

Analysis of Handoffs for Future En Route Automation

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The Federal Aviation Administration (FAA) is developing the En Route Automation Modernization (ERAM) system to replace the current air traffic controller automation. In order to support the developmental and operational testing of ERAM, a study was conducted by the Automation Metrics Test Working Group (AMTWG) with the objective to address questions related to the handoff of flights by air traffic controllers as the flights pass from one controlling sector to another. Specifically, how effective would an automatic initialization of handoff (auto-init) be? Furthermore, what are the best situations for an accurate automatic initialization? In order to address these questions, handoffs needed to be investigated to determine the different possible scenarios and then analyzed to determine the efficiency of an automatic initialization within each scenario. Prior to the implementation of any testing strategy, actual flight data was collected for analysis. The data was analyzed for different events to determine the frequency of occurrence, and accuracy was determined based on statistics within each event crossing. The same strategy will be applied to actual ERAM data when it becomes available. The main metric selected for this study was the comparison of the predicted sector to actual next sector of handoff.

Nomenclature

<i>AMTWG</i>	=	Automation Metrics Test Working group
<i>ARTCC</i>	=	Air Route Traffic Control Center
<i>ATC</i>	=	Air Traffic Control
<i>CMS</i>	=	Common Message Set
<i>CPT</i>	=	Conflict Probe Tool
<i>CSEP</i>	=	Certified Systems Engineering Professional
<i>DS</i>	=	Display System
<i>ERAM</i>	=	En Route Automation Modernization
<i>FAA</i>	=	Federal Aviation Administration
<i>FDP</i>	=	Flight Data Processing
<i>GMT</i>	=	Greenwich Mean Time
<i>HCS</i>	=	Host Computer System
<i>nm</i>	=	Nautical Miles
<i>SDP</i>	=	Surveillance Data Processing
<i>SQL</i>	=	Standard Query Language
<i>URET</i>	=	User Request Evaluation Tool
<i>WJHTC</i>	=	William J. Hughes Technical Center
<i>ZDC</i>	=	Washington Center at Leesburg, Virginia

I. Introduction

THE Federal Aviation Administration's (FAA's) En Route Automation Modernization (ERAM) Test Group formed the Automation Metrics Test Working Group (AMTWG) in 2004. The team's charter is to support the developmental and operational testing of ERAM, the system set to replace the current air traffic controller (ATC) automation, 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

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ERAM. They are designed also 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. Host Computer System)¹.

Due to the differences between the current system and the future ERAM, a study was conducted to address questions related to the handoff of flights by air traffic controllers as the flights pass from one controlling sector to another. Specifically, how effective would an automatic initialization of handoff be? Furthermore, what are the best situations for an accurate automatic initialization? In order to address these questions, handoffs needed to be analyzed to determine the different possible scenarios and then analyzed to determine the efficiency of an automatic initialization within each scenario. The results of this study form the topic of this paper. The same strategy will be applied to actual ERAM data when it becomes available.

II. Operational Data

Prior to the implementation of a testing strategy, actual flight data was collected for approximately six hours[‡] from the Washington Center at Leesburg, Virginia (ZDC) starting on March 17, 2005 around 18:00 GMT. A sample dataset was prepared from the actual data. Within the data sample, 2,491 flights were captured for a total of 558,587 track reports. The average number of track reports per flight was 224 and the median was 204.

Legacy software tools developed by the Simulation and Analysis Group for evaluating another ATC system known as the User Request Evaluation Tool (URET) were applied by the AMTWG to check for reasonableness of the collected data and interpolate it as necessary. New software tools were developed to extract data from the common message set (CMS), which is output from the Host Computer System (HCS) including the initialization of handoffs, the handoffs of the flights, and the controlling sectors of the flights. The CMS messages are defined in the ARTCC Host Computer System/Air Traffic Management Applications Interface Requirements Document². The observations in the data were updated in 12-second increments. Since a handoff event can take place at any time, the initialization and handoffs may have an error of up to 11 seconds lag. Additional tools were developed to calculate the physical sector where each data point of the flight occurs. All the results were stored in a relational database.

