

Physics-Based and Parametric Trajectory Prediction Performance Comparison for Traffic Flow Management

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ABSTRACT

A series of studies compared the predictive performance of a physics-based trajectory modeler with the conventional parametric prediction system currently employed in the operational Traffic Flow Management (TFM) decision support system. The results indicate that the physics-based system has increased performance over the parametric system for trajectories in which aircraft transition in altitude. These studies include a sample size covering thirty-six 24-hour periods in which traffic from 12 Continental US Air Route Traffic Control Centers were examined. Four TFM metrics were used in the studies: Meter Fix Arrival Time, Departure Center Exit Time, Sector Entry Time, and Sector Occupancy. The charts of the TFM metrics for a majority of the data samples share the same characteristics and strongly lead to a consistent interpretation of the results. These interpretations generalize across the metrics for total sample aggregate (all Centers, all dates).

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INTRODUCTION

The mission of the Federal Aviation Administration (FAA) Air Traffic Control System Command Center (SCC) is to coordinate management of aircraft in the National Airspace System (NAS). Air traffic specialists at the Command Center coordinate with managers at Air Route Traffic Control Centers (ARTCCs, or Centers), Terminal Radar Approach Control (TRACON) Traffic Management Units, and airline Air Operations Centers to strategically manage the national air traffic flow. These traffic flow managers use tools such as the Enhanced Traffic Management System (ETMS) to mitigate delays throughout the NAS.¹

Trajectory prediction is the ability to predict the future positions of an aircraft. The ETMS employs a parametric system, which does not utilize physics-based equations of motion, to predict future aircraft positions. These predictions are used by the SCC in their decision support tools, such as the Sector Monitor Alert tool. A principle advantage of using parametric methods is the relatively low computational load, a relevant factor when predictions must be computed for the thousands of aircraft that may populate the NAS at any given time.

In contrast to parametric predictive systems, physics-based trajectory synthesis involves consideration of thrust-drag polars and makes use of computationally expensive integration operations. These calculus methods may consume a magnitude or more computational load than the parametric methods. The higher computational load generated by physics-based computations may be less of an issue in the future, due to the expected increases in computer price/performance. These studies seek to establish the degree and kind of benefit that may be realized by

using physics-based methods as compared to parametric methods.

The particular parametric method studied is the one employed by the ETMS. The physics-based method used for comparison is the one instantiated in NASA's Traffic Flow Automation System (TFAS), a spin-off application of the Center/TRACON Automation System (CTAS). The FAA has accepted several CTAS decision support tools for operational deployment at selected Centers and TRACONS. CTAS tools, such as the Traffic Management Advisor (TMA) and the Final Approach Spacing Tool (FAST), are designed to expedite the flow of aircraft into and through an adapted TRACON airspace.²⁻⁴ These systems employ point-mass equations of motion to predict future aircraft positions. Previous analyses have shown that these tools increase the aircraft capacity for their domain without significantly increasing controller workload or compromising passenger safety.^{3,5} Based on CTAS technologies, NASA has investigated the applicability of utilizing these physics-based trajectory prediction techniques to potentially benefit the strategic TFM domain, and has engineered a TFAS prototype system to explore these issues. The TFAS project involves expanding CTAS from a tool that could only be applied to a single ARTCC to one that could cover the 20 contiguous ARTCCs that comprise the Continental US (CONUS) airspace.⁶

This paper is a study of the predictive reliability of the physics-based predictions generated by TFAS as compared to parametric kinematics-based trajectories generated by ETMS. The predictive reliability is measured using four Traffic Flow Management (TFM) metrics originally developed by Masalonis, et al, for analysis of the Collaborative Routing Coordination Tools (CRCT)⁷: Meter Fix Arrival Time Accuracy, Departure Center Exit Time Accuracy, Sector Entry Time Accuracy, and Sector Occupancy Accuracy.

In the analyses performed by Masalonis, et al, the relative predictive performance of CRCT to ETMS was evaluated under various conditions covering 4 days and 2 ARTCCs.⁷ The analyses described in this paper cover the aggregate of twelve ARTCCs and thirty-six 24-hour periods (although not all Centers are covered in any given period).

MOTIVATION

Although it is widely recognized that the largest TFM prediction errors are attributable to factors that occur before aircraft become airborne⁸ (defined by ETMS as active), relatively small predictive errors of active

aircraft may also have a large human factors impact on the Air Traffic Management (ATM) processes.⁹ Human factors problems may become most noticeable in areas where active aircraft are handed off between ATC facilities, e.g. at the meter fixes where ARTCC arrival controllers hand off aircraft to TRACON, or at coordination fixes where one ARTCC hands off aircraft to an adjacent Center. Sector controllers cannot judge the performance of predictions that concern events outside their airspace, so they may be inclined to base their opinions about TFM automation tools on the performance and reliability of the predictions that concern their own sector.

