

# **Evaluation of Prototype Enhancements to the En Route Automation Modernization Trajectory Modeler: Kinetic Vertical Modeling and Simple Turn Modeling**

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<b>16. Abstract</b> This technical note comprises four chapters that each detail a study evaluating prototype enhancements to the Trajectory Modeler (TM) of ERAM (En Route Automation Modernization). The first three chapters address the Kinetic Vertical Modeling (KVM) prototype enhancement, while the last chapter addresses the Simple Turn Modeling (STM) prototype. These prototype enhancements were developed to improve aircraft trajectory prediction and the studies specifically investigate trajectory prediction performance in descent modeling, climb modeling, and turn modeling.					
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## ***Executive Summary***

The Separation Management and Modern Procedures Project is an initiative of the Federal Aviation Administration (FAA) under the Next Generation Air Transportation System (NextGen) Program to implement improvements in the En Route Automation Modernization (ERAM) system, which supports all en route facilities in the United States. The FAA's Air Traffic Organization En Route Program Office (ATO-E) has tasked the FAA's Modeling and Simulation Branch (ANG-C55) to execute several studies investigating the impacts from various proposed prototypes and parameter changes in ERAM's Conflict Probe Tool (CPT). The overall objective is to improve the performance of the ERAM's CPT subsystem in preparation for integration of the CPT alert notification into the flight data block on the radar controller's main display.

This technical note comprises four chapters that each detail an analysis of data related to prototype enhancements to the Trajectory Modeler (TM) of ERAM. The first three chapters address the Kinetic Vertical Modeling (KVM) prototype enhancement, while the last chapter addresses the Simple Turn Modeling (STM) prototype.

### *KVM studies*

The KVM prototype enhancement created by Lockheed Martin implements a kinetic (physics-based) model that uses aircraft mass and speed profiles for each individual aircraft when building trajectories. To implement the kinetic model, the prototype makes use of EUROCONTROL's Base of Aircraft Data (BADA), which supplies aircraft performance information necessary to compute trajectories. This approach to trajectory prediction is designed to improve upon the limitations of the legacy kinematic (or parametric) model currently used in ERAM.

The first chapter covers a regression analysis to compare the performance of the current KVM prototype against an earlier version using the same data set - a flight scenario from the Air Route Traffic Control Center (ARTCC) in Seattle, Washington (ZSE). The objective is to confirm whether the current version has similar or improved performance to the earlier KVM prototype. The second chapter details a study to compare the performance of the KVM prototype against that of the current ERAM TM in modeling descents. The flight scenario is composed of aircraft performing Optimized Profile Descents (OPD) into George Bush Intercontinental Airport (KIAH) in Houston, Texas. The objective is to show the benefits of using the KVM prototype with Vertical Navigation (VNAV) modeling. The third chapter also compares the performance of the KVM prototype against that of the current ERAM TM when modeling climbs. The evaluated flight scenario includes flights performing continuous climbs within the Seattle ARTCC.

Analysis of data in the first study, which focuses on a select group of flights, indicates improved prediction performance of the TM when using the current KVM prototype. Improvements in Top of Descent prediction, descent rate, and trajectory accuracy are contrasted against the analysis of a previous KVM prototype and it is determined that, on average, the updated KVM prototype trajectory predictions are closer to the true track data than the previous KVM prototype. The study detailed in the second chapter finds improved trajectory prediction performance when comparing the KVM prototype to the legacy ERAM TM. Although the analysis was restricted to 20 flights, some significant average improvements are observed in this limited data set. The third study, on climb modeling, had mixed results. Slight improvements are observed in Top of Climb prediction metrics, but in analysis of traditional trajectory metrics improvements are only seen in some cases when segregating by trajectory maturity.

It should be noted that there are several updates and improvements to the KVM prototype included in the current version used for the experimental runs in these studies. Some changes are inspired by the findings of a previous study documented in [Schnitzer et al., 2015]. General modeling enhancements and updates include the use of track data to correct modeling for early descent, better handling of speed restrictions during descent, updates for the revised BADA atmospheric model, and implementation of the BADA climb speed schedule. In addition, VNAV modeling algorithms have been incorporated to support OPDs. These updates are detailed in [Torres, 2015].

### *STM study*

Finally, the fourth chapter describes an experiment to analyze the performance of the Simple Turn Modeling prototype. The current ERAM TM turn modeling is simplistic in nature, creating two adjacent linear trajectory segments at different headings. The Simple Turn Modeling (STM) prototype enhancement to the TM, created by Lockheed Martin, aims to improve the performance of the TM during turns by approximating a great circle route using piecewise linear segments.

The study detailed in Chapter 4 compares the performance, with respect to trajectory accuracy, of the STM prototype against that of the current ERAM TM. The approach of this study is to isolate segments of track during which a turn occurs, and to evaluate the performance of time-coincident trajectory segments for both the legacy and prototype TM. The flight scenario examined includes aircraft in the Seattle ARTCC.

This last study, which concentrates specifically on flights making inside turns within 10 NM of a fix on the filed route, finds that cross track error remains unchanged when STM is implemented. The along track error and vertical error are slightly degraded. Analysis and discussion indicate that several algorithmic issues were present in the version of the prototype scenario being evaluated, which have since been identified and corrected. The observed degradation and algorithmic issues suggest that the version of the STM prototype evaluated by ANG-C55 is problematic. However, the fact that correction of several software issues occurred prior to the evaluation strongly suggests that reevaluation is necessary prior to any useful recommendation regarding the suitability of the prototype for implementation into the operational ERAM.

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# Chapter 1 - Regression Test of Descent Modeling in Seattle Flight Data

## 1.1. Introduction

The Separation Management and Modern Procedures Project is an initiative of the Federal Aviation Administration (FAA) under the Next Generation Air Transportation System (NextGen) Program to implement improvements in the En Route Automation Modernization (ERAM) system, which supports all en route facilities in the United States. The FAA's Air Traffic Organization En Route Program Office (ATO-E) tasked the FAA's Modeling and Simulation Branch (ANG-C55) to conduct several studies investigating the impacts from various proposed prototypes and parameter changes to the Trajectory Modeler (TM) and/or Conflict Probe Tool (CPT) of ERAM. The overall objective is to improve the performance of the conflict probe in preparation for integration of the CPT alert notification into the flight data block on the radar controller's main display. Since predicted trajectories are a primary input to the CPT, the accuracy and stability of the TM impacts the quality of alerts.

Currently, the ERAM TM relies on kinematic (or parametric) modeling for descent and climb prediction. Referred to here as the legacy model, it uses population-average information from lookup tables to obtain speed, descent rate, and other factors for each aircraft type at a given altitude and temperature. The TM uses this information to determine Top of Descent (TOD), descent rate, and path. This parametric method works well for aircraft following step descents. At present, more flights are beginning to make use of advanced technologies to perform Continuous Descent Approaches (CDAs) at either idle-thrust or with a constant descent rate. Since the legacy kinematic model uses empirical data based primarily on flights making step descents, it is inadequate when modeling idle-thrust descents.

The Kinetic Vertical Model (KVM) prototype enhancement to the TM created by the ERAM development contractor Lockheed Martin aims to improve the prediction of TOD and descent rate for aircraft that descend at idle or near-idle thrust. The KVM prototype implements a kinetic (physics-based) model that uses aircraft mass and speed profiles (or other enhanced intent information) which are either provided or can be inferred for each individual aircraft when building trajectories. To implement the kinetic model the prototype also makes use of EUROCONTROL's Base of Aircraft Data (BADA) [Nuic, 2014], which supplies aircraft performance information necessary to compute trajectories. The KVM model is designed to improve upon the limitations of the legacy kinematic model. Flights following Optimized Profile Descents (OPD) and/or Continuous Descent Arrivals (CDA) will benefit from the updated modeling approach.

This specific study is designed to compare the performance, with respect to trajectory accuracy, of the current KVM prototype against the results of a previous study documented in [Schnitzer et al., 2015] that evaluated an earlier KVM prototype. The objective is to confirm whether the current version has similar or improved performance to the earlier prototype. As mentioned in the Overview, there are several updates and improvements to the KVM prototype included in the current version used for this study's experimental runs.

## 1.2. Methodology

This study is a regression test to evaluate performance of the updated prototype against that of the previous version analyzed in [Schnitzer et al., 2015].

### 1.2.1. Data Flow

For this study, the analysts used ERAM track and clearance messages along with wind data from March 14, 2014 at the Seattle (ZSE) ARTCC. The data was collected using Lockheed Martin's Sarbot tool. As detailed in [Schnitzer et al., 2015] and [Torres, Dehn, and Little, 2014], flights with continuous descent arrivals (CDA) consistent with idle or near-idle thrust profiles were selected as a subset of the original data. After analyzing the cruise and descent phases of these flights, the Top of Descent (TOD) was determined. For each flight, experimental interim altitude messages were created with altitude set equal to the cruise altitude. These messages were then inserted into the scenario with timestamps approximately 25 minutes prior to TOD. This forced the TM to build trajectories for these flights at approximately the same time relative to true TOD. Since trajectory accuracy varies with look ahead time, having all trajectories produced at the same time makes a fair comparison possible. Without these experimental interim altitude messages, trajectory build times could not be controlled.

Lockheed's Virtual Testing Laboratory (VTL), a laboratory version of ERAM, ran this 9-hour experimental scenario to produce output scenario data consisting of track and trajectory points. The ANG-C55 Modeling and Simulation Branch analyzed the output scenario with *CpatTools*, a customized software suite that takes flight traffic input files and creates a linked set of relational database tables. These tables include smoothed track, clearance, and route data, as well as trajectory metrics. The analysts used this output data for all subsequent trajectory analysis. The data input to VTL for the current study (flight plans, controller inputs, target data) is identical to the previous study in [Schnitzer et al., 2015]. However the version of ERAM simulated in the lab has been slightly updated since then and as a result, scenarios should not be compared directly across the two studies. To guarantee a fair basis for comparison, an updated baseline scenario is run in VTL (the impact on trajectories is found to be very small). Analysts measured the KVM prototype against this updated baseline, and compared the observed effect to the effect found in the previous study which used an identical approach.

### 1.2.2. Analysis Methods

The analysts conduct a regression test on the performance of an updated KVM prototype enhancement to the Trajectory Modeler, comparing it to an earlier version. Analysis includes the following scenarios:

- **Baseline** – Legacy trajectory prediction using kinematic modeling
- **KVM-All** – Trajectory prediction using kinetic modeling in current KVM prototype

#### 1.2.2.1. Data Collection and Reduction

There were 61 flights designated by Lockheed [Torres, Dehn, and Little, 2014] as CDA flights; however, the previous study incorporated only 55 flights. For consistency, this study focuses on the same 55 flights. The previous study [Schnitzer et al., 2015] elaborated on the exclusion of other flights. The analysts use custom *Oracle* SQL queries to retrieve the necessary scenario information produced through *CpatTools*. For each flight in the scenario, analysts identified the trajectory build triggered by the experimental interim altitude message. Next, the time and altitudes at TOD are calculated for both the track and trajectory. The analysts define Bottom of Descent (BOD) for each flight as 15,000 ft. in this scenario. This ensures that the descent segment is relatively continuous and not interrupted by altitude restrictions or other influences. The analysts confirmed that this altitude was appropriate through visual exploration of the data using *FliteViz4D*, an interactive 4D visualization tool developed by ANG-C55 [Crowell, Fabian, and Nelson, 2012].

#### 1.2.2.2. **Metrics**

Metrics for this study include a subset of the standard trajectory metrics used in many studies [Paglione and Oaks, 2007]. *Vertical error* is defined as the vertical distance between a track point and its time coincident trajectory point, and *along track error* is defined as the longitudinal distance between a track point and its time coincident trajectory point. The analysts briefly examined *cross track error* - defined as the lateral distance between a track point and its time coincident trajectory point - and observed no effect. Therefore, this study focuses on vertical error and along track error to assess trajectory accuracy.

In addition, the analysts apply metrics specific to descent prediction, detailed in [Paglione et al., 2011] and [Bronsvoort et al., 2011]. *TOD Error* is defined as the difference in time between the track-determined TOD and the trajectory TOD, where negative values indicate that the predicted TOD occurred prior to the actual TOD. Descent rate is the mean rate of descent of the aircraft over the region of time spanning the TOD to BOD, i.e. change in altitude divided by elapsed time. *Descent rate error* is the difference between the calculated descent rate for the actual path (track) and the predicted path (trajectory), where a negative value indicates that the predicted descent rate is steeper than the true descent rate.

## 1.3. Analysis

This section describes the results of the analyses described in Section 1.2.2. Section 1.3.1 details an evaluation of the parameters TOD and descent rate regarding how accurately they predict the track of each flight. As previously stated from [Schnitzer et al., 2015], TOD and descent rate can be analogous to the intercept and slope of a linear model; therefore, this analysis of descent metrics is an informal goodness-of-fit test to evaluate the KVM Trajectory Modeler. Section 1.3.2 presents an analysis of general trajectory accuracy for one critical trajectory built prior to TOD. Finally, Section 1.3.3 exhibits visual examples demonstrating flight track and trajectory differences for the previous and current KVM prototype enhancements to the TM.

### 1.3.1. Descent Statistics

This section presents the results for descent metrics (TOD, descent rate) comparing the predicted trajectory to the actual flight data. TOD errors of 0 seconds indicate the TM perfectly predicted the time at which TOD actually occurred. Negative TOD errors indicate that the TM predicts an early TOD, while positive TOD errors indicate a predicted TOD that is later than the true TOD. Table 1 presents summary statistics for TOD.

**Table 1. Statistics for top of descent prediction error**

	<b>TOD Error: Baseline</b>	<b>TOD Error: All</b>
<b>Mean (seconds)</b>	-151.3	47.7
<b>SD (seconds)</b>	102.1	70.5
<b>No. flights</b>	55	55

The Baseline scenario predicts TOD about 2.5 minutes (151.3 seconds) earlier than the truth. With application of the KVM algorithm, the KVM-All scenario reduces the magnitude of the TOD prediction error from 151.3 seconds to 47.7 seconds, an improvement of 68.5%. This reduction in magnitude reflects a TOD prediction that is more accurate than that of the Baseline scenario. The change in sign indicates that the KVM algorithm, on average, overestimates the true TOD time and the legacy algorithm underestimates the time.

The second descent error metric pertains to the rate of descent, expressing the difference in descent rate between the trajectory and the observed track data. A negative error indicates that the predicted descent rate is faster (steeper) than the true descent rate, while a positive error indicates that the descent rate is slower (shallower). Table 2 presents summary statistics for descent rate error.

**Table 2. Statistics for descent rate error**

	<b>Descent Rate Error: Baseline</b>	<b>Descent Rate Error: All</b>
<b>Mean (ft/min)</b>	375.4	-267.1
<b>SD (ft/min)</b>	282.1	254.1
<b>No. flights</b>	55	55

In the Baseline scenario, the results indicate a descent rate that is 375.4 ft/min shallower than the true descent rate, which the analysts expected as the early TOD prediction allows the flight more time to descend. In the KVM-All scenario the descent rate is 267.1 ft/min steeper than the true descent rate. It follows that a prediction of later TOD leaves less time for the flight to descend, and produces a negative descent rate error. In comparing the magnitude of descent rate error, the KVM-All scenario is more accurate, with 28.8% decrease in absolute error from the Baseline scenario. These results reflect an improvement in performance of the KVM prototype compared to the previous version (Table 3).

**Table 3. Descent error statistics for previous KVM study [Schnitzer et al., 2015]**

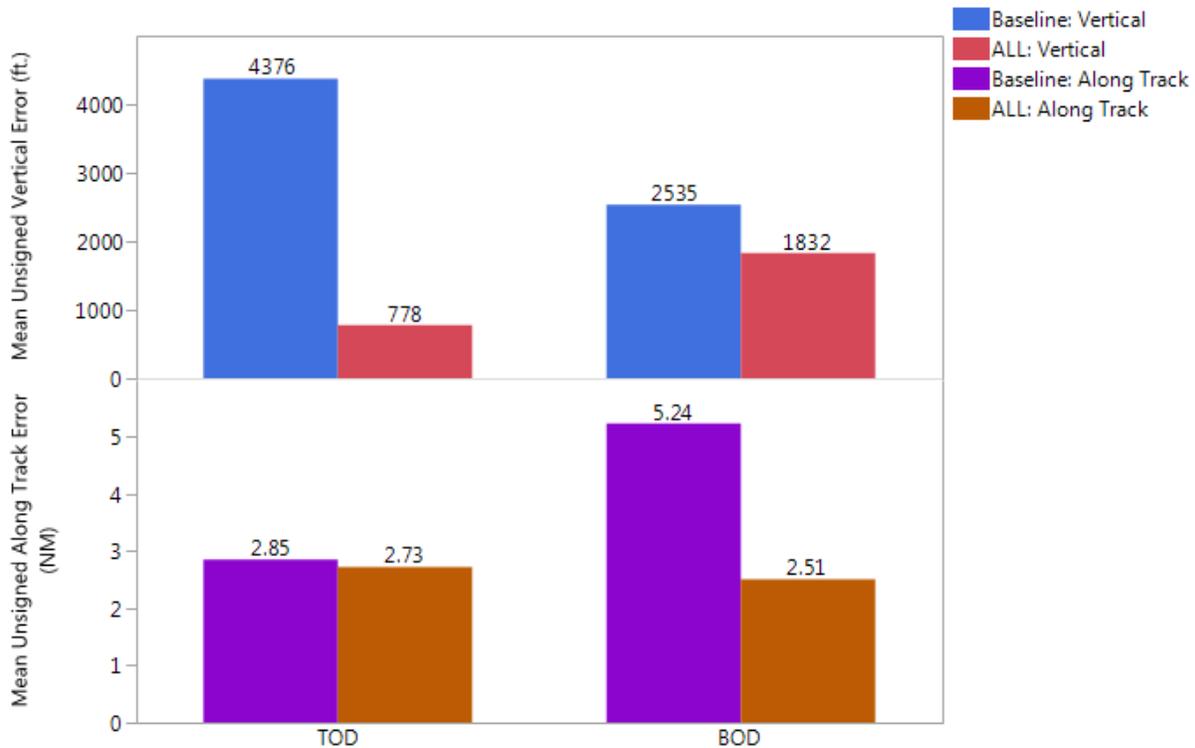
	<b>TOD: Baseline</b>	<b>TOD: KVM-All</b>		<b>Descent Rate: Baseline</b>	<b>Descent Rate: KVM-All</b>
<b>Mean (seconds)</b>	-149.0	71.2	<b>Mean (ft/min)</b>	372.8	-426.5
<b>SD (seconds)</b>	101.5	82.6	<b>SD (ft/min)</b>	279.4	299.4
<b>No. flights</b>	55	55	<b>No. flights</b>	55	55

In the previous study, TOD absolute error in the KVM-All scenario was 52.2% less than the Baseline scenario. Using similar Baseline trajectories in the current study, results indicate a decrease of 68.5%. In the previous study, descent rate error in the KVM-All scenario was 14.4% larger than the Baseline scenario. However, in the current study descent rate error in the KVM-All scenario is 28.8% smaller than the Baseline scenario.

### **1.3.2. Trajectory Accuracy**

For the overall trajectory error analysis, differences between the actual track and predicted trajectory are calculated using the metrics vertical and along track error, defined in Section 1.2.2. The critical trajectory selected for analysis is the one built at 25 minutes prior to TOD. If that trajectory is not available, then the earliest trajectory with associated track data is used. As in the previous study, the analysts calculate the time until TOD (*TimeToTOD*) to normalize the data based upon when true TOD occurred. For an accurate prediction, a TimeToTOD value of -120 seconds indicates that TOD will occur in 2 minutes.

Analysts examined trajectory accuracy at TOD and BOD, where BOD is defined as 15,000 ft. The top of Figure 1 displays the mean unsigned vertical error in feet, and the bottom displays mean unsigned along track error in nautical miles. The bars on the left of Figure 1 depict error at TOD, while the bars on the right depict error at BOD.



