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Analysis of Handoffs for Future En Route Automation

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16. Abstract

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. The same strategy will be applied to actual ERAM data when it becomes available. 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 main metric selected for this study was the comparison of the predicted sector to actual next sector of handoff.

17. Key Words

Aircraft flight paths
Auto-Init
Handoff
Controlling Sector
Sector Boundary
Trajectory
ERAM, En Route Automation Modernization
URET, User Request Evaluation Tool

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Finally, we would like to thank the FAA's ERAM Program Office for funding this study via the ERAM Test Group at the WJHTC.

Executive Summary

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 by developing a set of metrics that quantify the effectiveness of key system functions in ERAM. The targeted system functions are Surveillance Data Processing (SDP), Flight Data Processing (FDP), Conflict Probe Tool (CPT), and the Display System (DS) modules. The metrics are designed to measure the performance of ERAM. They 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.

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

The final project phase is the data collection and analysis phase. In this step, AMTWG will document the further refinement and application of these metrics on the current legacy systems in a series of Metric Reports. This technical note documents a strategy for testing and analyzing the auto-initialization of the handoff processes within the FDP sub-system. Analysis of flight data provides insights to potential capabilities and shortfalls of any auto-initialization process.

In preparation for transfer of control, auto-initialization of the handoff involves the transfer of radar identification for a controlled flight. In addition, handoff 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 a manual process by the air traffic controller.

To study handoff in this report, flight data was collected over a six-hour period from the Washington Center at Leesburg, Virginia (ZDC). Tools were developed to extract the necessary parameters and determine locations of each flight within sectors as well as locations of initialization and handoff for each sector of each flight. The primary metric for this study was the accuracy of predictions made at actual and hypothetical handoff initializations to the next sector boundary. For ERAM's automated handoff initialization process to be accepted by air traffic controllers, it will need to make accurate predictions of where to initiate a handoff. This technical note presents metrics to measure this accuracy and is applied to the legacy automation ERAM is replacing.

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1. Introduction

1.1 Purpose

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 by developing a set of metrics that quantify the effectiveness of key system functions in ERAM. The targeted system functions are Surveillance Data Processing (SDP), Flight Data Processing (FDP), Conflict Probe Tool (CPT), and the Display System (DS) modules. The metrics are designed to measure the performance of ERAM. They 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).

This paper outlines a strategy for testing and analyzing the automatic initialization of handoff (auto-init) functionality of ERAM. Based on modeling existing data, accuracy predictions of an auto-init function for a handoff are determined. A handoff involves the transfer of radar identification for a controlled flight in preparation for transfer of control. In addition, handoff 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 required to be manual.

1.2 Background

It is the responsibility of the FAA in monitoring the development of ERAM to ensure that the system when delivered meets the needs of the FAA. The charter of the AMTWG is to identify metrics that illustrate the effectiveness of ERAM Release 1 in the areas of SDP, FDP, CPT, and as of January 2005, the DS. These metrics will measure the performance of ERAM as well as the performance of the legacy En Route automation systems in operation today. Also they will allow comparison of similar functionality in ERAM to legacy systems (e.g. HCS) when appropriate.

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

The final project phase is the data collection and analysis phase. In this step, AMTWG will document the further refinement and application of these metrics on the current legacy systems in a series of Metric Reports. AMTWG delivered a series of Metric Reports for fiscal year 2005 with one covering each of the ERAM modules discussed above, SDP, FDP, CPT, and DS respectively. These reports were published in multiple drops to provide the ERAM Test Team on-time information. The drops coincided with the approaches used to implement the metrics. Further in-depth Metric Reports were planned for fiscal year 2006. This technical note addresses concerns with implementing FDP's automatic initialization of handoff process.

Due to the differences between the current HCS and future ERAM, there exists the following COI:

> *COI 1.0 – Does ERAM support air traffic control (ATC) operations, using current ATC procedures and methods to provide safe, orderly, and expeditious flow of traffic with at least the same effectiveness as the current system?*

This paper describes the strategy for comparing the effectiveness of the upgraded and current systems in the area of the auto-init functionality as a part of answering this COI. Specifically does ERAM system performance meet or exceed that of current En Route automation, and what is the expected system performance of the auto-init functionality?

1.3 Objectives of this Study

The objective of this study is 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 need to be analyzed to determine the different possible scenarios and then analyzed to determine the efficiency of an automatic initialization within each scenario. The same strategy will be applied to actual ERAM data, when it becomes available. The results of this study will provide supporting data related to the COI.

1.4 Document Organization

This technical note begins with the introduction and goals. Section 2 discusses the operational data that was used to perform the study. An analysis of the data reveals multiple events, which are described along with their frequency of occurrence in the sample. Section 3 consists of the analysis of the handoff-initialization events. First the actual handoff events are analyzed statistically. Using averages found from the actual events, situations are constructed using predefined distances from the sector boundary for initialization. Finally the conclusions are stated in section 4.

2. Operational Data

Prior to the implementation of any testing strategy, actual flight data was collected for approximately six hours[1] from the Washington Center at Leesburg, Virginia (ZDC) starting on

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

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 the User Request Evaluation Tool (URET) have been 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) 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 Document[2]. The observations in the data are 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 late. Additional tools were developed to determine 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 (details are provided in Section 2.2). 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. The results are partitioned by aircraft engine categories. There are three engine categories, including jets, turboprops, and piston engines. The approximate distance in nautical miles from the point of initialization to the physical sector crossing is 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 modeling tools were programmed to identify the different categories of handoff events and provide statistics related to frequency. These modeling tools were validated using a variety of methods[3]. 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 Standard 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, which includes jet, turboprop, and piston.

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 prior to handoff (the No Init Event) and situations where there was no handoff at a crossing (No Handoff Event). Section 2.1 provides a detailed description of these events while Section 3.1 provides statistics including which events were omitted from the final data. The final dataset contained

[2] See FAA (2000)
[3] See Sargent (2003) for a description of the stated validation and verification techniques.

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.

2.1 Handoff Events

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.

2.1.1 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 manual.

A specific field is extracted from the common message set[4] to identify the stages of the transfer. On the first observation 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 is recorded as a boundary crossing.

2.1.2 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 Host Computer System (HCS) attempts to use the converted route to make predictions for automating the initialization of handoff. Unfortunately, this function is not considered reliable enough currently for air traffic controllers to use consistently. ERAM will implement different techniques for computing the converted route[5], 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 3.3 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 3.4. For both sections, the URET converted

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[4] To be specific, the TH field is extracted. The information related to the CMS was obtained from Paglione (2004)

[5] See Baldwin (2005) for more information.

route is used as a stand-in for ERAM's converted route, and the trajectory predictions were simulated using tools developed by the AMTWG.

2.1.3 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, we shall see that this "ideal" event is not always the case.

In order to determine the different scenarios, flight data was graphed manually. Data points that consist of the location of the flight, the time, and the state of the handoff were extracted. These data points occur in ten second increments, assuming no data points are lost. Stringing sequential data points together for each flight, an analyst was able to determine a subset of the scenarios related to the controlling sector handoffs for each flight. Due to the size of the sample dataset and the effort required, the modeling tool described in section 2 was used to help identify scenarios.

2.1.3.1 Ideal Event

Prior to an aircraft entering a new controlling sector, an air traffic controller of this new sector must have navigational control of the aircraft. For this to occur, the aircraft must initialize contact with the controller, and handoff control from the current controller to the new controller. Only after these two events occur, the aircraft is allowed to cross the physical boundary into a new control sector. This sequence of events has been classified as an Ideal Event (see Figure 1 for a graphical depiction[6]).

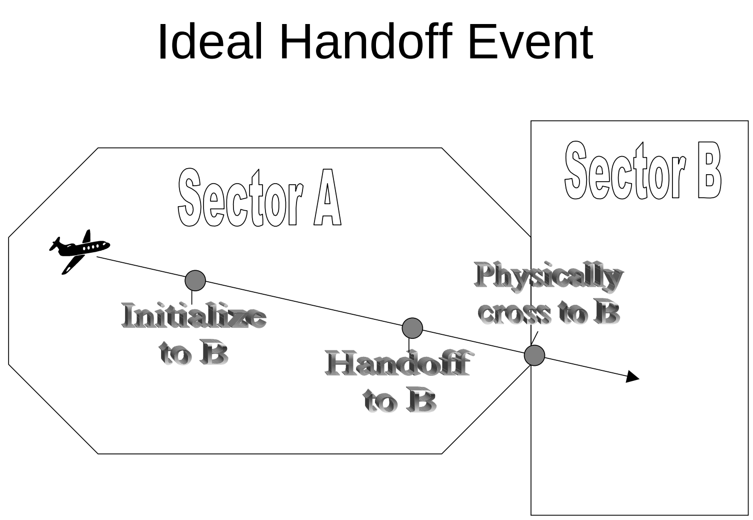

Figure 1: Ideal Event

[6] Sector identifiers in all figures are for illustrative purposes only and do not represent any actual sector.

2.1.3.2 Point-Out Event

Analysis of the sample flight data shows a situation where an aircraft does not correctly enter a new physical sector after handing off control. Instead of the normal case where an aircraft will handoff control to a sector prior to entering, in these cases described by air traffic controllers as Point-Out Events, an aircraft may cross the physical boundary of another sector before entering the desired and newly controlling sector. The aircraft uses this other, and non-initialized, sector as an intermediate piece of airspace between the last and future control sectors. See Figure 2 for a graphical description of this situation.

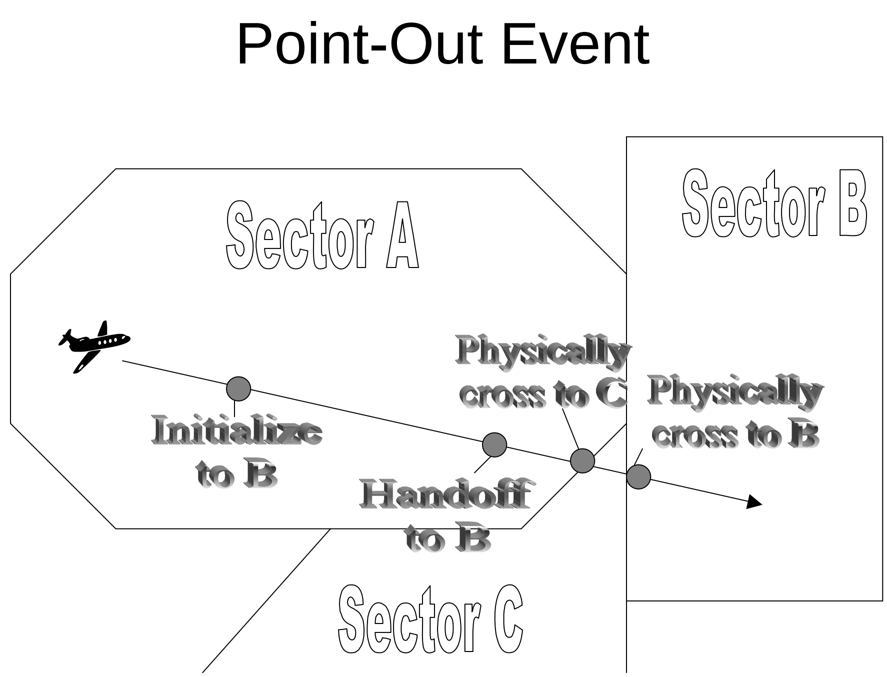

Figure 2: Point-Out Event

2.1.3.3 Skipping Sector Event

After successfully crossing the physical boundary to a new control sector, situations arose where an aircraft would "skip out" of their controlling sector. This action corresponds to the aircraft entering another sector and then returning to the correct physical sector. The duration of this time outside the controlling sector averaged approximately 130 seconds in length, with a median time of 60 seconds for this “Skipping Sector Event.” Although there is no way to verify this statement from the data, it is assumed that this situation is similar if not equivalent to the Point-Out Event. This situation is portrayed in Figure 3.