ANALYSIS METHODS AND MATERIALS

TFM Predictive Performance Metrics

This study focuses on four prediction performance metrics that have specific significance for the TFM domain:

- Meter Fix Arrival Time Accuracy
- Departure Center Exit Time Accuracy
- Sector Entry Time Accuracy
- Sector Occupancy Time Accuracy

This study has attempted to maintain compatibility with the TFM metrics outlined in Masalonis, et al, whenever practical to facilitate future comparative analyses. We have added Meter Fix and Departure Center Exit Time metrics because of their importance to arrival and departure management tools.

Meter Fix Arrival Time Prediction Performance

The meter fix is typically the point at which arriving flights are handed off from the ARTCC to the TRACON. In this metric we evaluate the performance of a decision support tool in predicting the crossing time at that point. The metric is defined as the difference between the predicted and observed meter fix crossing times:

$$\epsilon_{\text{meter fix}} = t_{\text{cross, predicted}} - t_{\text{cross, actual}} \quad (1)$$

In analyzing flight times at the meter fix, we characterize the performance of a tool in predicting trajectories for arrival aircraft in transition from cruise altitude.

For this and each of the successive metrics, a negative epsilon is an early prediction error and a positive epsilon is a late prediction error.

Departure Center Exit Time Prediction Performance

Similar to looking at predictions of times at the meter fix for arrivals, we look at predictions of ARTCC exit times for departures from adapted airports. The metric is defined as the difference between the predicted and observed ARTCC exit times:

$$e_{\text{center exit}} = t_{\text{exit, predicted}} - t_{\text{exit, actual}} \quad (2)$$

With this metric we analyze the behavior for departures in transition. We chose to examine the ARTCC exit time for departures in an attempt to provide a common point of comparison for each decision support tool. This also allows each departure to capture as much of the ascent portion of the flight as possible for as many aircraft as possible.

Sector Entry Time Prediction Performance

This metric, seen in figure 1, is defined as the difference between the predicted entry time of the aircraft into a sector of airspace and the observed entry time of the aircraft into that sector:

$$e_{\text{entry}} = t_{\text{entry, predicted}} - t_{\text{entry, actual}} \quad (3)$$

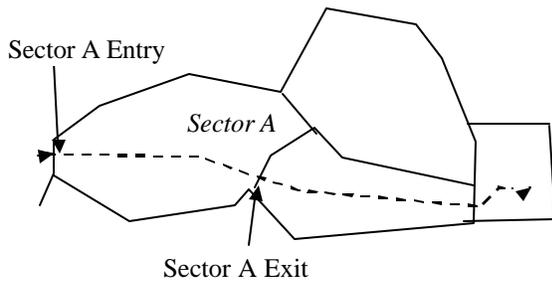


Figure 1: Sector entries and exits for a single trajectory.

While a similar study could be carried out for sector exit events, this yields little additional insight (as test cases have shown). The studies are in fact nearly identical; a sector exit event for one sector represents the sector entry event for the next sector of a trajectory.

Sector Occupancy Time Prediction Performance

The sector occupancy time for an aircraft in a sector is defined as the difference between the exit event time and the entry event time. The metric is defined as the difference between the predicted sector occupancy time and the observed occupancy time:

$$e_{\text{occ}} = (t_{\text{exit, pred}} - t_{\text{entry, pred}}) - (t_{\text{exit, act}} - t_{\text{entry, act}}) \quad (4)$$

While the sector entry time metric shows the performance of each tool in predicting events

dependent on initial conditions such as a ground or air delay, this metric shows the performance of each tool in predicting events independent of these initial conditions.

Data Sources and Analysis Processes

In this section, we describe the raw data sources, the algorithms used to process them, and the processes used to conduct the analyses in this study.

Primary Data Sources

For these analyses, we define two primary datasets. These primary datasets will be the input to all of the analyses conducted for this study:

- Trajectory Predictions (i.e., TFAS or ETMS)
- Observed (“truth”) Trajectories (taken from Host data)

The trajectory data consists of step-wise information about position, ground speed, heading, altitude and time for individual aircraft. Note that each tool to be analyzed has a set of trajectory predictions associated with it, while the “truth” data remains common for all tools. The steps representing the trajectories correspond to events of interest, in which we include sector entry and exit times, meter fix crossing times and center exit times. We refer to these representations of trajectories as “event lists”.

Obtaining Parametric Predictions

The parametric-based trajectory predictions come from the research version of the ETMS software that was modified to archive the internal ETMS event lists for each aircraft in the NAS as the lists were updated (due to a new position update or flight plan change, etc.). Among the possible ETMS events are sector entries and exits, fix crossings, and airway intersections. ETMS stores the predictions rounded to the nearest minute. Each of the event data files contains an hours’ worth of ETMS event lists.

