircraft's position is provided by the aircraft's range and azimuth from the radar and the aircraft's altitude. The range from the radar is measured in nautical miles with a granularity of 0.125 nautical mile. The aircraft's azimuth from the radar is measured clockwise from north with a granularity of 1 Azimuth Change Pulse (ACP), where $4096 \text{ ACPs} = 360^\circ$. The aircraft's altitude is provided from the Mode C transponder code, which is a 10-bit binary code that represents the pressure altitude of the aircraft in 100-foot increments and corrected for by an altimeter setting provided by the air traffic control facility.

Reinforced Messages

The Reinforced messages are Beacon messages that have a bit set indicating that a primary radar return reinforced the beacon radar report.

Search Real Time Quality Control (SRTQC) Messages

The SRTQC messages are special primary search messages that have an azimuth of about 0 ACPs (0°).

Mathematical Representation of Beacon Reports

This paper represents a beacon radar report for an aircraft by the vector function $\bar{P}(t)$ denoted as

$$\bar{P}(t) = \begin{pmatrix} \rho(t) \\ \theta(t) \\ a(t) \end{pmatrix}$$

where $\rho(t)$ represents the range from the radar site, $\theta(t)$ represents the azimuth from the radar site, $a(t)$ represents the aircraft's altitude, and t represents time.

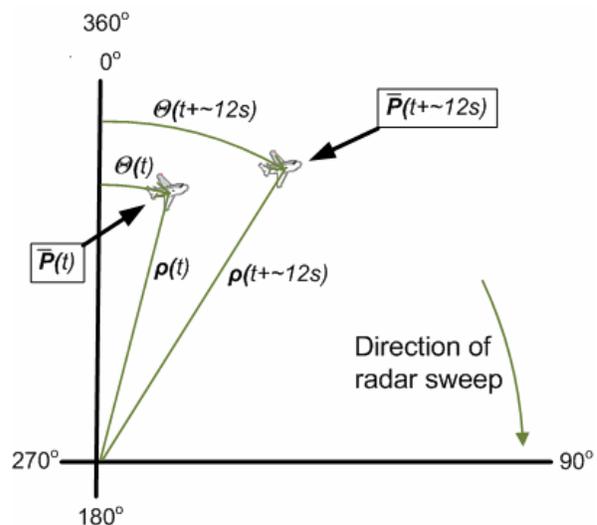


Figure 1. Aircraft Radar Targets In The Range-Azimuth Domain

As an example, Figure 1 shows an aircraft flying in an easterly direction. This figure shows the aircraft's positional information in a range-azimuth domain with respect to a radar site. At time t , the radar would generate a beacon radar report containing a range $\rho(t)$, an azimuth $\theta(t)$, and an altitude $a(t)$, which is not shown in the range-azimuth domain.

³ Reference 8 documents the format for each of these messages.

On the next radar scan the radar would generate another beacon radar report at approximately time $t + \sim 12s$ denoted as

$$\bar{P}(t + \sim 12s) = \begin{pmatrix} \rho(t + \sim 12s) \\ \theta(t + \sim 12s) \\ a(t + \sim 12s) \end{pmatrix}$$

Figure 2 depicts the same situation, but in the time-azimuth domain. The dots at the coordinates labeled $(t, \theta(t))$ and $(t + \sim 12s, \theta(t + \sim 12s))$ represent the two positions shown in Figure 1. The straight lines in this figure represent the radar's beam rotating repeatedly from 0° to 360° , such that the radar site will generate a beacon radar report only if the aircraft position is coincident with one of these lines.

The SRTQC messages mentioned in the previous section provide the timing of the radar scans. In Figure 2 the SRTQC messages occur at the line ends on the time axis; where the azimuth is equal to 0° ACPs. Figure 3 shows the more realistic situation in which the SRTQC message occurs at some time when the azimuth is not equal to 0° ACPs.

