# A GENERIC SAMPLING TECHNIQUE FOR MEASURING AIRCRAFT TRAJECTORY PREDICTION ACCURACY

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## Abstract

To support the goals of Free Flight, the FAA has sponsored the development of several ground-based decision support tools to aid the controller in managing aircraft separation. The underlying functionality of these tools is based on the prediction of the future flight paths, or trajectories, of the aircraft. Therefore, the overall performance of the tools depends directly on the accuracy of the aircraft trajectory predictions. This paper presents a generic sampling technique, called interval based sampling, for comparing actual aircraft radar tracks with predicted aircraft trajectories to measure trajectory prediction accuracy. Unlike the previous techniques applied by the developers of the decision support tools, the interval based sampling technique is designed from the point of view of the air traffic controller using the system. Longitudinal, lateral, and vertical deviations are defined as the relevant spatial errors. A sampling procedure is described which matches a track position report with the corresponding trajectory predicted position. The sampling method selects the correctly matching pairs of track/trajectory reports for the values of look ahead time intervals desired. This technique was used to measure the prediction accuracy of prototype decision support tools, most recently in the development of accuracy scenarios to be used for the FAA's acceptance testing of the Free Flight Phase 1 User Request Evaluation Tool (URET) Core Capability Limited Deployment (CCLD). An example of its application is presented by providing the accuracy data for a single flight through the Memphis Air Route Traffic Control Center (ARTCC) airspace and for an entire scenario of approximately 1500 flights.

## Introduction

To achieve the goals of Free Flight, broad categories of advances in ground and airborne automation are required. The Federal Aviation Administration (FAA) has sponsored the development of several ground based air traffic management decision support tools (DSTs) to support the en route and terminal air traffic controllers. A fundamental component of a DST's design is the trajectory modeler, upon which its functionality is based. The trajectory modeler provides a prediction of the aircraft's anticipated flight path, determined from the flight plan and radar track data received from the National Airspace System (NAS) Host Computer System (HCS). The trajectory accuracy, or the deviation between the predicted trajectory and the actual path of the aircraft, has a direct effect on the overall accuracy of these automation tools.

The Engineering and Integration Services Branch (ACT-250) at the FAA's William J. Hughes Technical Center has developed a generic method of sampling a set of aircraft trajectories for accuracy measurements, called interval based sampling. This data sampling technique is a two-step process that defines how to pair the track and trajectory points to measure the prediction errors. This technique has been used to measure the prediction accuracy of the NASA-developed Center-TRACON Automation System (CTAS) and the MITRE/CAASD-developed User Request Evaluation Tool (URET) prototype decision support tools [1]. The most recent use of the sampling technique was applied to the URET prototype in support of the development of accuracy scenarios to be used for the FAA's acceptance testing of the production version of URET, known as

URET Core Capabilities Limited Deployment (CCLD).

This paper describes the interval based sampling technique and provides an illustrative example based on actual air traffic data from the Memphis Air Route Traffic Control Center (ARTCC). The track and trajectory base data is described, the error measurements are specified, and the data sampling method is presented.

## Track -- Actual Aircraft Position Data

The track of the aircraft is defined as the set of surveillance radar position reports, which are filtered and output by the HCS as track messages. They are generated in real time and recorded for later analysis. The recorded track reports are a sequence of data points ordered in time ($x_1$, $y_1$, $z_1$, $t_1$), ($x_2$, $y_2$, $z_2$, $t_2$, ), ($x_3$, $y_3$, $z_3$, $t_3$) … where $t_1 < t_2 < t_3 <$ etc. Due to time stamping lags and other computer anomalies, ACT-250 does perform some reasonableness checking on the HCS track data before its use in accuracy measurements.

## Trajectory -- Predicted Aircraft Position Data

A DST's predicted path of an aircraft is referred to as the trajectory. The trajectory data has essentially the same form as the track data, but is generated by a set of computer algorithms that use data from several sources. The trajectory generation process requires data from the flight plan, preferential routing, altitude and speed restrictions, airspace geometry, weather, aircraft performance characteristics, and pilot or Flight Management System (FMS) procedures. A single flight will have multiple trajectories as the aircraft's information changes over time. Typically, each time a DST builds a new trajectory, the first point of the trajectory is the aircraft's current HCS track position.