Utilizing URET flight plan converted routes and 4-dimensional trajectories, another tool was developed to emulate the anticipated ERAM auto-handoff initialization function. The resulting data included variables for the time and location of the initialization, handoff, and physical sector crossings related to each flight as well as the predicted sector for handoff. These results were partitioned by the following three aircraft engine categories: jets, turboprops, and pistons. Also, the approximate distance in nautical miles from the point of initialization to the physical sector crossing was computed as well.

The AMTWG developed new modeling tools in order to analyze the actual handoff events and to model hypothetical crossing events using a set distance. Based on a set of observed occurrences, the tools were programmed to identify different categories of handoff events and provide statistics related to frequency. These modeling tools were validated using a variety of methods³. Analysts knowledgeable about the flight data performed event validation using output of the tool against selected samples of the data. Team members performed manual inspection based on their specialties in statistics, mathematics, and computer programming. Finally the completed simulation was verified using static testing techniques of a structured walk-through. Data results were verified manually by comparison to results extracted using Structured Query Language (SQL) commands and by manual observation.

Data was analyzed for different events to determine the frequency of occurrence, and efficiency was determined based on statistics within each event crossing. The metric selected for this study was the matching of predicted sector to actual next sector. Furthermore, the metric was analyzed by engine category of aircraft.

A total of 7,674 controlling sector changes were found. Of the total amount, 230 were eliminated due to anomalies such as unidentifiable crossing events or corrupted data. The remaining 7,444 crossings contained several crossing events that were inappropriate to include in the final analysis set. These events included situations where there was no initialization information prior to handoff (the No Init Event) and situations where there was no recorded handoff at a crossing (No Handoff Event). Section II.C provides a detailed description of these events while Section III.A provides statistics including which events were omitted from the final data. The final dataset contained 6,927 valid crossing events. The output dataset was formatted into comma-delimited text files. Using the commercial statistical software package SPSS for Windows (version 10.0.7), the comma-delimited files were imported and analyzed.

[‡] Actual start of first flight to end of last flight was 5 hours, 33 minutes and 30 seconds.

The air traffic recording discussed above contains a number of sector transition events referred to as handoff events. These will be defined in the following sub-sections.

A. Controlling Sector Handoff

Handoff involves the transfer of radar identification for a controlled flight in preparation for transfer of control. Handoff also changes the automation system view of control affecting command eligibility and output routing. Handoff can be initiated either manually by controller input or automatically. Acceptance of handoff is always manual⁴.

A specific field is extracted from the common message set[§] to identify the stages of the transfer. On the first observation at which the receiving sector code becomes populated, the time and location is marked as the point of the initialization of the handoff. When the controlling sector field changes, the event is considered a handoff. In the ideal scenario, the receiving sector would go blank when the controlling sector accepts the handoff. Also, the new controlling sector should be the same sector that is identified in the receiving sector.

Using tools developed for this study, the geometry of the sectors was compared to the physical location of the aircraft at each observation, which lead to identifying the current sector that the flight occupied. When a flight changed its physical location from one sector to another, the event was recorded as a boundary crossing.

B. Initialization of Handoff

Initialization of handoff requires some predictions. When the initializations are manual, an air traffic controller can make the predictions of the next sector and the approximate time of crossing to the next sector. For the activity to be automated, software must be capable of predicting the next sector and when to initialize the handoff. Two approaches have been identified for making these predictions – using the converted route and using the 4-D trajectory.

The HCS attempts to use the converted route to make predictions for automating the initialization of handoff. Unfortunately, this function is currently not considered reliable enough for air traffic controllers to use consistently. ERAM will implement different techniques for computing the converted route⁵, and these changes may be sufficient to improve the operations of the automated initialization function. The second approach for automating the initialization of handoff uses the 4-D trajectory information to make the necessary predictions.