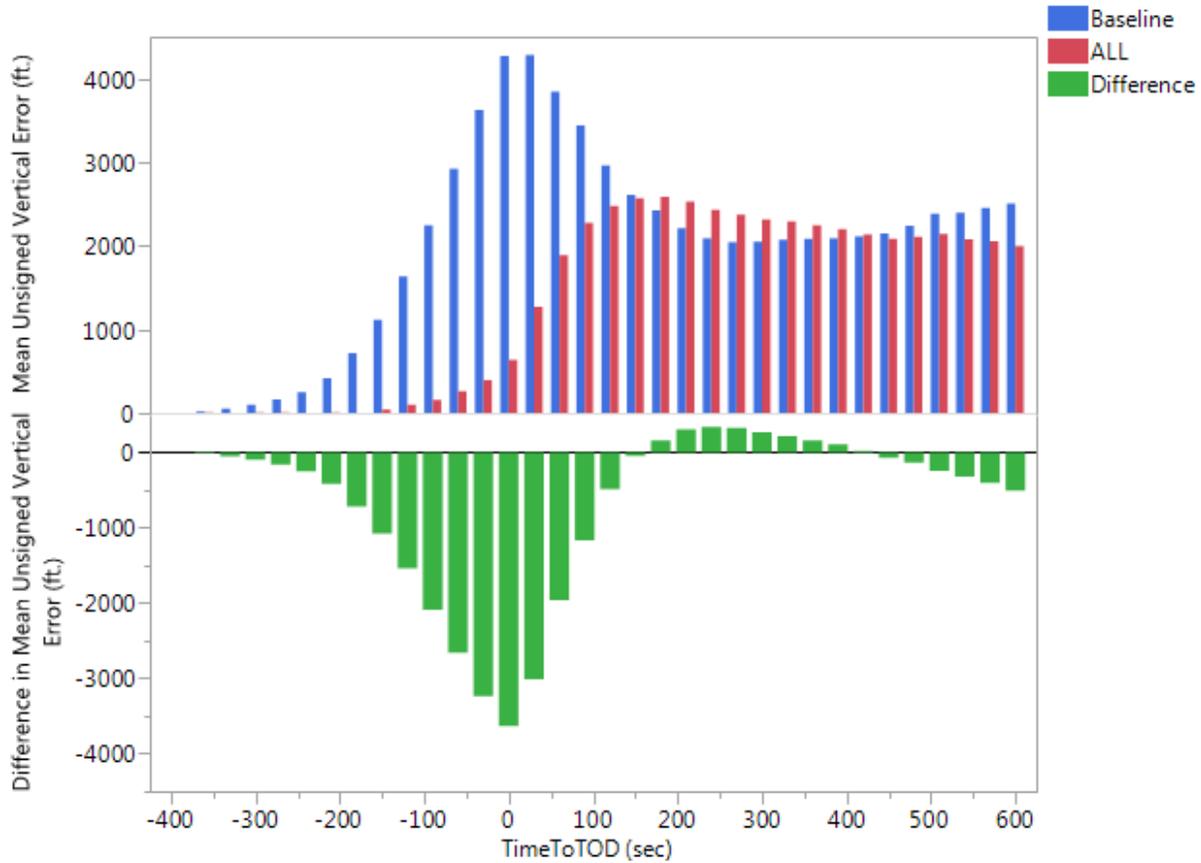
**Figure 1. Mean unsigned vertical and along track error at TOD and BOD**

The mean unsigned vertical error at TOD decreases from 4,376 ft. in the Baseline scenario to 778 ft. in the KVM-All scenario. This is an 82.2% improvement, attributed to the adjustment in TOD modeling, with the predicted TOD much closer to the true TOD. Due to the flights converging towards a common point as they approach BOD, the analysts expected the vertical error values to be much closer between the Baseline and KVM-All scenarios. At BOD, the Baseline has a vertical error of 2,535 ft. and the KVM-All has a vertical error of 1,832 ft., which is a 27.7% improvement.

The mean unsigned along track error at TOD is 2.85 NM for the Baseline scenario. The KVM-All scenario has an error of 2.73 NM on average, indicating a 4.2% improvement. The Baseline scenario has an average along track error of 5.24 NM at BOD, while the KVM-All scenario has an average error of 2.51 NM at BOD. This is an improvement of 52.1%.

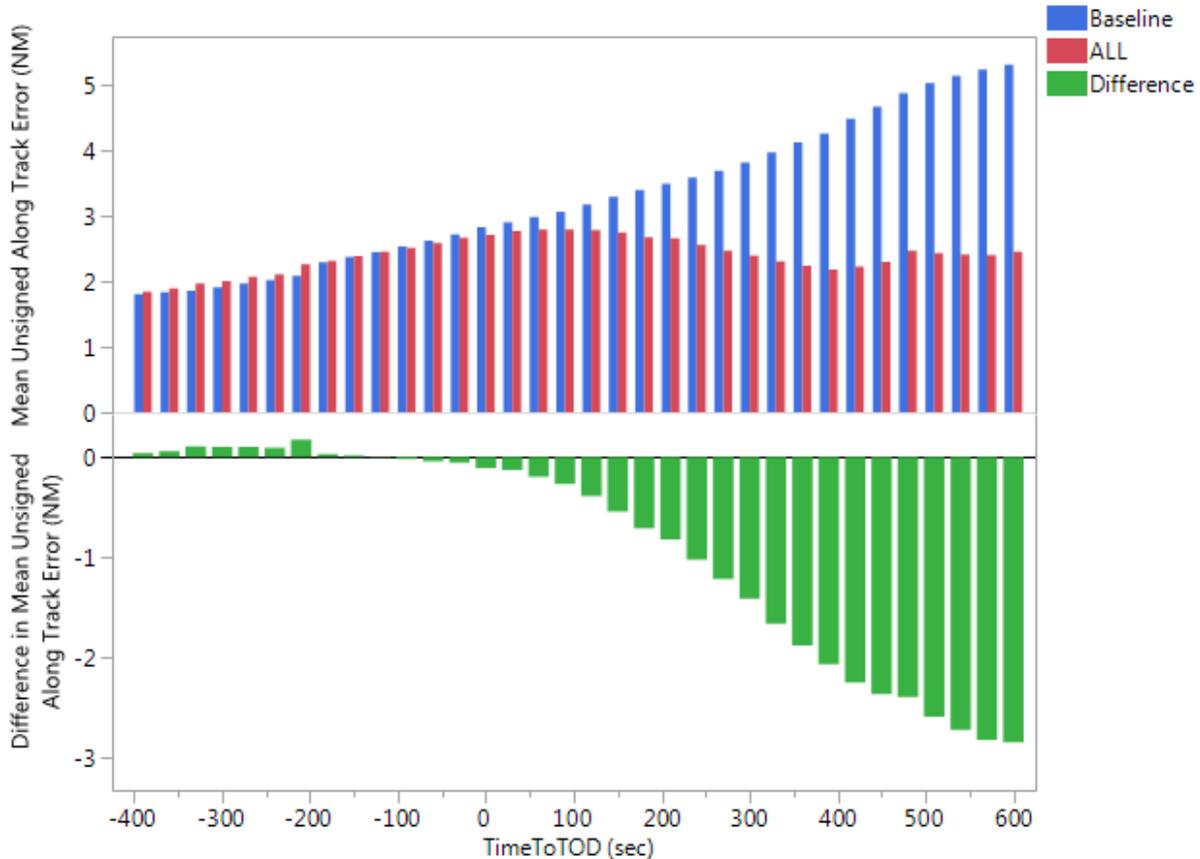
The previous study found an improvement in mean unsigned vertical error from the Baseline to the KVM-All scenarios of 82.5% and 16.0% at TOD and BOD respectively. Comparing to the current study, the improvements from Baseline to KVM-All are 82.2% and 27.7% at TOD and BOD. The previous study found improvements in mean unsigned along track error from the Baseline to the KVM-All scenarios of 5.6% and 25.5% at TOD and BOD, respectively. In the current study, improvements from Baseline to KVM-All are 4.2% and 52.1% at TOD and BOD, respectively.

For a broader view of trajectory accuracy, the analysts examine vertical and along track error throughout the entire descent to verify that any trajectory prediction errors are not specific to TOD and BOD. Figure 2 presents mean overall unsigned vertical error.



**Figure 2. Overall mean unsigned vertical error**

The top half of Figure 2 shows the vertical error during descent for both scenarios. At about 6 minutes prior to TOD, we see the Baseline scenario begin to accumulate vertical error (blue bars). The largest magnitude of vertical error for the Baseline scenario occurs at true TOD, which is consistent with an early prediction of TOD. As TimeToTOD approaches 0, the vertical error in the KVM-All scenario (red bars) begins to increase until reaching its peak value sometime after true TOD, which is consistent with a TOD predicted later. The bottom part of Figure 2 shows the difference in mean unsigned vertical error (green bars) over time between the Baseline and KVM-All scenarios. For these green bars, negative values represent an improvement, or reduction in trajectory error from the Baseline to KVM scenario. We see improvement in the KVM-All predictions up to and just after TOD. This is consistent with an improved TOD prediction by the KVM-All algorithm. There is a slight degradation between 3 and 7 minutes after TOD, but afterwards the KVM-All predictions continue to improve compared to the Baseline scenario. Overall, the KVM-All scenario demonstrates better trajectory accuracy performance than the Baseline scenario.



**Figure 3. Overall mean unsigned along track error**

The mean unsigned along track error is displayed in the top half of Figure 3. Both scenarios have roughly 2 NM error at 6 minutes before true TOD. Closer to the time of true TOD is the critical point in which the KVM-All algorithm outperforms the Baseline scenario. At TOD, the Baseline scenario has an average error of 2.85 NM that steadily increases to 5.24 NM at BOD. On the other hand, the KVM-All scenario has an error of 2.73 NM at TOD that decreases to 2.51 NM at BOD. The bottom half of Figure 3 shows the difference in mean unsigned along track error between the two scenarios. This represents a trajectory accuracy improvement in the KVM-All scenario over Baseline of 52.1% at BOD.

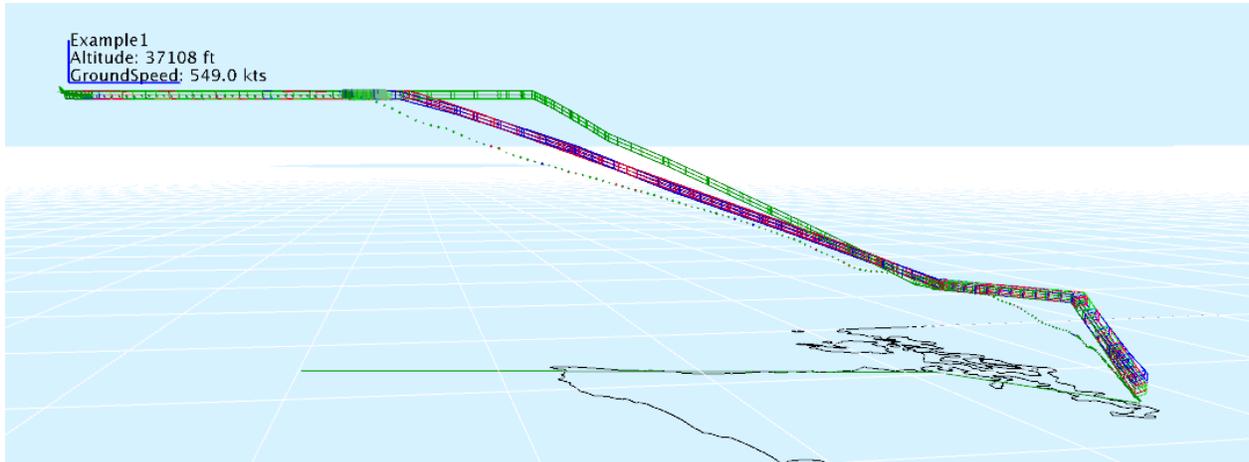
### 1.3.3. Flight Examples

The following flight examples demonstrate track and trajectory differences for the previous and current KVM prototype enhancements to the TM. Dotted lines depict flight track data and blue wireframes represent the Baseline trajectory. The red wireframes represent the trajectory from the current KVM prototype, while the green wireframes represent the trajectory from the previous KVM prototype. Cylinders of each respective color signify the trajectory predicted aircraft location at the time of true TOD.

#### 1.3.3.1. Flight Example 1

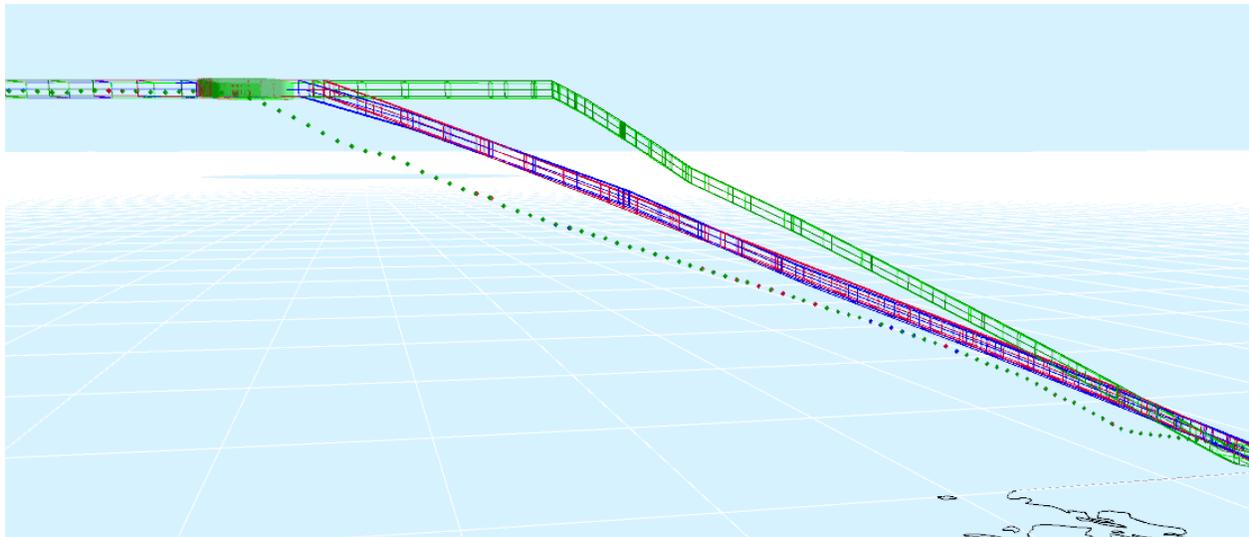
Example 1 displays a Boeing 787-8 (B788) out of Narita International Airport (RJAA) cruising at FL 371 at about 25 minutes prior to true TOD, corresponding to simulation time 60,410 seconds (Figure 4). The flight is entering its descent into Seattle-Tacoma International Airport (KSEA). Figure 5 presents a close-up view of the trajectories near TOD. The Baseline trajectory (blue) begins descent at 60,460 seconds,

which is 50 seconds after true TOD. The current KVM trajectory (red) predicts TOD at 60,478 seconds, which is 68 seconds after true TOD. The trajectory generated by the previous KVM prototype (green) predicts TOD at 60,634 seconds, which is 224 seconds after true TOD. In this example, the current KVM prototype produces a much better TOD prediction than the previous prototype.



**Figure 4. Example 1, side view of entire descent**

Figure 5 depicts the three descending trajectories and the track data. The average descent rate in the Baseline scenario is 1,927 ft/min, which is steeper than the true descent rate of 1,796 ft/min. The current KVM scenario descent rate is closer to the truth at 1,792 ft/min, which is much better than the previous KVM scenario descent rate of 2,767 ft/min.

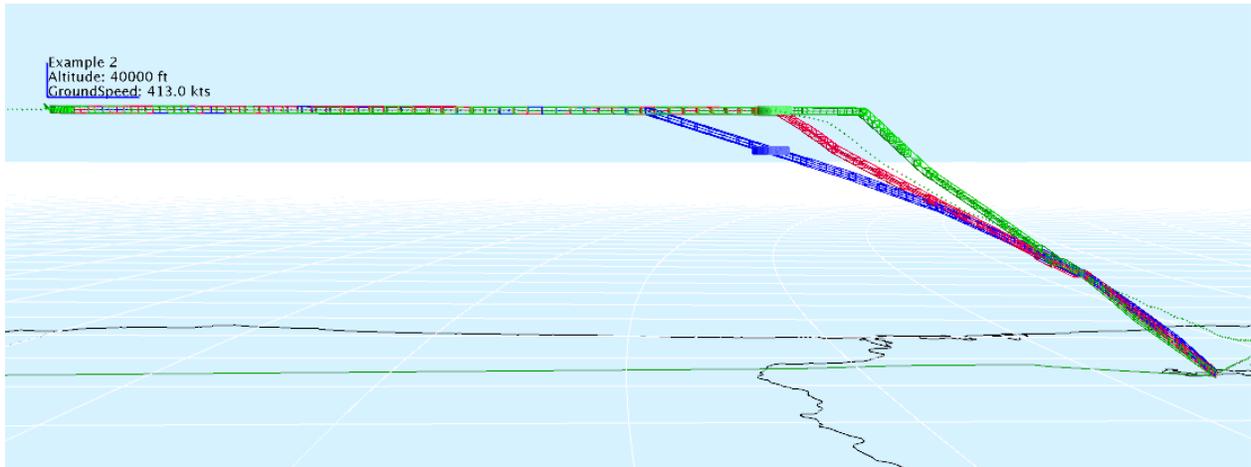


**Figure 5. Example 1, close-up at TOD**

### 1.3.3.2. *Flight Example 2*

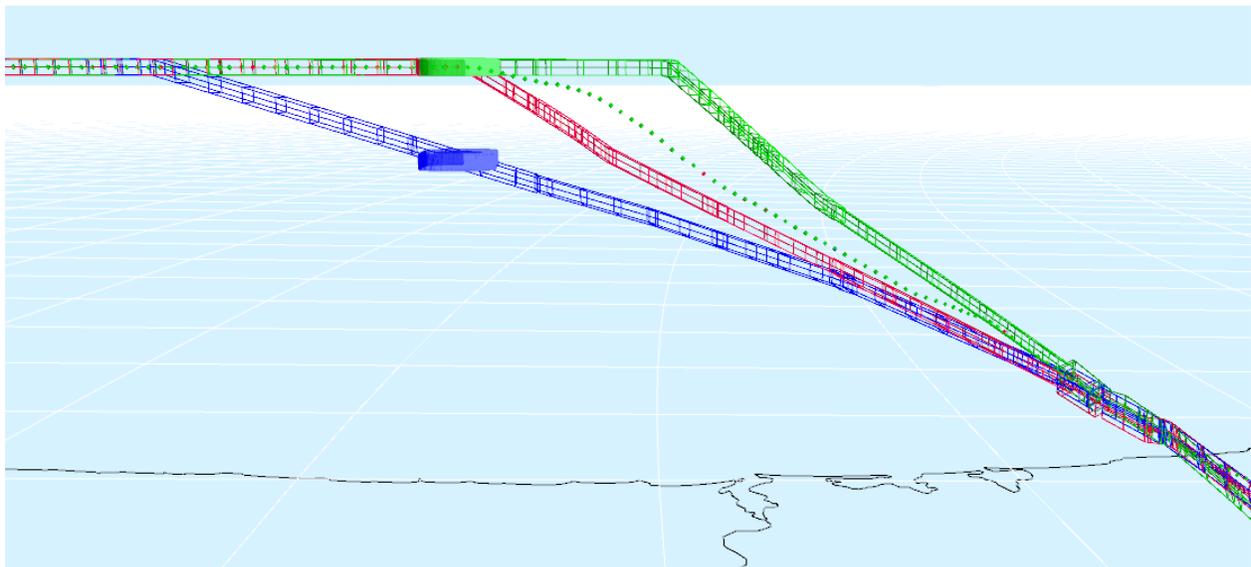
Example 2 displays a Boeing 737-800 (B738) out of Oakland International Airport (KOAK) cruising at FL400 about 25 minutes prior to true TOD, corresponding to simulation time 52,900 seconds (Figure 6). The flight is entering its descent into Seattle-Tacoma International Airport (KSEA). Figure 7 presents a

close-up view of the trajectories near TOD. The Baseline trajectory (blue) begins descent at 52,638 seconds, which is 262 seconds (almost 4.5 minutes) before true TOD. The current KVM trajectory (red) predicts TOD at 52,923 seconds, which is 23 seconds after true TOD. This is a 239 second improvement in magnitude over the Baseline TOD prediction. The trajectory generated by the previous KVM prototype (green) predicts TOD at 53,102 seconds, which is 202 seconds after true TOD. In this example, the current KVM prototype outperformed both the Baseline and previous KVM prototype.