## Measurement of Prediction Error

The accuracy or measure of the correctness of the trajectory predictions can be evaluated from two aspects: spatially or by time. Spatial errors are measured by calculating the deviations between the trajectory predictions and the actual positions the aircraft flew. Time errors are measured by calculating the differences between a time at a position along the trajectory and the actual time the aircraft was at the same position. The spatial errors are distance measurements between time coincident track and trajectory positions, while the time errors are time measurements between spatially coincident track and trajectory positions. The focus of this paper is on spatial errors.

A significant independent variable in prediction accuracy is what is termed look ahead time. The look ahead time is the time interval between the sample time and the future time at which the prediction is made. In other words, it is how far into the future the algorithm is peering from the current time. Usually, the farther into the future a prediction is made, the less accurate it is.

The spatial error includes the errors in all three dimensions (x, y, and z). It is the distance between the predicted trajectory position and the actual track position at a common time. It can be decomposed into three orthogonal components:

- longitudinal error in the horizontal plane
- lateral error in the horizontal plane
- vertical error perpendicular to the horizontal plane

A perfect prediction would have a spatial error of zero. The longitudinal and lateral errors are orthogonal components of the horizontal error. The horizontal error is the projection of the spatial error onto the horizontal plane. These measurement errors are vectors; however, for this study the statistical analysis was performed only on their scalar values. A sign convention was used for direction, where appropriate.

### Longitudinal Error

The longitudinal error represents the along track distance difference between a track and its trajectory. This error, depicted in Figure 1, lies in the x-y horizontal plane. It is the length of the perpendicular from the track point $TK_i$ to the line joining the consecutive trajectory points $TJ_i$ and $TJ_{i+1}$. As seen in Figure 1, a positive longitudinal error indicates that at a corresponding point

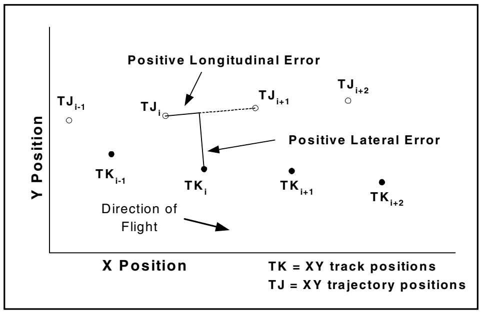

**Figure 1:** Longitudinal and Lateral Trajectory Error

in time the aircraft is ahead of where the trajectory predicted it would be.

**Lateral Error**

The lateral error represents the side-to-side, or cross track, difference between a track point and its corresponding trajectory point. This error, also represented in Figure 1, lies in a horizontal plane defined by the projections of the track point ($TK_i$) and two consecutive trajectory points ($TJ_i$ and $TJ_{i+1}$). A positive lateral error indicates that the aircraft is to the right of the predicted trajectory at a corresponding point in time.

**Vertical Error**

The vertical error represents the difference between the track altitude and the predicted altitude. This error, depicted in Figure 2, lies perpendicular to the horizontal plane. A positive vertical error indicates that at a corresponding point in time the aircraft is above where the trajectory predicted it would be.

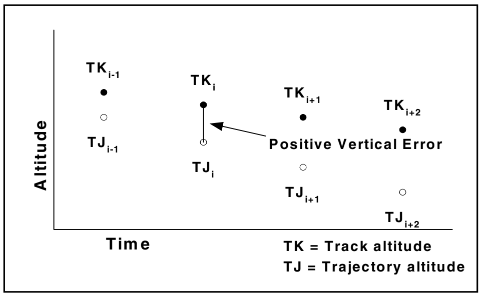

**Figure 2:** Vertical Trajectory Error

## Interpolation of Track and Trajectory Data

Trajectory modelers typically create trajectories containing points that are either equally spaced in time or that represent the nodes where the aircraft changes course. Track reports are recorded approximately every twelve seconds, but measurement problems can create larger or smaller steps. Since the spatial errors require time coincident track and trajectory data, ACT-250 interpolated the track and trajectory points to 10-second intervals that are synchronized with the hour.