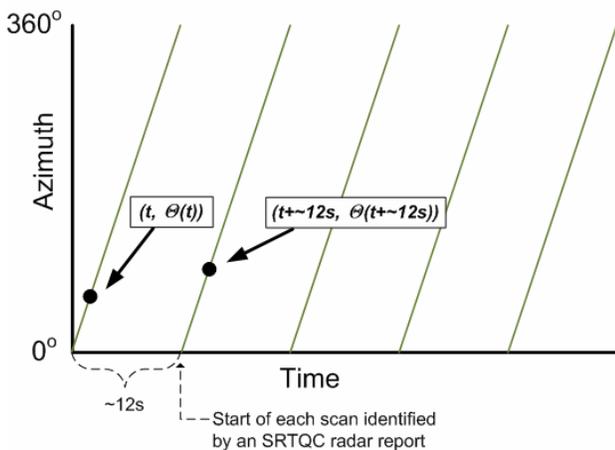


Figure 2. Aircraft Radar Targets in the Time-Azimuth Domain with SRTQC at 0 ACPs

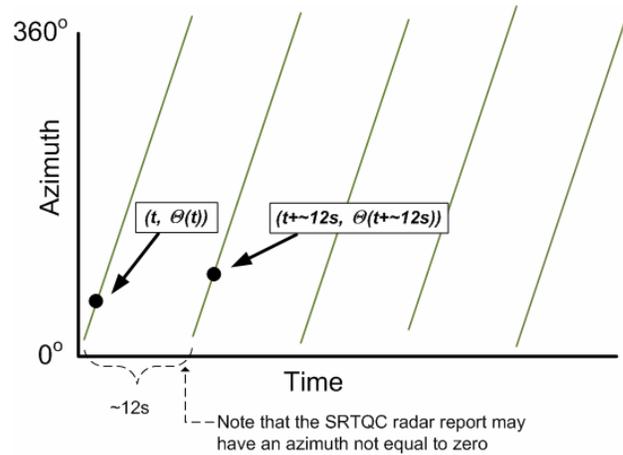


Figure 3. Aircraft Radar Targets in the Time-Azimuth Domain with SRTQC not at 0 ACPs

Time Shifting Beacon Radar Reports

Figure 4 shows that simply adding the desired delta time to the times associated with each beacon radar report does not work because this puts each of the beacon radar reports at times that are not coincident with the radar scan. Remember, when we time shift the flight, we want the flight to fly the same path, but at a different time. Therefore, with respect to the radar, the flight would have these same positions relative to the radar, but at a different time. This is evident in this figure since the value of the azimuths at the time shifted points are unchanged.