**Figure 6. Example 2, side view of entire descent**

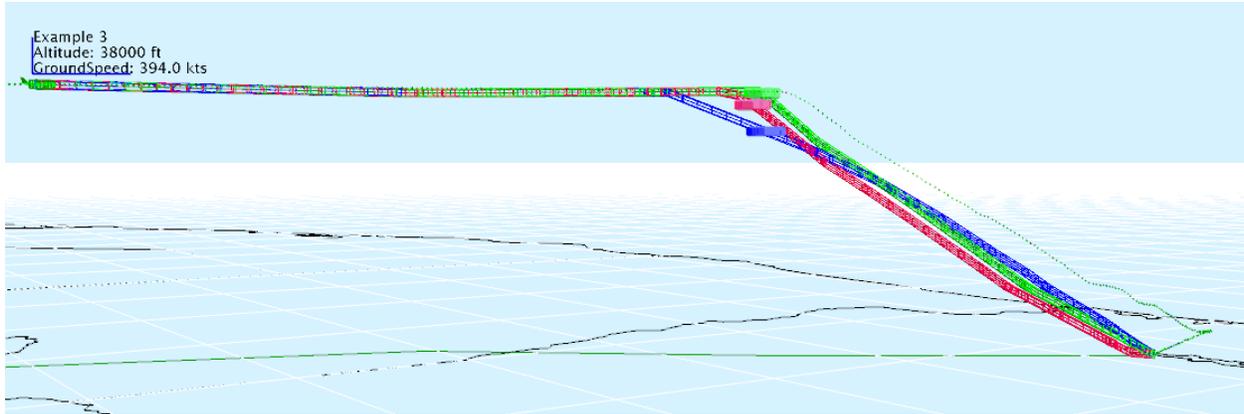
The predicted descent paths are easier to see in Figure 7. The average descent rate in the Baseline trajectory is 1,614 ft/min, which is shallower than the true descent rate of 2,111 ft/min. The current KVM trajectory has a more accurate descent rate of 2,193 ft/min, which is significantly better than the previous KVM prototype descent rate of 3,074 ft/min.



**Figure 7. Example 2, close-up at TOD**

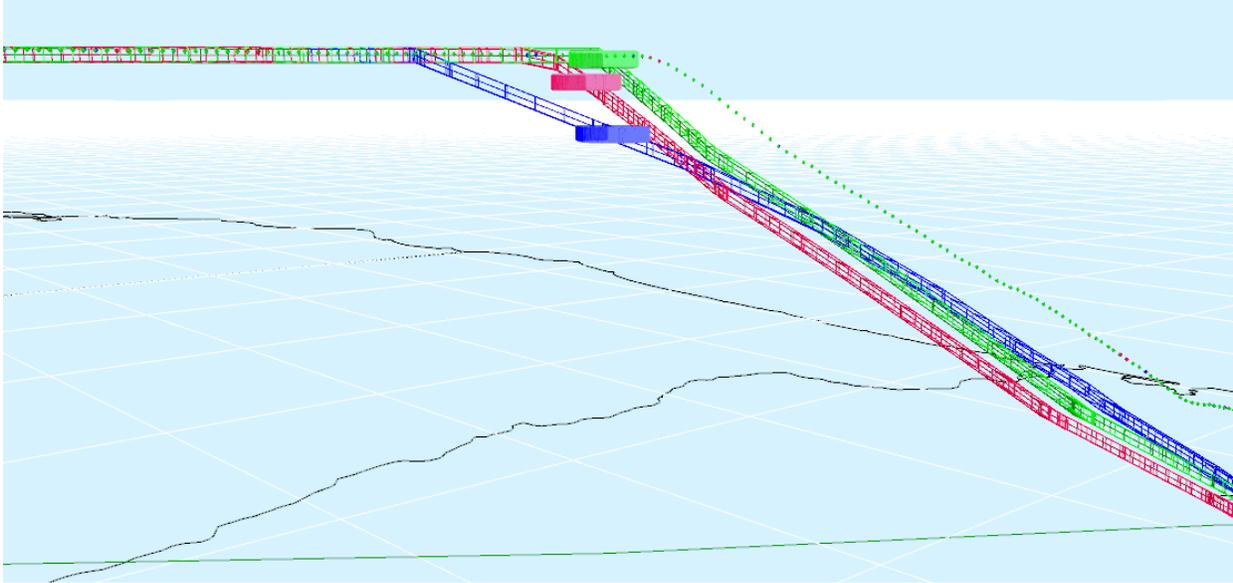
### 1.3.3.3. *Flight Example 3*

Example 3 displays a Boeing 737-700 (B737) out of Denver International Airport (KDEN) cruising at FL 380 about 25 minutes prior to true TOD, corresponding to simulation time 60,920 seconds (Figure 8). The flight is entering its descent into Seattle-Tacoma International Airport (KSEA). Figure 9 presents a close-up view of the trajectories near TOD. The Baseline trajectory (blue) begins descent at 60,726 seconds, which is 194 seconds (almost 3.5 minutes) before true TOD. The current KVM trajectory (red) predicts TOD at 60,857 seconds, which is 63 seconds before true TOD. This is a 131 second improvement in magnitude over the Baseline TOD prediction. However, the trajectory generated by the previous KVM prototype (green) predicts TOD at 60,924 seconds, which is only 4 seconds after true TOD and closer than the current KVM prediction.



**Figure 8. Example 3, side view of entire descent**

Figure 9 shows the three descending trajectories and the track data. The average descent rate in the Baseline trajectory is 2,004 ft/min, which is shallower than the true descent rate of 2,223 ft/min. The current KVM trajectory shows a descent rate of 2,516 ft/min, while the previous study shows the KVM trajectory with a descent rate of 2,814 ft/min. This flight example highlights one case where the updated KVM prototype predicted the descent rate better (i.e., closer to the true rate) than the previous KVM prototype; however, the TOD prediction was worse (i.e., farther from true TOD). The updated KVM prototype performed better than the baseline in TOD prediction, but not average descent rate.



**Figure 9. Example 3, close-up at TOD**

## 1.4. Conclusions and Discussion

Trajectory prediction provides an essential input to the conflict probe tool of ERAM, which supports air traffic controllers by anticipating potential conflicts up to 20 minutes in the future. The currently deployed ERAM Trajectory Modeler (TM) uses a kinematic modeling approach, which is sufficient for aircraft following traditional step descents. However, it is ill suited to modeling idle-thrust descents, which are becoming more prevalent as flights begin to make use of advanced technologies to perform continuous descent approaches. [Paglione and Oaks, 2009] showed that inaccurate trajectories can lead to degradation of performance in the conflict probe and an increase in alerts that may not be beneficial to the controllers. Lockheed Martin developed prototype enhancement to the TM that implements a kinetic modeling approach with the goal of improving the prediction of flights with continuous descent profiles at idle or near-idle thrust.

Schnitzer et al. [2015] evaluated a previous version of the BADA-based Kinetic Vertical Model (KVM) prototype. The current study evaluates an updated version of the KVM prototype, with modifications to improve prediction [Torres, 2015]. The current study compares the performance, with respect to trajectory accuracy, of the current KVM prototype against the earlier prototype investigated in [Schnitzer et al., 2015]. The objective is to confirm whether the current version has similar or improved performance.

The analysis, which focuses on a select group of flights with CDA-like characteristics, shows an average improvement in TOD prediction compared to the earlier KVM prototype. The previous study showed a reduction in average TOD prediction error of 52.2% compared to the Baseline scenario, while the current prototype showed a 68.5% reduction compared to the corresponding Baseline scenario. The better TOD prediction contributed to an improvement in the measured descent rate error; the current study demonstrated a 28.8% reduction in average descent rate error compared to Baseline. In the previous study the KVM prototype performed worse than the Baseline scenario, with a 14.4% higher descent rate error.

In assessing trajectory accuracy, the current study found a 27.7% reduction in the vertical error at BOD over Baseline, whereas the analogous error reduction in the previous study was only 16%. Along track error at BOD also indicated significant improvement: the current KVM prototype demonstrated a 52.1% improvement over Baseline, while the previous prototype had a 25.5% improvement.

Overall, the results of the current study indicate improved prediction performance of the TM when using the updated KVM prototype. The improvements in TOD prediction, descent rate, and trajectory accuracy are contrasted against the analysis of the previous KVM prototype detailed in [Schnitzer et al., 2015] and it is determined that, on average, the updated KVM prototype trajectory predictions are closer to the true track data.

# Chapter 2 - Analysis of Flights Following Houston OPD Procedure

## 2.1. Introduction

The Separation Management and Modern Procedures Project is an initiative of the Federal Aviation Administration (FAA) under the Next Generation Air Transportation System (NextGen) Program to implement improvements in the En Route Automation Modernization (ERAM) system, which supports all en route facilities in the United States. The FAA's Air Traffic Organization En Route Program Office (ATO-E) tasked the FAA's Modeling and Simulation Branch (ANG-C55) to conduct several studies investigating the impacts from various proposed prototypes and parameter changes to the Trajectory Modeler (TM) and/or Conflict Probe Tool (CPT) of ERAM. The overall objective is to improve the performance of the conflict probe in preparation for integration of the CPT alert notification into the flight data block on the radar controller's main display. Since predicted trajectories are a primary input to the CPT, the accuracy and stability of the TM impacts the quality of alerts.

Currently, the ERAM TM relies on kinematic (or parametric) modeling for descent and climb prediction. Referred to here as the legacy model, it uses population-average information from lookup tables to obtain speed, descent rate, and other factors for each aircraft type at a given altitude and temperature. The TM uses this information to determine Top of Descent (TOD), descent rate, and path. This parametric method works well for aircraft following step descents. At present, more flights are beginning to make use of advanced technologies to perform Continuous Descent Approaches (CDAs). Since the legacy kinematic model uses empirical data based primarily on flights making step descents, it is inadequate when modeling idle-thrust descents.

The Kinetic Vertical Model (KVM) prototype enhancement to the TM, created by the ERAM development contractor Lockheed Martin, aims to improve the prediction of TOD and descent rate for aircraft that descend at idle or near-idle thrust. The KVM prototype implements a kinetic (physics-based) model that uses aircraft mass and speed profiles (or other enhanced intent information) which are either provided or can be inferred for each individual aircraft when building trajectories. To implement the kinetic model the prototype also makes use of EUROCONTROL's Base of Aircraft Data (BADA) [Nuic, 2014], which supplies aircraft performance information necessary to compute trajectories. The KVM model is designed to improve upon the limitations of the legacy kinematic model. Flights following Optimized Profile Descents (OPD) and/or Continuous Descent Arrivals (CDA) will benefit from the updated modeling approach.

This specific study is designed to compare the performance, with respect to trajectory accuracy, of the enhanced KVM prototype against that of the current ERAM TM. The approach of this study is similar to the one performed in [Schnitzer et al., 2015]. The flight scenario examined includes aircraft performing Optimum Profile Descents into George Bush Intercontinental Airport (KIAH) in Houston, Texas. A major difference in the current study is higher variation in the timing of experimental interim altitude messages than in [Schnitzer et al., 2015]. The objective is to show the benefits of using the KVM prototype with Vertical Navigation (VNAV) modeling, an adaptation that includes window restrictions from the Area Navigation (RNAV) Standard Terminal Arrival Route (STAR).

## 2.2. Methodology

This study evaluates the performance of the enhanced KVM prototype utilizing VNAV procedure modeling for flights using the Houston DRLLR4 OPD arrival.

### 2.2.1. Data Flow

In this study, analysts utilized ERAM track and clearance messages in conjunction with wind data recorded on February 9, 2015 from the Houston (ZHU) ARTCC. Data was collected using Lockheed Martin's Sarbot tool. As described in [Torres, Dehn, and Little, 2014], only flights that followed the DRLLR4 RNAV STAR were considered for this study. Of these flights, there were 46 identified by Lockheed Martin as having CDAs. Of these, only 22 flights stayed within lateral conformance and these are the flights selected for analysis [S. Torres, personal communication, 12/02/2015].

Flights in the scenario followed VNAV altitude window restrictions along the STAR. The legacy ERAM TM does not incorporate the window restrictions found in the DRLLR4 RNAV STAR in its algorithms; however, this information was included in the adaptation and used by the prototype TM to improve trajectory prediction. One limitation of this study is that there is no way to separate the benefit due to the KVM prototype from the benefit due to the inclusion of altitude window restriction information using the experimental scenarios.

Lockheed Martin analyzed cruise and descent phases of flight to determine TOD and cleared cruise altitude for each flight. To force the TM to build a trajectory within a relevant time period, experimental interim altitude messages were created with altitudes equal to the cruise altitude. These messages were inserted in both the Baseline and KVM scenario runs. An important distinction in the current study is that the timing of experimental interim altitude messages is distributed between 5 and 20 minutes prior to TOD due to the layout of the airspace, whereas in [Schnitzer et al., 2015] the messages were all inserted approximately 25 minutes prior to TOD. It was not possible to produce trajectory build times at the same relative time for each flight in this scenario because flights descending by means of the DRLLR4 arrival cross an ARTCC boundary close to the approach, and portions of the flight outside of the ZHU ARTCC are not part of the experimental scenario.

This 9-hour experimental traffic scenario was entered into Lockheed's Virtual Testing Laboratory (VTL), a laboratory version of ERAM, to create an output scenario containing track and trajectory points. The output scenarios were used as input in the ANG-C55 Modeling and Simulation Branch's *CpatTools*, a customized suite of software tools that takes flight traffic input files and creates a linked set of relational database tables. Tables include smoothed track, clearance, and route data, along with trajectory metrics. The analysts used this output data during the ensuing trajectory analysis.

### 2.2.2. Analysis Methods

Analysts evaluated the enhanced KVM prototype for the Trajectory Modeler which includes VNAV procedure modeling, comparing it to the operational version. Analysis includes the following scenarios.

- **Baseline** – Legacy trajectory prediction using kinematic modeling
- **KVM** – Trajectory prediction using kinetic modeling with enhanced KVM prototype and adaptation for RNAV STAR window restrictions

#### 2.2.2.1. Data Collection and Reduction

Lockheed Martin [Torres, 2015] originally identified 22 flights as CDA; however, two flights failed to produce trajectories beyond initial trajectory builds. As a result, only 20 flights remained for analysis. The

analysts used custom *Oracle* SQL queries to extract pertinent scenario information from *CpatTools* output database tables, and performed the analysis using JMP<sup>®1</sup> software. Analysts identified and retrieved the trajectories produced as a result of the experimental altitude messages. For each flight, analysts calculated time and altitude at TOD for both the track and trajectories. Analysts defined Bottom of Descent (BOD) as 15,000 feet in this study since below that altitude, level trajectory segments often occurred as a result of altitude restrictions, STARS, and other influences that were not reflective of controller intent. The analysts confirmed that this altitude was suitable and above the highest constraining restriction through visual exploration of the data using FliteViz4D [Crowell, Fabian, and Nelson, 2012], a data visualization tool created by ANG-C55.

#### 2.2.2.2. **Metrics**

Metrics for this study include a subset of the standard trajectory metrics used in many studies [Paglione and Oaks, 2007]. *Vertical error* is defined as the vertical distance between a track point and its time coincident trajectory point, and *along track error* is defined as the longitudinal distance between a track point and its time coincident trajectory point. The analysts briefly examined *cross track error*, defined as the lateral distance between a track point and its time coincident trajectory point, and observed no effect. Therefore, this study focuses on vertical error and along track error to assess trajectory accuracy.

In addition, the analysts introduce metrics specific to examining TOD. *TOD error* is defined as the difference in time between the track-determined TOD and the trajectory TOD, where negative values indicate that the predicted TOD occurred prior to the actual TOD. Descent rate is the mean rate of descent of the aircraft over the region of time spanning the TOD to BOD, i.e. change in altitude divided by elapsed time. *Descent rate error* is the difference between the calculated descent rate for the actual path (track) and the predicted path (trajectory), where a negative value indicates that the predicted descent rate is steeper than the true descent rate.

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<sup>1</sup> JMP<sup>®</sup> is statistical discovery software from SAS<sup>®</sup>. See [www.jmp.com](http://www.jmp.com)

## 2.3. Analysis

This section describes the results of the analyses defined in Section 2.2.2. Section 2.3.1 presents an assessment of the descent metrics TOD prediction and descent rate and evaluates the accuracy of track prediction for each flight. As previously acknowledged in [Schnitzer et al., 2015], TOD and descent rate can be analogous to the intercept and slope of a linear model; therefore, this analysis of descent metrics is an informal goodness-of-fit test to evaluate the KVM Trajectory Modeler. Section 2.3.2 details the analysis of general trajectory accuracy for one critical trajectory built prior to TOD. Lastly, Section 2.3.3 displays visual flight examples revealing track and trajectory differences between the legacy TM and KVM prototype predictions.

### 2.3.1. Descent Statistics

This section presents the results for descent metrics (viz., TOD prediction and descent rate) that compare the predicted trajectories to the actual flight data. Perfect TOD predictions by the TM will have an error of 0.0 seconds. A negative TOD error indicates an early TOD prediction by the TM, while a positive TOD error indicates a predicted TOD that is later than the true TOD. Table 4 displays the summary statistics for TOD.

**Table 4. Statistics for TOD prediction error**

	<b>TOD: Baseline</b>	<b>TOD: KVM</b>
<b>Mean (seconds)</b>	-207.9	53.5
<b>SD (seconds)</b>	106.4	106.2
<b>N (CDA flights)</b>	20	20

In the Baseline scenario, TOD prediction is 207.9 seconds (about 3.5 minutes) earlier than true TOD. After application of the KVM algorithm with VNAV procedure modeling, the KVM scenario reduces the magnitude of the TOD prediction error to 53.5 seconds, an improvement of 74.3%. The reduction in magnitude reflects a TOD prediction that is more accurate than the Baseline scenario. The change in sign indicates that the legacy algorithm tends to substantially underestimate the TOD, while the KVM algorithm tends to overestimate the TOD.

The second descent metric is rate of descent. A negative error indicates a descent rate that is faster (steeper) than the actual descent rate, while a positive error indicates a descent rate that is slower (shallower) than the true descent rate. Table 5 displays the summary statistics for descent rate error.