An example of the relationship between trajectory data and interpolated trajectory data is shown in Figure 3. In this figure, the line represents the trajectory of an aircraft that is flying from the left side of the figure toward the right. The solid circle represents the position of a node along this trajectory at the time 16:25:13 (59113 seconds). The open circles represent the interpolated trajectory points that software calculates at 10-second intervals.

The interpolation function uses a 2nd order method in which the acceleration is assumed to be constant throughout the interpolation interval. The ground speeds are needed as input for the quadratic interpolation method; if they are not available this method degenerates to a linear interpolation method. The details are described in reference [1].

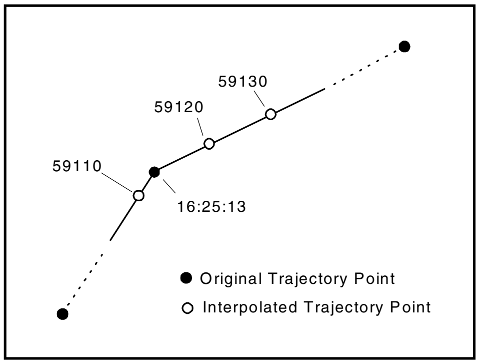

**Figure 3:** Interpolation of Trajectory Data

## Interval Based Sampling Technique

The interval based sampling technique is a two-step process that pairs the track and trajectory points to measure the prediction errors for an entire flight. This sampling technique takes the perspective of the DST user, the air traffic controller. The active trajectory at the time the controller is looking at the display may be several minutes old and in error. Consequently, in the interval based sampling technique the trajectories are sampled at the current time for a look ahead time of zero and at a number of parameter times in the future (e.g. 300, 900, and 1200 seconds). This is contrasted with a sampling technique that uses the internal build time of the trajectory to start the sampling [3][7].

The age of the trajectory, which is internal to the DST, is irrelevant to the controller; only the accuracy of the prediction is important. The controller uses track data to safely separate aircraft and a DST to resolve future aircraft conflicts. The interval based sampling technique is designed from the perspective of the air traffic controller to answer two fundamental questions:

1. *How accurately is the DST's trajectory currently predicting the present position of the aircraft?*
2. *How accurately is the DST's trajectory currently predicting the future position of the aircraft?*

The sampling technique is broken into two steps, which are described in the following sections.

**First Sampling Step**

An aircraft is selected for measurement and the track points are sampled in succession a parameter number of minutes (e.g. two minutes) until the end of the track is reached. Each track point selected as a sample has a specific time associated with it, referred to as the sample time. The aircraft's trajectories are then searched to find the most recent trajectory for the given sample time. This operation is repeated for every track point that is sampled.

This first sampling step obtains position prediction error data for a look ahead time of zero seconds. This answers the first of the air traffic controller's questions on accuracy, namely the accuracy of the DST's prediction for the present position of the aircraft. A second sampling operation is necessary to obtain error data for other look ahead times into the future.

**Second Sampling Step**

Once a track point and its current trajectory are selected for sampling, a second sampling step is executed. The second step samples future points on the trajectory relative to the current sample time. As discussed previously, the first sampling step selects a point on the trajectory that has the same time value as the current track point, corresponding to a look ahead time of zero seconds. The second step selects points on the trajectory that are defined a parameter set of times into the future (e.g. 5, 10, 15, and 30 minutes). It then finds the future track reports that have the same times as the selected trajectory points. For each look ahead time, the spatial errors are calculated between the selected trajectory points and their corresponding track points. This second step answers the second of the air traffic controller's questions on accuracy, namely the accuracy of the DST's prediction of the future position of the aircraft.

## Graphic Depiction of Selection of Pairs of Track and Trajectory Data Points

A graphic depiction of the interval based sampling technique is shown Figure 4. The line labeled "Track" represents the time line for an aircraft track. The time point labeled $T_S$ represents the initial interpolated track point. The sampling time to start computing metrics for this track is represented by $T_0$, where

$T_0 = T_S +$ `traj_delta_time`

The `traj_delta_time` is a parametric value (a multiple of the 10-second interpolation interval) that establishes the starting time at a point where the track is more stable[1].

