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
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 \((x_1, y_1, z_1, t_1), (x_2, y_2, z_2, t_2), (x_3, y_3, z_3, t_3) \ldots \) where \(t_1 < t_2 < t_3 < \text{etc.} \) 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 differences 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
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 (TKi) and two consecutive trajectory points (TJi and TJi+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.

**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].
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 Traj0, Traj1, Traj2, and Traj3. 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 Traj0 would be

\[^1\text{In the example in the following section, the } \text{traj\_delta\_time} \text{ is set to zero, but in previous ACT-250 studies 40 seconds was used to start the accuracy measurement after the DST’s predictions stabilized [1].}\]
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

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

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 $T_i + \text{traj\_lookahead\_win}$, a parametric input. Then the next track sampling time $T_{i+1}$ will be computed as

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

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\textsuperscript{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

\textsuperscript{2} MITRE developed URET Daily Use system, Release URET32R2LMP1C. 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

<table>
<thead>
<tr>
<th>Sample Time</th>
<th>Traj Build Time</th>
<th>Look Ahead Time</th>
<th>Measure Time</th>
<th>Horz Err</th>
<th>Lat Err</th>
<th>Long Err</th>
<th>Vert Err</th>
<th>Out Bound Flag</th>
<th>Clear Flag</th>
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<tr>
<td>50340</td>
<td>50266</td>
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<td>50340</td>
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<td>0.00</td>
<td>-5.54</td>
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<td>0</td>
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<td>0</td>
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<tr>
<td>900</td>
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<td>0.23</td>
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<td>0</td>
<td>0</td>
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<tr>
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<td>0.14</td>
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<td>0</td>
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<td>0.08</td>
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<td>0</td>
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<tr>
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<tr>
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<td>2.62</td>
<td>0.25</td>
<td>2.61</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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| 51540       | 50458          | 0              | 51540        | 1.43     | 0.11    | 1.43     | 0        | 0              | 0          |
| 300         | 51840          | 3.07           | 0.24         | 3.06     | 0        | 0        | 1        | 0              | 0          |
| 600         | 52140          | 5.33           | 0.09         | 5.33     | -4000   | 0        | 1        | 0              | 0          |
| 900         | 52440          | 8.04           | 0.16         | 8.04     | -4000   | 0        | 1        | 0              | 0          |
| 1200        | 52740          | 11.71          | 0.05         | 11.70    | -4000   | 0        | 1        | 0              | 0          |
| 51660       | 51660          | 0              | 51660        | 0.22     | 0.19    | 0.11     | 0        | 0              | 0          |
| 300         | 51960          | 0.71           | 0.29         | 0.65     | -550    | 0        | 1        | 0              | 0          |
| 600         | 52260          | 1.90           | -0.06        | 1.90     | -4000   | 0        | 1        | 0              | 0          |
| 900         | 52560          | 3.94           | 0.10         | 3.94     | -4000   | 0        | 1        | 0              | 0          |
| 1200        | 52860          | 6.81           | 0.06         | 6.81     | -4000   | 0        | 1        | 0              | 0          |

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| 53460       | 53266          | 0              | 53460        | 0.41     | -0.03   | -0.41    | 0        | 1              | 0          |
| 300         | 53760          | 0.87           | 0.02         | -0.87    | 0        | 1        | 0        | 0              | 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](image)

**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

**References**


**Biographies**

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