Section III.C provides the results of the study using the operational data's actual point of initializations of handoff. The results of a computed hypothetical set distance point of initialization of handoff are provided in Section III.D. For both sections, the URET converted route is used as a stand-in for ERAM's converted route, and the trajectory predictions were simulated using tools developed by the AMTWG.

C. Sector Crossing Events

An ideal situation for any flight is the scenario where initialization of the handoff to the next sector occurs prior to entering that sector. Shortly thereafter and immediately prior to traversing into the next sector, the air traffic controller in the next sector accepts the handoff. Within a short amount of time, the aircraft crosses the border into the next sector. Although this appears to be the textbook example, it was found that this "ideal" event does not always occur.

In addition to the ideal crossing event, other crossing scenarios were discovered. As shown in Table 1 and Table 2, some of these events were included in our data set while others were discarded. An event was included if the necessary data points for initialization, handoff, and the boundary crossing could be determined. One example of an alternative acceptable crossing event is a point-out scenario, which occurs when an aircraft has handed off control to the desired sector but crosses the physical boundary of another sector before entering the newly controlling sector. In this case, it is possible to determine when the initialization and handoffs occurred and when the aircraft entered the specific sector. Figure 1 depicts a point-out event. Other events lacked the information required to perform the analysis and were, therefore, excluded from the data set. The most frequently occurring event that was discarded from the data set was the no init scenario, which occurs when an aircraft successfully completes a handoff prior to entering the new controlling sector with no indication in the data that the aircraft initialized the handoff.

[§] To be specific, the TH field is extracted. The information related to the CMS was obtained from Ref. 6.

Point-Out Event

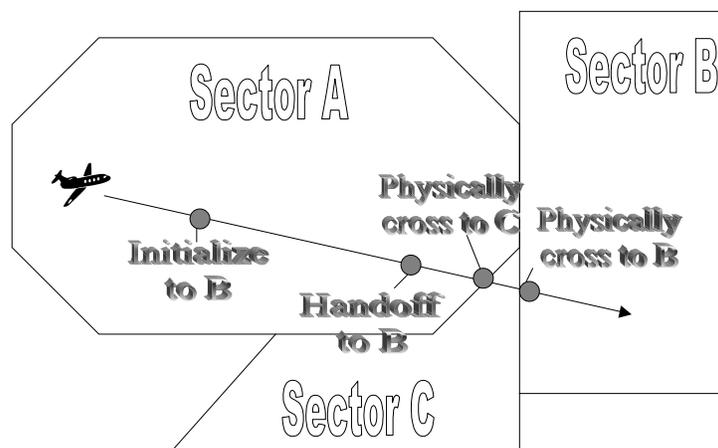


Figure 1: Point-Out Event

III. Analysis of Handoff Initialization Events

An analysis strategy can be applied to process the results. The proposed strategy identifies a set of scenarios that occur during handoff and then applies a set of descriptive statistics⁷. The end result indicates how effective auto-initialization would be under different circumstances and the expected frequency of the situation.

To determine the moment of initialization, two approaches were taken for both the converted route processing results and the trajectory based simulation results. The first approach used the actual time of the manually initiated handoff. When an initialization was recorded, analysis for accuracy was performed using that moment. For the second approach, a hypothetical set distance for initiation of handoff was used. At the hypothetical distance, an accuracy analysis was performed similar to the first approach. Due to the different speeds of aircrafts, three set distances were used relating to three categories of engine types for jet engine, turboprop engine, and piston engine. Since there is a direct correlation between distance and time, the results were valid using a set time as well. The same statistics are applied to both datasets.

The first approach was to analyze the sector crossings with no modifications. If adopted, this approach would have the benefit of reality based on current conditions but the disadvantage of requiring extensive adaptation in an automatic model.