The trajectories for this aircraft are presented in Figure 4 by the time lines labeled $Traj_0$, $Traj_1$, $Traj_2$, and $Traj_3$. The trajectory to be sampled for a particular track sampling time is the trajectory with the latest trajectory build time not exceeding the track sampling time. The selected trajectories are interpolated using the technique described previously. In Figure 4, the trajectory labeled $Traj_0$ would be

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[1] In the example in the following section, the `traj_delta_time` is set to zero, but in previous ACT-250 studies 40 seconds was used to start the accuracy measurement after the DST's predictions stabilized [1].

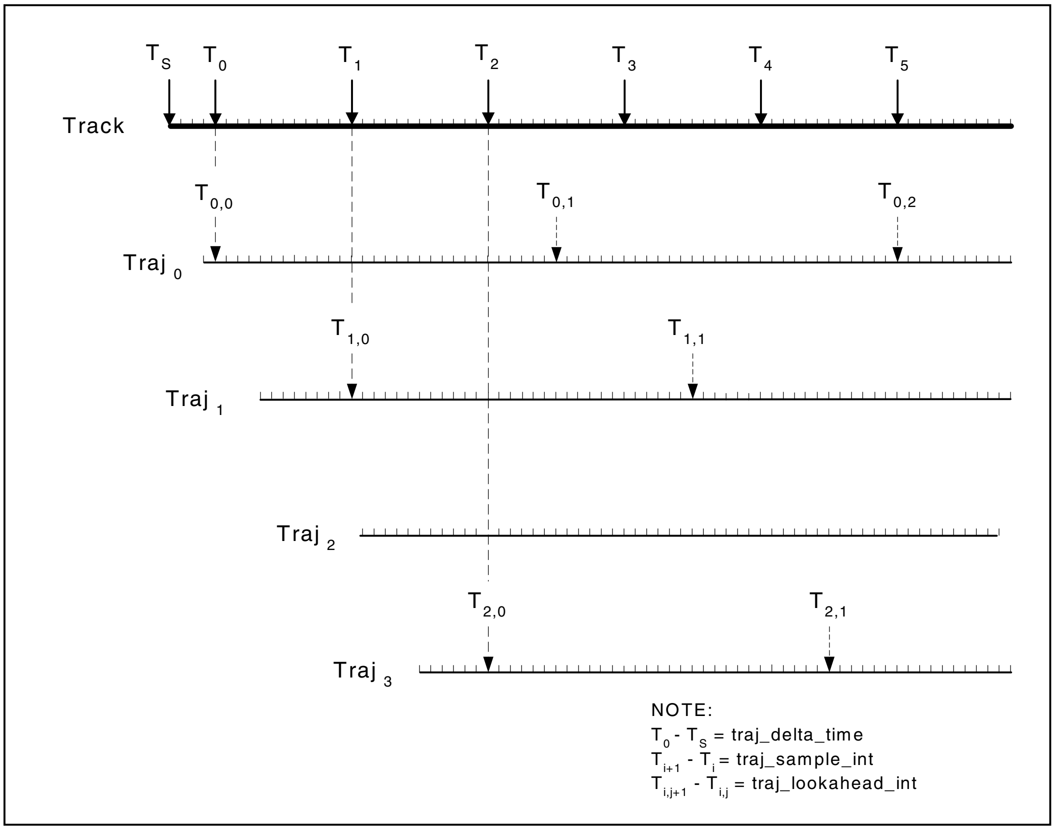

**Figure 4**: Interval Based Sampling

sampled for sampling time $T_0$. This point is labeled $T_{0,0}$ and represents the look-ahead time of zero seconds for the trajectory sampling time $T_0$.

Metrics are computed at the time point labeled $T_0$ and at the incremented time points $T_{0,1}$ and $T_{0,2}$ where

$$T_{i,j+1} = T_{i,j} + \texttt{traj\_lookahead\_int}$$

The `traj_lookahead_int` is the parametric sampling interval for a specific sampling time.

The trajectory sampling process continues until either the end of the track is reached, the end of the trajectory is reached, or the time exceeds $T_0$+`traj_lookahead_win`, a parametric input. Then the next track sampling time $T_{i+1}$ will be computed as

$$T_{i+1} = T_i + \texttt{traj\_sample\_int}$$

The sampling time, `traj_sample_int`, is the parametric sampling interval for sampling a specific track and trajectory.