The primary source of air traffic data for the ETMS comes from each of the Host data feeds supplied by each ARTCC every 60 seconds. These data are supplemented by TRACON, oceanic, and foreign data sources. ETMS calculates aircraft predictions based on the route of flight generated from the flight plan, conditions from the latest position update, and wind data.¹⁰ These wind data come from Rapid Update Cycle (RUC) files provided by the National Centers for Environmental Prediction.¹¹

Obtaining Physics-Based Predictions

Since the results of this study focus on a comparison of physics-based and parametric systems, it is important that both candidate systems share the same data source as the basis for their respective prediction calculations. As mentioned above, the parametric system, ETMS, obtains flight plan and track data directly from the facilities controlling aircraft across the NAS and from other various sources throughout the Northern hemisphere. ETMS not only uses these data for internal event predictions, but also archives the position and route data messages. The physics-based system, TFAS, uses these message archives as the primary aircraft data source for the analyses.

Input Data

The ETMS field site data feed is available to TFAS through data archive files, called *orig* files, written out every hour and archived at the Volpe National Transportation Systems Center.¹⁰ The *orig* file contains a log of every message sent from the ETMS Hub site to each ETMS field site.

For each 24-hour analysis, the physics-base system (TFAS) uses 39 hours of *orig* file data. This includes 15 hours of data before the start of the analysis, necessary to ensure that TFAS receives the scheduled flight plans that appear during the previous day. We chose 15 hours as the lead-time based on the ETMS functional description, which states that scheduled (based on historical data) flight plans are activated in the system 15 hours prior to the scheduled take off.

Weather Data

TFAS requires wind and atmospheric data for generating trajectory predictions. The data come from the 2-hour RUC forecast to model predictions of an operational system.

Creating the Event List

The physics-based event-lists are created by TFAS during an analysis run resulting in the production of a data set of sector and meter fix predictions, rounded to the nearest second.

Observed (Truth) Data

ARTCC Host data is used as ‘truthing’ data, to determine the actual aircraft performance and positions at particular times along its flight path.

A radar track hit for a specific aircraft refers to the state information of that aircraft at a particular time. An aircraft has a set of track hits throughout the archived Host data file that trace its course through the airspace. From this information, observed sector and meter fix times are produced according to the following algorithm:

- For each aircraft appearing in a file containing ARTCC Host history data, analyze the track data and determine the first and last track hits occurring in each sector crossed by the aircraft.
- The time of the first track hit inside a sector is considered the sector entry time. The sector exit time is the same as the sector entry time of the adjacent sector. Since the Host update rate is 12 seconds, which is smaller than the parametric system’s prediction resolution, we did not attempt to interpolate observed entry times.
- For aircraft identified as arrivals to an adapted airport, take the track hit closest to the assigned meter fix as the observed meter fix crossing time.
- For aircraft identified as departures, use the groundspeed and heading to extrapolate the Center boundary crossing from the last track hit inside the ARTCC. This value is extrapolated due to some ARTCC tracks being dropped from the system before the aircraft actually cross the boundary.
- Eliminate any entry times from the event lists where the difference between the first track hit in the sector and the previous track hit is greater than 18 seconds. This removes erroneous entry times based on the first track hit of an aircraft. The number of events filtered out based on this filter was relatively small.
- Eliminate aircraft from the analysis that have the following characteristics: military aircraft (for security reasons), aircraft with no observed events, and aircraft that start and end at the same airport. This represents a very small portion of the aircraft in the database.

The analysis software uses the same sector definitions to determine the observed and predicted sector crossings for both the physics-based and parametric systems. The result of this process is a file

containing observed sector entry and exit times for each aircraft, rounded to the nearest second.

Measuring Performance

A suite of software tools has been developed to evaluate the metrics described above. The tool suite ingests predicted event lists from the physics-based and parametric systems, compares the predicted events to observed (truth) event lists derived from ARTCC Host data, and produces a comparison of the two systems' predictive performance. The tools operate in the following manner:

- For each instance of an observed aircraft/event pair (a sector, Center, or meter fix crossing), search the prediction data for sets of predictions made for that aircraft before the observed event occurred.
- When such a prediction set is found, search the prediction set for the event referenced by the observed data.
- If the observed event is found, compute the metrics described by equations 1 through 4. For each of these measurements also record the difference between the time the event was observed and the time at which the prediction was made. This is defined as the look-ahead time (LAT).
- Delete any prediction errors/times in which the prediction error is greater than 12 hours (or less than -12 hours), as these indicate events occurring for the same flight number on different days.
- Reject flights that do not appear in both systems' prediction data.

Data Sample

The preferred experimental protocol required ARTCC samples of 24 hours of uninterrupted Host data acquisition, and matching ETMS orig files that contained the same 24-hour period, along with fifteen hours of data prior to the beginning of that period. A variety of factors could result in interrupting a particular data acquisition, and in some cases those dates or ARTCCs could not be used for analysis.

