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State Vector Based Near Term Trajectory Prediction

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Air traffic control automation requires predicting where the aircraft are going to fly to avoid conflicts and to route aircraft efficiently. Air traffic controllers frequently vector aircraft off of their designated routes to avoid conflicts and when they do this vectoring they do not usually enter the re-route information into the Host Computer System. As a result the automation is unable to accurately predict the flight paths of the aircraft. Under these conditions, the accuracy of the near term predictions can be improved by using a dead reckoning method some of the time instead of always using flight plan based extrapolations. A study has been conducted that illustrates this improvement. The accuracy of the predictions is measured by comparing the flight path predictions to the radar tracks of the aircraft and by determining the missed and false conflict alert rates, using recorded field data.

Nomenclature

ARTCC	=	Air Route Traffic Control Center
ATM	=	Air Traffic Management
ATC	=	Air Traffic Control
ATO-P	=	Air Traffic Services – Operations Planning Services
DST	=	Decision Support Tool
FAA	=	Federal Aviation Administration
FP	=	Flight Plan
FPP	=	Flight Plan Predictor
HCS	=	Host Computer System
LPP	=	Linear Path Predictor
MA	=	Missed Alert
MITRE	=	A federally funded research and development agency supporting the FAA
TP	=	Trajectory Predictor
URET	=	User Request Evaluation Tool
VA	=	Valid Alert
ZDC	=	Washington ARTCC

I. Introduction

MOST air traffic air traffic service providers in the United States and Europe anticipate significant growth in air traffic that is expected to out pace the capacity limits of our aviation systems, resulting in greater congestion and inefficiency. Broad advances in ground-based and airborne automation, such as decision support tools (DSTs), are envisioned to mitigate the problem. These tools have many purposes and typically serve to lower the complexity of airspace problems faced by the current human decision makers operating the system. They include tools that serve to predict future conflicts between aircraft, both for ground based controllers and airborne pilots, allowing more strategic separation management of aircraft. Traffic management DSTs include capabilities to forecast congestion allowing air traffic supervisors to adjust airspace and/or staffing to mitigate the condition.

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A common thread in the DSTs is the accurate and timely modeling of the aircraft's anticipated future flight path. This function is referred to as the trajectory predictor (TP) process. The trajectory is the predicted 4-dimensional path of the aircraft. TP accuracy can be measured by using post flight analysis to compare actual flight paths flown to the predicted paths. Since the predicted trajectory is the fundamental input that sustains the DST's capabilities and functions, the accuracy of the trajectory prediction has a direct impact on the DST's overall performance and usability. As the trajectories are used to predict conflicts, the missed and false conflict alert rates also measure the prediction accuracy.

This paper describes a study performed to evaluate the efficacy of replacing the standard prediction method used by the User Request Evaluation Tool (URET) with a method that combines dead reckoning and flight plan following to predict near term flight paths. The key to the performance of this method is the determination of when to substitute this method for the standard prediction method. This method is to be used only when the aircraft is not following its preplanned route. The method has been applied and evaluated on a scenario of several hundred flights, recorded at the Washington Air Route Traffic Control Center (the ZDC ARTCC).

In the following sections these topics will be presented: (1) a description of the problem (2) the resulting algorithm, (3) the performance metrics, (4) the experiment, and (5) the results. A detailed flight example will illustrate the application of the technique.

II. Trajectory Prediction Problem

A trajectory predictor uses all the available information on a flight to predict its flight path for up to the next 20 minutes. The predicted flight path is used by Air Traffic Management (ATM) to re-route the flight if necessary to avoid conflicts with other aircraft. The flight plan, which gives the planned route of the aircraft, together with any air traffic controller directives, the performance capabilities of the aircraft, and the winds aloft, are the main input sources used by the trajectory predictor.

Often an air traffic controller will temporarily re-route a flight without entering the information into the air traffic control computer. When this happens the TP cannot accurately predict the flight path. This situation is often referred to as a "intent uncertainty" or a "lack of intent" event. A study by MITRE[5] found that 95 % of the altitude clearances were entered but only 30 % of the route clearances were entered and none of the speed clearances. Usually these deviations from the planned route are short – for just a few minutes, and then the aircraft rejoins its planned route. Although these deviations are relatively brief, they are critically important because they have been made to avoid pending conflicts.