## Application of the Sampling Technique on One Flight

To illustrate the sampling technique, a flight has been selected from a Memphis ARTCC (ZME) test scenario. The DST used for this example is URET Daily Use[2] (DU). Flight ABC1000 is an overflight, entering the ZME airspace at Flight Level 350 (FL350), descending to FL310, and then exiting the ZME airspace at this altitude. The route of the flight through the ZME airspace is shown in Figure 5. The track position vertical profile of the flight (altitude versus time) is shown in Figure 6. The Top Of Descent (TOD) time is at 51910 seconds. The handoff time is at 53280 seconds when

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[2] MITRE developed URET Daily Use system, Release URETD32R2LMP1C. It is referred to as the baseline URET prototype for URET CCLD.

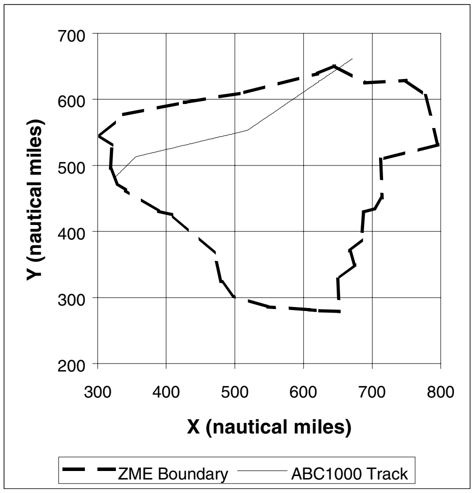

**Figure 5:** Flight of ABC1000 through ZME Airspace – Horizontal Profile

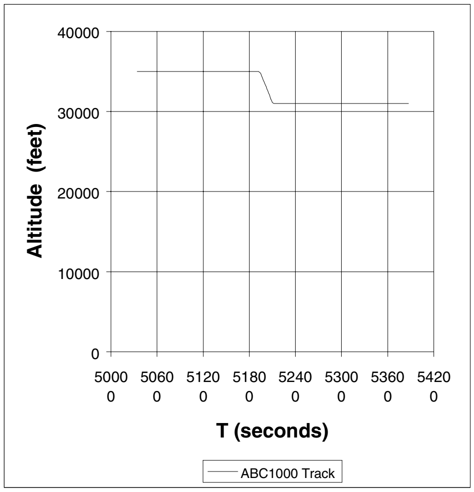

**Figure 6:** Flight of ABC1000 through ZME Airspace – Vertical Profile

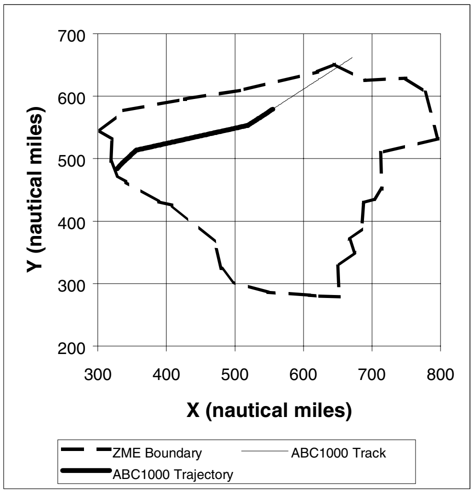

**Figure 7:** Trajectory 51660 Route for ABC1000

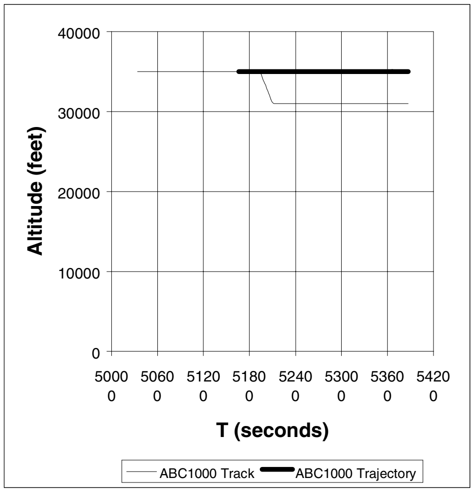

**Figure 8:** Trajectory 51660 Vertical Profile for ABC1000

control of the aircraft is passed to the Fort Worth ARTCC (ZFW).