**Table 5. Difference between trajectory and observed path descent rates**

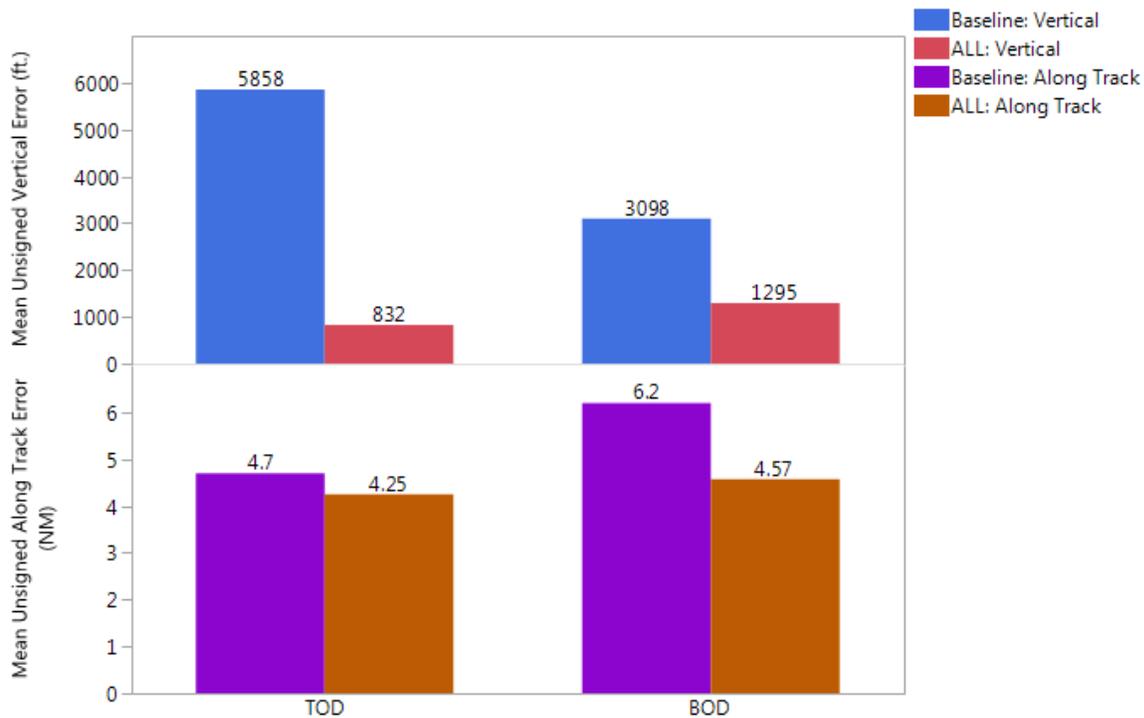
	<b>Rate of Descent Error: Baseline</b>	<b>Rate of Descent Error: KVM</b>
<b>Mean (ft/min)</b>	200.5	-333.0
<b>SD (ft/min)</b>	304.0	489.3
<b>N (CDA flights)</b>	20	20

In the Baseline scenario, the results indicate an average descent rate that is 200.5 ft/min shallower than the true descent rate. This is to be expected with early TOD predictions, which give flights more time to descend. In the KVM scenario, the average descent rate is 333.0 ft/min steeper than the true rate of descent. A delayed TOD prediction leaves less time for flights to descend, and typically result in a negative descent rate error. In assessing the magnitude of descent rate error, the KVM scenario is less accurate than the Baseline scenario, with an increase in magnitude of 66.1%.

### 2.3.2. Trajectory Accuracy

As defined in Section 2.2.2, the metrics vertical and along track error are considered for the overall trajectory analysis in order to calculate differences between the actual track and predicted trajectory. As stated in Section 2.2.1, it is not possible to utilize trajectories built at a fixed time relative to TOD. The build times vary from 5-20 minutes prior to TOD. The critical trajectory selected for analysis is the one built within 12 seconds of the experimental interim altitude injection time. As with other analyses, the time until TOD (*TimeToTOD*) was calculated and used to normalize data. For an accurate prediction, a TimeToTOD value of -120 seconds denotes that TOD will occur in 2 minutes.

Figure 10 depicts trajectory accuracy at TOD and BOD, where BOD is artificially capped at 15,000 feet in order to avoid the influence of altitude restrictions on the trajectories. The top bars of Figure 10 display the mean unsigned vertical error in feet, and the bottom bars show mean unsigned along track error in nautical miles. The bars on the left of Figure 10 show error at TOD while the bars on the right display error at BOD.



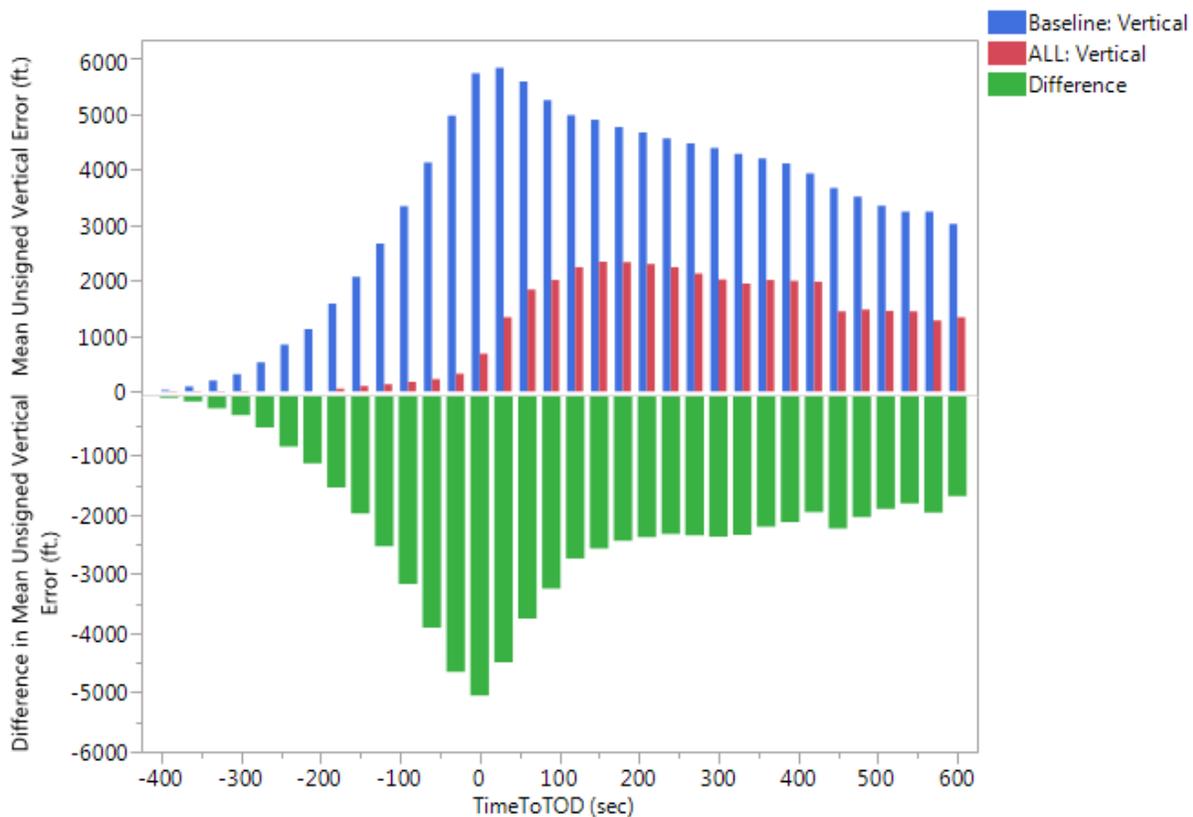
**Figure 10. Mean unsigned vertical and along track error at TOD and BOD**

Mean unsigned vertical error at TOD decreases from 5,858 feet in the Baseline scenario to 832 feet in the KVM scenario. This is an 85.8% improvement, attributable to the improved TOD prediction by the KVM algorithm. As flights converge towards a common point near BOD, the analysts expect to see a reduction in vertical errors for the two scenarios due to constraints on trajectory builds. Specifically, the trajectories

are typically built using the same arrival fixes. At BOD, the Baseline scenario has a vertical error of 3,098 feet and the KVM scenario has a vertical error of 1,295 feet. This is a 58.2% improvement, and is smaller than the difference at TOD as predicted.

The mean unsigned along track error at TOD is 4.70 NM for the Baseline scenario. The KVM scenario has an average error of 4.25 NM, which is a 9.6% improvement. The Baseline scenario has an average along track error of 6.20 at BOD, while the KVM scenario has an average error of 4.57 NM at BOD. This is an improvement of 26.3%.

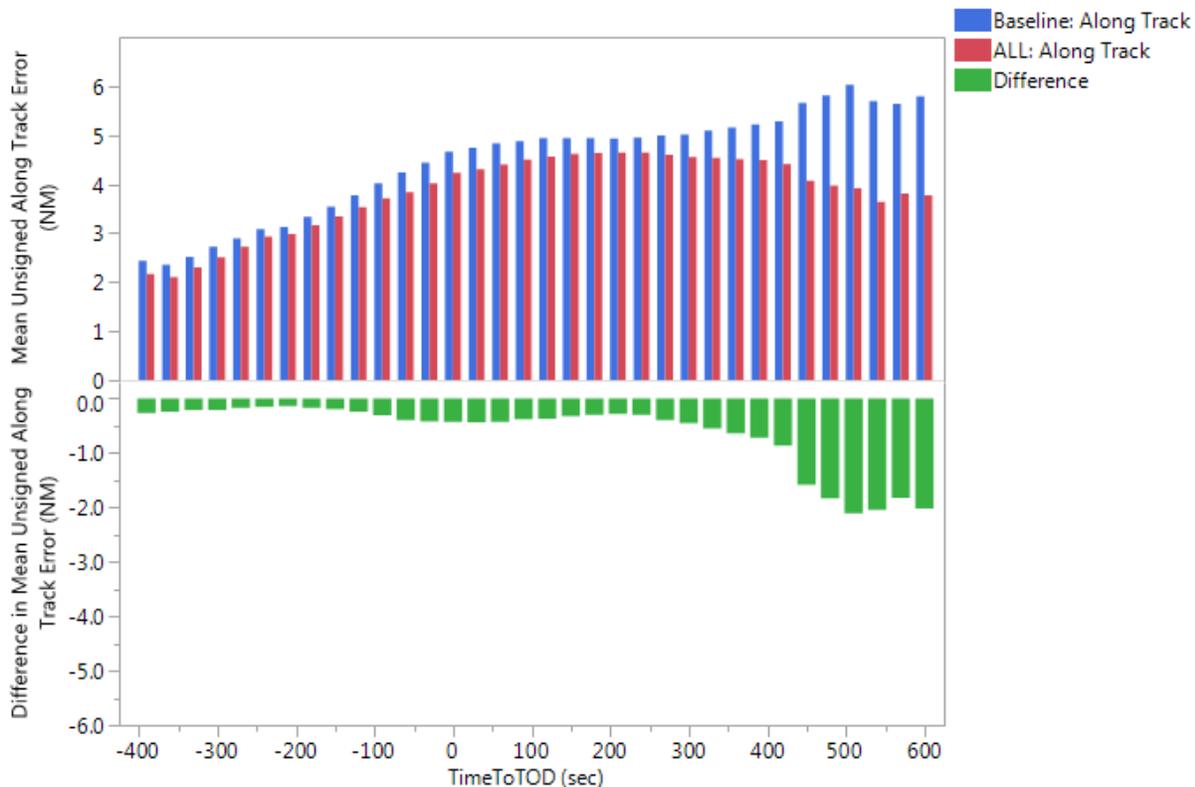
Additionally, for a more general view of trajectory accuracy, an examination of vertical and along track error during the entire descent helps to verify that any trajectory prediction errors are not specific to the time and location of TOD and BOD. Figure 11 displays the overall mean unsigned vertical error.



**Figure 11. Overall mean unsigned vertical error**

The top half of Figure 11 displays the mean unsigned vertical error during descent for both scenarios. At approximately 6.5 minutes (390 sec) prior to TOD, it is evident that the Baseline scenario (blue bars) begins to exhibit an increasing vertical error. The largest magnitude of vertical error in the Baseline scenario peaks around true TOD, which is consistent with an early prediction in TOD. At true TOD the Baseline trajectory has already begun its descent, leading to increased vertical error. As TimeToTOD approaches 0.0, vertical error in the KVM scenario (red bars) begins to accrue until peaking at about 2.5 minutes (150 sec) after true TOD, which is consistent with a late prediction of TOD. At true TOD the KVM trajectory has not yet begun its descent, and it will initially remain at cruise while the track begins its descent. The bottom half of Figure 11 depicts the difference in mean unsigned vertical error between the Baseline and KVM scenarios. For these green bars, negative values indicate an improvement (reduction) in trajectory error from the Baseline to the KVM scenario. There is an immediate

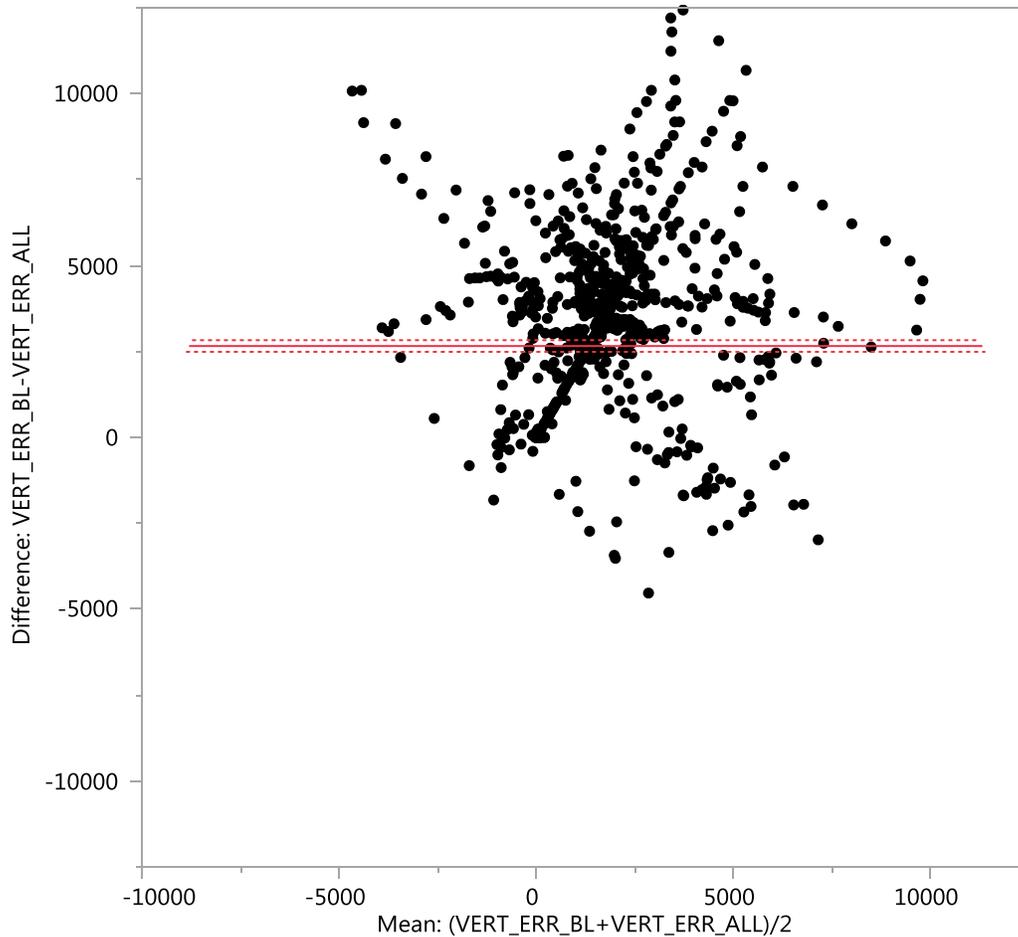
improvement in KVM predictions beginning about 6.5 minutes prior to true TOD, and continuing for the duration of the descent. This demonstrates an improvement in trajectory accuracy by the KVM scenario over the Baseline scenario.



**Figure 12. Mean unsigned along track error over entire descent**

The top half of Figure 12 depicts the mean unsigned along track error. At 6.5 minutes prior to true TOD the trajectories in both scenarios have roughly 2 NM in along track error. Errors in both scenarios are similar until approximately 5 minutes after true TOD. At this time, the critical point in which the KVM algorithm outperforms the Baseline scenario. At TOD, the Baseline scenario has an average error of 4.70 NM that steadily increases to 6.20 NM at BOD. In contrast, the KVM scenario has an error of 4.20 NM at TOD that slightly increases to 4.57 NM at BOD. The bottom half of Figure 12 shows the difference in mean unsigned along track error between the Baseline and KVM scenarios. This indicates that the KVM scenario has an improvement in trajectory accuracy of 26.3% at BOD as compared to the Baseline scenario.

In addition to the standard trajectory analysis the analysts performed a matched pairs analysis, or paired *t*-test, similar to that detailed in [Crowell et al., 2011]. An evaluation can be performed on a flight by flight basis since the two scenarios share the same set of flights. Data is segregated by flight and look-ahead time, resulting in a sample size of 969 points. Figure 13 shows the Tukey mean-difference plot comparing vertical error between the Baseline and KVM scenarios, with the difference between the two errors on the vertical axis plotted against the mean of the two on the horizontal axis. The mean difference is 2,657 ft. with a standard error of 86 ft., generating a *t*-Ratio greater than 30 and a negligible *p*-value. The null hypothesis of the paired *t*-test, that the mean errors between the two scenarios are the same, is therefore rejected. There is clearly a significant difference in average vertical error between the two scenarios, with the average error in the baseline greater than in the KVM scenario.



**Figure 13. Matched pairs analysis for vertical error**

The red horizontal line in Figure 13 denotes the mean of the differences, while dotted lines above and below represent the 95% confidence interval. The fact that the confidence region does not include zero is a visual representation of the finding of significant difference by the paired *t*-test. The overall trend of greater error in the Baseline scenario than the KVM scenario is observable in that most of the data points have positive values for difference, along the vertical axis.

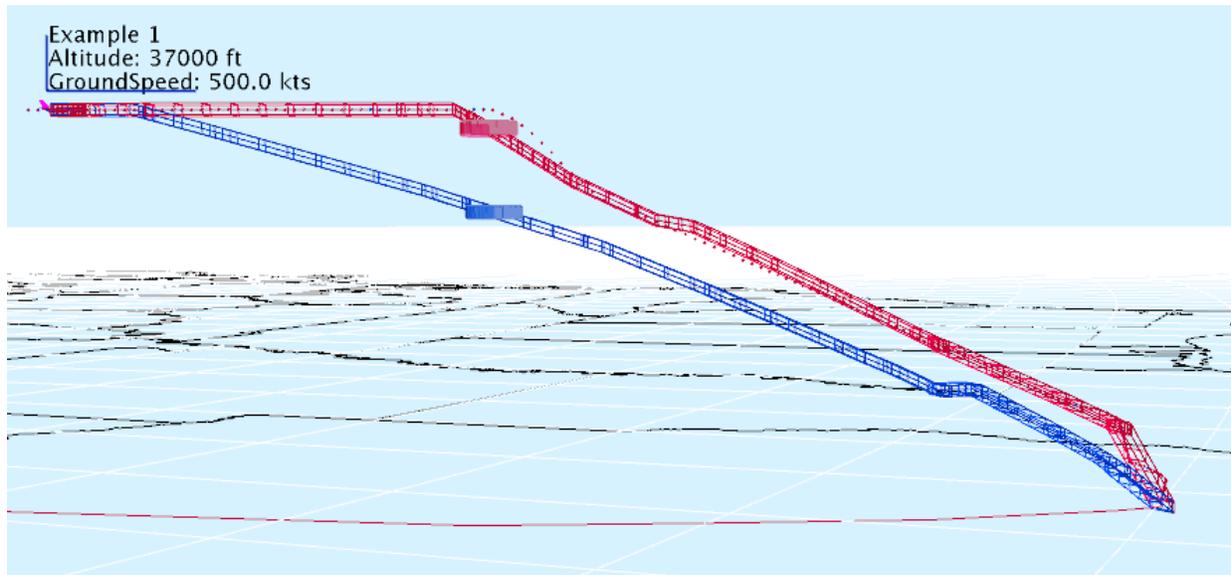
### 2.3.3. Flight Examples

The following sections present flight examples for the Baseline and KVM prototype enhancements to the TM. Dotted lines represent the flight track data. Blue wireframes signify the Baseline trajectory, while red wireframes signify the KVM trajectory. Cylinders of each respective color characterize the aircraft location predicted by the trajectory at the time of the true TOD.