The nominal way of predicting the future flight path is to assume that the aircraft will follow its filed flight plan. The Air Traffic Control (ATC) computer adds additional intermediate way points to the filed flight plan making an expanded flight plan, called the converted route. The details added to the flight plan are local adaptations and procedures unknown to the pilot filing the flight plan but known to the ATC system and used by the Controllers. In the simplest case the aircraft is following its converted route, flying level at a constant speed and the automation can easily predict its future flight path. If the aircraft is climbing or descending it is assumed that the aircraft will level off at its cleared altitude. A pilot has some discretion in choosing when to start his climb or descent. This discretion adds uncertainty to the aircraft's altitude.

If the aircraft is not on its converted route and /or its heading does not match that of the converted route, another prediction method is needed. In the absence of the required air traffic directive information, it is necessary to make some assumptions about where the aircraft is flying. The next section lists the most common route deviations.

III. Route Deviations

Most deviations from the planned route are initiated by the air traffic controller to maintain aircraft separation, to expedite a flight, or to avoid convective weather. These are the typical route deviations.

A. Speed

The Controller may direct the pilot to either slow down or to speed up.

B. Vector

The Controller, to add delay, may vector the aircraft away from its route for a short period and then return it to its route.

C. Direct to Future Fix

The pilot may request (to save time) and the Controller may approve, the aircraft to leave its planned route and fly directly to a downstream fix.

D. Turns

The pilot when flying a turn in the route, may cut the corner by flying inside the turn, or he may overshoot the turn and fly outside of the turn.

E. Parallel

Sometimes a pilot may fly offset and parallel to his planned route.

The Controller frequently issues interim altitude clearances to temporarily hold an aircraft at an altitude when it is either climbing from it departure airport or when it is descending to its arrival airport. The Controllers usually enter these clearances into the computer system and the information is available to the flight path prediction processing. However, as mentioned above, the pilots' discretion in initiating climbs and descents adds uncertainties to the predicted altitudes.

The simplest flight path prediction is the dead reckoning method and can be used when no reliable intent information is available. The dead reckoning method assumes that the aircraft will maintain its current speed, heading, and rate of climb or descent.

IV. Trajectory Prediction Algorithms

In the long term the aircraft will rejoin its converted route unless there is a route amendment. In the near term the aircraft may fly away from its converted route, fly parallel to, or rejoin the route at the next or almost next fix. The first step is to determine whether or not the aircraft is on its route or not. The geometry of the method is illustrated in Figure 1. This figure is reproduced from one of the referenced papers[10]. The logic steps are shown in the flow chart of Figure 2.

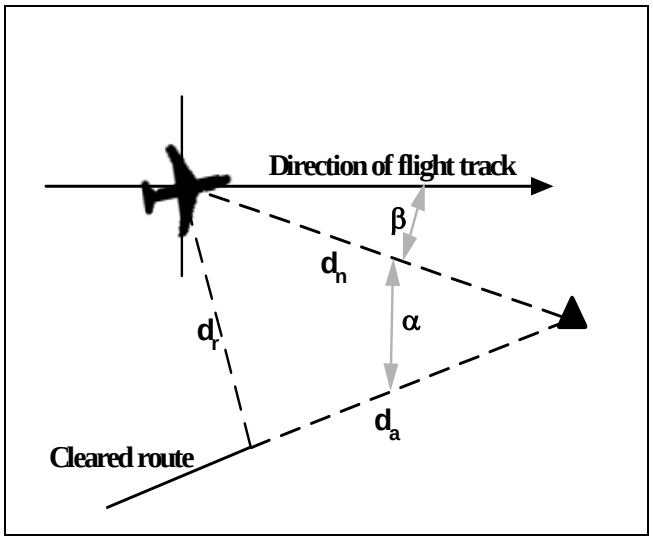


Figure 1: Return to Route Geometry (adapted from Ref. 10)

The distance from the current position of the aircraft from its route is calculated. This distance is illustrated in Figure 1 as d_r. If it is less than a threshold value D_1, it is assumed that the aircraft is flying on its route. The first

point of the trajectory (the predicted flight path) is taken as the closest point of the route. The rest of the trajectory is the flight path. This method is called the *Flight Path Predictor* (FPP). If the distance is greater than a threshold D_2, it is assumed that the aircraft is no longer flying its route. In this case a dead reckoning algorithm is applied. Estimates of the current speed, heading, and rate of climb are made from the track data. These estimates are used to generate a linear track of the aircraft for the immediate future. The horizontal and vertical accelerations are assumed to be zero. These accelerations are often zero or low and are also difficult to estimate accurately from the HCS radar tracking data. If the aircraft is climbing or descending, it is predicted to level off at its cleared altitude. As mentioned above, the altitude amendments are almost always entered into the Host Computer System (HCS). This method is called the *Linear Path Predictor* (LPP).