Airspace Coverage

This study considers data samples from 12 of the 20 CONUS ARTCCs, highlighted in light gray in figure 2.

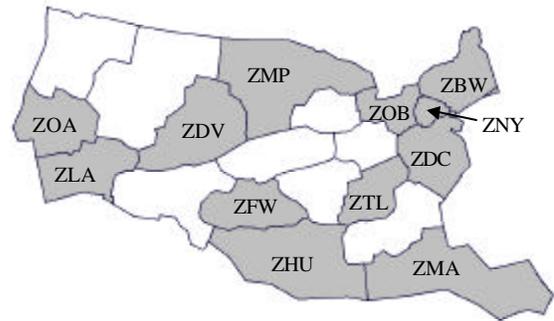


Figure 2: ARTCCs captured in the study

The selection of these particular Centers was based on the availability of ATC Host computer data. NASA has been granted access to Host data, which includes real-time radar data, for these Centers, and did not have such access to the remaining eight CONUS Centers at the time of the data collections.

Airports

The Meter Fix Arrival Prediction and Departure Center Exit Prediction metrics focus on the characteristics of arrivals and departures. For these studies, we look only at arrivals and departures to and from the 19 adapted primary airports in the Centers of interest. They are shown graphically in figure 3.

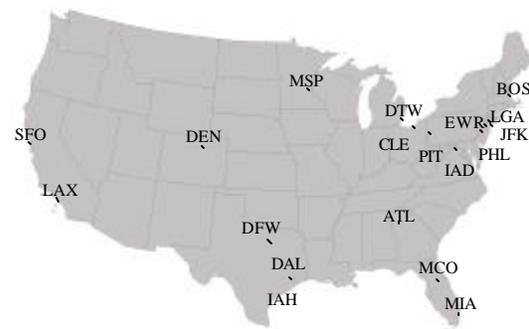


Figure 3: Focus airports for the study

These airports were selected because they are defined as the "pacing airports" in the ARTCCs analyzed by this study and are defined as the primary airports in the physics-based system's adaptation for the corresponding ARTCC.

The meter fixes used for the Meter Fix Arrival metric are defined in the adaptation for the 19 airports.

Aircraft Coverage

Segments of Flight

This study differentiates between trajectory prediction performance for en route flights, arrivals,

and departures. Flight segments in the TRACON and other special airspaces are not examined, since the focus of this report is evaluation of performance of tools for Traffic Flow Management. The TFM tools in question have not been designed to deliver benefit in these regions.

Airborne (aka 'active') flights are the focus of these analyses. Studies have indicated that in current operations, departure time prediction for flights is a primary cause of prediction error of en-route events.⁹ This study does not attempt to address these pre-departure uncertainties.

RESULTS

This study analyzed a sample size of thirty-six 24-hour periods. The fewest number of ARTCCs analyzed in any period was three (one instance) and the largest number of ARTCCs covered was eleven (five instances). The median number of ARTCCs analyzed in a period was 9. A total of 310 twenty-four hour periods were analyzed over the 12 different ARTCCs.

Standard Deviation of Error

For the analysis plots, we have provided the averages of the signed and absolute prediction error, as well as the standard deviations of the signed error. All data points that lie outside of 3 standard deviations from the average, for both candidate systems, have been filtered and are not represented in the results of this study. This represents 2.30% of the ETMS data points and 2.10% of the TFAS data points. A discussion of rationale for filtering the 'third sigma' population follows.

The majority of the aircraft trajectories that fall in the third standard deviation (3-sigma) category can be attributed to one of the following error sources.

1. Positional altitude: The aircraft position messages stored in the ETMS orig files do not always supply the Mode-C altitude. If an aircraft is in transition, the Flight Plan cruise speed is provided.
2. Aircraft re-routing: In the course of normal flight operations, aircraft are routinely re-routed for a variety of reasons. These include weather avoidance maneuvers, ATM flow management support, and pilot/airline flight path "direct to" requests. These ATC procedures, defined by amendments to the flight plan, can change the time aircraft are predicted to reach downstream sectors. Though both candidate systems generate

new predictions based on the modified flight plan, previously accurate trajectory predictions will, in many cases, become outliers.