The second approach was to use a set distance prior to the sector boundary crossing. After analyzing the output data, the medians of the distance difference for each of the three engine categories were computed. Modifying the initialization of each sector crossing to the point when the predicted distance to the sector boundary is first within the set median distance prior to the physical boundary crossing produces a second set of results. This approach has the advantage that it would apply universally but has the disadvantage that it cannot compensate for unusual situations (such as described in Section II.C).

A. Event Statistics

For the approach using a set distance prior to boundary crossing as the moment of automatic initialization, actual initializations in the sample data were observed. The distance between initialization and physical crossing of the sector boundary was recorded along with the flight's engine type (jet, turboprop, or piston). The median distance, in nautical miles, was computed for each of the three engine types. These three median statistics were used to analyze each flight assuming an automatic initialization of handoff.

A total of 7,444 identified boundary events were identified in the sample dataset of 2,491 flights. Within the 7,444 boundary events, 517 or 6.9% were discarded as anomalous, resulting in 6,927 acceptable sector boundary-crossing events. These acceptable sector boundary-crossing events consisted of 6,306 jet crossings, 439 turboprop

crossings, and 107 piston crossings. The remaining 75 crossings had unidentified engine types at the point of initialization of handoff**.

The accepted crossings can be grouped into several crossing events, which were used in the final analysis and were explained in Section II.C. Most of the anomalous crossing events were identified but were discarded nonetheless. The breakdown of accepted crossing events is listed in Table 1. Table 2 lists the discarded crossing events.

Table 1: Acceptable Sector Crossing Events

Event	Count	Percent of Identified Boundaries	Percent of Valid Events
Ideal	6,143	82.5%	88.7%
Point-Out	424	5.7%	6.1%
Other Valid Events	360	4.8%	5.2%
Total Valid Events	6,927	93.0%	100.0%
Total Identified Boundaries	7,444		

Table 2: Discarded Sector Crossing Events

Scenario	Observations	Percent of Identified Boundaries
No Init	363	4.9%
Other Discarded Events	154	2.1%
Total Discarded	517	7.0%

B. Definition of Accuracy Metrics

As defined in Section I, the primary objective of the study was to determine an expected effectiveness of ERAM's automatic initialization of handoff function. A direct measure of the function's effectiveness is how often ERAM accurately predicts the next sector of the flight. As described above there were two approaches to answer this question: (1) determining how accurate the prediction of the next sector is at the recorded manual handoff initialization time and (2) determining how accurate the prediction of the next sector is when the predicted distance to the sector boundary crossing falls below a given threshold. The thresholds are defined in terms of aircraft engine category (i.e. jet, turboprop, and piston). Therefore, the basic equation is listed below.

** The 75 aircraft were unidentified since they were not within the author's aircraft database. Further manual analysis could be performed to determine their status but was deemed unnecessary due to the large dataset available.

$$\forall e: \frac{(\tau)}{(N_e)} \tag{1}$$

where e is the engine category, N_e is the total number of sampled crossing events for the engine category, and τ is the number of correctly predicted events from the same sample.

Upon further inspection, it was determined that the first 30 seconds of each track report was questionable in several circumstances. In order to eliminate the disputed data, the first 30 seconds of all track reports were discarded. Although this process reduced the available data for the study, the remaining data was more than sufficient for statistically significant results.

For each of the two metrics defined above (operational versus predicted distance handoffs), predictions were made using the flight plan and using the aircraft trajectory. The result was an analysis performed using four sample data sets.

C. Results for Operational Based Handoff Events

The operational based handoff events are actual initializations and handoffs of flights from sector to sector. Using the actual point of initialization, a prediction of the next sector is made based on the flight plan and the aircraft trajectory. Once the aircraft passes into the next sector, a determination can be made as to the accuracy of the prediction.