#### 2.3.3.1. Flight Example 1 – Improvement using KVM

Flight Example 1 displays a Boeing 737-800 (B738) out of Calgary International Airport (CYYC) cruising at FL370. The flight is nearing its descent into George Bush Intercontinental Airport (KIAH) in Houston, Texas. The aircraft is shown at about 7.5 minutes prior to true TOD, corresponding to simulation time 62,290 seconds. Figure 14 displays the two descending trajectories and the track data. The Baseline trajectory (blue wireframe) begins descent at 61,923 seconds, which is 367 seconds (about 6 minutes) prior to true TOD. The KVM trajectory predicts a TOD at 62,264 seconds, which is 26 seconds

before true TOD. In this example, the KVM prototype produces a considerably better TOD prediction than the legacy algorithm. The average descent rate in the Baseline scenario is 1,667 ft/min. The KVM scenario has an average descent rate of 2,264 ft/min, which is closer in accuracy to the true descent rate of 2,398 ft/min.



**Figure 14. Flight Example 1, side view of entire descent**

#### **2.3.3.2. Flight Example 2 – Improvement using KVM**

Flight Example 2 displays an Embraer ERJ 145 (E145) out of Rick Husband Amarillo International Airport (KAMA) in Amarillo, Texas cruising at FL330. The flight is nearing its descent into George Bush Intercontinental Airport (KIAH) in Houston, Texas. The aircraft is shown at about 14 minutes prior to true TOD, corresponding to simulation time 52,230 seconds. Figure 15 shows the differences in descent paths. The Baseline trajectory (blue) begins descent at 51,840 seconds, which is 390 seconds (6.5 minutes) before true TOD. The KVM trajectory (red) predicts a TOD at 52,302 seconds, which is 72 seconds after true TOD. This is a 318 second improvement in magnitude over the Baseline TOD prediction. The track descent rate is 2,403 ft/min. The average descent rate in the Baseline scenario is 1,735 ft/min, which is about 668 ft/min too shallow. The KVM scenario has a descent rate of 2,938 ft/min, which is about 535 ft/min too steep, yet is more accurate than the Baseline scenario.

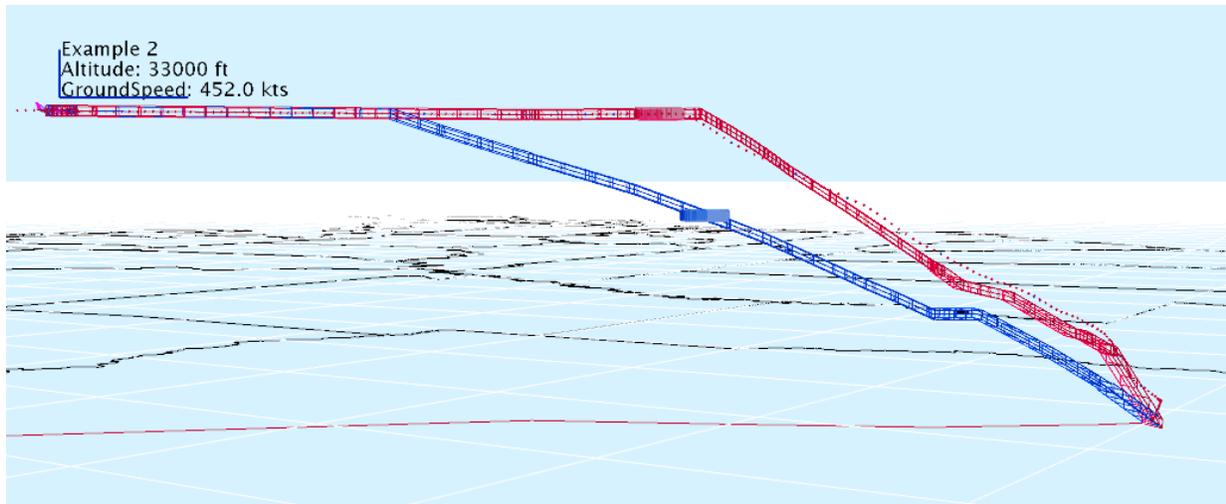


Figure 15. Flight Example 2, side view of entire descent

### 2.3.3.3. Flight Example 3 – Degradation using KVM

Flight Example 3 displays a Gulfstream G200 (GALX) out of Centennial Airport (KAPA) in Denver, Colorado cruising at FL370. The flight is nearing its descent into George Bush Intercontinental Airport (KIAH) in Houston, Texas. The aircraft is shown at about 10 minutes prior to true TOD at simulation time 55,820 seconds. Figure 16 shows the two descending trajectories and track data near TOD. The Baseline trajectory (blue) begins descent at 55,777 seconds, which is 43 seconds before true TOD. The KVM trajectory (red) predicts a TOD at 56,082 seconds, which is 262 seconds (about 4.25 minutes) after true TOD. The KVM trajectory is 219 seconds (more than 3.5 minutes) less accurate than the TOD prediction in the Baseline scenario. The true descent rate is about 2,001 ft/min. The Baseline scenario has an average descent rate of 2,068 ft/min, which is very slightly steeper than the true descent rate with a difference of 67 ft. The average descent rate in the KVM scenario is 3,077 ft/min, about 1,076 ft/min steeper than the track. This flight example illustrates one case in which the Baseline scenario performed better than the KVM prototype in both TOD prediction and rate of descent. All of the KVM scenarios predicted a later TOD prediction than the corresponding Baseline scenario, and in this instance the KVM prediction is significantly late, leading to significant degradation in the accuracy of the trajectory prediction.

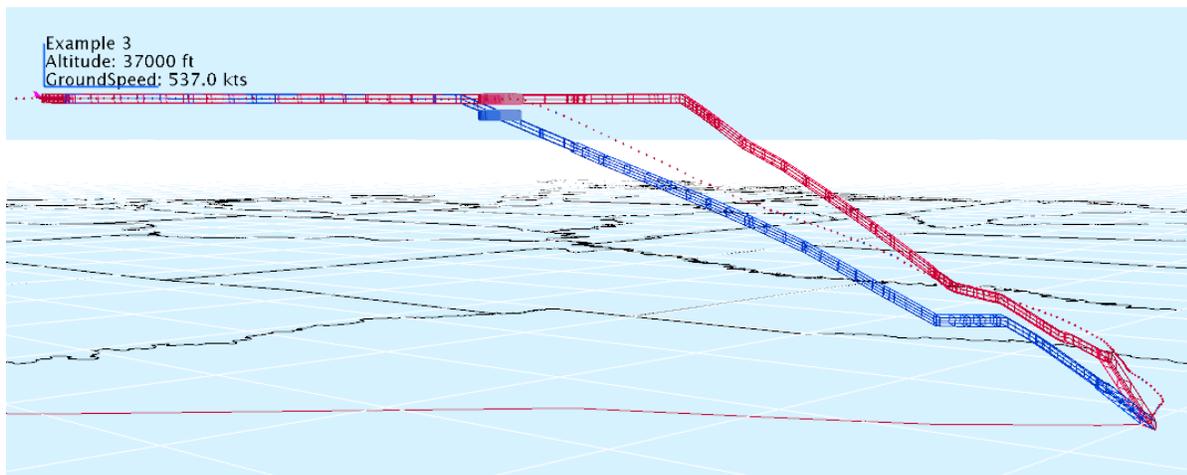


Figure 16. Flight Example 3, side view of entire descent

## 2.4. Conclusions and Discussion

ERAM's conflict probe tool supports air traffic controllers in anticipating conflicts by providing aircraft trajectory predictions upwards of 20 minutes into the future. The operating version of ERAM's TM uses a kinematic modeling approach, which works well for aircraft following traditional step descents. However, more aircraft are using idle-thrust descents as newer technologies are allowing for the performance of continuous descent approaches, and the legacy TM is insufficient for this purpose. [Paglione and Oaks, 2009] showed that inaccurate trajectories can lead to degradation of performance in the conflict probe and an increase in alerts that may not be beneficial to controllers. A prototype enhancement to the TM by Lockheed Martin aims to utilize a kinetic modeling approach with the goal of improving trajectory prediction for flights with continuous descent profiles at idle or near-idle thrust.

This study evaluates a BADA-based KVM prototype that utilizes RNAV STAR window restrictions following the DRLLR4 arrival route into Houston. This enhancement to the TM intends to improve the accuracy of TOD prediction and trajectory predictions of flights that are following an idle-thrust descent from TOD down to the highest constraining restriction before switching to a geometric approach [Torres, 2015]. This study compares the performance, with respect to the prediction of TOD and trajectory accuracy, of the KVM prototype to the legacy model. The objective is to confirm the benefits of using the KVM prototype with window restrictions over the legacy ERAM model.

The analysis, which concentrates specifically on flights following the DRLLR4 arrival route with CDA-like characteristics, shows an average improvement of 74.3% in TOD prediction by the KVM prototype over the legacy ERAM TM model. The TOD prediction using the KVM prototype is, on average, later than the true TOD, and as a result the descent rate is steeper than the observed path. However, the error in rate of descent when using KVM decreases by 39.8% compared to the Baseline scenario.

In evaluating trajectory accuracy, this study found vertical error at TOD and BOD improved with the application of the KVM by 85.8% and 58.2% respectively. Additionally, along track error improved at TOD and BOD by 9.6% and 26.3% respectively. Overall, the results of this study indicate improved trajectory prediction performance when employing the enhanced KVM prototype over the legacy ERAM TM.

# Chapter 3 – Analysis of Climb Modeling in Seattle Flight Data

## 3.1. Introduction

The Separation Management and Modern Procedures Project is an initiative of the Federal Aviation Administration (FAA) under the Next Generation Air Transportation System (NextGen) Program to implement improvements in the En Route Automation Modernization (ERAM) system, which supports all en route facilities in the United States. The FAA's Air Traffic Organization Operational Concepts, Validation & Requirements Directorate (AJV-7) tasked the FAA's Modeling and Simulation Branch (ANG-C55) to conduct several studies investigating the impacts from various proposed prototypes and parameter changes to the Trajectory Modeler (TM) and/or Conflict Probe Tool (CPT) of ERAM. The overall objective is to improve the performance of the conflict probe in preparation for integration of the CPT alert notification into the flight data block on the radar controller's main display. Since predicted trajectories are a primary input to the CPT, the accuracy and stability of the TM impacts the quality of alerts.

Currently, the ERAM TM relies on kinematic (parametric) modeling for descent and climb prediction. Referred to here as the legacy model, it uses population-average information from lookup tables to obtain speed, climb rate, and other factors for each aircraft type at a given altitude and temperature. When predicting departure profiles, the TM uses this information to determine Top of Climb (TOC), climb rate, and path. This parametric method works well for aircraft following step climbs. At present, more flights are beginning to make use of advanced technologies to perform continuous climbs on departure. The legacy kinematic model uses empirical data based primarily on flights making step climbs, and is less suited to modeling continuous climbs.

The Kinetic Vertical Model (KVM) prototype enhancement to the TM, created by the ERAM development contractor Lockheed Martin, aims to improve the prediction of TOC and climb rate for aircraft performing continuous climbs on departure. The KVM prototype implements a kinetic (physics-based) model that uses aircraft mass and speed profiles (or other enhanced intent information) which are either provided or can be inferred for each individual aircraft when building trajectories. To implement the kinetic model the prototype also makes use of EUROCONTROL's Base of Aircraft Data (BADA) [Nuic, 2014], which supplies aircraft performance information necessary to compute trajectories. The KVM enhancement is designed to improve upon the limitations of the legacy kinematic model.

This specific study is designed to answer whether KVM can be effectively applied to predicting the trajectory of climbing aircraft. The objective is to compare the performance, with respect to trajectory accuracy, of the enhanced KVM prototype against that of the legacy ERAM TM. The evaluated flight scenario includes flights performing continuous climbs observed within the Seattle (ZSE) Air Route Traffic Control Center (ARTCC).

## 3.2. Methodology

This study evaluates the performance of the enhanced KVM prototype in modeling flights performing continuous climbs on departure.

### 3.2.1. Data Flow

For this study, the analysts used ERAM track and clearance messages along with wind data from March 14, 2014 at the Seattle ARTCC. The flight scenario data was collected using Lockheed Martin's Sarbot tool. Unlike the experiments described in Chapters 1 and 2 there were no forced trajectory builds in this study, and the trajectory build times were not controlled. Trajectory accuracy varies with look ahead time, so the variation in trajectory build times makes comparison between scenarios complicated. To capture this source of variance, the relative build time of each trajectory is defined as a factor of interest and is included in the analysis.

Lockheed Martin's Virtual Testing Laboratory (VTL), a laboratory version of ERAM, ran this 9-hour experimental scenario to produce output scenario data consisting of track and trajectory points. The ANG-C55 team analyzed the output scenario with *CpatTools*, a customized software suite that takes flight traffic input files and creates a linked set of relational database tables. These tables include smoothed track, clearance, and route data, as well as trajectory metrics. The analysts used this output data for all subsequent trajectory analysis. Flights with continuous climb paths were selected as a subset of the original data. After analyzing the climb and cruise phases of these flights, the Top of Climb (TOC) was determined for each. Further analysis of track data and trajectory builds established that a total of 150 flights had appropriate data to be included in this analysis.

### 3.2.2. Analysis Methods

The analysts evaluated the performance of the KVM prototype enhancement to the Trajectory Modeler, comparing it to the operational version. Analysis includes the following scenarios:

- **Baseline** – Legacy trajectory prediction using kinematic modeling
- **KVM** – Trajectory prediction using kinetic modeling in enhanced KVM prototype

#### 3.2.2.1. *Data Collection and Reduction*

The analysts use custom Oracle SQL queries to retrieve the necessary scenario information produced through *CpatTools*. Examining the selected subset of flights with continuous climb paths, the analysts define TOC as the time in which an aircraft reaches its cruise altitude. Analysts then filtered the flights in order to remove any flights in which the cruise altitude does not equal its cleared altitude. This ensures that the track data and predicted trajectories accurately reflect the intent of the aircraft. In addition, flights are removed from analysis if all trajectory builds before TOC contain a level segment below TOC (i.e., do not model a continuous climb).

In the absence of artificially injected interim altitude messages, analysts define two trajectory collections of interest: one contains the earliest trajectory build that does not model a level segment below TOC, and another group comprises this trajectory and all subsequent trajectories generated until 300 seconds prior

to TOC. For a given trajectory (and associated track data), Bottom of Climb (BOC) is defined as the interpolated trajectory and track points closest to (but not before) the trajectory build time. Times and altitudes for BOC and TOC are identified and confirmed through visual exploration of the data using FliteViz4D, an interactive 4D visualization tool developed by ANG-C55 [Crowell, Fabian, and Nelson, 2012].

#### 3.2.2.2. **Metrics**

Metrics for this study include a subset of the standard trajectory metrics used in many studies [Paglione and Oaks, 2007]. *Vertical error* is defined as the vertical distance between a track point and its time coincident trajectory point, and *along track error* is defined as the longitudinal distance between a track point and its time coincident trajectory point. This study focuses on vertical error and along track error to assess trajectory accuracy.

In addition, the analysts apply metrics specific to climb prediction accuracy. These metrics are analogous to metrics for descent prediction detailed in [Paglione et al., 2011] and [Bronsvort et al., 2011]. *TOC Error* is defined as the difference in time between the track-determined TOC and the trajectory TOC, where negative values indicate that the predicted TOC occurred prior to the actual TOC. Climb rate is the mean rate of ascent of the aircraft over the region of time spanning the BOC to TOC, i.e. change in altitude divided by elapsed time. *Climb rate error* is the difference between the calculated climb rate for the actual path (track) and the predicted path (trajectory), where a negative value indicates that the predicted climb rate is less steep than the true climb rate.

### 3.3. Analysis

This section describes the results of the analyses outlined in Section 3.2.2. Section 3.3.1 examines the error metrics for TOC prediction and climb rate error, considering one trajectory for each flight (the earliest trajectory build of interest, as defined in Section 3.2.2.1). Similar to metrics for descent analysis in [Schnitzer et al., 2015], TOC and climb rate are analogous to the intercept and slope of a linear model; therefore, this analysis of climb metrics is an informal goodness-of-fit test to evaluate the KVM Trajectory Modeler. Section 3.3.2 presents an analysis of general trajectory accuracy for the larger, more inclusive collection of trajectories described in 3.2.2.1. Finally, Section 3.3.3 exhibits visual examples demonstrating flight track and trajectory differences between the legacy TM and KVM prototype predictions.

#### 3.3.1. Climb Statistics

This sub-section presents the results for climb metrics (TOC prediction and climb rate errors) comparing the predicted trajectory to the actual flight data. A TOC error of 0 seconds indicates the TM perfectly predicted the time at which TOC actually occurred. Negative TOC error indicates that the TM predicts an early TOC, while a positive TOC error indicates the predicted TOC is later than the true TOC. Table 6 presents summary statistics for TOC error.

**Table 6. Statistics for top of climb prediction error**

	<b>TOC Error: Baseline</b>	<b>TOC Error: KVM</b>
<b>Average Error (seconds)</b>	-43.2	-6.1
<b>Standard Deviation (seconds)</b>	157.3	157.5
<b>Number of Flights</b>	150	150
<b>Average Absolute Error (seconds)</b>	120.1	112.1

The Baseline scenario, on average, predicts TOC at 43.2 seconds earlier than actually occurred. With application of the KVM algorithm the TOC is still predicted early, but the magnitude of the TOC prediction error is reduced from 43.2 seconds to 6.1 seconds, an average improvement of 37.1 seconds in this case. The reduction in magnitude indicates the TOC prediction by the KVM algorithm is more accurate on average than the Baseline scenario, although it still tends to predict TOC too early. However, the calculated standard deviation indicates high variance in the results for both scenarios; i.e., the observed error values are widely distributed. It should be noted that the mean effect size relative to the standard deviation is less than in the previous studies on descent metrics (see Chapter 1 and 2). Although the distribution of error values seems to have shifted to the right, the high variance means that the absolute error in predictions is not, on average, close to zero. The average magnitude of time errors (or average absolute error) is presented in the last row of Table 6. The decrease of 8 seconds points to a very slight improvement in the precision of TOC prediction.

The second climb error metric relates to the rate of climb, comparing the difference in climb rate between the trajectory and the observed track data. A negative error indicates that the predicted climb rate is slower (shallower) than the true climb rate, while a positive error indicates that the predicted climb rate is faster (steeper). Table 7 presents summary statistics for climb rate error.