3. ATC imposed delays: Air Traffic Controllers delay aircraft when the airspace is constrained to alleviate downstream problems. Since the controller is imposing measures to delay aircraft, the predictions made before the aircraft was delayed will be early by the amount of the delay.
4. Redundant sector entry times: For aircraft arriving to any of the fully adapted airports for arrival traffic, the physics-based trajectory is broken into two parts, from the current position to the Meter Fix and from the Meter Fix to the Runway. Under certain conditions the Meter Fix to Runway portion of the trajectory is written out twice to the Event List, causing sector entry times for the last sector before the TRACON to be off by several minutes. This is not the intended algorithm behavior and will be fixed in future releases of the software.
5. Incorrect modeling of departure procedures: For departures from the fully adapted airports, the departure route and procedures are not currently being modeled completely in the candidate physics-based system. This causes inaccurate predictions of aircraft that are climbing out of the TRACON. It is hoped that systems such as the Expedite Departure Path Tool may address such problems in the near future.
6. Incorrect modeling of some descent procedures: Air Traffic Controllers manage aircraft in their airspace using the Letters of Agreement (between two different facilities) and Standard Operating Procedures (internal to a single facility). The altitude and speed restrictions at the Meter Fix are an example of those procedures. The candidate physics-based system currently considers the procedures at the Meter Fix for all fully adapted airports (e.g. DFW and DAL for ZFW). However, TFAS may not model descents for aircraft at other locations such as the ARTCC boundary or secondary airports (e.g. TUL for ZFW).

Categories 1, 2, and 3 can affect both candidate systems. Category 1 errors could be mitigated by

improvements in ETMS altitude data reports (i.e. a ‘Garbage-In-Garbage-Out’ problem). Category 2 (flight-plan changes) affects both systems equally, and in the same manner. A tighter coupling between tactical and strategic ATM systems may mitigate Category 3 effects. It is beyond the scope of this study to analyze the additional mechanisms that may cause ETMS ‘third sigma’ behavior.

The last three categories affect only the candidate physics-based system, and are attributable to well-understood mechanisms in the software. These anomalies have been identified and will be addressed in the course of future phases of software development. Since the cause and remedy of these ‘outliers’ are understood, they have been filtered to prevent artifacts from misleading inferences concerning the physics-based method’s efficacy.

Aggregated Results

This section represents the aggregation of all of the data in the study. It shows the underlying trends in the performance of both methods over the thirty-six days and twelve Centers captured in our research.

In Figures 4 – 15, the Y-axis represents the prediction error of the sample in minutes. This will vary by type of plot to be the signed or absolute difference between the predicted and observed times, or in the case of the standard deviation, it shows the variability of the data in minutes. The X-axis samples these errors in 5 minutes intervals depicting the difference between the time the event was observed and the time at which the prediction was made (or look-ahead time). Data generated by the parametric-methods system (ETMS) are represented by a plus (+) symbol and data generated by the physics-based method system (TFAS) are represented by an asterisk (*) symbol.

For the data plots, we have chosen a look-ahead time of up to 100 minutes to be representative of active aircraft. After the 100-minute bin, the sample size begins to significantly decrease. The exception is the Departure Center Exit metric, where we plot the data through the 45-minute bin. The number of aircraft that take longer than 45 minutes to cross the ARTCC boundary after takeoff is very small.

For each of the analyses, plots representing the signed and absolute value prediction error are shown. The signed plots demonstrate the bias and stability of each tool. The absolute value error shows the magnitude of the error for a given metric. The standard deviation of the signed sample is also given.

It demonstrates the variability of each tool for calculating predictions for a given metric.

The number of aircraft used for each analysis is the same for both systems under consideration. However, the sample size for the metrics is based on the calculated trajectories for each of the aircraft. Each system only archives predictions when a new trajectory produces different event times than the previous one. Since the physics-based method embodiment (TFAS) stores event times to the nearest second, it produces more updates than ETMS, which only stores event times to the nearest minute.

It should be noted that the differences between the means of each of the data points seen in these analyses are statistically significant. The probability that the differences are due to random fluctuations in the data has been calculated to be less than 0.1%.

Meter Fix Arrival Time

Figures 4-6 depict the analysis of the aggregate of the Meter Fix Arrival Time Prediction Error. This analysis was based on 2,324,466 parametric prediction (ETMS) samples and 6,533,568 physics-based prediction (TFAS) samples. The signed difference shows a positive (late) bias for ETMS (1.24 minutes) while TFAS has a negative (early) bias of -0.34 minutes. The magnitude of the differences is seen in figure 5 where TFAS predictions have an average absolute error of 1.56 minutes, as opposed to ETMS average error of 2.64 minutes. The data, as seen in figure 6, also reflect less variability for TFAS predictions with a TFAS standard deviation of 2.51 vs. ETMS’s 3.47.

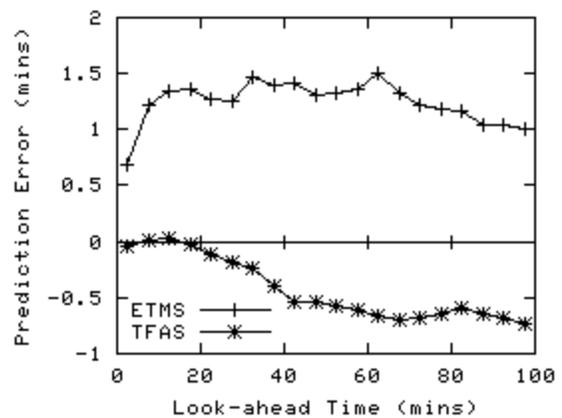


Figure 4: Meter Fix Arrival (Signed)