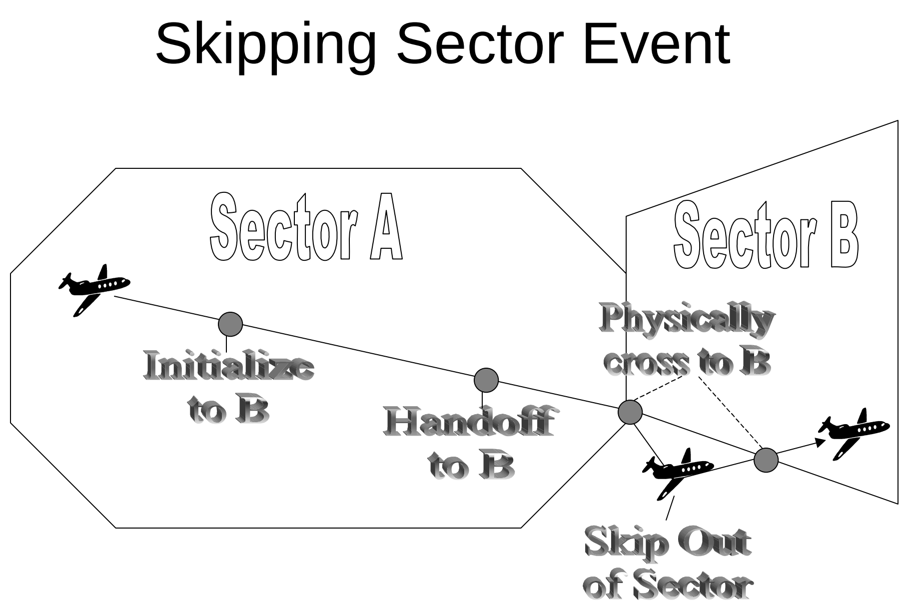

Figure 3: Skipping Sector Event

2.1.3.4 False Init Event

For the flights tracked in this study, there were instances where the connection between the two sectors was dropped after the aircraft made contact and initialized with the next control sector. The aircraft would then re-initialize with the control sector before handing off control. Figure 4 presents a graphical representation of this situation.

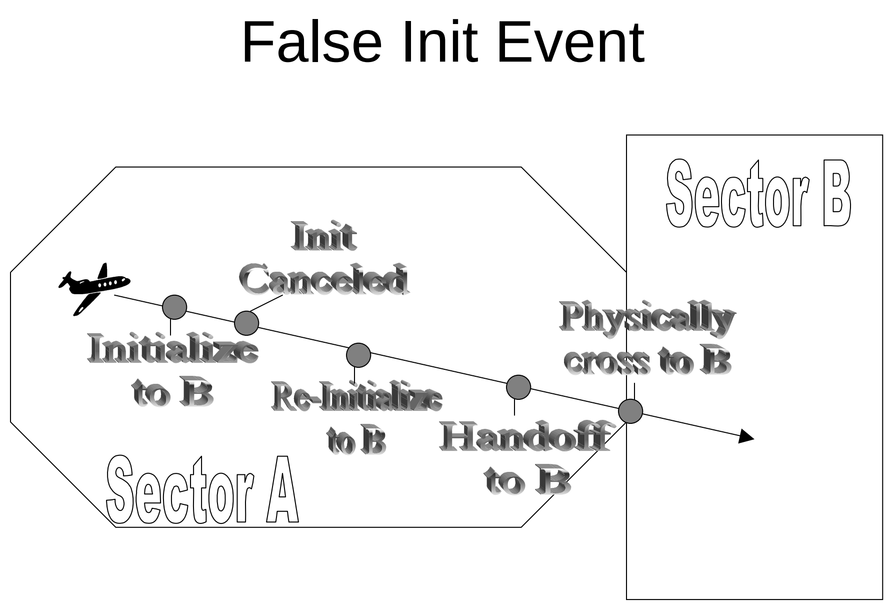

Figure 4: False Init Event

2.1.3.5 Late Handoff Event

Whenever an aircraft completes a valid sector boundary crossing, it is imperative the aircraft is under the control of the new controlling sector. However, for a small number of observed situations, it was found that an aircraft did not handoff control prior to crossing a physical boundary. During these situations, the aircraft did indeed initialize with the intended control sector, but failed to complete a handoff in the correct amount of time, designating it as an occurrence of a "Late Handoff Event." Furthermore, other situations were discovered that have the trait of a handoff and physical crossing reported at the same point in time. Whether the handoff or the crossing occurred first is unknown because of the time delay between data points. One view of this situation is depicted in Figure 5.

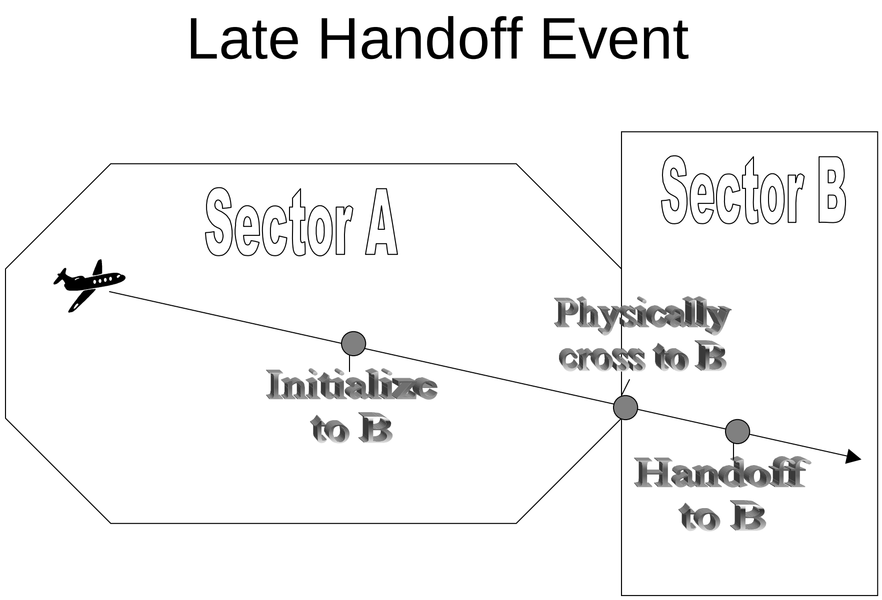

Figure 5: Late Handoff Event

2.1.3.6 No Init Event

The largest documented non-ideal boundary-crossing event dealt with situations where there was no indication that an aircraft initialized with a new control sector, even though the aircraft would successfully complete a handoff prior to entering the new control sector. Due to the time interval between data points, a possible explanation is that an init can occur shortly before the handoff without being recorded in the data. Flights belonging to this particular scenario, the "No Init Event," occurred the most often of the rejected data set. One can easily see in Figure 6 that this data must be rejected since there is no initialization on which to perform the statistics.

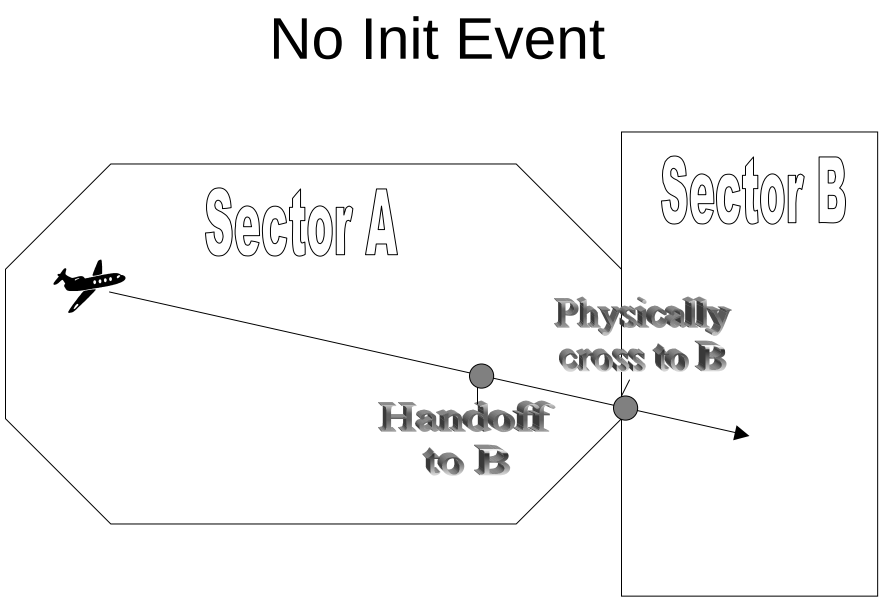

Figure 6: No Init Event

2.1.3.7 Reverse Order Event

A scarcely occurring group of flight sequences include those referred to in this study as "Reverse Order Events." For an insignificant number of valid sector crossings, an aircraft would not perform an init until after crossing into the next physical boundary. After crossing the boundary, the initialization occurs with the sector recently entered, followed by a handoff. See Figure 7 for the graphical depiction.

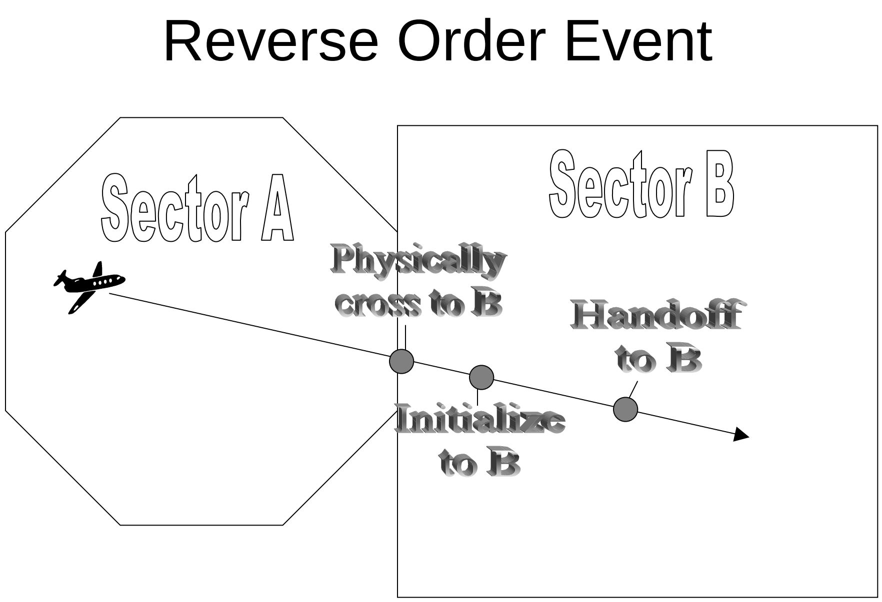

Figure 7: Reverse Order Event

2.1.3.8 Late Handoff with No Init Event

This scenario is the combination of a Late Handoff Event depicted in Figure 5 and a No Init Event depicted in Figure 6. In seven (7) recorded situations, an aircraft would enter a control sector's airspace without any indication of prior contact. Shortly after entering the new control sector, a handoff would occur, minus any indication of an initialization. Figure 8 illustrates this situation.