There were 6,927 flights where a prediction of sector could be made. Of this number, 75 were unidentifiable due to errors with transient state data. In order to obtain steady-state data, observations with handoff-init times within the first 30 seconds of each track were discarded due to the questionable nature of these observations. Once these observations were excluded, there were 5,543 flights remaining for analysis. Of the flights in the final sample, 5,088 were jets, 365 were turboprops, and 90 were pistons.

1. Overall Statistical Results

As shown in Table 3, an accurate prediction was determined for 64.9% of the crossing events overall when the prediction was based on the flight plan at the actual operational handoff-init point. Examination of each engine category reveals that the jets had the highest accuracy with 65.7%, with turboprops following at 58.6% and the piston engine aircraft with 47.8%. Since jets comprise 91.8% of the observations, it is not surprising that the overall accuracy of 64.9% is close to the jet accuracy of 65.7%. Furthermore, it makes sense intuitively that the prediction accuracy decreases with aircraft speed, the piston engine aircraft having the slowest velocity, since they had the most time to change course from the flight plan^{††}. The median time between handoff-init and the sector boundary was 280 seconds for jets, 330 seconds for turboprops, and 425 seconds for piston aircraft.

Table 3: Operational Based Handoff Events Using Flight Plan Predictions

	Accurate Prediction		Row Total	
	Count	Row %	Count	Table %
Jet	3,342	65.7%	5,088	91.8%
Piston	43	47.8%	90	1.6%
Turboprop	214	58.6%	365	6.6%
Column Total	3,599	64.9%	5,543	100.0%
Start Time ≥ 30 seconds				

^{††} For an analysis of the converted route flight plan, see Ref. 5.

When a prediction was based on the aircraft trajectory instead of the flight plan, the accuracy improved somewhat as shown in Table 4. Again there is a definite correlation between engine speed and accuracy with 72.5% accuracy for jets, 58.6% for turboprops, and 48.9% for piston aircraft.

Table 4: Operational Based Handoff Events Using Trajectory Predictions

	Accurate Prediction		Row Total	
	Count	Row %	Count	Table %
Jet	3,690	72.5%	5,088	91.8%
Piston	44	48.9%	90	1.6%
Turboprop	214	58.6%	365	6.6%
Column Total	3,948	71.2%	5,543	100.0%
Start Time \geq 30 seconds				

2. Comparative Statistical Results

As stated previously, this study used the flight path and the trajectory to predict the next sector of an aircraft. Table 5 attempts to display in a form conducive to understanding the different results based on the operational data.

Table 5: Comparison of Operational Data Prediction Accuracy

	Trajectory Miss	Trajectory Predicted
Flight Path Miss	1,415 (25.5%)	529 (9.5%)
Flight Path Predicted	180 (3.2%)	3,419 (61.7%)

As shown in Table 5, the trajectory accurately predicted the next sector 9.5% of the time when the flight path failed. Although the results are significant in favor of the trajectory, it must be noted that both techniques failed to make a correct prediction over 25% of the time.

D. Results for Predicted Distance Handoff Events

The predicted distance handoff events are based on the statistics of the actual initializations and handoffs of flights from sector to sector. Since the AMTWG was unaware of the actual settings for auto-init handoff, it was decided to use a threshold based on operational data. The median distance from initialization to handoff of jets was found to be 34.5 nautical miles, of piston aircraft was 20.0 nm, and of turboprops was 23.5 nm. These median distances were used as thresholds for hypothetical initializations of handoff. This metric was measured in an attempt to mimic a potential implementation of auto-init handoff.

Based on these median distances, an initialization was said to occur when the predicted distance to the next sector boundary fell within the defined threshold. At that hypothetical point of initialization, a prediction of the next sector was made using the flight plan and again using the trajectory. If a prediction could not be made due to geography or aircraft orientation, the observation was discarded.