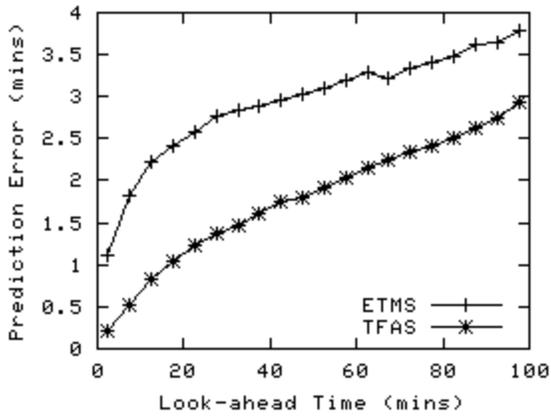


Figure 5: Meter Fix Arrival (Absolute)

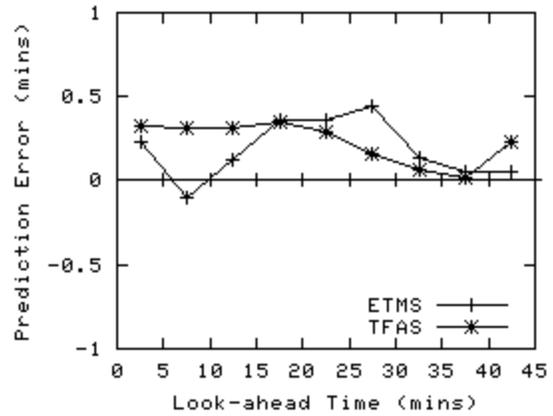


Figure 7: Departure Center Exit (Signed)

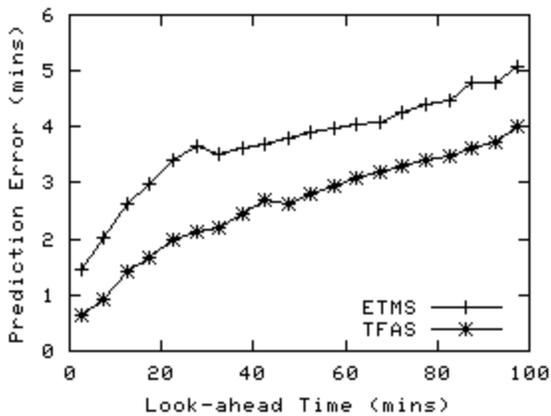


Figure 6: Meter Fix Arrival (Standard Deviation)

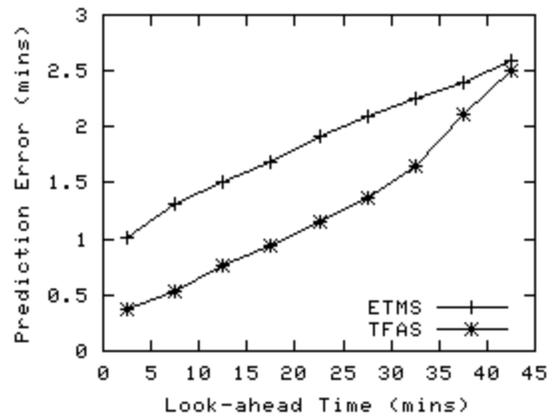


Figure 8: Departure Center Exit (Absolute)

Departure Center Exit Time

The analysis of the aggregate Departure Center Exit Time Prediction Error covers 1,389,497 parametric and 3,540,649 physics-based trajectory predictions. The signed plot in figure 7 shows an ETMS positive bias of 0.19 minutes and a TFAS bias of 0.28 minutes. Figure 8 demonstrates that TFAS predictions have an average magnitude error of 0.88 minutes, as opposed to ETMS average magnitude error of 1.61 minutes. Overall less variability is reflected in the standard deviations of the physics-based predictions (1.76) as compared to the parametric predictions (2.35). However, these results are mixed; as TFAS tends to become more variable than ETMS the farther the aircraft is away from the ARTCC boundary.

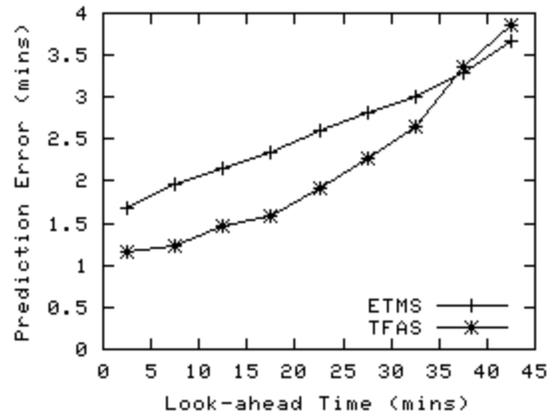


Figure 9: Departure Center Exit (Standard Deviation)