In this example, the DST generates six trajectories while the aircraft is passing through the ZME airspace. The trajectories are identified by the times in seconds when they are generated (e.g. 50266, 50458, 51660, 51905, 52330, and 53266). Figures 7 and 8 show the route and the vertical profiles predicted by the third trajectory, which was generated at 51660. The trajectory starts at the aircraft track position at 51660 seconds. The vertical profile in Figure 8 shows that the DST does not predict the change in altitude from FL350 to FL310 with trajectory 51660.

For this example, the aircraft's track data was sampled every 120 seconds, until the end of the track data was reached. For each sample point, error measurements were made at the look ahead times of 0, 300, 600, 900, and 1200 seconds. The first sample point is the first track report for ABC1000 in the scenario at 50340 seconds. The active trajectory was selected and compared to the track data at this sample time plus the four look ahead times. Successive samples were chosen at 50460, 50580, 50700, and up to 53820 seconds.

The sampling procedure produced 124 measurement times to compare the track to a current trajectory. A subset of the error measurements made at these times is listed in Table 1. For this example, the lateral (cross track) errors between the aircraft track and the current trajectory are small. The longitudinal (along track) errors are up to several nautical miles. The largest longitudinal sampled error is 11.7 nautical miles (measurement time is 52740) with a look ahead time of 20 minutes and a trajectory age of 38 minutes. As expected, the vertical errors are zero when the prediction and track agree that the aircraft is in level cruise. Referring to Table 1, not all sample times include all five measurement times, since no measurements can be made when the sample time plus the look ahead time is greater than the end of the track.

The first three trajectories do not predict a descent, resulting in large vertical errors after the actual TOD for these trajectories. For example, the vertical error at measurement times of 52140 (using the second trajectory, 50548) and of 52260 (using the third trajectory, 51660) have vertical errors of 4000 feet. The fourth trajectory (51905, not shown in the abbreviated table) starts with the aircraft in descent. The trajectory predicts the BOD (Bottom Of Descent) within 30 seconds of actual. After the BOD, the vertical errors become small when the aircraft levels off.

As the interval based sampling technique was implemented by ACT-250, all the accuracy measurements, processed track reports, and parsed trajectories are stored in a relational database. Utilizing this database implementation, the accuracy statistical analysis can exclude some of the measurements if required. For example, if the DST is predicting past the time of handoff to the next ARTCC, the measurement is flagged with a 1 and excluded in the statistical results. In Table 1's column, labeled "Out Bound Flag", a 1 identifies these measurements. In this example, handoff occurs at 53280 seconds, so measurements past that time are flagged accordingly. If the DST is predicting past an air traffic control directive, this measurement is also flagged and excluded for certain analyses. In the Table 1 column labeled "Clear Flag", a 1 identifies these measurements. The measurements of a vertical error of 4000 feet would be excluded for this reason. The aircraft is given a clearance to descend from FL350 to FL310 at time 51905. The DST does not know when the aircraft is cleared to descend prior to this clearance. For example, in the accuracy testing for URET CCLD, the software specification required these measurements to be excluded.

## Application of the Sampling Technique on a Scenario

The accuracy measurements presented in the previous section also were made on a full air traffic scenario of flights run through the URET DU. The scenario contains about five hours of traffic and approximately 1500 aircraft in the Memphis ARTCC. This data is a subset of that used to determine the FAA acceptance of URET CCLD.