**Table 7. Statistics for climb rate error**

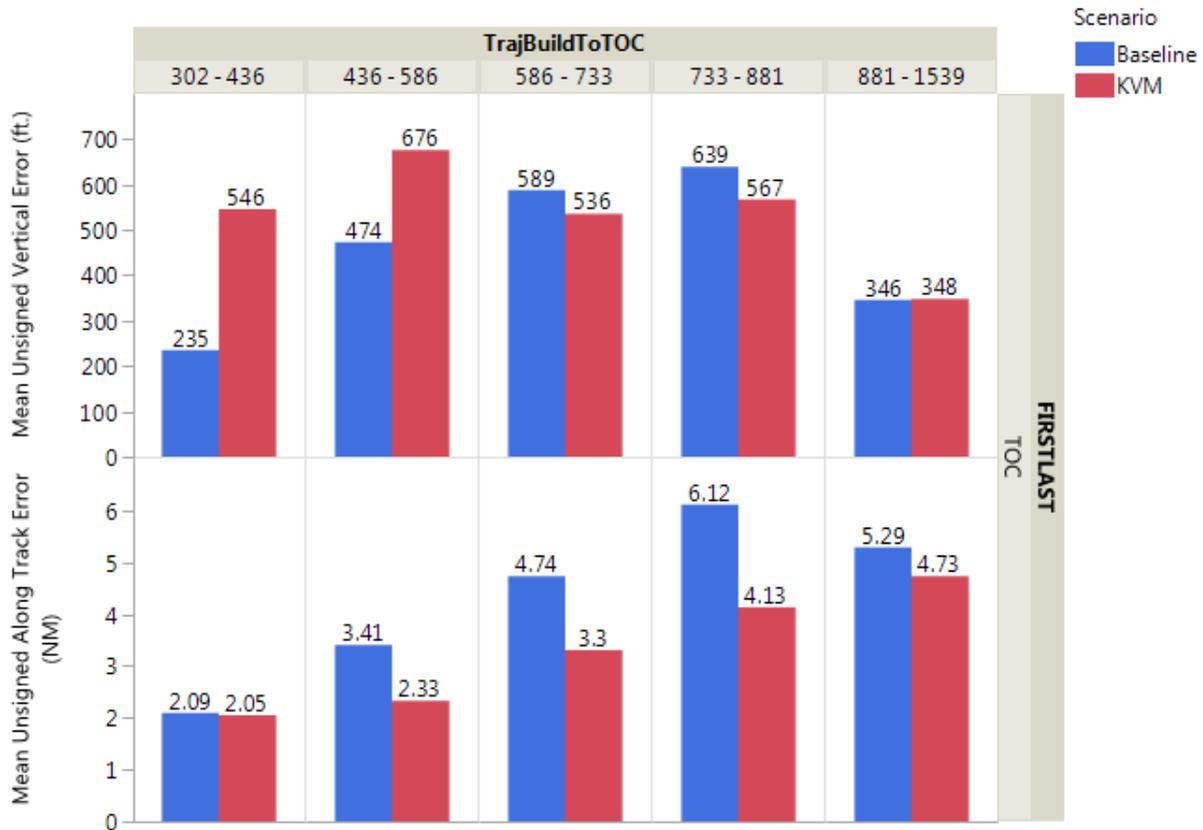
	<b>Climb Rate Error: Baseline</b>	<b>Climb Rate Error: KVM</b>
<b>Average Error (ft/min)</b>	104.8	17.9
<b>Standard Deviation (ft/min)</b>	287.4	330.4
<b>Number of Flights</b>	150	150
<b>Average Absolute Error (ft/min)</b>	233.0	216.8

In the Baseline scenario, the results indicate an average climb rate that is 104.8 ft/min steeper than the true average climb rate. This was expected due to the early TOC prediction leaving the flight less time to climb to cruising altitude. In the KVM scenario the climb rate is only 17.9 ft/min steeper on average than the true climb rate. It follows that a later prediction of TOC causes the KVM scenario trajectories to have a reduced climb rate error. In comparing the magnitude of climb rate error, the KVM scenario is more accurate and demonstrates an 82.9% decrease in average absolute error from the Baseline scenario.

### **3.3.2. Trajectory Accuracy**

For the overall trajectory error analysis, differences between the actual track and predicted trajectory are calculated using the vertical and along track error metrics as defined in Section 3.2.2. In this analysis the larger, more inclusive collection of trajectories for each flight is collected. As described in Section 3.2.2.1, this group comprises the earliest trajectory of interest and all subsequent trajectories generated until 300 seconds prior to TOC. Similar to the previous study involving descents, the analysts calculate the time until TOC (*TimeToTOC*) to normalize the data based upon when true TOC occurred. For an accurate prediction, a TimeToTOC value of -120 seconds indicates that TOC will occur in 2 minutes. Additionally, the analysts calculate the interval between the time a trajectory is built and the TOC (*TrajBuildToTOC*), and use this relative build time to group data with similar trajectory ‘ages’.

Trajectory accuracy at TOC is examined (the prediction errors at BOC are very close to zero and do not merit examination). TimeToTOC is not relevant in this particular analysis because the analysis point is fixed at TOC; however, the TrajBuildToTOC is used to group the data into bins of similar trajectory age. The top of Figure 17 displays the mean unsigned vertical error in feet, and the bottom displays mean unsigned along track error in nautical miles. Data on the x-axis are grouped in TrajBuildToTOC time bins.

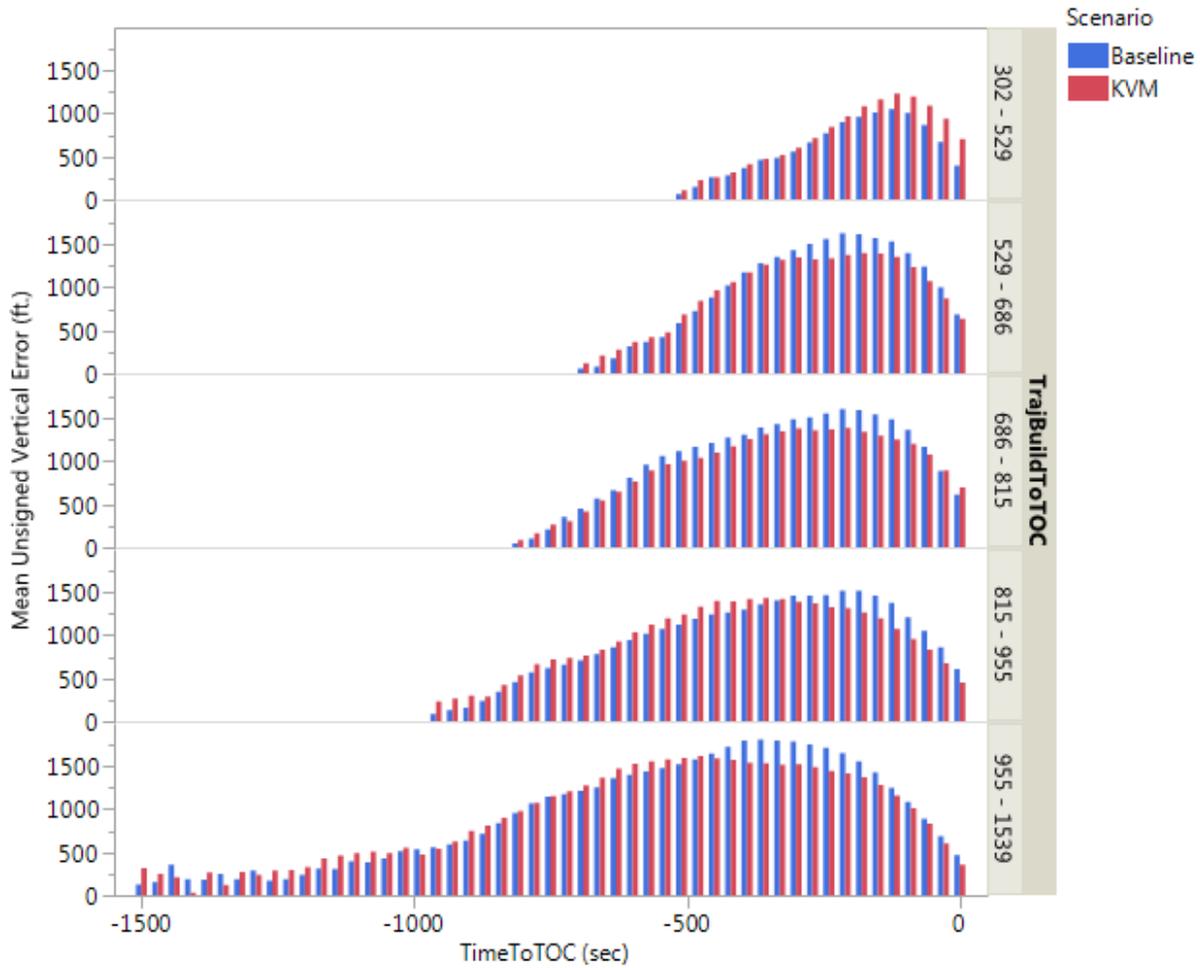


**Figure 17. Mean unsigned vertical (ft.) and along track error (NM) at TOC, binned by TrajBuildToTOC (sec)**

Starting at the top right of Figure 17, the mean unsigned vertical error for the earliest trajectories at TOC has virtually identical magnitudes of 346 ft and 348 ft for Baseline and KVM, respectively. The next four bins from earliest to latest (right to left) reflect the improvement in performance by the KVM scenario over the Baseline scenario of 72, 53, -202, and -311 ft, respectively. As seen in the graph and the last two negative values, for trajectory build times approaching the true TOC the Baseline scenario outperforms the KVM scenario.

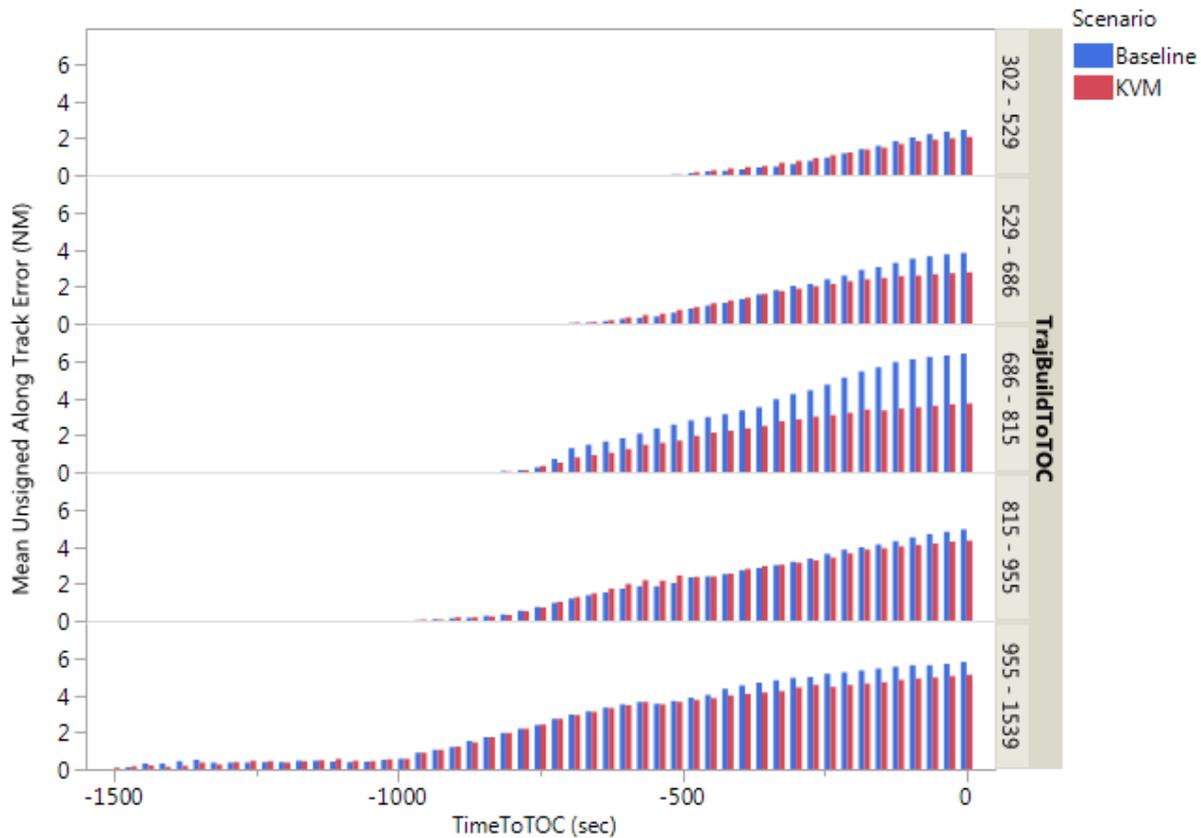
The mean unsigned along track errors at TOC in the earliest trajectories have magnitudes of 5.29 NM and 4.73 NM for the Baseline and KVM scenarios, indicating a 10.6% accuracy improvement for the KVM prototype. The next four bins from earliest to latest reflect an improvement in performance by KVM over the Baseline scenario of 1.99, 1.44, 1.08, and 0.04 NM, respectively, which translates to improvements of 32.5%, 30.4%, 31.7%, and 1.9% over the average Baseline error. For along track error, the KVM scenario outperforms the Baseline scenario across all five bins of the TrajBuildToTOC factor.

For a broader view of trajectory accuracy, the analysts also examine vertical and along track error throughout the entire descent. Figure 18 presents mean overall vertical error plotted against TimeToTOC in seconds.



**Figure 18. Overall mean unsigned vertical error**

Figure 18 shows the mean unsigned vertical error during descent for both scenarios grouped by similar TrajBuildToTOC on the y-axis. In this figure, it is evident that during the four earliest time bins (shown towards the bottom of the graph) there is an interval between 2 and 4 minutes (120-240 sec) prior to TOC in which the KVM scenario noticeably outperforms the Baseline scenario in vertical error. In the top section (encompassing trajectories built closer to TOC) the KVM performs worse in predicting positions within 2 minutes of TOC.



**Figure 19. Overall mean unsigned along track error**

The mean unsigned along track error is presented in Figure 19. The KVM scenario slightly outperforms the Baseline scenario for all TrajBuildToTOC bins. The most noticeable improvement occurs in trajectories built around 12 minutes prior to TOC (mid-range bin of 686 to 815 seconds).

### 3.3.3. Flight Examples

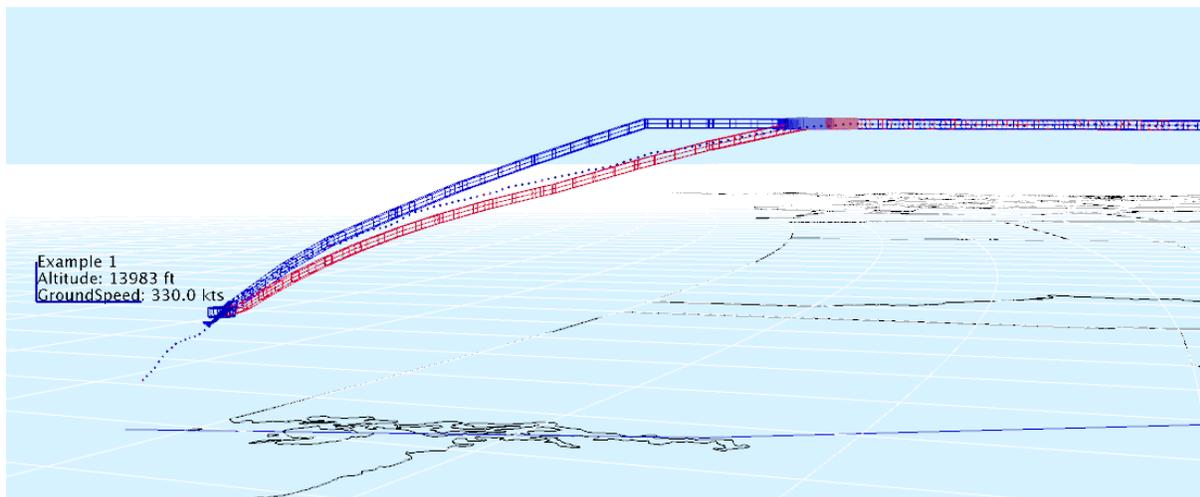
The following sections present flight examples for the Baseline and KVM prototype enhancement to the TM. Dotted lines represent the flight track data. Blue wireframes represent the Baseline trajectory, while red wireframes signify the KVM trajectory. Cylinders of each respective color characterize the aircraft location predicted by the trajectory at the time of true TOC.

#### 3.3.3.1. *Flight Example 1 – Improvement using KVM*

Example 1 displays an Airbus 320 (A320) departing Vancouver International Airport (CYVR) climbing to FL 350 en route to Phoenix Sky Harbor International Airport (KPHX). Figure 20 displays the aircraft, two predicted trajectories, and the track data. Both the Baseline and KVM trajectories are generated at simulation time 56,406 seconds. This is roughly 16 minutes prior to true TOC, which occurs at simulation time 57,360 seconds. The Baseline trajectory (blue wireframe) predicts a TOC at 57,136 seconds, which is 224 seconds (about 4 minutes) prior to true TOC. The KVM trajectory (red wireframe) predicts a TOC

at 57,333 seconds, which is 27 seconds before true TOC. Hence, the KVM prototype produces a noticeably better TOC prediction than the legacy algorithm.

The true climb rate for Example 1 calculated from track data is 1,293 ft/min. The average climb rate in the Baseline scenario is 1,727 ft/min, which is 434 ft/min too steep. The average climb rate in the KVM scenario is 1,368 ft/min, which is 75 ft/min too steep. In this example, the KVM scenario produces a better TOC prediction and a more accurate climb rate (an improvement of 359 ft/min) than the Baseline scenario.

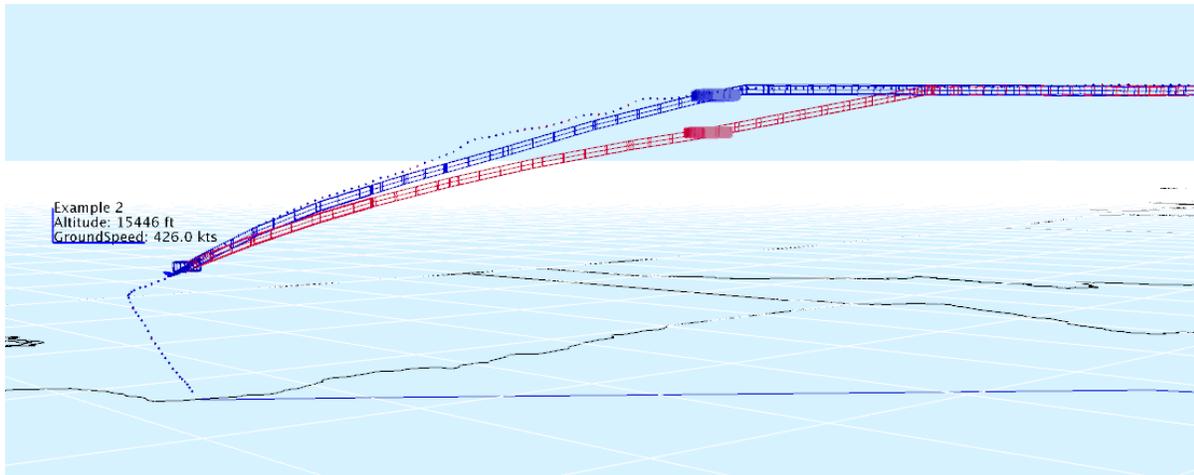


**Figure 20. Example 1, side view of entire climb**

### **3.3.3.2. Flight Example 2 – Degradation using KVM**

Flight Example 2 displays an Airbus 319 (A319) departing Portland International Airport (KPDX) climbing to FL350 en route to Phoenix Sky Harbor International Airport (KPHX). Figure 21 illustrates the differences in trajectory climb predictions. Both the Baseline and KVM trajectories are generated at simulation time 66,853 seconds. This is roughly 12.5 minutes prior to true TOC, which occurs at simulation time 67,600 seconds. The Baseline trajectory (blue) predicts a TOC at 67,642 seconds, which is 42 seconds after the true TOC. The KVM trajectory (red) predicts a TOC at 67,899 seconds, which is 299 seconds (about 5 minutes) after the true TOC. In this example the KVM produces a considerably less accurate (by 257 seconds) TOC prediction than the legacy algorithm.

The true climb rate for Example 2 calculated from track data is 1,549 ft/min. The average climb rate in the Baseline scenario is 1,484 ft/min, which is 65 ft/min too shallow. The KVM scenario has an average climb rate of 1,119 ft/min, which is 430 ft/min too shallow. In this example, the Baseline scenario better predicts both TOC and climb rate (an improvement of 365 ft/min) as compared to the KVM scenario.