Sector Entry Time

The analysis of the aggregate Sector Entry Time Prediction Error covers 26,601,673 parametric and 79,641,090 physics-based trajectory predictions. The signed plot seen in figure 10 demonstrates a slight positive TFAS bias of 0.22 minutes, while ETMS has an overall negative bias of -0.20 . The plot of the

magnitude of the difference seen in figure 11 shows a different trend. Although TFAS appears to be slightly more accurate for the first 35 minutes (this accounts for aircraft less than 35 minutes from the predicted sector boundary), ETMS appears to have a slight advantage beyond 65 minutes. For the sample, TFAS predictions have an average magnitude error of 2.38 minutes as opposed to ETMS average magnitude error of 2.66 minutes. The plots of the standard deviations in figure 12 show a similar trend with a TFAS standard deviation of 4.15 vs. ETMS's 3.97.

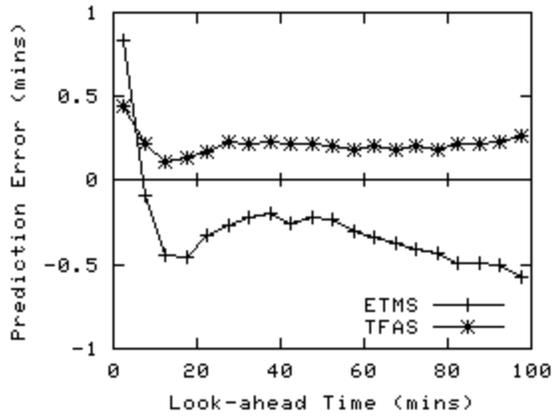


Figure 10: Sector Entry (Signed)

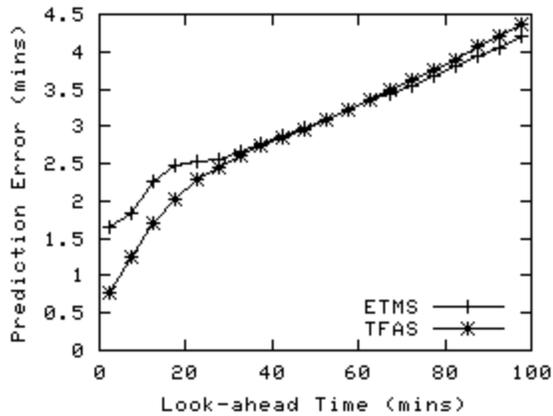


Figure 11: Sector Entry (Absolute)

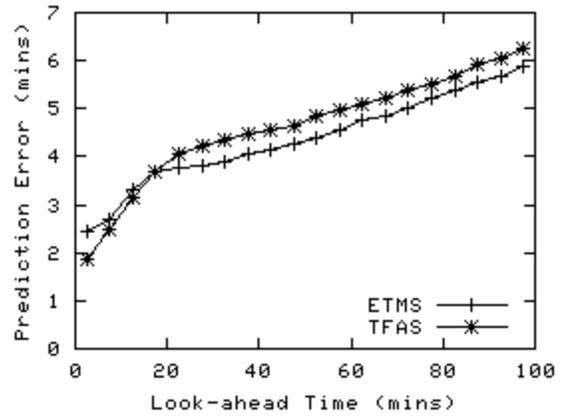


Figure 12: Sector Entry (Standard Deviation)

Sector Occupancy Time

The analysis of the aggregate Sector Occupancy Time Prediction Error covers 26,372,858 parametric and 78,849,672 physics-based trajectory predictions. The signed difference plot in figure 13 demonstrates a positive bias for both TFAS (0.53) and ETMS (1.05). The trends seen in the plots of the absolute difference and standard deviations (figures 14 and 15) mirror the trends from the Sector Entry plots (figures 11 and 12). The TFAS predictions have an average magnitude error of 2.70 minutes, as opposed to ETMS average magnitude error of 2.83 minutes, and a TFAS standard deviation of 4.28 vs. ETMS's 4.09.

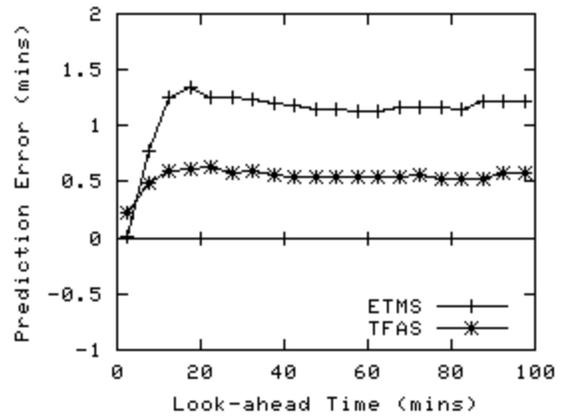


Figure 13: Sector Occupancy (Signed)