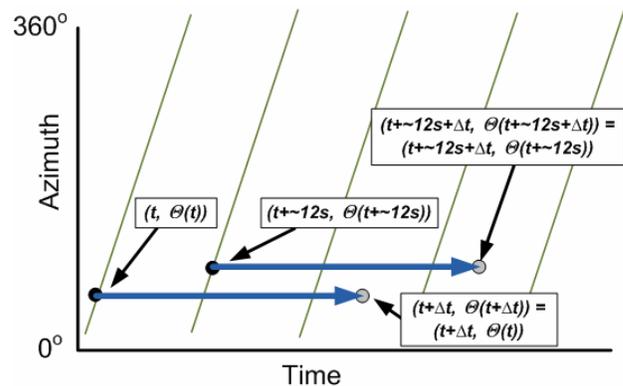


Figure 4. Time Shifting Beacon Radar Reports Individually

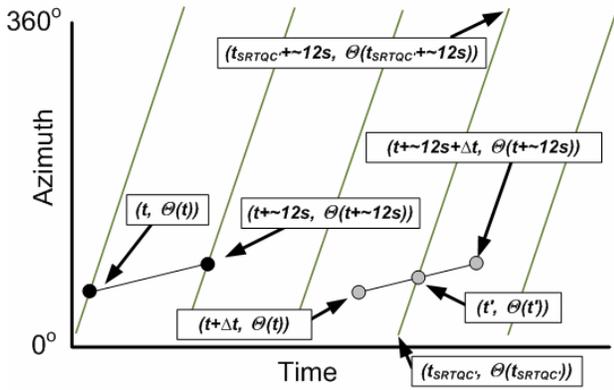


Figure 5. Time Shifting Beacon Radar Reports as Pairs

Figure 5 shows that the desired time shift can be approximated by noting that the time shift is equivalent to shifting the line defined by the coordinate endpoints $(t, \theta(t))$ and $(t + \sim 12s, \theta(t + \sim 12s))$ to the line defined by the coordinate endpoints $(t + \Delta t, \theta(t))$ and $(t + \sim 12s + \Delta t, \theta(t + \sim 12s))$ (note that $\theta(t + \Delta t) = \theta(t)$ and $\theta(t + \sim 12s + \Delta t) = \theta(t + \sim 12s)$ because only the time dimension is shifted), then solving for the time and azimuth when the radar would illuminate the aircraft. This point is denoted in Figure 5 by the coordinate $(t', \theta(t'))$. Then the time shifted range and time shifted altitude can be approximated by linear interpolation, using the time t . Note, as a result of this interpolation, that the beacon radar report time shifting algorithm has created a single interpolated beacon radar report from the original two recorded beacon radar reports.

Implementation

CPAT implemented this beacon radar report time shifting algorithm in a Java application program. The algorithm was implemented independently for each aircraft in the recorded scenario. Figure 6 shows an example consisting of five position points in the time-azimuth domain. As implemented, the beacon radar report time shifting algorithm first time shifts the line between the first and second points. Then the beacon radar report time shifting algorithm time shifts the line between

the second and third points. This process continues through all of the paired position points.

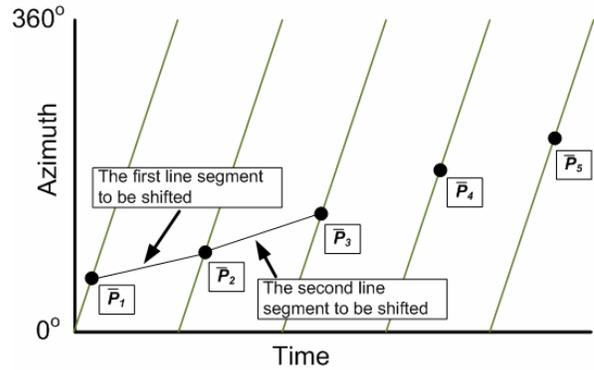


Figure 6. Example Showing Line Segments

Test scenarios generated by this Java application were successfully used for testing the accuracy of ERAM's SDP and FDP functions. As with any mathematical algorithm, complications arise when it is implemented using real world data. Some of the complications CPAT encountered during the implementation of this beacon radar report time shifting algorithm include: data granularity, the existence of zero Mode C altitude values, the existence of invalid Mode C altitude values, missing beacon radar reports, being unable to find an intersecting radar scan line, and finding multiple aircraft using the same beacon code. These are discussed in the following subsections.

Data granularity

The beacon radar report time shifting algorithm creates beacon radar reports approximating the beacon radar reports generated by radars if a flight had flown at a different time. As such, the results of the beacon radar report time shifting algorithm are floating point numbers, whereas the range and azimuth with beacon radar reports are binary numbers with a specific granularity. Specifically, as stated previously, the range has a granularity of 0.125 nautical miles and the azimuth has a granularity of 1 ACP, which is exactly equal to 0.000244140625° . CPAT implemented the beacon radar report time shifting algorithm so that it truncates these range and

azimuth values to their specified granularity to emulate real world radar functionality.

Zero Mode C Altitude

Occasionally in the recorded air traffic data the Mode C altitude in a beacon radar report is zero. CPAT resolved this problem through the following process: If the altitudes in both of the beacon radar reports used for interpolation are valid, then an interpolated altitude is calculated. If either of the altitudes in these beacon radar reports is zero, then the altitude in the first beacon radar report is always used. This is done to retain "zero altitude" beacon radar reports in the scenario data.