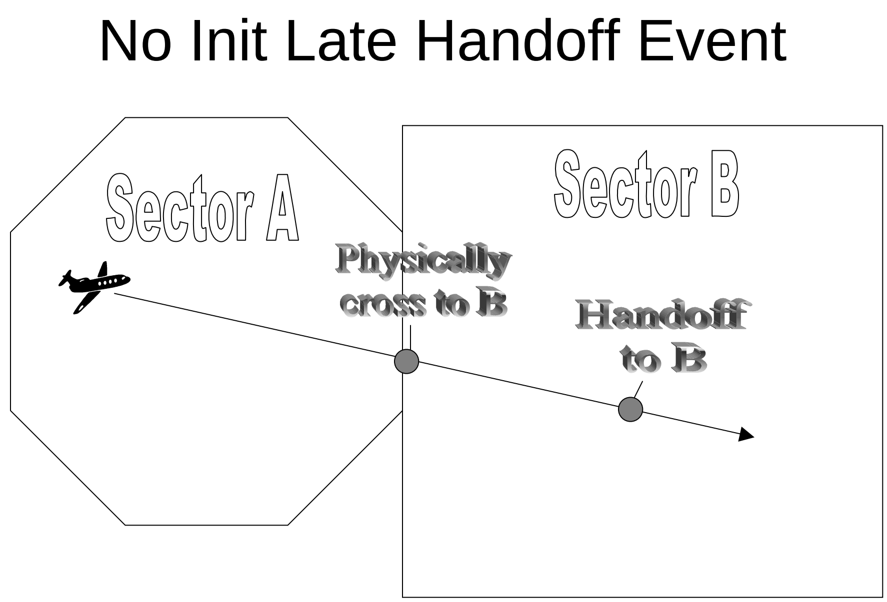

Figure 8: Late Handoff with No Init Event

2.1.3.9 Look Ahead Event

In this crossing event, the "Look Ahead Event," an aircraft will deal with three different control sectors in the time between the first init and boundary crossing. This event is similar to that of a Point-Out Event from Section 2.1.3.2, except where Point-Outs have no initializations or handoffs, all instances of this event do have these. Referring to the diagram in Figure 9, for the aircraft's ultimate goal of reaching sector B, it must cross through sector C. Between the handoff and boundary crossing to sector C, the aircraft initializes and handoffs to sector B. Effectively, the aircraft is controlled by sector B throughout its trip through sector C, as well as its entry into sector B.

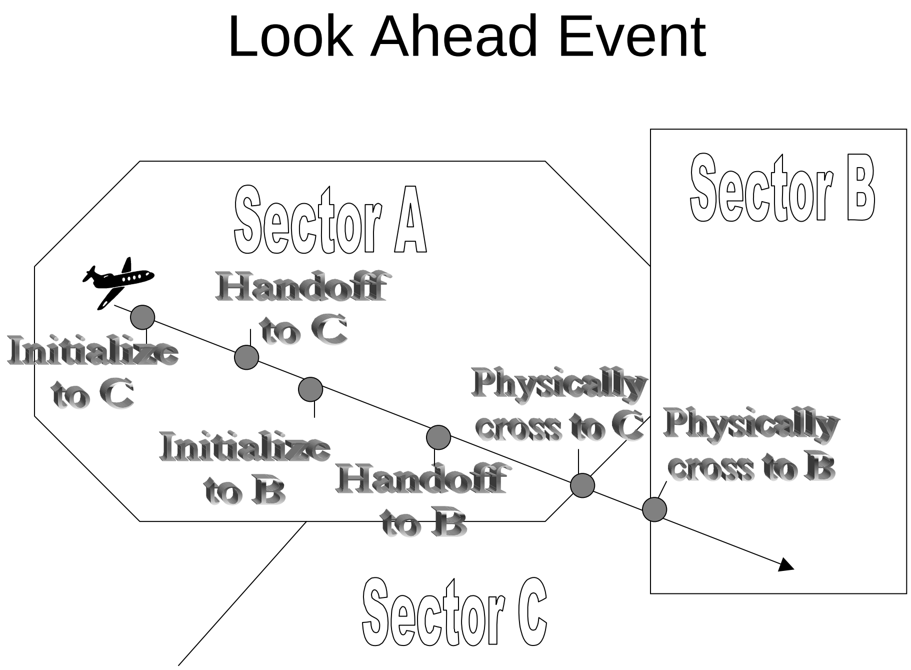

Figure 9: Look Ahead Event

2.1.3.10 No Handoff Event

The instances of the aptly named "No Handoff Event" appear identical to instances of the Ideal Scenario of section 2.1.3.1, with the exception of a missing handoff. An aircraft will initialize with the next controlling sector, then later cross the physical boundary with no handoff. As shown in Figure 10, there is no point in time when the aircraft comes under control of the newly entered sector. Through visual inspection, it was observed that typically this newly entered sector would act as an intermediate sector, similar to the Point-Out and Look Ahead Events from sections 2.1.3.2 and 2.1.3.9, respectively.

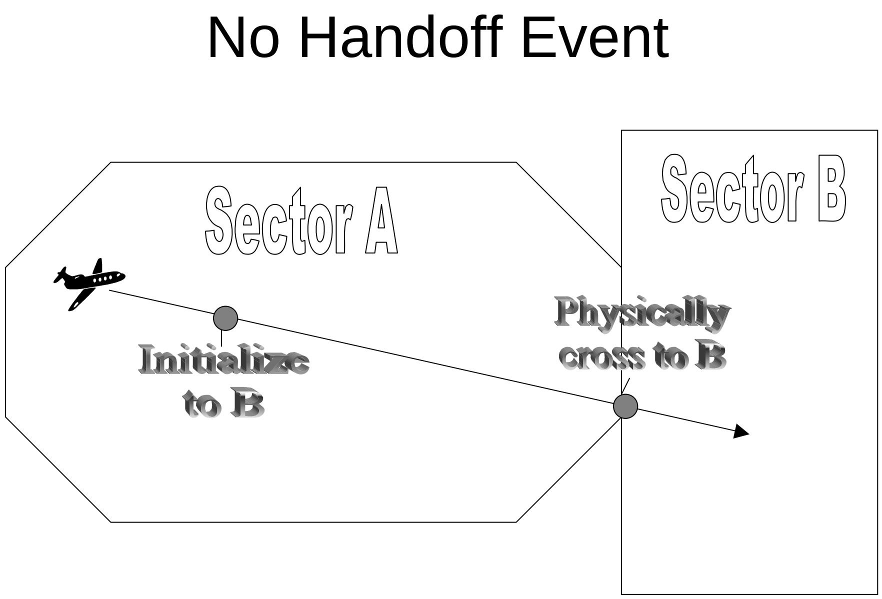

Figure 10: No Handoff Event

2.2 Processing for Predicted Handoff Events

To evaluate the auto-handoff initialization function in ERAM, the traffic scenario and events presented in Section 2.1 would need to be input into the system and the output auto-handoff predictions recorded. This would require ERAM to be available to the FAA. However, at the time of this study these ERAM capabilities were still in development. Therefore, the AMTWG authors of this study developed a software tool that would emulate these anticipated functions from ERAM utilizing the traffic scenario described previously and output from the User Request Evaluation Tool (URET)[7]. Since at the start of this study the auto-handoff initialization function in ERAM was still being finalized, two possible yet distinct approaches were modeled in this tool.

[7] Many of the prediction functions in ERAM find their basis in current URET functionality. The very functionality of the automated-handoff capability is based on URET predicted aircraft trajectories.

First, the prediction to the next sector was based on a Flight Plan Trajectory. In the tool, this prediction was based on two sources. For the horizontal dimension, URET was input with the recorded traffic scenario and its converted routes were recorded. These routes are URET's expansion of the traffic scenario's flight plan messages. They provide a path in the horizontal reference plane. The vertical profiles were predicted from the current vertical air traffic clearances. Both the horizontal and vertical profiles were supplemented with information from the current surveillance track reports. The ground speed estimates provided horizontal velocity estimates and similarly the vertical gradient speeds provided the same in the vertical dimension.

Next, another prediction to the next sector crossing was calculated by utilizing URET's 4-dimensional aircraft trajectory predictions. These were captured by inputting URET with the same traffic scenario described previously in Section 2.

For both the route predicted handoff event and the trajectory based version, the overall processing is listed in the following Figure 11. There are a number of labels used in Figure 11. If a route is available for the given aircraft at a given time, it is labeled as RA. If the aircraft trajectory of the same aircraft and time is available, it is labeled as TA. The results of the prediction tool populate a large relational database table. Two main fields indicate whether the predictions are valid. For the route predicted handoff, the field is labeled "is_sector_pred." A valid predicted sector based on the route is labeled "is_sector_pred=1." For the trajectory-based prediction, the indicator field is labeled "traj_is_not_pred." A valid predicted sector based on the trajectory is labeled "traj_is_not_pred=0."

The various results for the fields above and the overall decision tree are illustrated in Figure 11. The decision tree starts with an "or" statement deciding whether a route is available, a trajectory is available, or both. If both are not available, the flight and time point is simply logged and no entry is found in the database table. If one or both are available, the decision tree branches to separate processing for both predictions.

For the route based predictions, if the route was not available at all, the indicator field is labeled "is_sector_pred=-1." If the route is available, a prediction is attempted. This is a two-step process. The track reported position is projected onto the current route. The physical sector of this projected position is calculated. Next, the route is incremented forward in time, in increments of one second, until the position on the route is on a physical sector different than the projected sector or until the route ends without reaching another sector. If the sector along the route does change, the new sector is the predicted sector. This is labeled a valid prediction, stored as "is_sector_pred=1" from Figure 11. If the end of the route is reached before the sector changes, the indicator field is labeled "is_sector_pred=0."

For the trajectory based predictions, if the trajectory is not available at all for the given aircraft and time, the indicator variable is labeled "traj_is_not_pred=-1." If this was not the case (i.e. a trajectory is available), the next decision listed in Figure 11 checks to see if the current time is within the duration of the active trajectory. If it is not, a prediction to the next sector is not possible and the indicator label is set to "traj_is_not_pred=3." The actual prediction process, like the route-based version, is broken into two steps. First, the current track position is projected onto the active trajectory. For the projected position, the physical sector is determined. Next, starting at the projected position the physical sector is determined at one-second increments along the trajectory. If this sector changes from the original projected position's sector, it becomes the predicted sector. Under this condition, the indicator label is set to "traj_is_not_pred=0." This is a valid predicted sector.

Also as illustrated in Figure 11, if the projected sector on the trajectory is not within the ARTCC under study and the predicted sector reaches the end of the trajectory outside the ARTCC, the indicator label is set to "traj_is_not_pred=2," indicating the prediction is invalid. If the projected sector is within the ARTCC but the prediction sector reaches the end of the trajectory without changing, the prediction is again invalid and indicator label is set to "traj_is_not_pred=1."

There are more details of the processing for both the route predicted sector and trajectory predicted sector in the following sub-sections. In Section 2.2.1, the detailed algorithms are described for the route predicted sector. In Section 2.2.2, the same is provided for the trajectory predicted sector processing.