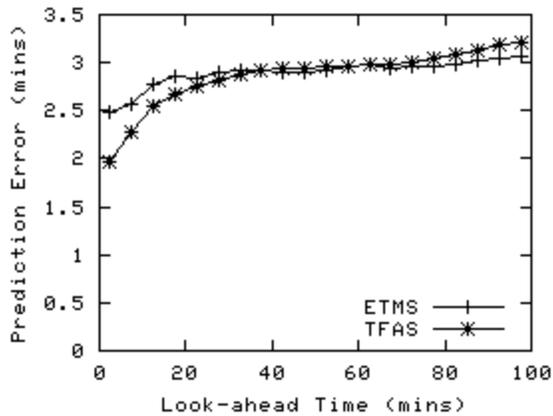


Figure 14: Sector Occupancy (Absolute)

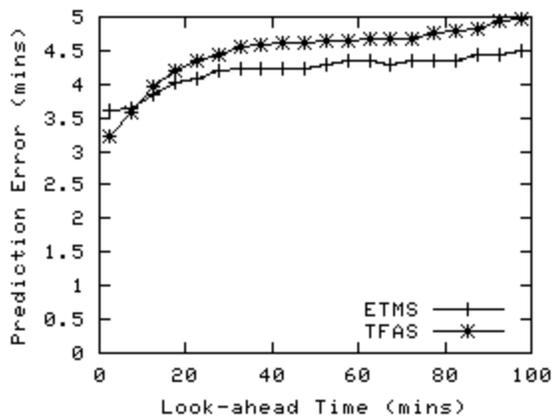


Figure 15: Sector Occupancy (Standard Deviation)

The results of the four metric analyses may be summarized as follows:

- The physics-based method demonstrates less predictive variability than the parametric method in the Arrival Meter Fix and Departure Center Exit analyses, covering trajectories in which aircraft change altitude.
- The physics-based method does not demonstrate advantage in the Sector Entry Time and Sector Occupancy Time Prediction metrics in which most trajectories do not involve significant altitude changes or flight path deviations.
- The physics-based method demonstrates less of an overall system bias than ETMS in each of the metrics, except for the Departure Center Exit analysis for which no conclusion can be drawn.

DISCUSSION

The physics-based method employed by TFAS consistently demonstrates significant improvements

over the parametric method employed by ETMS in both average and standard deviation in Meter Fix Arrival Time and Departure Center Exit Time metrics. Both of these metrics primarily deal with trajectories of aircraft that contain altitude transitions. For instance, the Meter Fix Arrival Time metric covers arrival aircraft exclusively. Conversely, the Departure Center Exit Time metric covers departure aircraft, which climb from take-off to cruise altitude. In both cases the physics-based method produces predictions that are consistently more accurate than the parametric method, indicating an advantage when calculating aircraft trajectories in which altitude transition is a major component.

A primary concern in the comparison of any TFM toolsets is the differences in adaptation. For TFAS and ETMS the adaptation controls, among other things, the routing and altitude profiles of the aircraft. The TFAS adaptations used for these analyses were created using ETMS data as a guide, specifically altitude restrictions at the meter fixes. However, some differences still exist. Most notably, En Route interim altitude descents, which are not only missing from TFAS adaptation, but also not currently addressed in TFAS algorithms. The effects of the adaptation differences on prediction performance should be analyzed in depth.

As seen from the Sector Entry and Sector Occupancy plots in figures 11 and 14, much of the difference between ETMS and TFAS for all aircraft is in the first 20 – 30 minutes of look-ahead time. ETMS and TFAS produce similar error rate accuracies for the Sector Entry and Sector Occupancy samples which are beyond the 30-minute look-ahead time horizon. The reason for this has not yet been determined, and is currently being investigated.

As discussed above, the temporal resolution of the ETMS predictions is in minutes, while for TFAS it is in seconds. For these analyses we decided not to degrade the TFAS predictions by rounding and compared the toolset predictions as they are currently calculated. However, the differences between the observed and predicted events were rounded to the nearest minute for both toolsets. This lessened the effects of this decision. An analysis of the nature of the prediction error due to rounding is warranted.

The principle distinction between TFAS and ETMS trajectory prediction methods is that TFAS employs physics-based trajectory methods while ETMS employs parametric kinematics methods. The TFAS predictions that provide the improvements seen for aircraft analyzed in the Meter Fix Arrival and

Departure Center Exit metrics indicate that the physics-based methods prove advantageous over the simpler parametric methods when predicting ascent and descent profiles.

On the other hand, the data indicate that physics-based methods may not always provide advantages in all segments of flight. Physics-based and parametric methods perform comparably in both the en-route Sector Entry Time and Sector Occupancy metrics. The predominant characteristic of the en-route trajectories that comprise most of the data covered in these metrics is that the aircraft are conforming to their filed flight plan and are cruising at relatively unchanging altitudes.

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