Invalid Mode C Altitude

In addition to zero Mode C altitude data, occasionally in the recorded air traffic data the Mode C altitude in a beacon radar report is obviously invalid. This is usually apparent because it varies drastically from data in preceding and succeeding beacon radar reports. Since the validity of the altitude within a beacon radar report is not as easily detected, CPAT resolved this problem by estimating the ascent /descent rate of the aircraft based on the altitudes in the two beacon radar reports. If the ascent/descent rates are below and parametric value, then an interpolated altitude is calculated. If the ascent/descent rate exceeds the parametric value, then the altitude in the first beacon radar report is always used. This is done to retain the invalid beacon radar reports in the scenario data.

Missing reports

Occasionally during a single rotational scan of a radar site a beacon radar report for an aircraft is missing. Figure 7 shows a graphical example of this phenomenon. If this happens, the beacon radar report time shifting algorithm generates a beacon radar report for the "first" scan, but not for the subsequent scans.

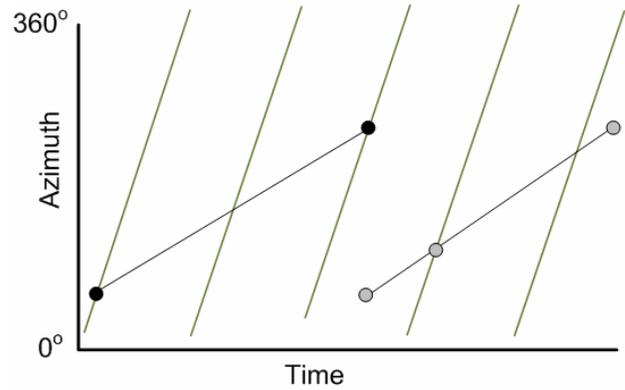


Figure 7. Missing Reports

Non-intersection

In the recorded air traffic data the scan rate for a radar site varies from scan to scan. Therefore, it is possible that the time shifted line segment does not intersect a scan line. Figures 8 and 9 depict examples of how this may occur. If this happens, a beacon radar report will be lost by the beacon radar report time shifting algorithm.