If the distance of the aircraft from its route is between the two threshold distances, the angle between the aircraft heading and a direct path to the next fix on the route is calculated. This angle, β is illustrated in Figure 1. If β is less than a threshold value P_1 the aircraft is assumed to be flying on its route and the trajectory follows the route. If β is greater than the threshold, the dead reckoning method is used to generate the trajectory.

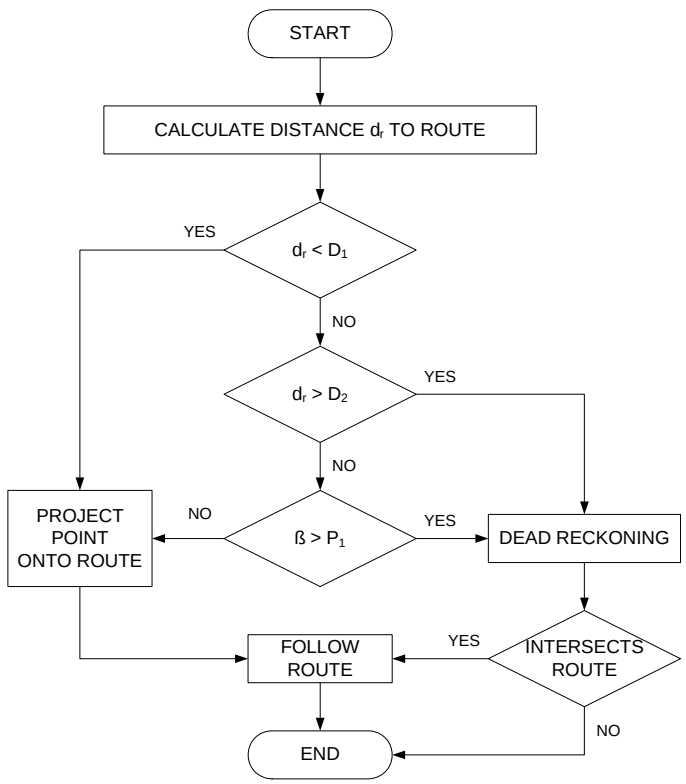


Figure 2: Selection of Flight Path Following or Dead Reckoning

If the linear trajectory intersects the converted route, it is assumed that from the point of intersection the aircraft will follow its planned route. This class of trajectory is then a combination of a linear prediction and a flight plan trajectory.

In summary, if the aircraft is close to its flight plan route, it will follow its route. If the aircraft is far away from its route, it will follow a dead reckoning route and if this route intersects the converted route it will then follow the route. In summary, the three trajectory construction methods are called (1) linear prediction (LPP), (2) flight plan following (FPP), and (3) a linear prediction followed by flight plan following (LPP & FPP). The combination of these three trajectory construction methods are referred to here as the state vector method. The basic algorithms used by URET to construct trajectories are documented in the referenced Mitre publication[1] and have been refined over the years.

The threshold values used in this study, which have been selected empirically to determine whether or not the aircraft is close to its route are given in Table 1.

Table 1: Trajectory Generation Thresholds

THRESHOLD PARAMETER	SYMBOL	VALUE
Outer Lateral Threshold	D_2	1.5 nm
Inner Lateral Threshold	D_1	0.5 nm
Heading Offset	P_1	30 Degs

V. Experiment Overview

This section describes the validation of the algorithm using two test scenarios of recorded air traffic.

A. Scenarios

The air traffic in the en route (upper altitude) airspace in the continental US is controlled by 20 Air Route Traffic Control Centers (ARTCC's). Each ARTCC has a DST called the User Request Evaluation Tool (URET) which predicts the flight paths of the aircraft in the ARTCC airspace. Several trajectories are generated for each flight as it flies through the ARTCC airspace. Every time the flight plan or the assigned altitude of an aircraft is changed a new trajectory is generated. The flight plans, altitude clearances, trajectories and the actual flight paths as they were tracked by the surveillance radars were recorded over a several hour period for the Washington ARTCC.

The accuracy of the predictions depends on how far into the future they are predicting. This time factor is termed the look ahead time. Usually the greater the look ahead time the greater the prediction error. Useful predictions can be made up to about 20 minutes into the future.

The data for approximately 2200 flights over a period of 5 hours at the Washington ARTCC (ZDC) was recorded. Two test scenarios were extracted from this field recording. The first scenario was a random selection of 500 of the 2200 flights. This scenario was used to measure the accuracy of the technique to predict flight paths or trajectories. A second scenario was generated to test the ability of the technique to predict strategic conflicts. The recorded scenario was time shifted[7] to induce conflicts. (In a real traffic recording there are few if any conflicts.) The flights which had induced conflicts were selected to form the second test scenario. There were 418 such flights.