There were 6,841 flights where a prediction of sector could be made using a set distance based on the trajectory and 6,835 flights based on the flight plan. The difference in these two numbers is related to prediction problems using the two techniques. In order to ensure the data sets were equivalent, observations with a hypothetical handoff-init time within the first 30 seconds of each flight track were excluded in the same manner as explained in Section III.B.

1. Overall Statistical Results

As shown in Table 6, an accurate prediction was determined for 73.7% of the crossing events overall when the prediction was based on the flight plan at the set distance handoff-init point. Examination of each engine category reveals again that the jets had the highest accuracy with 74.5% and comprised 92.5% of the events. The initialization was said to occur when the predicted distance to the next sector boundary first fell within 34.5 nm for jets, 20.0 nm for pistons, and 23.5 nm for turboprops. In the event that the predicted distance to the next sector was within the threshold at the moment of handoff, the initialization of handoff to the next sector was said to occur at the immediate next track point after the preceding handoff.

Table 6: Predicted Distance Handoff Event Using Flight Plan

	Accurate Prediction		Row Total	
	Count	Row %	Count	Table %
Jet	3,799	74.5%	5,096	92.5%
Piston	47	59.5%	79	1.4%
Turboprop	213	64.0%	333	6.0%
Column Total	4,059	73.7%	5,508	100.0%
Initialization Time \geq 30 seconds after start of track				

When a prediction was based on the aircraft trajectory instead of the flight plan, the accuracy improved to 78.5% as shown in Table 7. Again there is a definite correlation between engine speed and accuracy with 79.3% accuracy for jets, 71.0% for turboprops, and 58.7% for piston aircraft.

Table 7: Predicted Distance Handoff Event Using Trajectory

	Accurate Prediction		Row Total	
	Count	Row %	Count	Table %
Jet	4,065	79.3%	5,125	92.8%
Piston	44	58.7%	75	1.4%
Turboprop	230	71.0%	324	5.9%
Column Total	4,339	78.5%	5,524	100.0%
Initialization Time \geq 30 seconds after start of track				

2. Comparative Statistical Results

Two different approaches were used to predict the next sector when the point of initialization of handoff was a set distance prior to the sector boundary. Table 8 attempts to display the results of the two approaches so that the reader can see any advantages or disadvantages.

Table 8: Comparison of Hypothetical Initialization Prediction Accuracy

	Trajectory Miss	Trajectory Predicted
Flight Path Miss	824 (15.7%)	452 (8.6%)
Flight Path Predicted	286 (5.4%)	3,692 (70.3%)

Using set distances as the point of automatic initialization resulted in higher accuracy than using the actual initializations of the operational data (compare to Section III.C). As shown in Table 8, the set distance initializations failed only 15.7% of the time for both approaches. Similar to the operational data case, the trajectory produced better results than using the flight path.

One obvious question regards the observation count in the table. The different transient states of the data cause the observations in the table to sum to 5254, which is less than either dataset alone. As stated previously, the first 30 seconds of each flight was dropped due to anomalies caused by the flight observation capture process. Since Table 8 is intended to be a comparison, only observations that were available from both datasets were used in the table calculations.

E. Flight Example

The following example illustrates a common cause of prediction error. A point out event as explained in Section II.C causes the trajectory's prediction to be wrong while the flight plan's prediction is correct.

This flight example is an over flight out of Fort Lauderdale/Hollywood International Airport in Fort Lauderdale, Florida which passed through the Washington ARTCC with a destination of Cleveland Hopkins International Airport in Cleveland, Ohio. The aircraft is a large Airbus A-320 with twin jet engines.

A position plot for the flight, trajectory, flight plan, physical sector, and predicted sectors can be seen in Figure 2. For a sector crossing at time 19:58:40, the trajectory's sector prediction is wrong while the flight plan's prediction is accurate. At the time of initialization to sector 16, 19:54:50, the flight is physically in and controlled by sector 38. Control is then handed off to sector 16; however, the next sector this flight physically enters, though briefly, is sector 36. This example illustrates a point out scenario as described in Section II.C. Figure 3 is a close view of the two predicted points and shows the flight and trajectory passing through the corner of sector 36 while the flight plan directly enters sector 16 from sector 38. While the trajectory prediction does not match the next controlling sector, one could say that it is a correct prediction since it matches the next sector physically entered.