**Table 1:** Trajectory Metrics for ABC1000

| Sample Time | Traj Build Time | Look Ahead Time | Measure Time | Horz Err | Lat Err | Long Err | Vert Err | Out Bound Flag | Clear Flag |
|---|---|---|---|---|---|---|---|---|---|
| 50340 | 50266 | 0 | 50340 | 5.54 | 0.00 | -5.54 | 0 | 0 | 0 |
| | | 300 | 50640 | 7.15 | 0.00 | -7.15 | 0 | 0 | 0 |
| | | 600 | 50940 | 8.19 | 0.08 | -8.19 | 0 | 0 | 0 |
| | | 900 | 51240 | 9.36 | 0.23 | -9.36 | 0 | 0 | 0 |
| | | 1200 | 51540 | 10.24 | 0.14 | -10.24 | 0 | 0 | 0 |
| 50460 | 50458 | 0 | 50460 | 0.07 | -0.07 | 0.01 | 0 | 0 | 0 |
| | | 300 | 50760 | 0.62 | 0.00 | 0.62 | 0 | 0 | 0 |
| | | 600 | 51060 | 0.83 | 0.16 | 0.81 | 0 | 0 | 0 |
| | | 900 | 51360 | 1.08 | 0.08 | 1.08 | 0 | 0 | 0 |
| | | 1200 | 51660 | 2.02 | 0.19 | 2.01 | 0 | 0 | 1 |
| 50580 | 50458 | 0 | 50580 | 0.30 | -0.26 | 0.14 | 0 | 0 | 0 |
| | | 300 | 50880 | 0.95 | 0.26 | 0.92 | 0 | 0 | 0 |
| | | 600 | 51180 | 0.91 | 0.06 | 0.91 | 0 | 0 | 0 |
| | | 900 | 51480 | 1.28 | 0.04 | 1.28 | 0 | 0 | 0 |
| | | 1200 | 51780 | 2.62 | 0.25 | 2.61 | 0 | 0 | 1 |
| . . . . . . . . . | | | | | | | | | |
| 51540 | 50458 | 0 | 51540 | 1.43 | 0.11 | 1.43 | 0 | 0 | 0 |
| | | 300 | 51840 | 3.07 | 0.24 | 3.06 | 0 | 0 | 1 |
| | | 600 | 52140 | 5.33 | 0.09 | 5.33 | -4000 | 0 | 1 |
| | | 900 | 52440 | 8.04 | 0.16 | 8.04 | -4000 | 0 | 1 |
| | | 1200 | 52740 | 11.71 | 0.05 | 11.70 | -4000 | 0 | 1 |
| 51660 | 51660 | 0 | 51660 | 0.22 | 0.19 | 0.11 | 0 | 0 | 0 |
| | | 300 | 51960 | 0.71 | 0.29 | 0.65 | -550 | 0 | 1 |
| | | 600 | 52260 | 1.90 | -0.06 | 1.90 | -4000 | 0 | 1 |
| | | 900 | 52560 | 3.94 | 0.10 | 3.94 | -4000 | 0 | 1 |
| | | 1200 | 52860 | 6.81 | 0.06 | 6.81 | -4000 | 0 | 1 |
| . . . . . . . . . | | | | | | | | | |
| 53460 | 53266 | 0 | 53460 | 0.41 | -0.03 | -0.41 | 0 | 1 | 0 |
| | | 300 | 53760 | 0.87 | 0.02 | -0.87 | 0 | 1 | 0 |
| 53580 | 53266 | 0 | 53580 | 0.33 | -0.11 | -0.31 | 0 | 1 | 0 |
| 53700 | 53266 | 0 | 53700 | 0.50 | -0.03 | -0.50 | 0 | 1 | 0 |
| 53820 | 53266 | 0 | 53820 | 1.02 | 0.90 | -0.47 | 0 | 1 | 0 |

Figure 9 presents the mean horizontal error as a function of look ahead time. It illustrates how the statistical results can be partitioned by flight factors. This figure contains three traces, which show the effect of one factor (navigational equipage) on horizontal error. The bottom trace shows the horizontal error for aircraft that are equipped with navigational aids. The top trace shows the horizontal error for aircraft that are not equipped with navigational aids. The middle trace shows the horizontal error for all aircraft in the scenario. There is a clear increase in horizontal error as the prediction moves ahead in time and the navigation equipage reduces horizontal prediction error consistently for all look ahead times.