B. Trajectory Accuracy Metrics

The trajectory is a prediction of the aircraft's flight path. The predictions are compared to the actual paths flown by the aircraft by off line, post processing of recorded data. The trajectories and the radar tracks are recorded and sampled at 10 second intervals and then compared on a point by point basis using the ARTCC's stereographic (XYZ) coordinate system. The sampling method used to select the trajectory points from the active trajectories are described in the reference[7]. The shortest horizontal distance between a track point and the predicted track or trajectory is calculated for each track point. This distance is usually the length of a perpendicular from the track point to a point on the trajectory. The shortest distance may not be perpendicular if the trajectory is turning. This horizontal distance is the cross track error – ideally the trajectory should be coincident with the track. The along track error is the distance measured along the trajectory from the point located on the trajectory by the perpendicular to the point on the trajectory which is time coincident with the track point. The horizontal error is the distance from the track point to the time coincident point on the trajectory. These metrics are explained in detail in the references[3,8,13]. As routes are defined in two dimensions the vertical errors were not considered.

The trajectory accuracy metrics are then the averages of the horizontal, cross track and along track errors. They have been calculated and tabulated for all of the trajectories generated in the first of the two test scenarios. The horizontal errors have been graphically illustrated as histograms for the URET trajectories and for the state vector based trajectories. Plots of the horizontal error rates versus look ahead times show how each predictor type performed.

C. Conflict Prediction Metrics

The trajectories are used to predict aircraft to aircraft conflicts or loss of minimum allowed separation. The accuracy of the conflict prediction is then a measure of the accuracy of the trajectories. The conflict prediction metrics are missed alert and false alert rates. Detailed descriptions of the conflict alert metrics have been described in the reference[9]. The missed and false alert rates have been determined for the second test scenario which was derived by time shifting, to induce conflicts, from a representative test scenario of en route air traffic.

D. Comparison with Existing Methods

The current ARTCC computer system calculates trajectories and predicts conflicts. This processing is done by the URET DST. The results obtained with the algorithm presented in this paper are compared with the existing technique.

VI. Example of State Vector Based Trajectory Generation

A flight has been selected from the scenario to illustrate the operation of the state vector based trajectory generation algorithm. Flight ABC100 is an Airbus 300 flying from Memphis to Rayleigh/Durham, descending into Rayleigh/Durham. The flight plan route and the route actually flown are shown in Figure 3. This is an example where the airplane deviated considerably from its planned route. In the study a trajectory was generated every 10 seconds. Four trajectories have been selected to illustrate the generation of trajectories by the state vector based method presented here. They are shown in are illustrated in Figure 4. The first trajectory, #1, was generated when the aircraft was more than a mile off its flight plan route. A linear (dead reckoning) trajectory was generated. At the time the second trajectory (#2) was generated the aircraft was close to its route and a flight plan trajectory was generated. (The aircraft was predicted to follow its flight plan route.) At the time of the third trajectory (#3), the aircraft was again off its route, and a linear trajectory was generated. Again at the time of the fourth trajectory (#4), the aircraft was even more off its route and again a linear trajectory was generated. In this case the linear trajectory intersected the flight plan route downstream and after that point of intersection the trajectory followed the flight plan route. In Figure 4 all of the plot of Trajectory #2 and part of the plot of Trajectory #4 lie on top of the plot of the flight plan route.