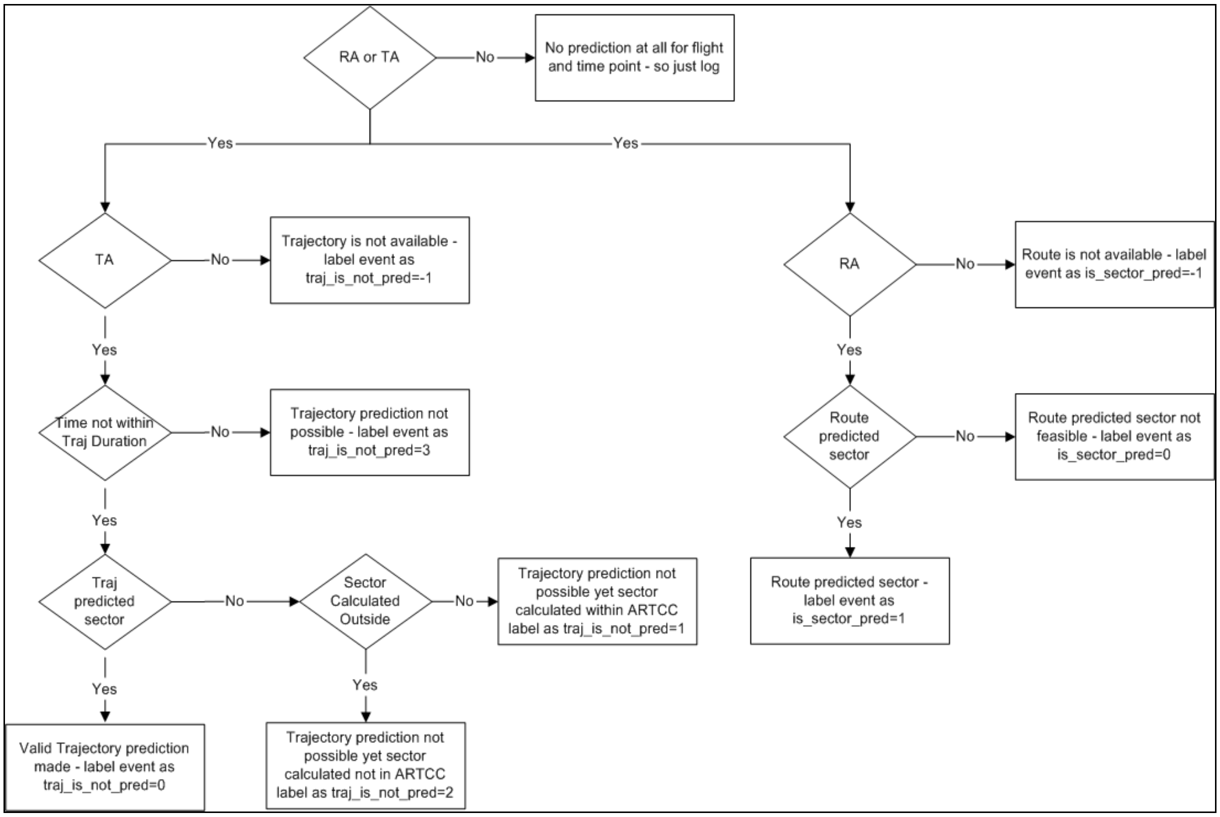

Figure 11: Overall Prediction Process

2.2.1 Processing of Route Predicted Sector

There are two simultaneous processing steps to generate the predicted sector from the aircraft's route of flight, representing the Flight Plan Trajectory in ERAM. The horizontal position is a predicted position on the converted route consistent with the current flight plan. The vertical position is an altitude consistent with the current cleared altitude. The various algorithms to calculate this position use a set of parameters. These are listed in the following Table 1. They will be referenced in the subsequent paragraphs as these algorithms are described.

Table 1: Reference Parameter List

Name of Parameter	Value	Units
timeIncrement	1	Seconds
timeWindowGspd	60	Seconds
timeWindowVert	30	Seconds
Thres1	300	Feet per minute
Thres2	-300	Feet per minute
Thres3	300	Feet

For the horizontal position, the current track report is projected on to the current active converted route. The projected position is the closest lateral position from the track report to the closest segment along the converted route. The current ground speed and ground speed's acceleration is estimated using a parameter of past surveillance track data (timeWindowGspd in Table 1). Equation 1 uses these estimated ground speed values to increment forward a distance along the route from the projected position on the route by a parameter time (timeIncrement in Table 1). Each new position incremented forward is evaluated for its physical sector.

$$\Delta d = \frac{1}{2}at^2 + tv \qquad \text{Equation 1}$$

where Δd is the distance along the route while the t is a parameter time increment, and v is the estimated ground speed and a is the estimated acceleration of the ground speed

While the horizontal position was incremented forward, the vertical position was calculated simultaneously using the same time increment. First, Figure 12 illustrates the calculation of vertical conformance status. The vertical conformance calculates a vertical speed using the altitudes of the track reports a parameter time in the past (timeWindowVert in Table 1). It uses the current altitude from the current track reported altitude and the current cleared altitude from the current air traffic control clearance messages. Thresholds one, two and three are listed in Table 1. Vertical conformance status is the descriptor of the current vertical state and conformance of the flight in terms of vertical speed and conformance to the active vertical clearance.

```
if ( (curVertSpeed > thres1) AND (curAlt < curClrAlt) ) {
    verticalConformanceStatus = "inCnfAscent" ;
} else if ( (curVertSpeed < thres2) AND (curAlt > curClrAlt) ) {
    verticalConformanceStatus = "inCnfDescent" ;
} else if ( (|curAlt - curClrAlt| < thres3) AND
            (thres2 ≤ curVertSpeed ≤ thres1) ) {
    verticalConformanceStatus = "inCnfLevel" ;
} else if ( (|curAlt - curClrAlt| < thres3) OR (first track position) ) {
    verticalConformanceStatus = "inCnfDefault" ;
} else {
    verticalConformanceStatus = "outOfCnf" ;
}
```

Figure 12: Vertical Conformance Status Pseudo Code

Next, the predicted vertical position was calculated by multiplying the vertical speed estimate described previously by the time increment (same as the horizontal algorithm). However, depending on the vertical conformance status the altitude is limited to the cleared altitude. In particular, if the aircraft is climbing and below the cleared altitude, the maximum altitude prediction is the cleared altitude. Similarly if the aircraft is descending and above the cleared altitude, the minimum altitude prediction is the cleared altitude. If the aircraft is within a threshold of the cleared altitude (see thres3 in Table 1), the prediction is the cleared altitude. This process is summarized in Figure 13. Notice the additional check at the bottom of Figure 13. The additional check limits predictions to above sea level and below 60,000 feet.

```
predAlt = curVertSpeed * timeIncrement
if ( at first track report ) {
   finalPredAlt = predAlt
} else if ( vertCnfStatus = "inCnfDescent" ) {
      finalPredAlt = maximum ( curClrAlt, predAlt)
} else if ( vertCnfStatus = "inCnfAscent" ) {
      finalPredAlt = minimum (curClfAlt, predAlt)
} else if ( vertCnfStatus = "inCnfLevel" OR
               vertCnfStatus = "inCnfDefault" ) {
      finalPredAlt = curClrAlt
} else {
      finalPredAlt =  predAlt
}
if ( finalPredAlt < 0.0 ) {
      finalPredAlt = 0.0
} else if (finalPredAlt > 60000.0) {
      finalPredAlt = 60000.0
}
```

Figure 13: Route Based Vertical Prediction Psuedo Code

Thus, the horizontal and vertical positions are calculated and the physical sector of this position is calculated. The process iterates (stepping forward in time by the timeIncrement parameter in Table 1) and each new position's physical sector is calculated. Once the new position is determined to be at a different sector than the projected position, the process ends and this new position is the predicted position and sector in which it falls is the predicted sector.

2.2.2 Processing of Trajectory Predicted Sector

The predicted sector based on the 4-D predicted trajectory is a somewhat simpler process. First, the active trajectory is selected from output trajectories from URET. For the current track report time, this is the latest trajectory built for the given aircraft up to the time of the current track report. The current track position is projected on to the trajectory. In a similar manner as the processing of the route-based prediction, the process steps forward a parameter time (timeIncrement parameter in Table 1) from the projected position and interpolates along the trajectory to determine the predicted position. The physical sector is evaluated and the process ends when the predicted position's sector does not match the projected position's sector. This new position is the predicted position and the sector in which it falls is the predicted sector. If the sector never changes by the time the prediction goes to the end of the trajectory, it is labeled invalid as discussed previously and as illustrated in Figure 11.

3. 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 statistics. 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 for 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 2.1.3.2).

3.1 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 flights 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[8].

The accepted crossings can be grouped into six (6) crossing events, which were used in the final analysis and were explained in detail in Section 2.1. An additional five (5) crossing events were identified but resulted in erroneous data that was discarded. The breakdown of accepted crossing events is listed in Table 2. Table 3 lists the discarded crossing events.

Table 2: Acceptable Sector Crossing Events

Event	Count	Percent of Identified Boundaries	Percent of Valid Scenarios
Ideal	6,143	82.5%	88.7%
Point-Out	424	5.7%	6.1%
Skipping Sector	35	0.5%	0.5%
False Init	120	1.6%	1.7%
Look Ahead	167	2.2%	2.4%
Multiple[9]	38	0.5%	0.5%
Total	**6,927**	**7,444**	**93.0%**

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

[9] This category caught situations where a crossing event could be categorized as more than one type of valid event.

Table 3: Discarded Sector Crossing Events

Scenario	Observations	Percent of Identified Boundaries
No Init	363	4.9%
Late Handoff	8	0.1%
Reverse Order	14	0.2%
No Handoff	62	8.3%
Late Handoff w/No Init	7	0.1%

3.2 Definition of Accuracy Metrics

As defined in Section 1.3, the primary objective of this study is 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 actual 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 in Equation 2.

$$\forall e : \frac{(\tau)}{(\mathrm{N}_e)} \qquad \textbf{Equation 2}$$

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.

3.3 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.

3.3.1 Overall Statistical Results

As shown in Table 4, 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[10]. 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 4: Operational Based Handoff Events Using Flight Plan Predictions

	Accurate Prediction		Row Total	
	Count	Row %	Count	Table %
Jet	3342	65.7%	5088	91.8%
Piston	43	47.8%	90	1.6%
Turboprop	214	58.6%	365	6.6%
Column Total	3599	64.9%	5543	100.0%
Start Time ≥ 30 seconds				

When a prediction was based on the aircraft trajectory instead of the flight plan, the accuracy improved somewhat as shown in Table 5. 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.

[10] For an analysis of the converted route flight plan, see Baldwin (2005).

Table 5: Operational Based Handoff Events Using Trajectory Predictions

	Accurate Prediction		Row Total	
	Count	**Row %**	**Count**	**Table %**
Jet	3690	72.5%	5088	91.8%
Piston	44	48.9%	90	1.6%
Turboprop	214	58.6%	365	6.6%
Column Total	3948	71.2%	5543	100.0%
Start Time ≥ 30 seconds				

In an attempt to determine a cause for the lack of accuracy, statistical analysis was performed on the horizontal, vertical, and cross track errors. Although all three variables showed some correlation to the prediction, only the vertical error had any significant correlation for both flight path and trajectory based predictions. Figure 14 shows the 95% confidence interval for the flight plan based and Figure 15 shows the 95% confidence interval for the trajectory based.