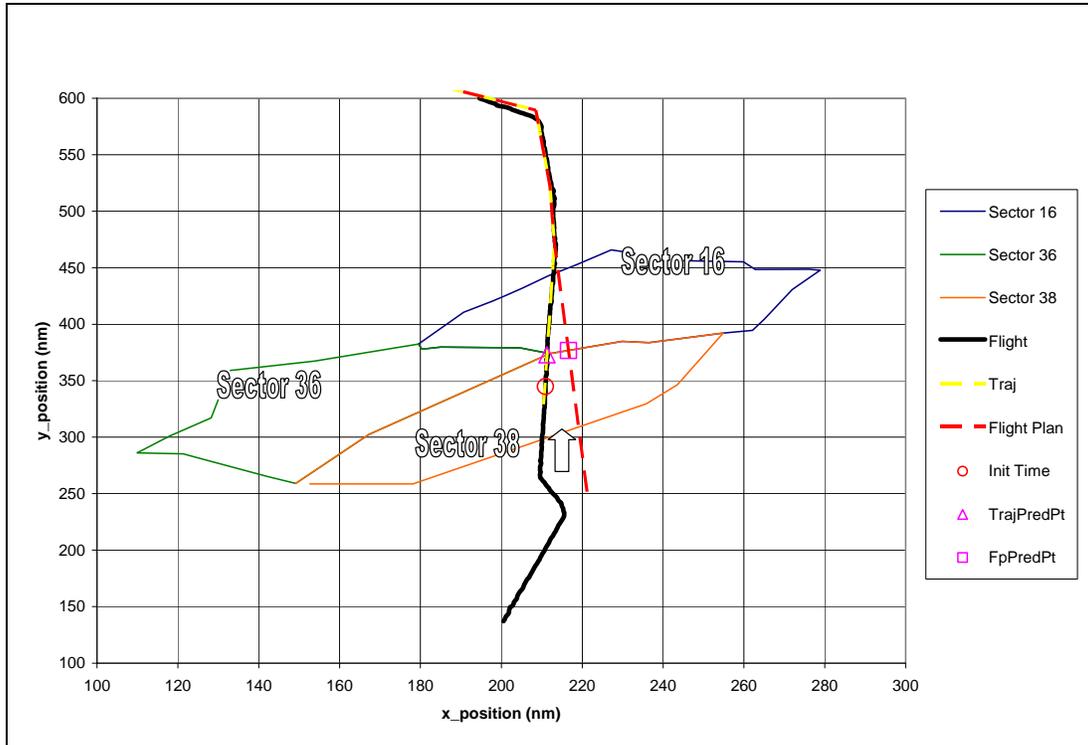


Figure 2: XY Position Plot for Flight Example #1

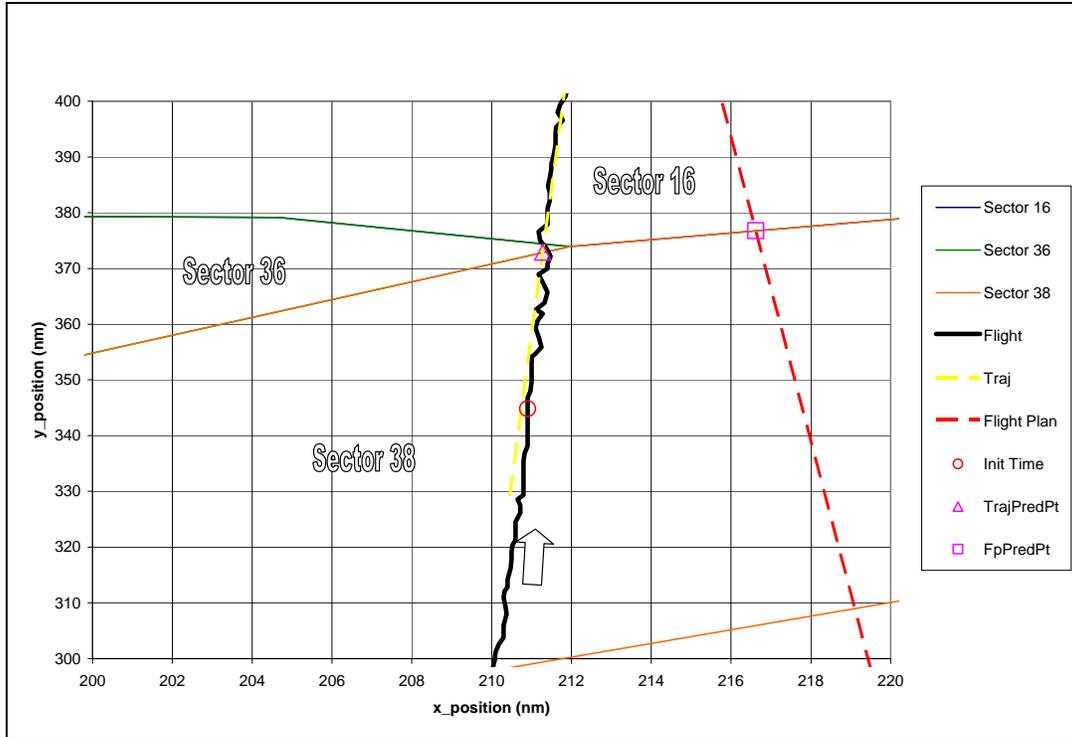


Figure 3: Close-up of Point Out for Flight Example #1

IV. Conclusion

The study measured the performance of an automated process for initial handoff of flights between sectors from an objective viewpoint. These statistics are based on an unbiased sample of flights from ZDC. As described thoroughly in Section III, the study developed and analyzed two methods of predicting the handoff sector: (1) based on the flight plan converted route, referenced as the Flight Plan Trajectory and (2) based on a full 4-D trajectory prediction, referenced as the Aircraft Trajectory in ERAM documentation⁸. As one might expect intuitively, the aircraft trajectory-based predictions performed at a higher accuracy rate than the flight path predictions. Since a flight path prediction assumes the aircraft is on its flight path⁹, there is an additional assumption not present with a trajectory-based prediction, which automatically checks the conformance of the prediction against the current aircraft prediction and builds a new trajectory accordingly^{††}. When the assumption is incorrect (aircraft are deviating from the known flight plan), the flight path-based prediction should have a lower probability of success.

Besides the type of prediction, the performance of the predictions to the next controlling sector, as described in Section 3, is calculated based on two reference positions: at the actual recorded operational initialization of handoff to the next sector and at a hypothetical predicted distance to the next sector. The predicted distance initializations had a higher accuracy than the actual initializations. This result is attributed to the large variation in the actual distance at which handoffs were initialized to the next sector. Hence, the trajectory-based predicted-distance initializations of handoff had the highest probability of success in this study and were usually physically closer to the next sector than the recorded operational distance.

To approximate the overall success rate of an auto-init handoff function, results of this study can be applied to a basic calculation. Of all initialization-handoff events, 93% could be identified by current automation. Of the resulting sample space, a 78.5% success rate was determined for trajectory-based predicted-distance initializations. Therefore an auto-init handoff function should be at least 73% accurate for all events. Alterations to the algorithms used and choosing alternate distances for the initializations could impact the accuracy of an auto-init function. To compensate, the software tools developed for this study are flexible and can be easily modified for future studies.

^{††} This processing of rebuilding a trajectory based on an out of conformance situation is referred to as reconformance.

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