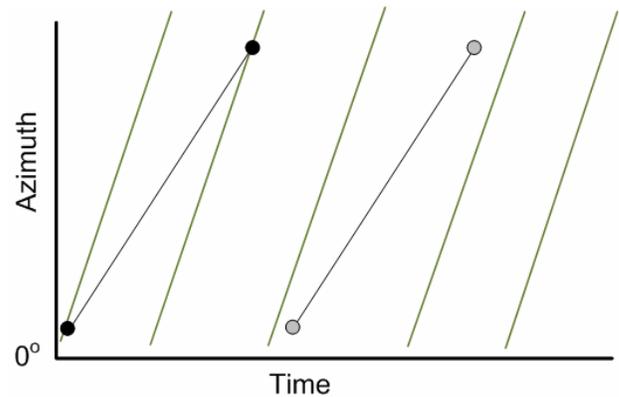


Figure 8. Non-intersecting Example 1

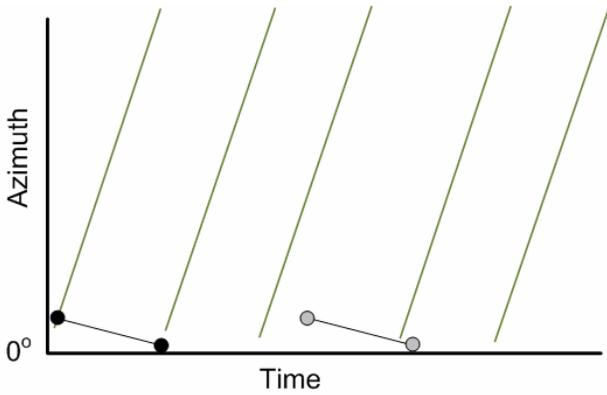


Figure 9. Non-intersecting Example 2

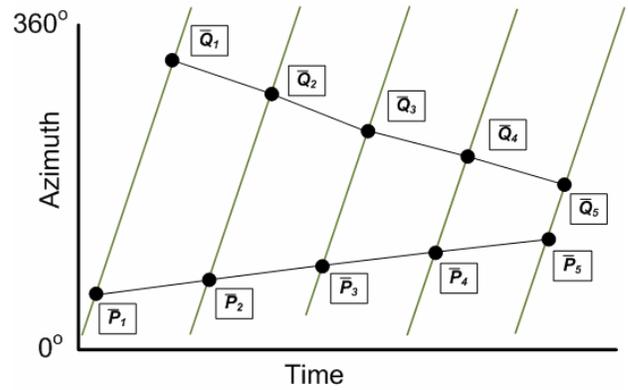


Figure 11. Graphical Depiction of the Resolution of Multiple Aircraft

Multiple aircraft

In the recorded air traffic data it is possible that a radar site sees multiple aircraft with the same beacon code during a scan. Figure 10 shows how this would appear to the beacon radar report time shifting algorithm. To resolve this problem the beacon radar report time shifting algorithm groups beacon radar reports into red-black binary tree data structures containing beacon radar reports that appear to be from the same aircraft. Figure 11 graphically shows how this technique resolves this problem.

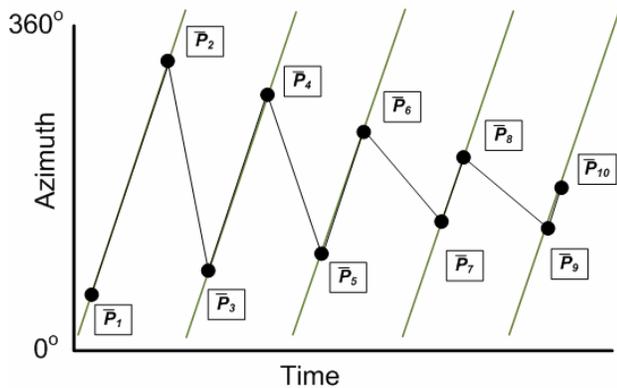


Figure 10. Multiple Aircraft Problem

Validation

The previous sections provide a complete description of the time shifting algorithm, including a description of some of the challenges, however the technique was not validated. Validation is the process of establishing evidence that a system, service, or an algorithm, as in this paper, accomplishes its intended objective. The objective of the radar data time shifting algorithm is to shift the radar positional data for each aircraft in time without altering the original radar data in any other way. This means not adding errors or filtering out the existing errors.

For testing en route operational systems, the radar data is input for the operational tracking software in the HCS or future replacement in ERAM. Since the overall testing goals are evaluation of the later sub-systems in the HCS or ERAM, the resulting track reports can be compared, time shifted versus non-time shifted. The radar time shifted data is supplied only to the ERAM system. Thus, if the HCS and ERAM track positions for the non-time shifted data is compared to the matching time shifted version for the same traffic sample, it could be concluded that the radar time shifting algorithm achieved its objective of not adding or removing radar positional error.

The tracking performance may vary for each aircraft based on the particular geometry, speeds, and other factors associated with the flight. The tracking performance may also be different between the HCS and ERAM sub-systems. The validation exercise needs to block these factors out and focus the experiment on the difference between the non-time shifted (i.e. control run) versus the time shifted version (i.e. treatment run). This is achieved by calculating the average unsigned difference in position for a given flight between the HCS and ERAM systems. This is calculated for each flight for the non-time shifted run and repeated for the time shifted version. The difference between the means are calculated and tested against zero. The hypothesis is the mean difference for all flights between the two systems is zero. The alternate hypothesis occurs if they do have a statistically significant difference.