**Figure 21. Example 2, side view of entire climb**

### 3.4. Conclusions and Discussion

Trajectory prediction provides an essential input to the conflict probe tool of ERAM, which supports air traffic controllers by anticipating potential conflicts up to 20 minutes into the future. The currently deployed ERAM Trajectory Modeler (TM) uses a kinematic modeling approach, which is sufficient for aircraft following traditional step climbs. However, it is less suited to modeling continuous climbs, which are becoming more prevalent in departures as flights begin to make use of advanced technologies to perform these operations. Paglione and Oaks [2009] showed that inaccurate trajectories can lead to degradation of performance in the conflict probe and an increase in alerts that may not be beneficial to the controllers. Lockheed Martin developed a prototype enhancement to the TM that implements a kinetic modeling approach, with the goal of improving the prediction of flights with continuous climb profiles on departures.

Schnitzer et al. [2015] evaluated prototypes of the BADA-based Kinetic Vertical Model (KVM) in previous studies. The previous studies focus on Continuous Descent Approaches (CDA), whereas this chapter focuses on continuous climbs on departures. In addition, previous studies used artificially injected interim altitude messages to force trajectory build times at a common point before Top of Descent (TOD). In the absence of these injected messages, this study has a collection of initial trajectory build times that are spread out from 4 to 25 minutes prior to Top of Climb (TOC). This study analyzes the initial trajectory builds and also successive trajectories to compare the KVM prototype against the legacy TM.

The analysis reveals a slight improvement in average TOC prediction error with the KVM prototype of 37.1 seconds compared to the Baseline scenario (albeit with relatively high variance in the data). However, the average absolute error improved by only 8 seconds. The shifted TOC predictions contributed to a decrease in climb rate error in the KVM scenario of 86.9 ft/min, which represents an 82.9% improvement from the Baseline scenario.

In assessing the trajectory accuracy, a TrajBuildToTOC parameter was defined to group data by trajectory age (relative to TOC). Analysts observed mixed results in mean unsigned vertical error at TOC, and improvement in mean unsigned along track error. When considering the entire climb sequence, a time period between 2 and 4 minutes prior to TOC showed improvements in the KVM scenario over the Baseline scenario in all but one category of TrajBuildToTOC times. In inspecting the mean unsigned along track error at TOC, the KVM scenario outperformed the Baseline scenario in all trajectory build time groups. The most noticeable improvement in Figure 19 is within the mid-range trajectories (built around 12 minutes prior to TOC), where the average along track error is considerably lower in the KVM scenario.

# Chapter 4 - Analysis of Simple Turn Modeling in Seattle Flight Data

## 4.1. Introduction

The Separation Management and Modern Procedures Project is an initiative of the Federal Aviation Administration (FAA) under the Next Generation Air Transportation System (NextGen) Program to implement improvements in the En Route Automation Modernization (ERAM) system, which supports all en route facilities in the United States. The FAA's Air Traffic Organization Operational Concepts, Validation & Requirements (AJV-7) tasked the FAA's Modeling and Simulation Branch (ANG-C55) to conduct several studies investigating the impacts from various proposed prototypes and parameter changes to the Trajectory Modeler (TM) and/or Conflict Probe Tool (CPT) of ERAM. The overall objective is to improve the performance of the conflict probe in preparation for integration of the CPT alert notification into the flight data block on the radar controller's main display. Since predicted trajectories are a primary input to the CPT, the accuracy and stability of the TM impacts the quality of alerts.

Currently, the ERAM TM turn modeling is simplistic in nature. Referred to here as legacy turn modeling, the current TM incorporates turns into trajectories by creation of two adjacent linear trajectory segments at different headings. The Simple Turn Modeling (STM) prototype enhancement to the TM, created by the ERAM development contractor Lockheed Martin, aims to improve the performance of the TM during turns by modeling turns by approximating a great circle route using piecewise linear segments.

This specific study compares the performance, with respect to trajectory accuracy, of the STM prototype against that of the current ERAM TM. The approach of this study is to isolate segments of track during which a turn occurs, and to evaluate the performance of time-coincident trajectory segments for both the legacy and prototype TM. The flight scenario examined includes aircraft in the Seattle (ZSE) Air Route Traffic Control Center (ARTCC).

## 4.2. Methodology

This study evaluates the performance of the Simple Turn Modeling prototype utilizing flights in the Seattle ARTCC.

### 4.2.1. Data Flow

In this study, analysts utilized ERAM track and clearance messages in conjunction with wind data recorded on March 14, 2014 from the Seattle ARTCC. Data was collected using Lockheed Martin's Sarbot tool. This 9-hour experimental traffic scenario was entered into Lockheed's Virtual Testing Laboratory (VTL), a laboratory version of ERAM, to create an output scenario containing track and trajectory points. The output scenarios were used as input in the ANG-C55 Modeling and Simulation Branch's *CpatTools*, a customized suite of software tools that takes flight traffic input files and creates a linked set of relational database tables. Tables include smoothed track, clearance, and route data, along with trajectory metrics. The analysts used this output data during the ensuing trajectory analysis.

### 4.2.2. Analysis Methods

Analysts evaluated the Simple Turn Modeling (STM) prototype for the Trajectory Modeler, comparing it to the operational version. Analysis includes the following scenarios.

- **Baseline** – Legacy trajectory prediction
- **STM** – Trajectory prediction using the Simple Turn Modeling prototype enhancement to the TM

#### 4.2.2.1. Data Collection and Reduction

The scenario in the *CpatTools* relational database contains 1,212 flights. For this study, analysts considered only flights whose track included a turn. To be considered a turn, the track must reflect a heading change over a minimum span of 30 seconds. In addition, the heading change of the first and last track point in the span must be at least 1 degree, and the heading change of all interior segments must be at least 2 degrees. In examining the track data, analysts identified 2,921 distinct turns. However, these may include turns that occur in the track but are not reflected in the route or are otherwise unavailable to the automation, such as verbally cleared path stretches. Since these turns overly complicate the data set, analysis is done to identify this type of turn segment via a custom application (*TurnAdherenceCalculator*) and exclude the associated data from analysis. This application calculated the distance of a turn segment's midpoint from the nearest fix on the route.

Analysts filtered out turns occurring more than 10 NM from a route fix. Filtering was also performed to exclude: 26 flights for which the TM stopped building trajectories in the STM scenario, 48 flights which had extremely high or extremely low trajectory build rates, and 6 other flights which were either not following their route or engaged in holding activities. In addition, analysts filtered out 46 military flights from the scenario, since military flights frequently deviate from their filed routes. The combined filters reduced the data set to 1,775 track-defined turn segments from 669 flights.

In collecting predicted trajectories, the analysts considered all trajectories built from the beginning of a flight up to 10 seconds after the end of the track-defined turn segment, resulting in 3,263 usable trajectories. Analysts then extracted trajectory metrics and other pertinent scenario information from

*CpatTools* output database tables using custom designed *Oracle* SQL queries. All analyses utilized JMP<sup>®</sup> statistical software.

#### 4.2.2.2. **Metrics**

Metrics for this study include standard trajectory metrics used in many studies [Paglione and Oaks, 2007].

*Cross track error* is the lateral distance between a track point and its time coincident trajectory point.

*Along track error* is the longitudinal distance between a track point and its time coincident trajectory point.

*Vertical error* is the vertical distance between a track point and its time coincident trajectory point.

## 4.3. Analysis

This section describes the results of the analyses defined in Section 4.2.2. Section 4.3.1 evaluates the track-trajectory errors for each flight. Section 4.3.2 displays visual flight examples revealing track and trajectory differences between the legacy TM and STM prototype predictions.

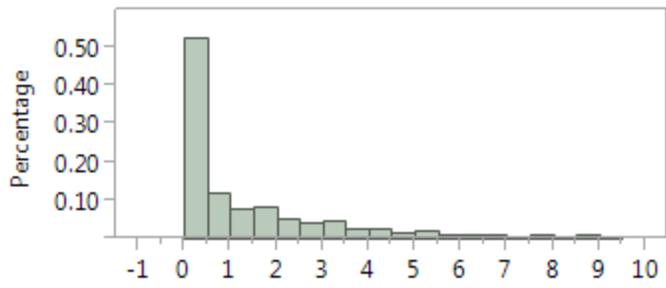
### 4.3.1. Trajectory Accuracy

As defined in Section 4.2.2, the metrics cross track, vertical and along track error are utilized in order to calculate differences between the actual track and predicted trajectory. For each track-defined turn segment, data consisted of trajectories and trajectory samples that meet the following conditions:

- Trajectory build time occurred at least 40 seconds from start of track for a given flight
- Trajectory build time occurred no later than 10 seconds after the end of a track-defined turn segment
- Trajectory sample time occurred in the temporal range of 10 seconds prior to the start of the track-defined turn segment and 10 seconds after the end of the track-defined turn segment

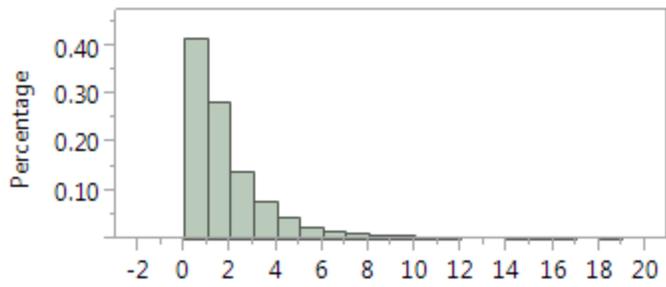
For each track-defined turn, the cross track, along track, and vertical errors from all of the usable data were aggregated. Figure 22 and Figure 23 depict distributions of the unsigned trajectory error as well as relevant statistics in the Baseline and STM scenarios, respectively.  $N$  is the number of track-defined turn segments considered in the aggregate analysis. Mean cross track error is 1.22 NM in the Baseline scenario and 1.26 NM in the STM scenario; mean along track error is 1.76 NM in the Baseline and 2.12 NM in the STM; and vertical error is 1,142 ft. in the Baseline and 1,226 ft. in the STM.

**Legacy Cross Track Error (NM)**



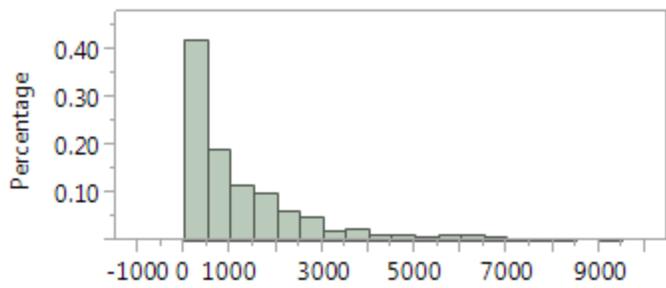
Summary Statistics	
Mean	1.2223498
Std Dev	1.6543824
Std Err Mean	0.0445992
Upper 95% Mea	1.3098395
Lower 95% Mean	1.13486
N	1376

**Legacy Along Track Error (NM)**



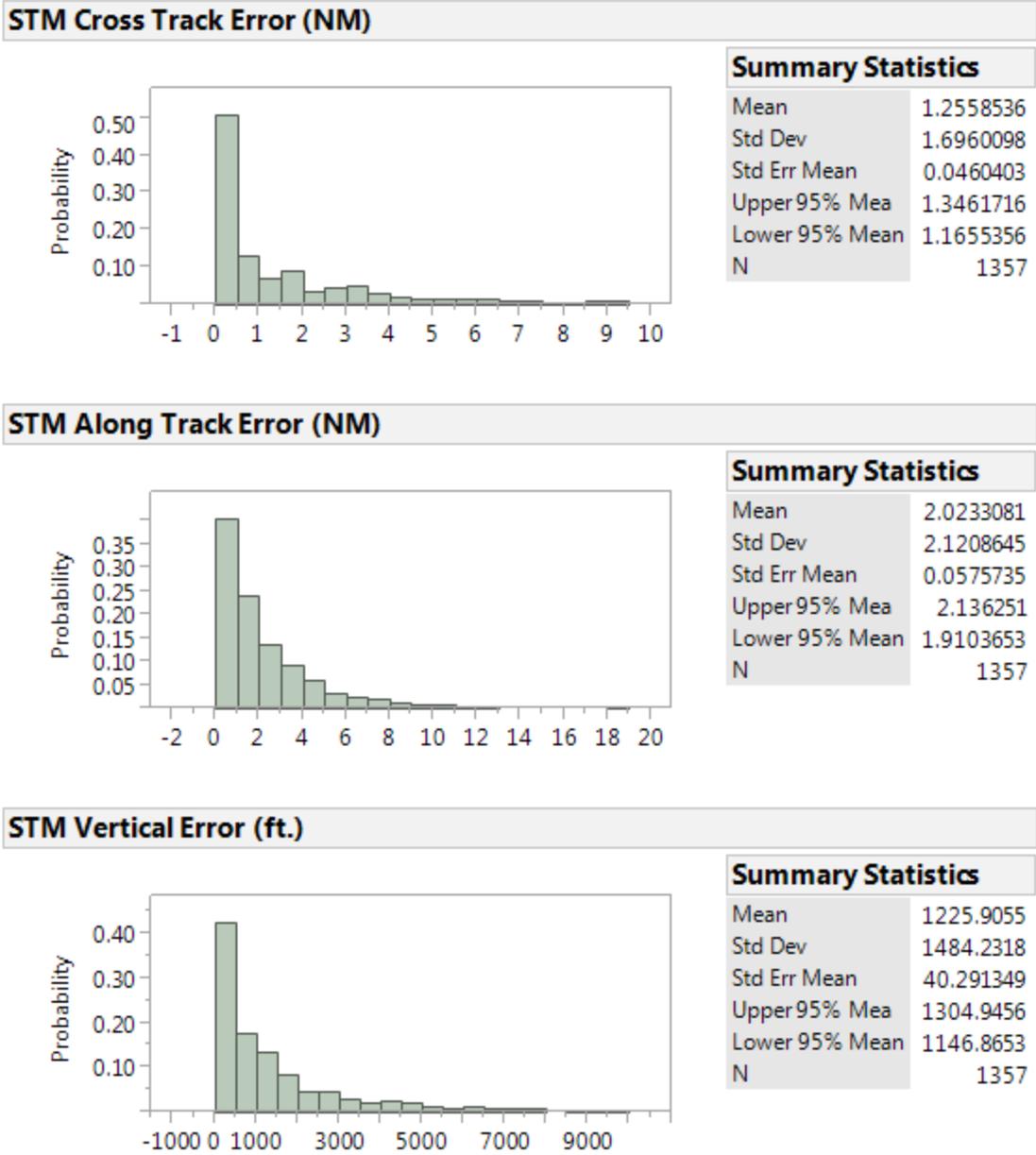
Summary Statistics	
Mean	1.7636539
Std Dev	1.883028
Std Err Mean	0.050763
Upper 95% Mea	1.8632352
Lower 95% Mean	1.6640725
N	1376

**Legacy Vertical Error (ft.)**



Summary Statistics	
Mean	1141.6572
Std Dev	1325.1366
Std Err Mean	35.723287
Upper 95% Mea	1211.7352
Lower 95% Mean	1071.5791
N	1376

**Figure 22. Distribution of unsigned trajectory errors near track-defined turn segments in Baseline scenario**



**Figure 23. Distribution of unsigned trajectory errors near track-defined turn segments in STM scenario**

Table 8 presents the results of a matched pairs statistical analysis (one-sided *t*-test) comparing the trajectory accuracy for track-defined turn segments in the Baseline scenario to the trajectory accuracy for the same segment in the STM scenario. Positive values indicate that the trajectory error is greater in the STM scenario than it is in the Baseline scenario. Using a significance threshold of  $p=0.01$ , along track error and vertical error are observed to be greater in the STM scenario than they are in the Baseline scenario by an average of 0.243 NM and 75 ft., respectively. From a practical standpoint, the observed increase in along track error is marginally significant while the increase in vertical error is relatively minor.

**Table 8. Matched pairs analysis of Baseline and STM scenarios**

	Difference	Standard Error	N Turns	p-value
<b>Cross Track Error (NM)</b>	0.036	0.018	1357	0.02
<b>Along Track Error (NM)</b>	0.243	0.042	1357	<0.0001
<b>Vertical Error (ft.)</b>	75	24.8	1357	<0.01

### 4.3.2. Flight Examples

The following sections present flight examples for the legacy TM and prototype enhancements. Dotted lines represent the flight track data, with track sampled at 10 second intervals. Blue wireframes signify the Baseline trajectory while red wireframes signify the STM trajectory. Solid lines represent the filed route. The circle represents the spatial location of the aircraft at the time indicated.

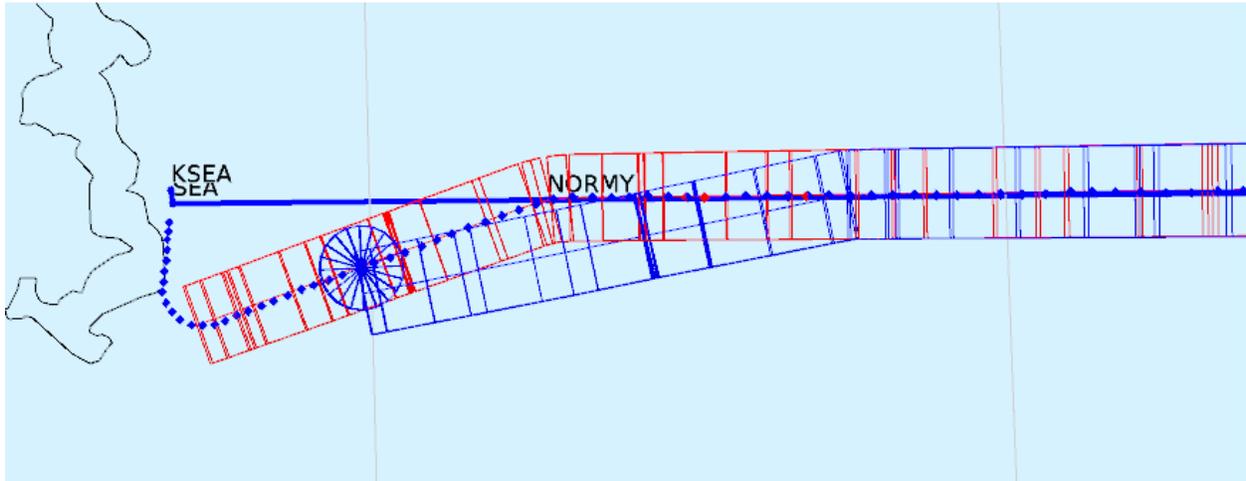
#### 4.3.2.1. Flight Example 1 – Trajectory improvement in STM

Flight Example 1 depicts a Boeing 737-900 departing Seattle Tacoma International Airport (KSEA). The flight rejoins its filed route via a turn near the fix NORMY. The turn begins at approximately 55,840 sec and ends at approximately 55,880 sec. Figure 24 displays the aircraft at 55,640 seconds. The Baseline trajectory is 4 seconds old (build time 55,636 sec) and the STM trajectory is 22 seconds old. Trajectory rebuilds follow the initial turn out of KSEA and represent the automation’s attempt to rejoin the filed route. The STM trajectory builds to the turn fix (NORMY) while the Baseline trajectory rejoins the route at a greater along route distance from the current position of the aircraft. The displayed STM trajectory better matches the path actually taken by the aircraft (dotted blue lines), with an average cross track error of 0.03 NM vs. 2.91 NM for the displayed Baseline trajectory. Note that the Baseline trajectory consists of two distinct linear segments with a single joint, whereas the STM trajectory consists of two large linear segments joined by several small linear segments that approximate a circular turn.