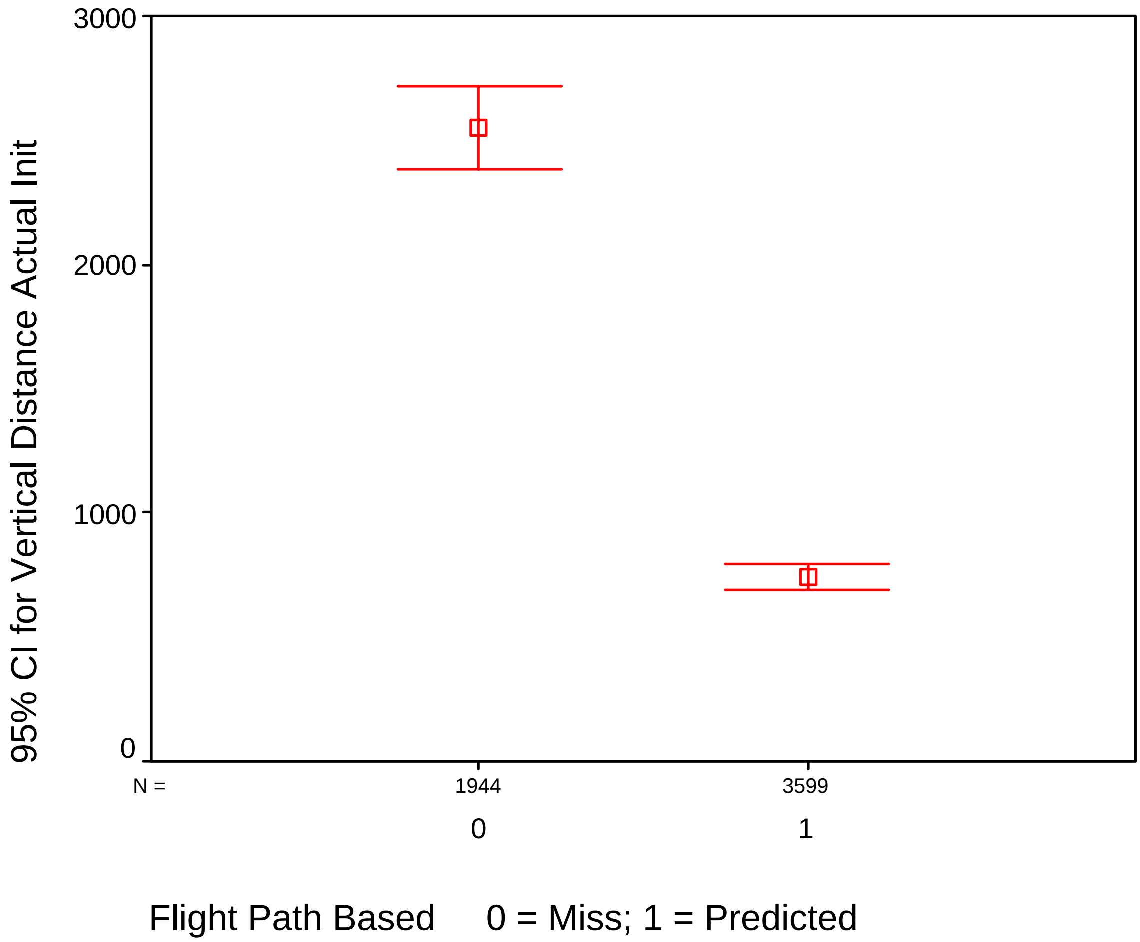

Figure 14: Vertical Distance Actual Init Flight Path Based Error Box-and-Whisker Graph

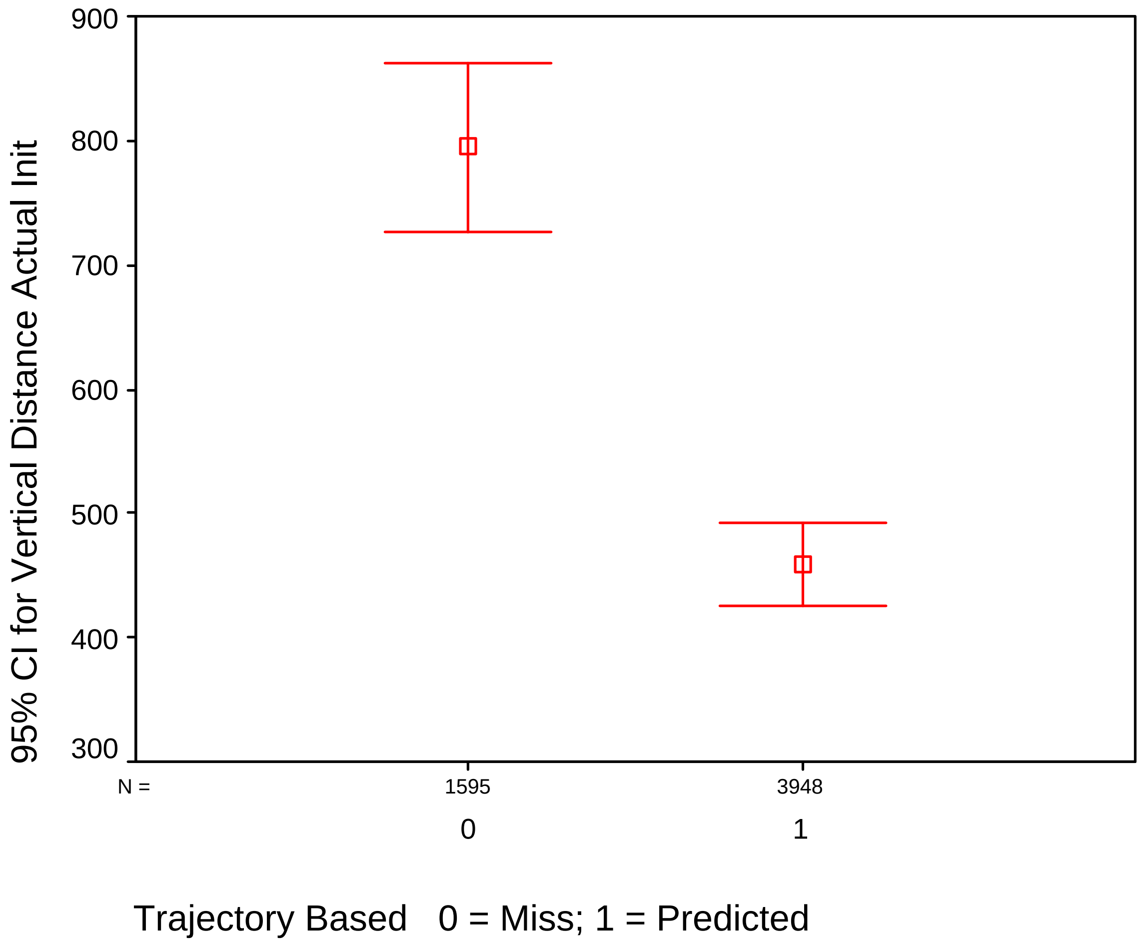

Figure 15: Vertical Distance Actual Init Trajectory Based Error Box-and-Whisker Graph

In both figures, the vertical axis represents feet of vertical deviation error; the 0 represents the category of missed predictions; and the 1 represents a successful prediction.

Although there was a significant correlation between the prediction accuracy and the vertical error, more analysis is required to establish cause and effect. It is possible that both effects are the result of an unknown factor. Furthermore, additional metrics were calculated at the location of the predicted sector that may further explain the error sources of the prediction. Due to resource constraints, the analysis of these effects will be left for future study.

3.3.2 Comparative Statistical Results

As stated previously, this study used the flight path and the trajectory to predict the next sector of an aircraft. Table 6 attempts to display in a form conducive to understanding the different results based on the operational data.

Table 6: Comparison of Operational Data Prediction Accuracy

	Trajectory Miss	**Trajectory Predicted**
Flight Path Miss	1415 (25.5%)	529 (9.5%)
Flight Path Predicted	180 (3.2%)	3419 (61.7%)

As shown in Table 6, 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.

3.3.3 Flight Examples

The following examples illustrate two common causes of prediction error. Flight example 1 is a case where the trajectory's sector prediction is wrong while the flight plan's prediction is right. In this example, a point out event as explained in Section 2.1.3.2 causes the error. On the other hand, the second flight example is a case where the flight plan's sector prediction is incorrect and the trajectory's prediction is correct. The altitude of the flight plan's predicted point is much higher than the actual altitude, causing the wrong sector to be predicted.

3.3.3.1 Flight Example 1

The first flight example is of 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. This 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 16. For a sector crossing at time 19:58:40, the trajectory's sector prediction was wrong while the flight plan's prediction was 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 2.1.3.2. Figure 17 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 did not match the next controlling sector, one could say that it is a correct prediction since it matches the next sector physically entered.