There were four metrics used to compare the two systems and validate the time shifting algorithm. They include:

- *Horizontal Error* which is the straight line stereographic distance between time coincident positions
- *Vertical Error* which is the altitude difference between time coincident positions
- *Cross Track Error* which is the side-to-side stereographic distance between spatially coincident positions
- *Along Track Error* which is the longitudinal stereographic distance between spatially coincident positions

To summarize, unsigned versions of these metrics are calculated between HCS track positions and ERAM track positions for the non-time shifted runs and then repeated for the time-shifted run. Both systems and methods were input with a 5.5 hour traffic recording from March 2005 recorded in Washington en route center, amounting to over 2200 flights and several hundred thousand track positions. For each flight, the sample mean is calculated for each run and the difference between the two runs (non-time shifted and time shifted) is calculated. The distribution of these differences is illustrated for each of these metrics in Figures 12-15. All the distributions are symmetric around zero

and are assumed to be approximately normally distributed⁴. Table 1 provides descriptive statistics on these distributions and results of the hypothesis test of zero mean difference. If the p-value column in Table 1 results in a small value, typically less than 0.05, then the test provides evidence to reject the null hypothesis. Only the vertical metric's hypothesis of zero mean difference could not be rejected statistically. The horizontal, cross and along track metrics all had statistically significant differences between the two runs. However, the magnitude of these differences is extremely small. The mean horizontal error difference is only 0.006 nautical miles or 40 feet. This is well under the precision of the radar data of 0.125 nautical miles (about 750 feet). Similarly the cross track and along track errors both have statistically significant results but extremely small average differences. Even the standard deviation metrics provide evidence of no practical significant difference with values ranging from about 90 to 170 feet. The high positive correlations listed in Table 1 indicate that aircraft difficult to track in the non-time shifted scenario exhibit the same behavior in the time shifted run. This indicates performing this paired test is the correct choice (i.e. pairing the same flights between runs). The merits of a paired hypothesis test are described in reference [10]. Therefore, the time shifting algorithm is producing a very slight effect on the tracking as compared to the non-time shifting method. Even though the difference is statistically significant for the stereographic metrics calculated, the net effect yields no practical significance.

Conclusion

To measure the accuracy of operational systems that predicts potential aircraft-to-aircraft conflicts (i.e. violations of separation) sometime in the future, time shifting the aircraft positions is CPAT's primary technique to induce these events for testing [5]. In the past, CPAT applied these time shifts to HCS track positions effectively.

⁴ Technically, the tails are larger than a true Normal Distribution and the center is too peaked, but the statistical hypothesis test applied produced matching results to a nonparametric Wilcoxon Signed Rank Test [9], which does not require normally distributed data.