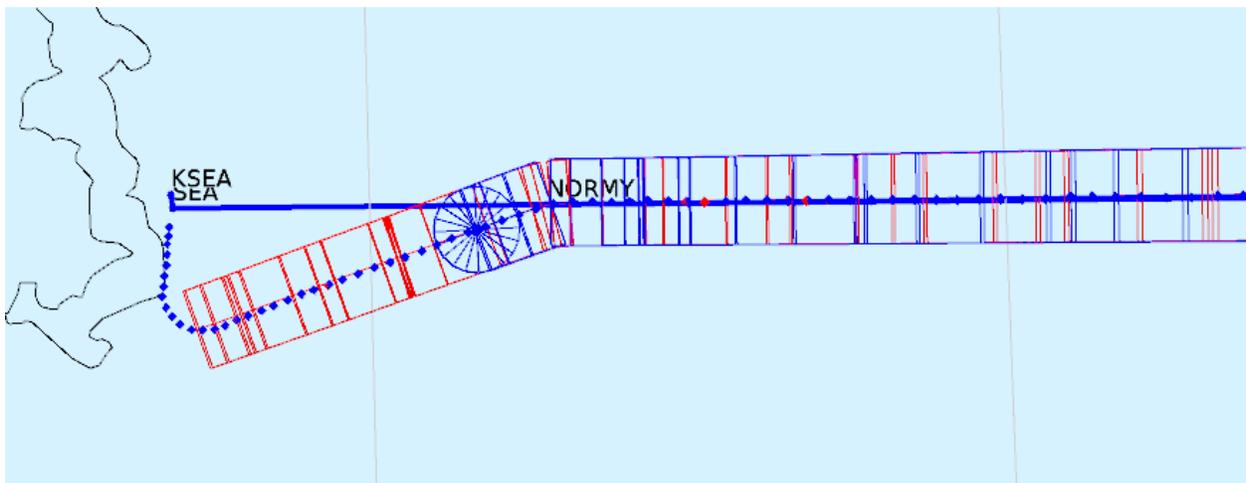
**Figure 24. Flight example 1 after departing KSEA, at 55,640 sec**

Figure 25 depicts flight example 1 at 55,742 seconds, capturing a trajectory reconformance that occurs in the Baseline scenario. In this scenario the legacy TM persists in modeling a rejoin to the filed route beyond the NORMY fix. The STM trajectory is still accurate, with an age of 124 seconds since last rebuild.



**Figure 25. Flight example 1, Baseline trajectory reconformance at 55,742 sec**

Figure 26 presents the next Baseline trajectory rebuild for flight example 1. This trajectory, generated at 55,815 sec, rejoins the route near the fix NORMY and is virtually indistinguishable from the STM trajectory in terms of accuracy from this point forward. However, the age of the STM trajectory is 197 sec at this point, and no rebuilds were needed throughout the turn.

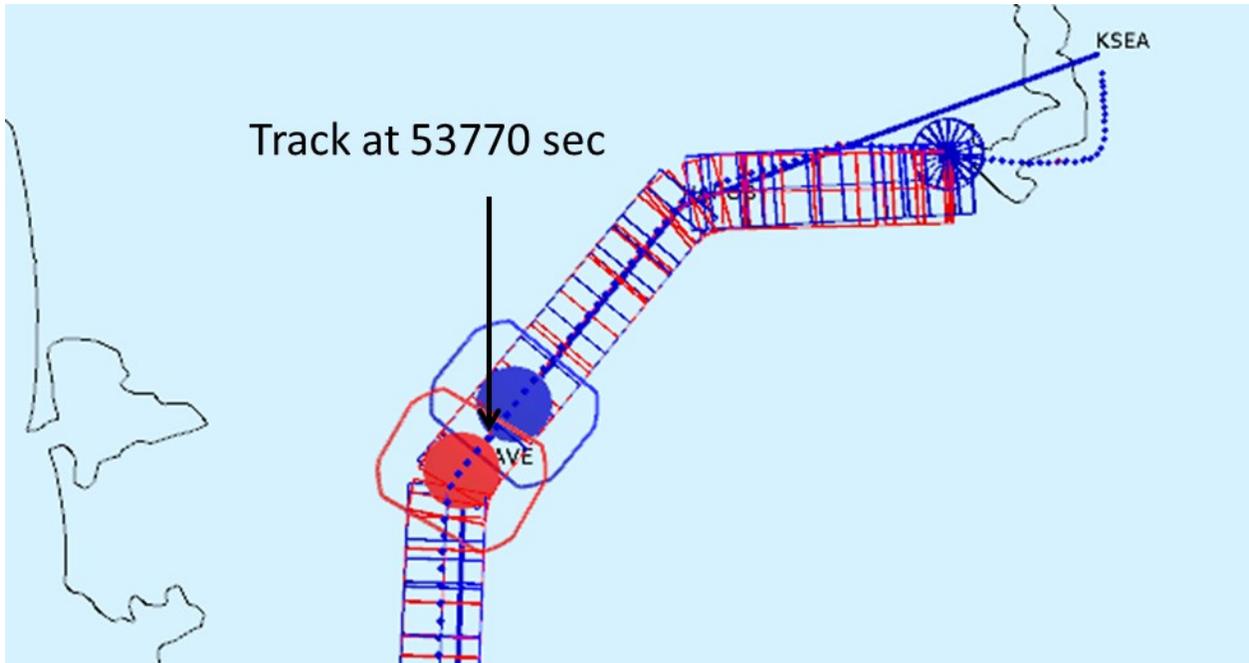


**Figure 26. Flight example 1, Baseline trajectory reconformance at 55,815 sec**

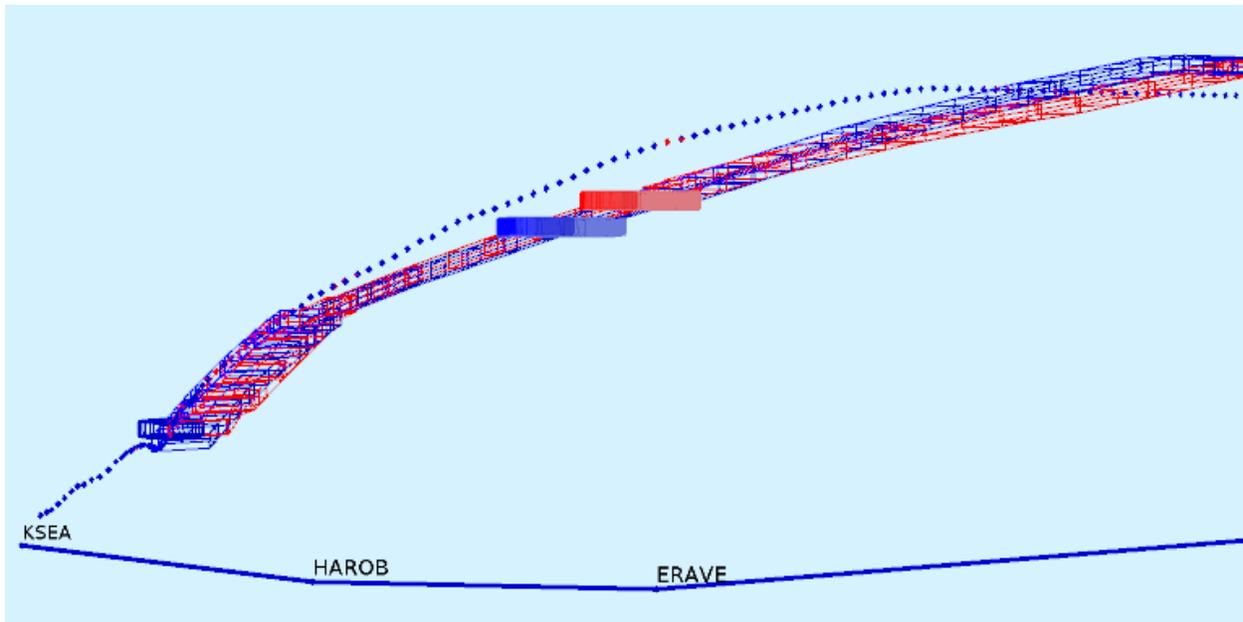
#### **4.3.2.2. Flight Example 2 – Trajectory degradation in STM**

Flight example 2 involves a Boeing 737-900 departing KSEA. The flight leaves the airport in a southerly direction and then heads west to rejoin its filed route, seen in Figure 27 and Figure 28. The turn under

consideration occurs at the fix ERAVE; it begins at about 53,770 sec and ends at about 53,870 sec. At the time shown (53,300 sec), the Baseline trajectory is 23 seconds old and the STM trajectory build just occurred. The along track error for the Baseline trajectory at the start of the turn (53,770 sec) lags 1.85 NM behind the track and the along track error for the STM trajectory is 3.75 NM ahead of the track. The difference in unsigned error (magnitude) yields a degradation of 1.9 NM. While the Baseline trajectory predicts a slower speed than indicated by the track data, the STM trajectory predicts a significantly faster speed than actually occurred.

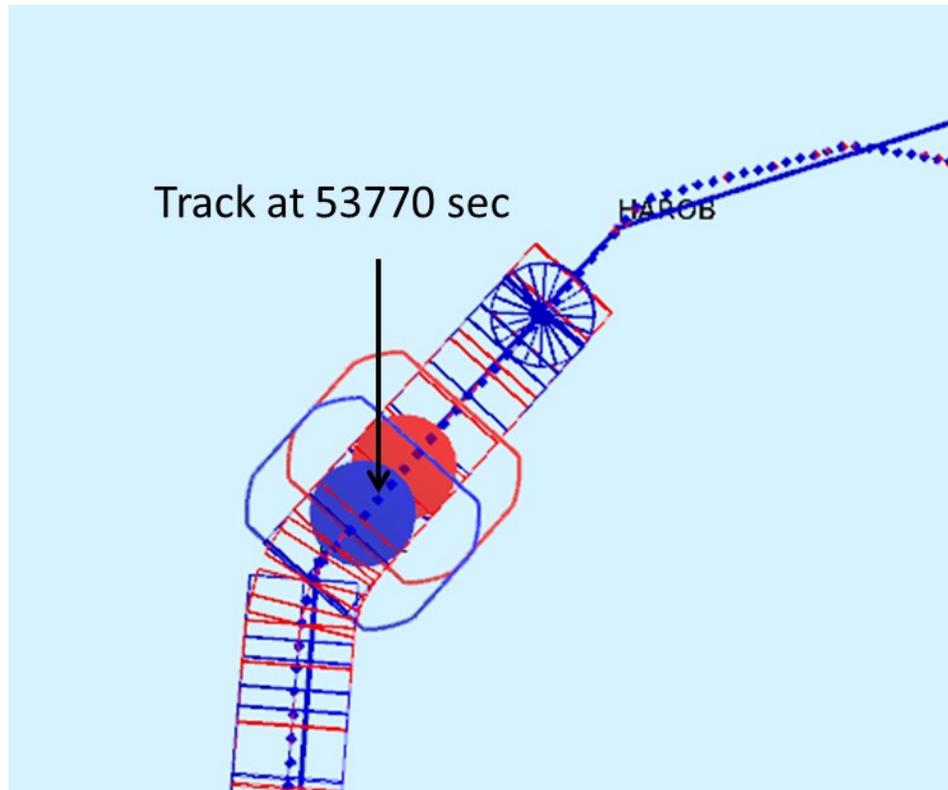


**Figure 27. Flight example 2 at time 53,300 sec, top-down view**



**Figure 28. Flight example 2 at time 53,300 sec, side view**

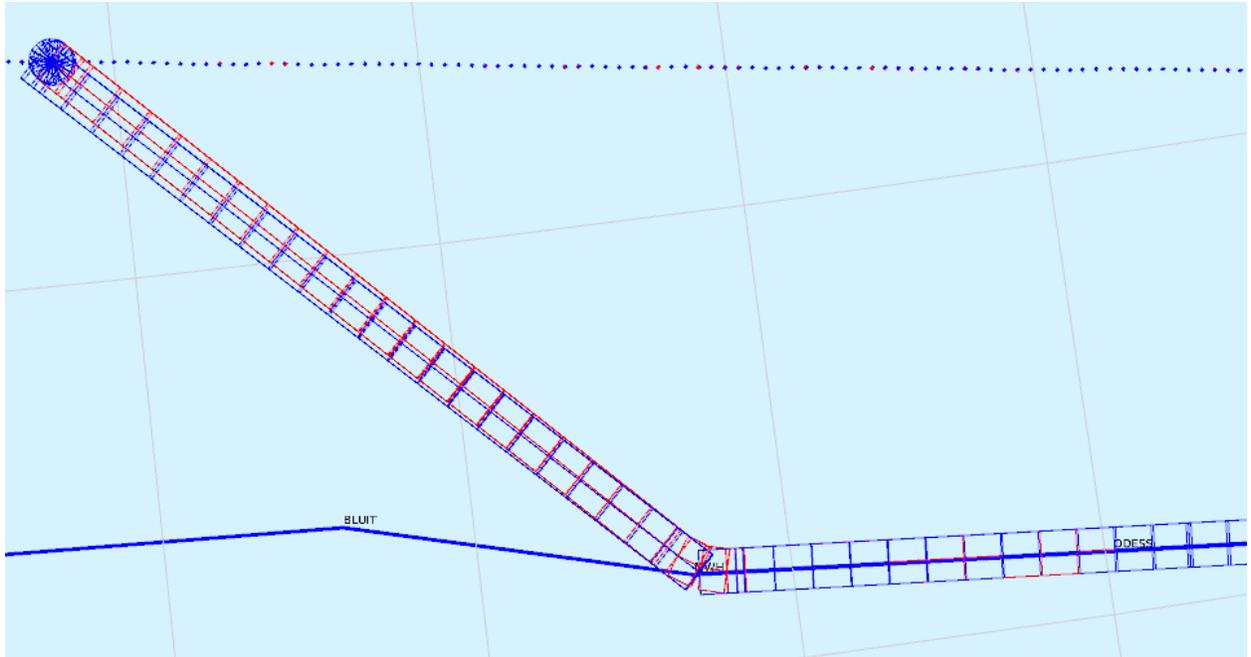
Figure 29 depicts flight example 2 at 53,630 sec, 5.5 minutes later. The Baseline along track error at this point is only 0.01 NM while the STM along track error is 2.89 NM. The difference in unsigned error has increased to 2.88 NM at this point, even though the trajectory predictions are closer together than in Figure 27. This peculiarity is due to the fact that the difference in signed error has decreased (from 5.6 to 2.88 NM) while the unsigned difference increased, from 1.9 to 2.88 NM. Signed error difference is less relevant to accuracy metrics, where the magnitude of deviation from truth is often the more important consideration.



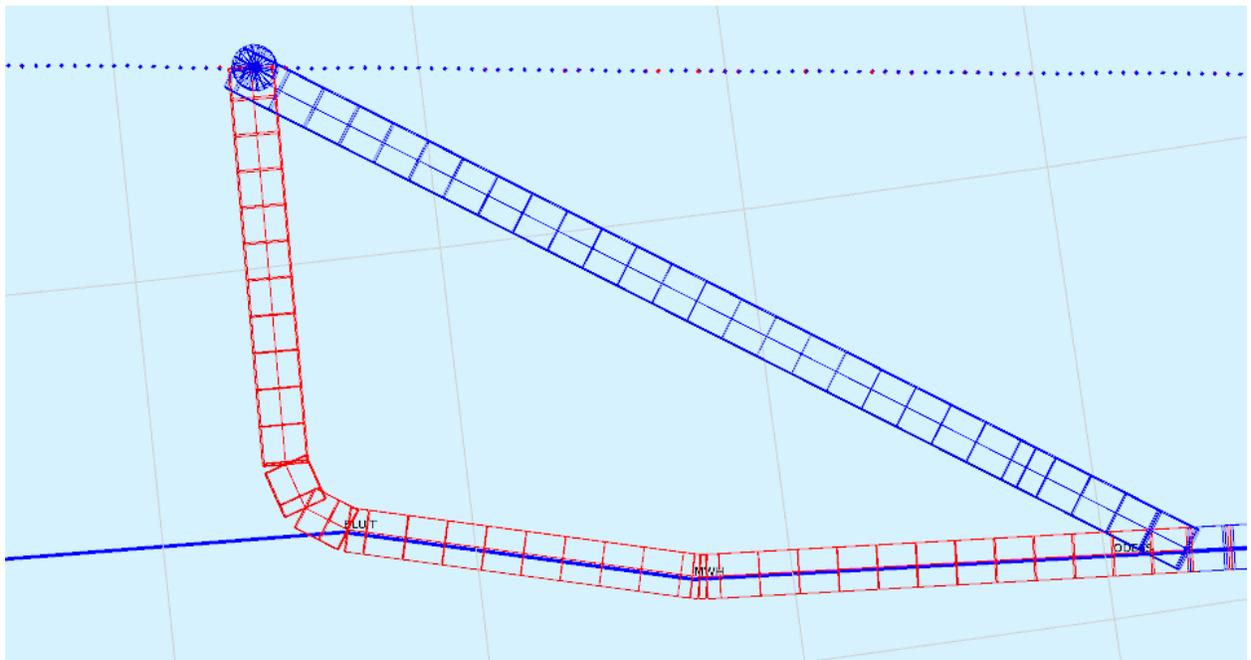
**Figure 29. Flight example 2 at 53,630 sec**

#### **4.3.2.3. Flight Example 3 – Issue with Readherence Logic**

Example 3 demonstrates an issue with readherence logic in the STM prototype. The flight, a Boeing 777-300ER out of Incheon International Airport in South Korea (RKSI) is not following its filed route, so it was not included in the trajectory analysis described in 4.3.1. However, observing this situation is valuable when attempting to evaluate how the turn modeling prototype performs when route rejoin logic is used. Figure 30, depicting the flight at 43,893 sec, reveals that Baseline and STM trajectories rejoin the route at the fix MWH. However, at time 44,047 sec (seen in Figure 31) the Baseline trajectory rejoins the route shortly after the next fix (ODESS) while the STM trajectory rejoins the route at BLUIT, which involves a predicted turn almost completely orthogonal to the current flight path. This suggests that there is some problem with the rejoin logic in the STM prototype. This issue affects the In Lateral Route Adherence logic, as identified through personal correspondence with the development contractor [E.McKay, personal communication, March 21-22, 2016], and has already been remedied at the time of this report.



**Figure 30. Flight example 3 at time 43,893 sec**



**Figure 31. Flight example 3 at time 44,047 sec**

#### 4.4. Conclusions and Discussion

ERAM's conflict probe tool supports air traffic controllers in anticipating conflicts by providing aircraft trajectory predictions upwards of 20 minutes into the future. Inaccurate trajectories can lead to degradation of performance in the conflict probe and an increase in alerts that may not be beneficial to controllers. The operating version of the ERAM TM uses a simple turn modeling approach, utilizing two linear segments of different headings to represent a turn. However, turns can be represented by using a sequence of linear segments to approximate inside turns [Nagl, 2011] without significantly increasing the load on, or decreasing the accuracy of, the trajectory modeler. A prototype enhancement to the TM by Lockheed Martin aims to utilize this approach with the goal of improving trajectory prediction for flights predicted to make inside turns.

This study evaluates a TM prototype that upgrades the legacy turn modeling by using linear segments as great circle arc approximations. This enhancement to the TM intends to improve the accuracy of trajectory prediction for flights during inside turns. This study compares the performance of the Simple Turn Modeling (STM) prototype as compared to the legacy TM. The objective is to evaluate the benefits of using the STM prototype over the legacy ERAM model.

The analysis, which concentrates specifically on flights which make inside turns within 10 NM of a fix on the file route, shows that the cross track error remains unchanged when the STM is implemented, while the along track error and vertical error are slightly degraded by 0.243 NM and 75 ft., respectively.

Analysis revealed anecdotal evidence of outliers in the various distributions of trajectory errors, even with the filtering described in Section 4.2.2.1. Discussion with the ERAM development contractor led to the realization that several algorithmic issues were present in the version of the prototype scenario provided to ANG-C55 for evaluation. Identification and correction of these issues had occurred as of the time of this analysis. However, an updated version of the STM scenario updated could not be obtained for this evaluation due to time constraints.

The observed degradation and algorithmic issues suggest that the version of the STM prototype evaluated by ANG-C55 is problematic. However, the fact that correction of several software issues occurred prior to this evaluation strongly suggests that reevaluation is necessary prior to any useful recommendation regarding the suitability of the prototype for implementation into the operational ERAM.

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