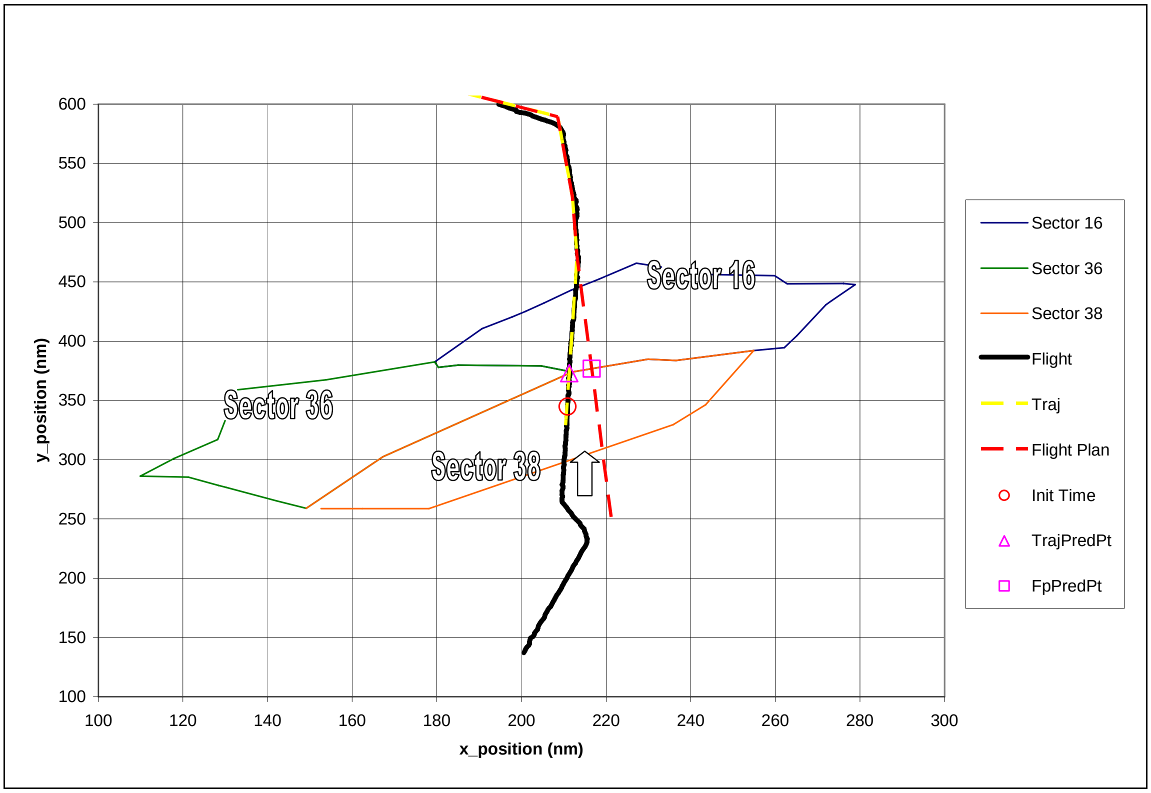

Figure 16: XY Position Plot for Flight Example #1

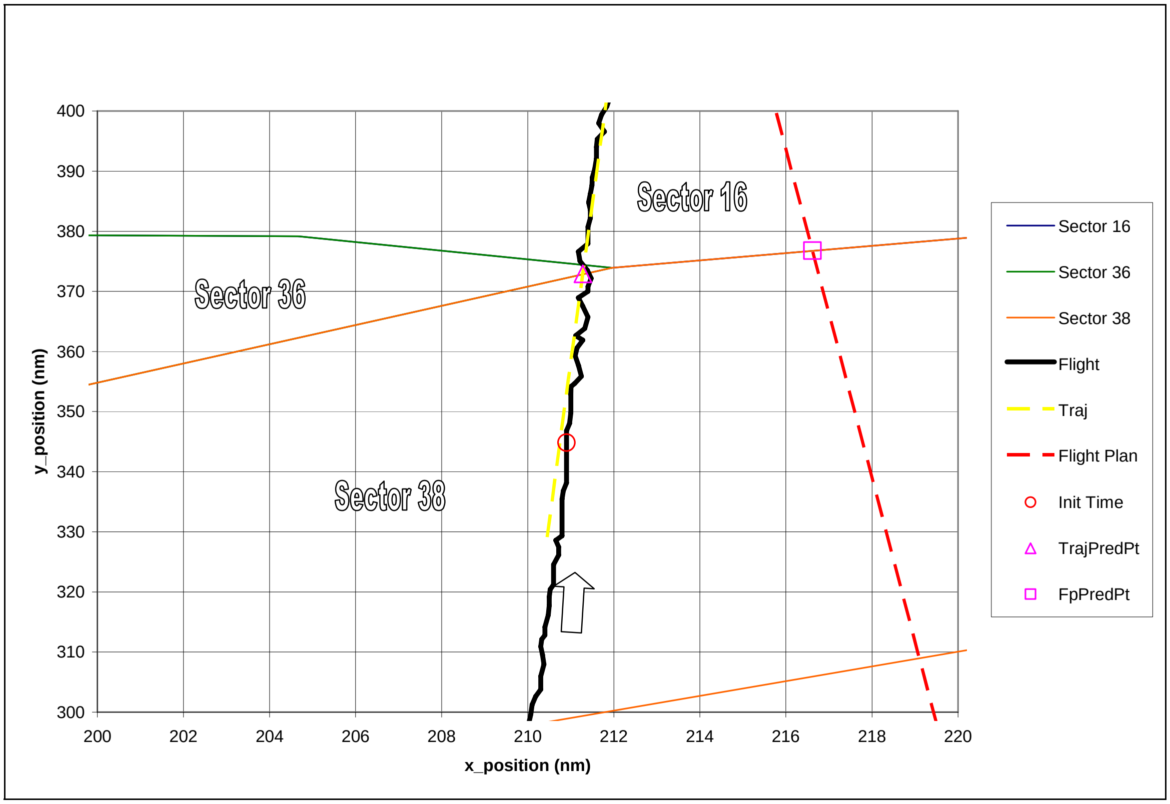

Figure 17: Close-up of Point Out for Flight Example #1

3.3.3.2 Flight Example 2

Example flight #2 is a departure flight that started its track in the Washington center at Raleigh-Durham International Airport in North Carolina with a destination of Philadelphia International Airport in Pennsylvania. This aircraft is a Boeing 737, large jet with twin engines.

Figure 18 is a position plot for the flight, trajectory, flight plan, physical sector, and predicted sectors. Control of this flight was initialized to sector 17 at 20:15:40 and actually crossed into sector 17 at 20:22:40. In this case, the trajectory's prediction was correct while the flight plan's prediction was not. The inaccuracy of the flight plan for this flight was due to a high altitude prediction. At the predicted time constructed from the initialization time, the flight plan's altitude was 29000 feet while the actual altitude was around 15150 feet. The altitude at the trajectory's predicted time was almost 23000 feet while the actual flight plan at that time was 23008 feet. Figure 19 is a graph of the flight's altitude and sector location based on time. The trajectory predicted point, flight plan predicted point, and sector altitudes are also shown in Figure 19. One can clearly see that the flight plan's predicted point is far beyond the top altitude of sector 17 and, instead, is within the altitudes of sector 19.

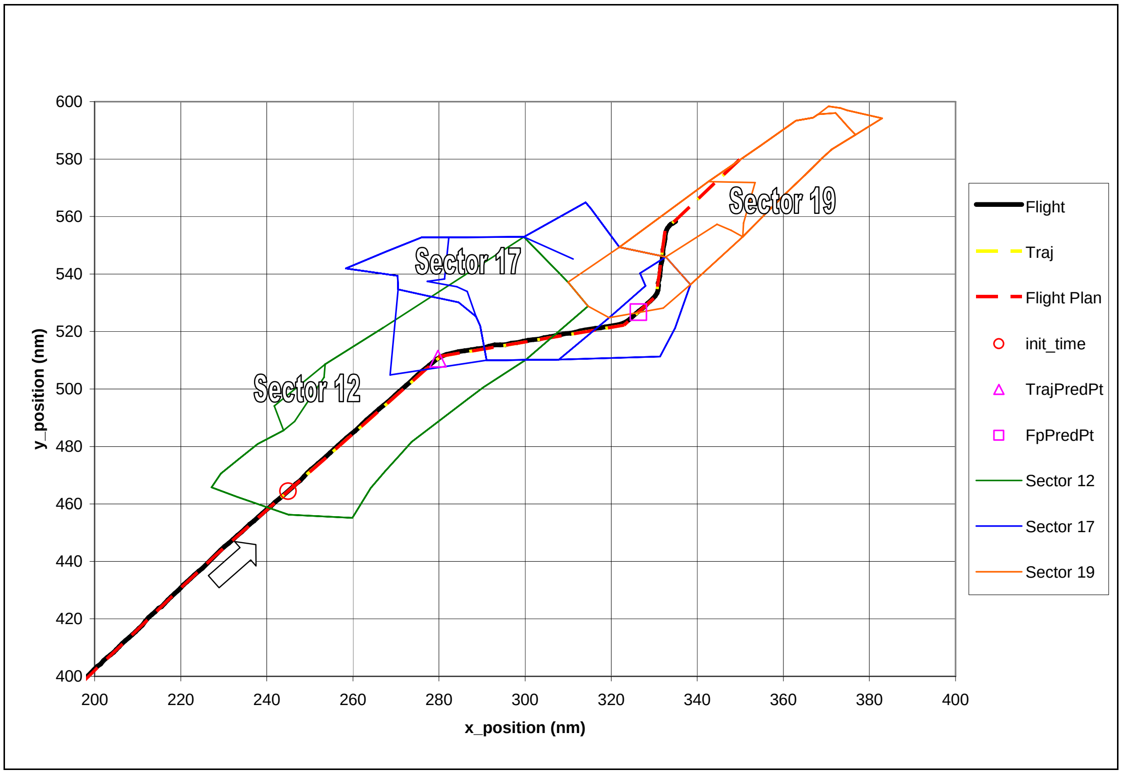

Figure 18: XY Position Plot for Flight Example #2

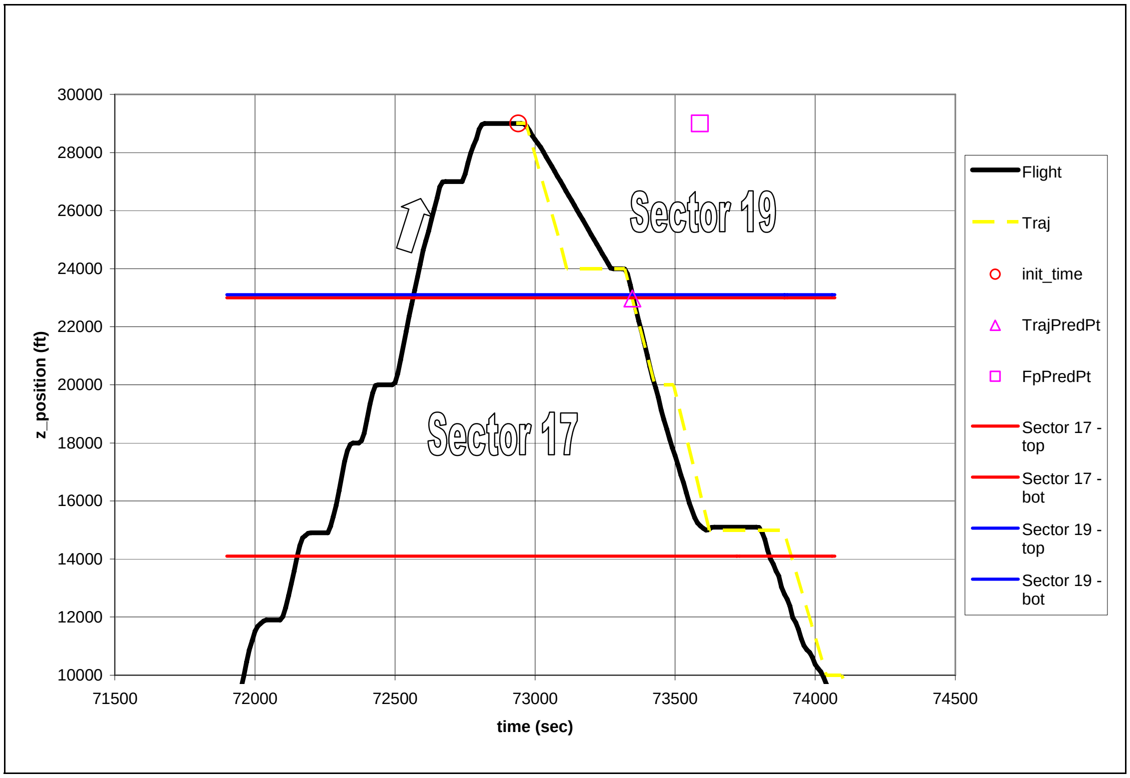

Figure 19: Altitude of Flight Example #2 by Time

3.4 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. These predictions were applied to Equation 2 as further metrics. 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 3.3.

3.4.1 Overall Statistical Results

As shown in Table 7, 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 7: Predicted Distance Handoff Event Using Flight Plan

	Accurate Prediction		Row Total	
	Count	Row %	Count	Table %
Jet	3799	74.5%	5096	92.5%
Piston	47	59.5%	79	1.4%
Turboprop	213	64.0%	333	6.0%
Column Total	4059	73.7%	5508	100.0%
Initialization Time ≥ 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 8. 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 8: Predicted Distance Handoff Event Using Trajectory

	Accurate Prediction		Row Total	
	Count	Row %	Count	Table %
Jet	4065	79.3%	5125	92.8%
Piston	44	58.7%	75	1.4%
Turboprop	230	71.0%	324	5.9%
Column Total	4339	78.5%	5524	100.0%
Initialization Time ≥ 30 seconds after start of track				

Similar to the actual initialization cases, an attempt was made to determine a cause for the lack of accuracy by performing statistical analysis on the horizontal, vertical, and cross track errors. As expected, the vertical error was the only significant correlation of the three errors for both flight path and trajectory based predictions. Figure 20 shows the 95% confidence interval for the flight plan based and Figure 21 shows the 95% confidence interval for the trajectory based. In both figures, the vertical axis represents feet of vertical deviation error; the 0 represents the category of missed predictions; and the 1 represents a successful prediction.