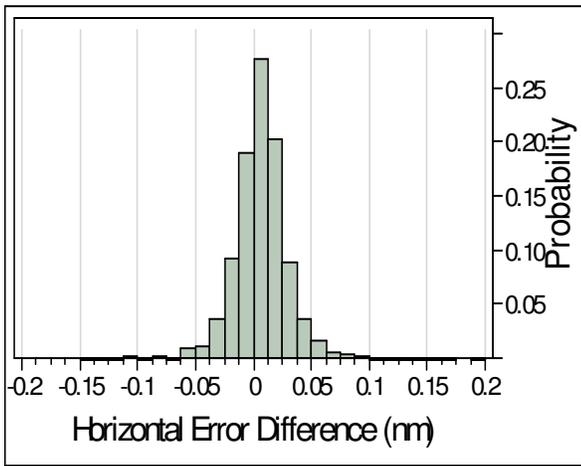


Figure 12: Distribution of Horizontal Error

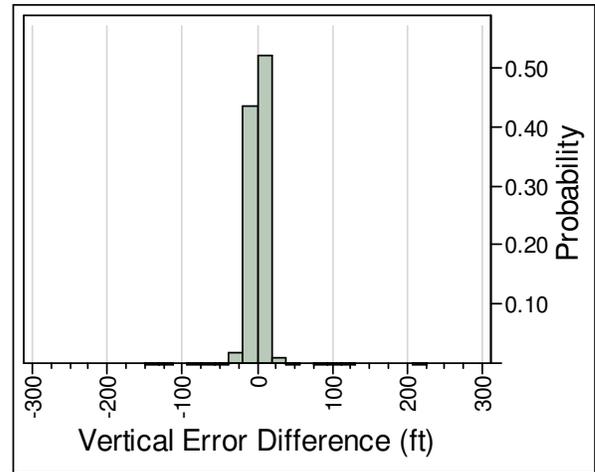


Figure 13. Vertical Error Distribution

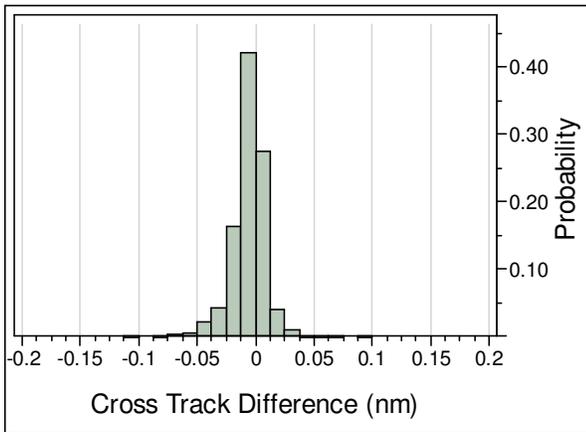


Figure 14. Cross Track Error Distribution

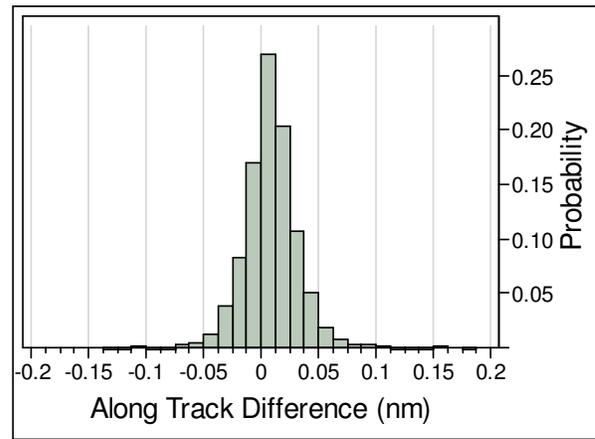


Figure 15. Along Track Error Distribution

Table 1. Error Distribution Summary Statistics

Metric	Sample Mean	Sample Standard Deviation	P-Value for t-Test for Mean $H_0=0$	Correlation Coefficient
Horizontal Error (nm)	0.00672	0.02659	<0.0001	0.99579
Along Track Error (nm)	0.00891	0.02793	<0.0001	0.95188
Cross Track Error (nm)	-0.00580	0.01458	<0.0001	0.99562
Vertical Error (ft)	-5.27780	209.471	0.2356	0.73217

Now for the more recent ERAM testing, raw radar surveillance positions are the input data source that the time shifting is applied to. However, for radar data that requires aircraft positions to fall within the cyclic scans of the radar, the legacy techniques were inadequate. As a result, the software was upgraded through a special interpolation scheme, described in this paper. Validation in both the horizontal and vertical dimensions had illustrated that the difference had no practical significance with magnitudes well below the precision of the data itself.

Acronyms

ACP	Azimuth Change Pulse
ASCII	American Standard Code for Information Interchange
ATCRBS	Air Traffic Control Radar Beacon System
CCLD	Core Capability Limited Deployment
CPAT	Conflict Probe Assessment Team
CTAS	Center TRACON Automation System
ERAM	En Route Automation Modernization
FAA	Federal Aviation Administration
FDP	Flight Data Processing
HCS	Host Computer System
NAS	National Airspace System
SDP	Surveillance Data Processing
SRTQC	Search Real Time Quality Control
TRACON	Terminal Radar Approach Control
URET	User Request Evaluation Tool

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