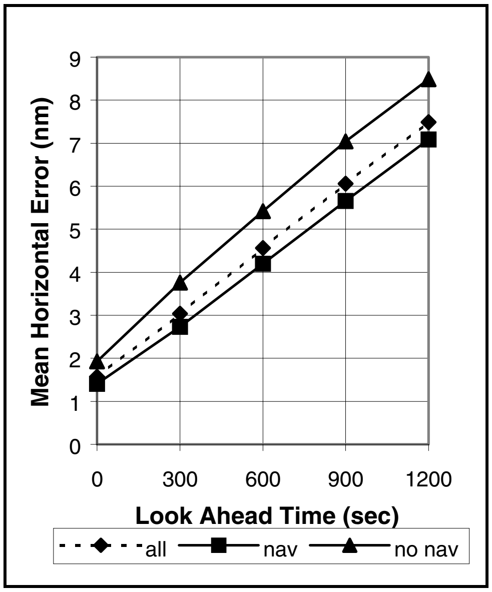

**Figure 9**: Mean Horizontal Error versus Look Ahead Time for Navigation Equipped, Non-navigation Equipped, and All Aircraft

## Conclusion

ACT-250's ongoing work developing analysis tools is an essential part of the FAA's development and evaluation process of DST applications. A generic methodology has been developed to provide independent scenario based trajectory accuracy measurements for any DST. The core of this generic methodology is the interval based sampling technique. Unlike the previous techniques applied by the developers of the DSTs, the interval based sampling technique is designed from the point of view of the air traffic controller using the system. In 1999, this sampling technique proved beneficial in the evaluation of the trajectory accuracy of both CTAS and URET DSTs [1]. Currently, it is the trajectory accuracy technique being used for FAA acceptance testing of URET CCLD. For the current URET CCLD testing, the accuracy measurements have been made on approximately 9000 flights and over 100,000 trajectories. In addition, it is anticipated that this generic methodology can be applied to the development of performance requirements for a common trajectory modeling service.

## Acronyms

| | |
|---|---|
| ACT-250 | Engineering and Integration Services Branch at the FAA WJHTC |
| ARTCC | Air Route Traffic Control Center |
| BOD | Bottom Of Descent |
| CAASD | Center for Advanced Aviation System Development |
| CCLD | Core Capability Limited Deployment |
| CTAS | Center-TRACON Automation System |
| DST | Decision Support Tool |
| DU | Daily Use |
| FAA | Federal Aviation Administration |
| FMS | Flight Management System |
| HCS | Host Computer System |
| NAS | National Airspace System |
| NASA | National Aeronautics and Space Administration |
| TOD | Top Of Descent |
| TRACON | Terminal Radar Approach Control |
| URET | User Request Evaluation Tool |
| UTC | Universal Coordinated Time |
| WJHTC | William J. Hughes Technical Center |
| ZFW | Fort Worth ARTCC |
| ZME | Memphis ARTCC |

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## Biographies

Mary Lee Cale is a Computer Scientist with the FAA at the FAA W. J. Hughes Technical Center, Atlantic City International Airport, NJ, 08405, where she is currently the FAA lead of the En Route Area Work Team of the FAA/NASA Interagency Air Traffic Management Integrated Product Team (IAIPT). She has extensive experience in the design, development, and evaluation of operational real time air traffic control systems, and the simulation of such systems. She holds a BS in Mathematics from Oklahoma State University and an MS in Computer Science from Drexel University.

Shurong Liu is a Senior Software Engineer with Signal Corporation at the FAA W. J. Hughes Technical Center, Atlantic City International Airport, NJ, 08405. He has strong experience in software development and design for the simulation and analysis of air traffic control systems and aircraft navigation aids, real time control, and the testing of analog and digital communication system. He is currently testing and evaluating aircraft conflict probes. He holds a B.A.Sc.degree in Electrical Engineering from Northern Jiao-Tong University, Beijing, China, and a M.S. degree in Electrical Engineering from Drexel University.

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Dr. Hollis F. Ryan is Senior Systems Engineer with Signal Corporation at the FAA W. J. Hughes Technical Center, Atlantic City International Airport, NJ, 08405. He has extensive experience in computer simulation, modeling, and algorithm development including the simulation and analysis of air traffic control systems and the modeling of aircraft navigational aids. He is currently testing and evaluating aircraft conflict probes. He holds a B.A.Sc. in Engineering Physics from the University of Toronto, and M.S. and Ph.D. degrees in Electrical Engineering from the University of Illinois.

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