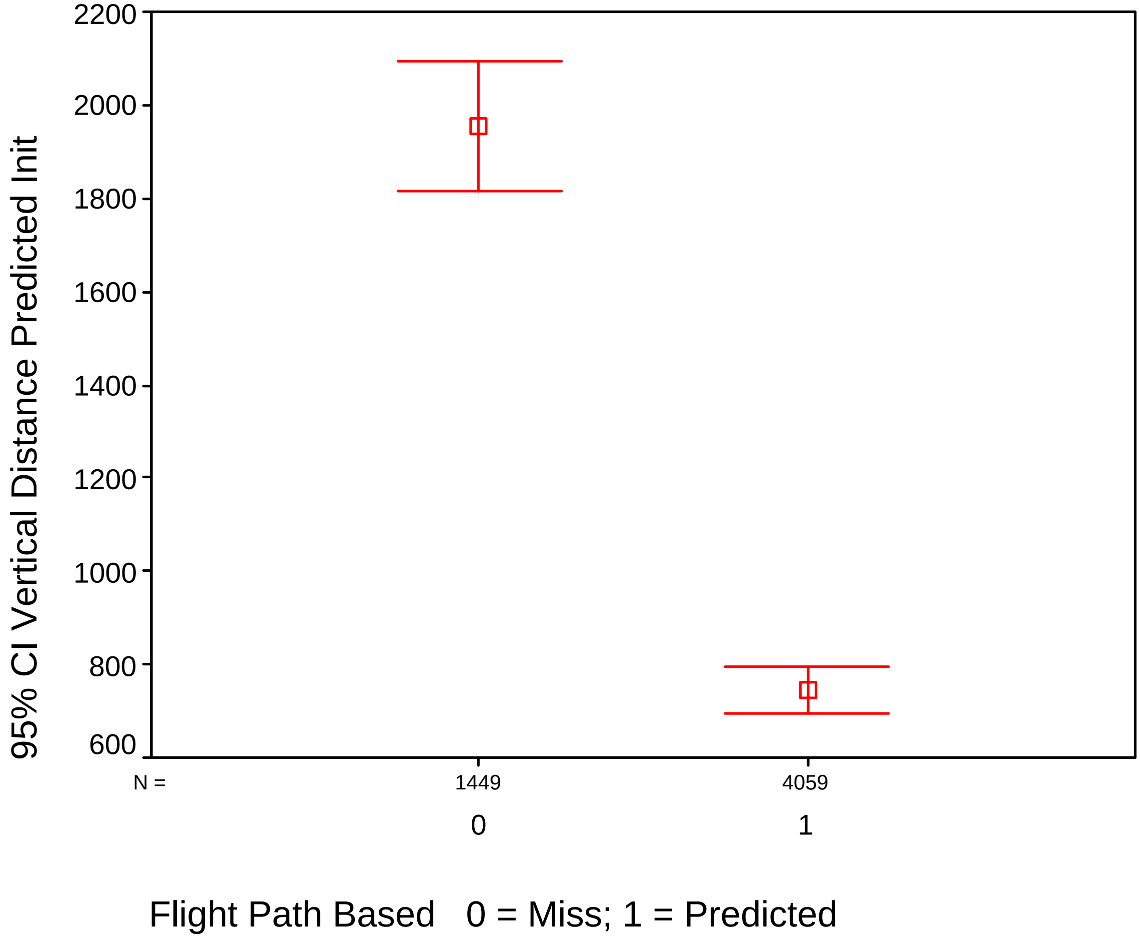

Figure 20: Vertical Distance Predicted Init Flight Path Based Error Box-and-Whisker Graph

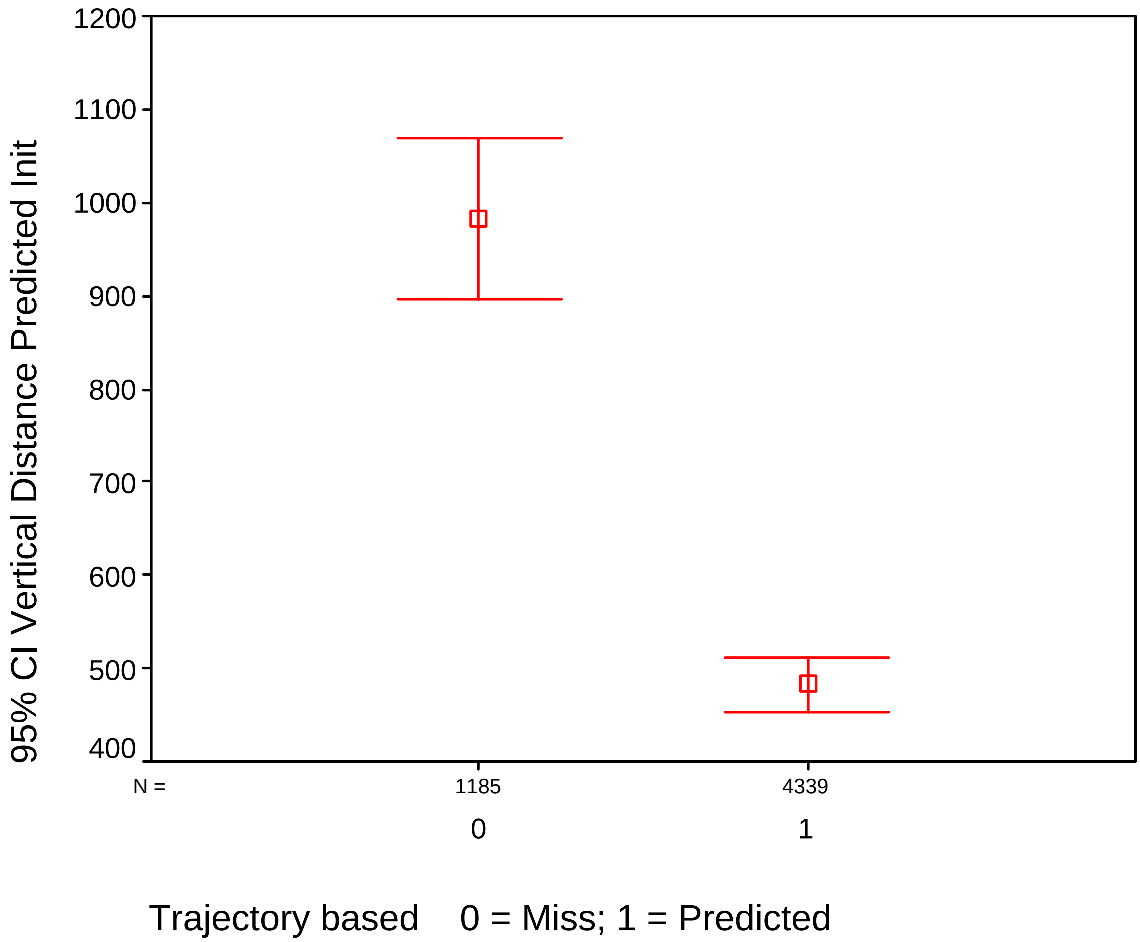

Figure 21: Vertical Distance Predicted Init Trajectory Based Error Box-and-Whisker Graph

As in the operational data case, cause and effect cannot be established from this study. Similarly, additional metrics were calculated at the location of the predicted sector that may further explain the error sources of the prediction. Due to resource constraints, the analysis of these effects will be left for future study.

3.4.2 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 9 attempts to display the results of the two approaches so that the reader can see any advantages or disadvantages.

Table 9: 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%)	3692 (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 3.3.2). As shown in Table 9, 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 9 is intended to be a comparison, only observations that were available from both datasets were used in the table calculations.

3.4.3 Flight Examples

The flight examples below represent two common causes of prediction error. For flight example 3, an exaggerated altitude prediction by the flight plan caused its sector prediction to be incorrect while the trajectory's prediction was correct. The fourth flight example is a point out scenario, which causes the trajectory's prediction to be wrong while the flight plan's sector prediction was right. Since the predictions for these examples are based on the distance to the crossing sector, the initialization time is not the same as the operational initialization time. Instead, it indicates the latest time at which the distance to the crossing sector falls below a specified threshold. While this time can be different for the flight plan and trajectory, the chosen examples have the same initialization time.

3.4.3.1 Flight Example 3

Our third flight example is a large Canadair Regional Jet 200 series with twin engines. An arrival flight departing from Greenville-Spartanburg International Airport in Greer, South Carolina, this flight landed in the ZDC center at the Ronald Reagan Washington National Airport in Arlington County, Virginia.

A position plot for the flight, trajectory, flight plan, physical sector, and predicted sectors can be seen in Figure 22. Note that sectors 16 and 20 share most of their position boundaries, but sector 16 covers higher altitudes than sector 20 as can be seen in Figure 23. This graph shows the altitude of the flight and predicted points based on time. The flight plan's predicted point occurs at the predicted time 21:41:04, and its altitude is 29,000 feet while the actual altitude at that time is around 26,000 feet. At the predicted time of the trajectory's predicted point, 21:41:25, the trajectory's altitude is 25,000 feet while the actual altitude at that time is 26,000 feet. This causes the flight plan to incorrectly predict the sector above the crossing sector and the trajectory's prediction to be correct.

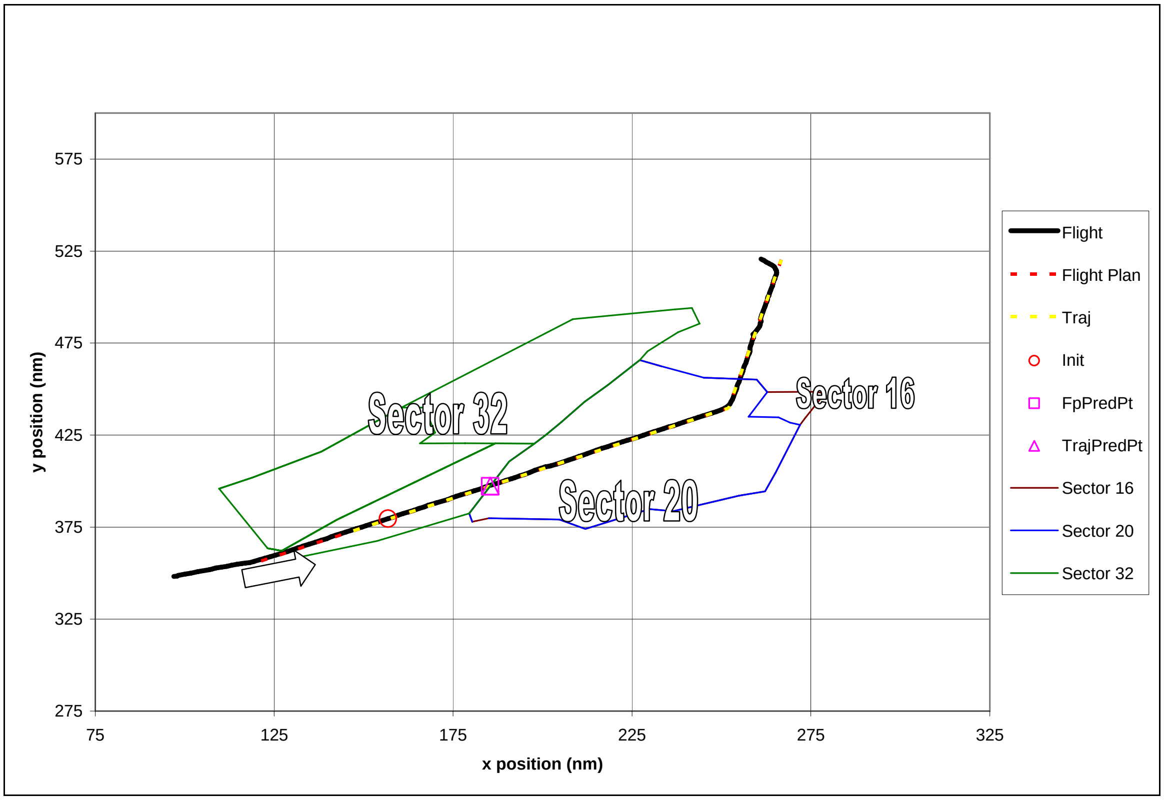

Figure 22: XY Position Plot for Flight Example #3

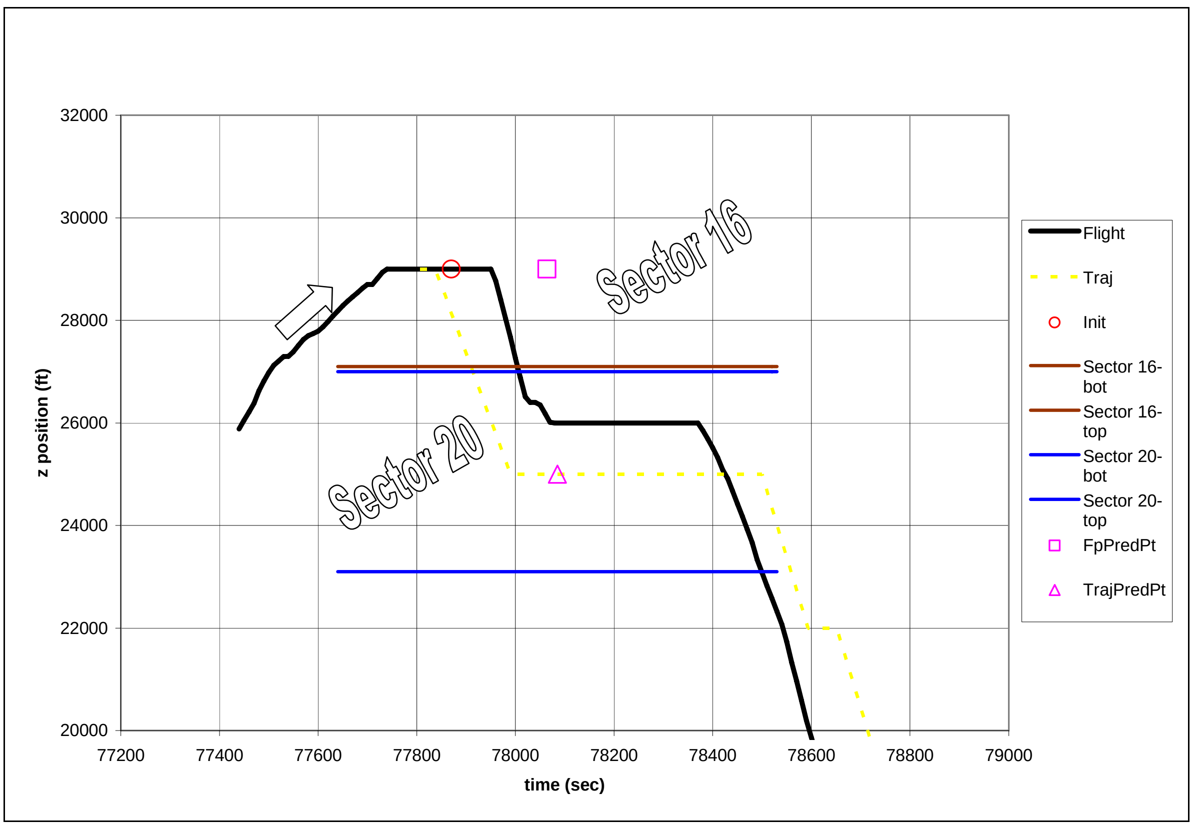

Figure 23: Altitude of Flight Example #3 by Time

3.4.3.2 Flight Example 4

Finally, the fourth flight example departed from Pittsburgh International Airport in Pennsylvania and flew through and landed in the ZDC center at Richmond International Airport in Virginia. This aircraft is an Embraer 145, large Regional Jet with twin engines.

Figure 24 is a position plot for the flight, trajectory, flight plan, physical sector, and predicted sectors. The latest time at which the distance to the sector boundary crossing is less than the specified threshold is 18:55:10 and the actual crossing occurs at 18:58:30. Figure 25 is a close-up of the same XY position plot and clearly shows the flight track and trajectory passing through sector 2 before entering sector 31 while the flight plan directly enters sector 31 from sector 29. However, sector 2 was never in control of the flight; thus, this is another example of a point out scenario and, as before, one could say that the trajectory is not wrong in this case as it correctly predicts the flight's entrance into sector 2.

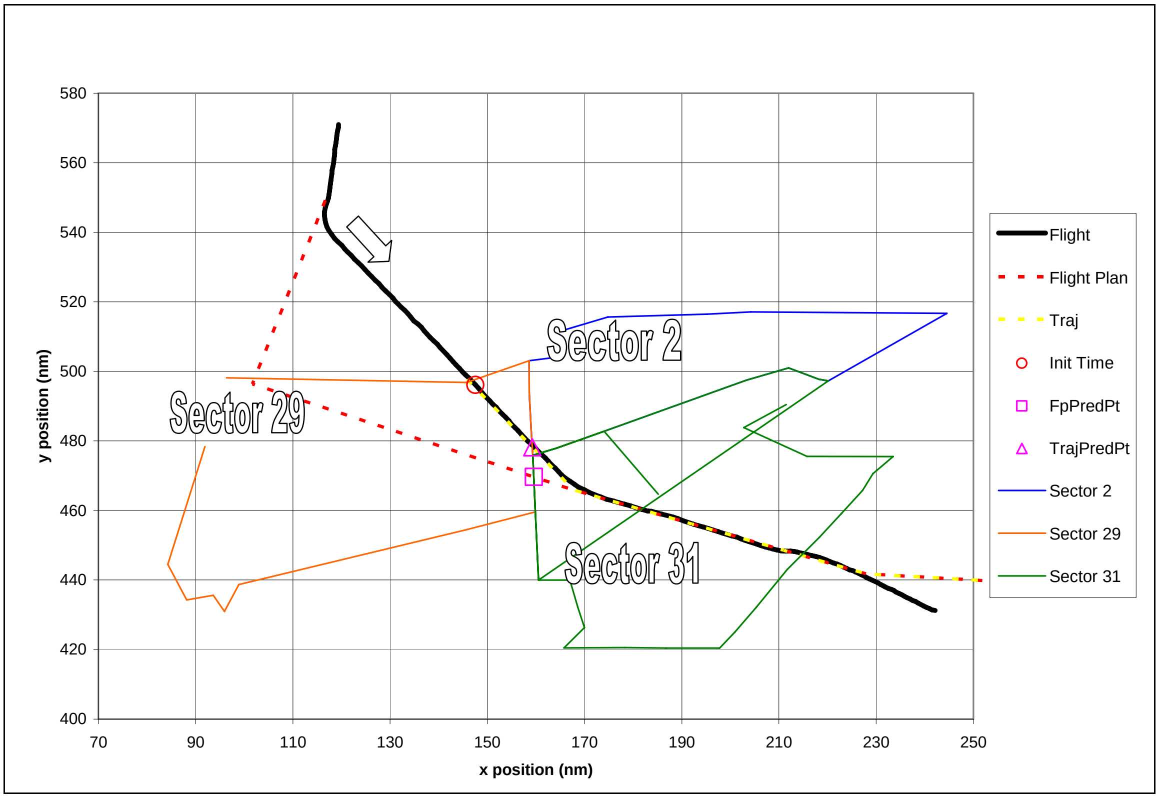

Figure 24: XY Position Plot for Flight Example #4

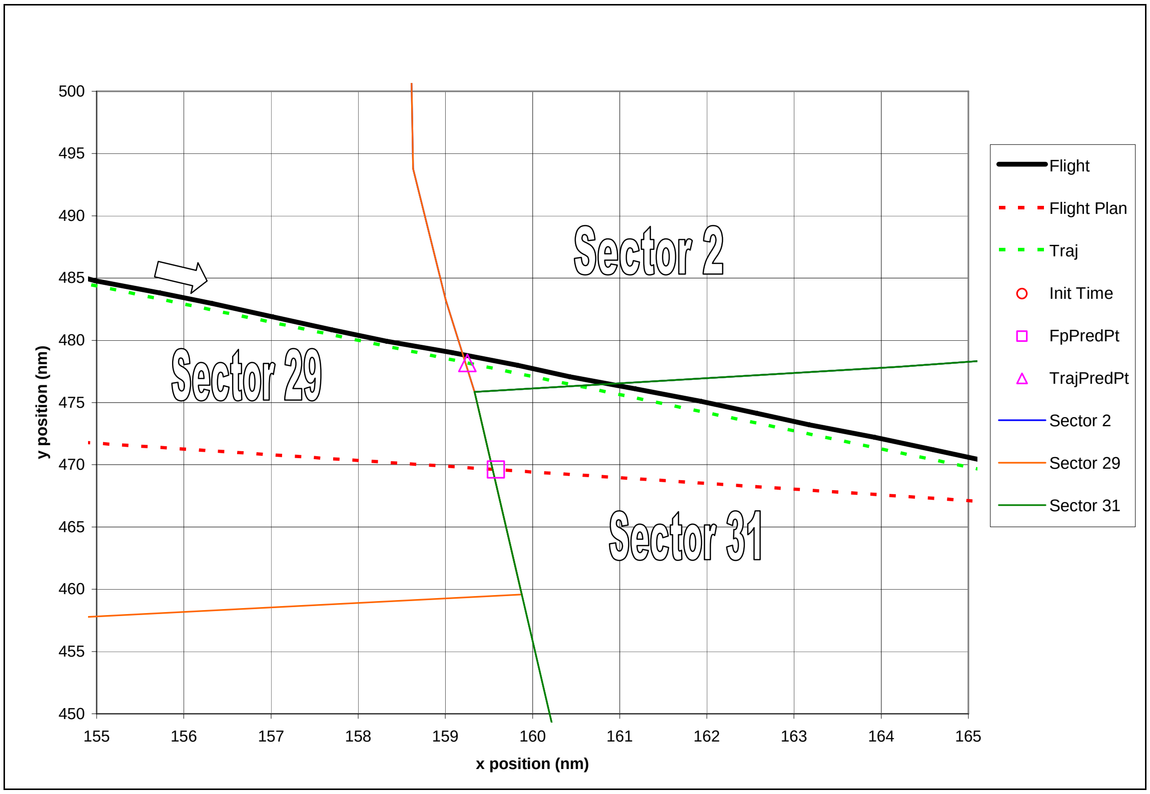

Figure 25: Close-up of Point Out for Flight Example #4

4. Conclusion

The study measured the performance of an automated process of 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 2.2, the study developed and analyzed two methods of predicting the handoff sector: (1) based on the flight plan converted route, referred to as the Flight Plan Trajectory and (2) based on a full 4-D trajectory prediction, referred to as the Aircraft Trajectory in ERAM documentation. 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 path, there is an additional assumption not present with trajectory-based predictions, which automatically checks the conformance of the prediction against the current aircraft prediction and builds a new trajectory accordingly[11]. When the assumption is incorrect (aircraft are deviating from the known flight plan), the prediction should have a lower probability of success.

Besides the type of prediction, the performance of the predictions of 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

[11] This processing of rebuilding a trajectory based on an out of conformance situation is referred to as reconformance.

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.

Besides the detailed flight examples that did provide insights into the sources of error, statistical methods were applied as well. Correlations were calculated between successfully predicted sectors and the prediction error at the prediction location (e.g. sector handoff initialization time) in the horizontal and vertical dimensions. Although there was a significant correlation between the prediction accuracy and the vertical error, more analysis is required to establish cause and effect. It is possible that both effects are the result of an unknown factor. Additional metrics were calculated at the location of the predicted sector that may further explain the error sources of the prediction. Due to resource constraints, further investigation and analysis of these effects will be left for future study.

5. Acronym List

AMTWG – Automation Metrics Test Working Group

ARTCC – Air Route Traffic Control Center

ATC – Air Traffic Control

COI – Critical Operational Issue

CPT – Conflict Probe Tool

DS – Display System

ERAM – En Route Automation Modernization

FAA – Federal Aviation Administration

FDP – Flight Data Processing

GMT – Greenwich Mean Time

HCS – Host Computer System

NAS – National Airspace System

nm – Nautical Miles

SDP – Surveillance Data Processing

TPM – Technical Performance Measurements

URET – User Request Evaluation Tool

WJHTC – William J Hughes Technical Center

ZDC – Washington Center at Leesburg, Virginia

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