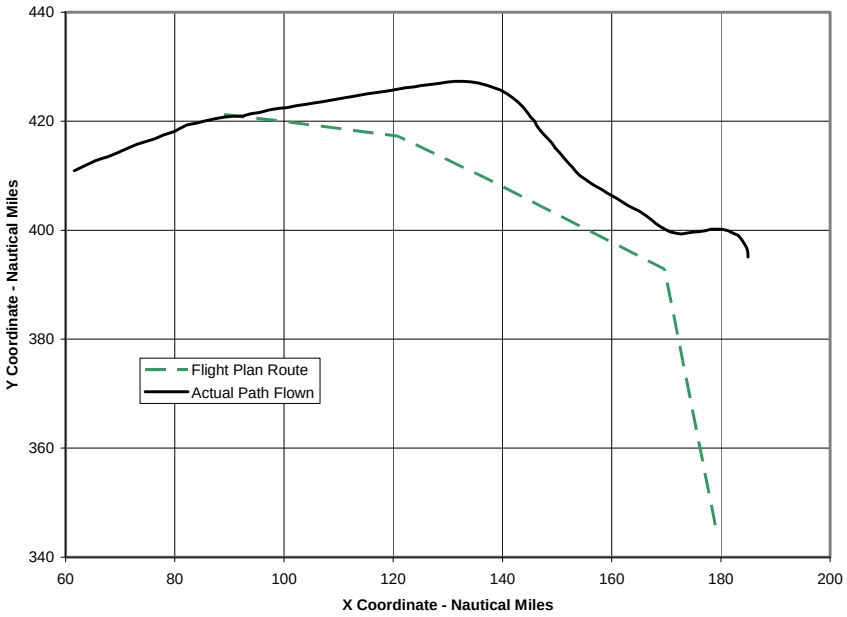


Figure 3: Example Flight - Planned Route and Actual Route

VII. Example of State Vector Based Conflict Alert Determination

An example has been selected to illustrate the difference between the near term URET conflict alert generation and the state vector based conflict alert determination. In the example two aircraft are flying the same route and one aircraft is vectored away from the route for a short period and then returned to the route. The URET trajectories predict a conflict which is a false alarm and the state based trajectories do not. Flight ABC2000, a McDonnell-Douglas Series 82, is an over flight in ZDC flying from Dallas-Ft Worth to Philadelphia. Flight ABC3000, an Airbus, Model 300 Series, is also an over flight, flying from Memphis to Philadelphia. Both aircraft start their descent into Philadelphia while in ZDC airspace. The tracks of the two aircraft are shown in Figure 5. Both aircraft are following the same route. However flight ABC300 is vectored away from the route; that is the "bump" shown in the figure. URET posts a conflict alert while aircraft number 2 is out, away from the route. The two trajectories that form the basis of the alert are given in Figure 6. ABC3000 is predicted to rejoin the route downstream from its current position (the start of the trajectory). ABC2000 is predicted to continue following the route. A conflict is predicted when the ABC3000 approaches the route. The trajectories predicted by the state vector based method are shown in Figure 7. The trajectory for ABC2000 follows the flight path as does the URET trajectory. However the trajectory for ABC3000 is significantly different. It is similar to the URET trajectory, both are straight line paths which rejoin the route. The URET joins at a selected fix; the state based trajectory continues on its original, dead reckoned path until it intersect the route. As a result, a conflict is correctly not predicted by the state based trajectories.

VIII. Experimental Results

A. Comparison of Trajectory Accuracy

The trajectory accuracy is directly measured by comparing the predicted aircraft tracks with the tracks actually flown. The horizontal, cross track, and along track differences (errors) between the tracks and the trajectories are calculated for every sample track point. The errors are then averaged across the test scenario of 500 flights. The variation of the horizontal error rate as a function of look ahead time is presented for all of the methods in the Figure 8.

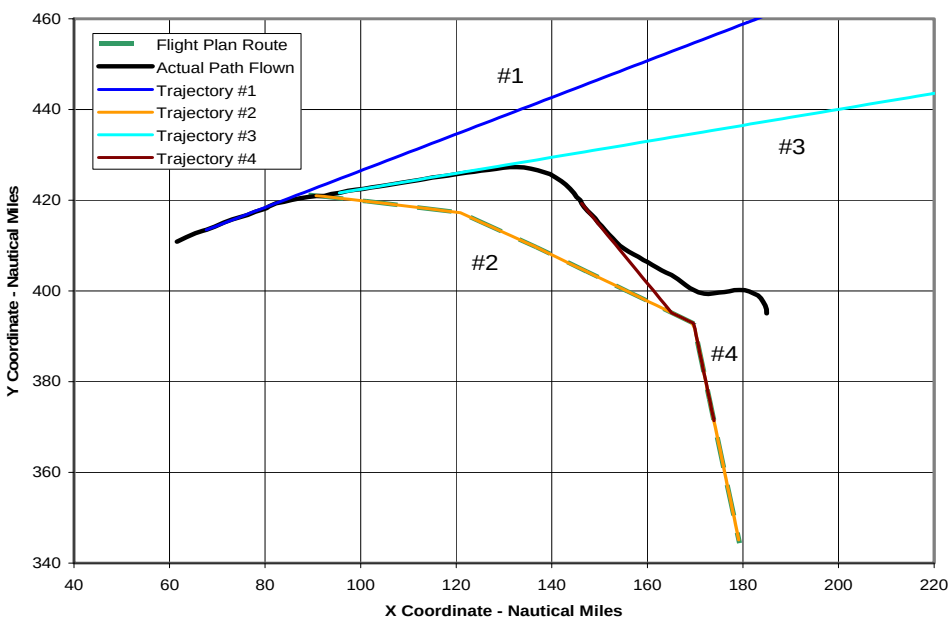


Figure 4: Example Trajectories for Flight ABC1000

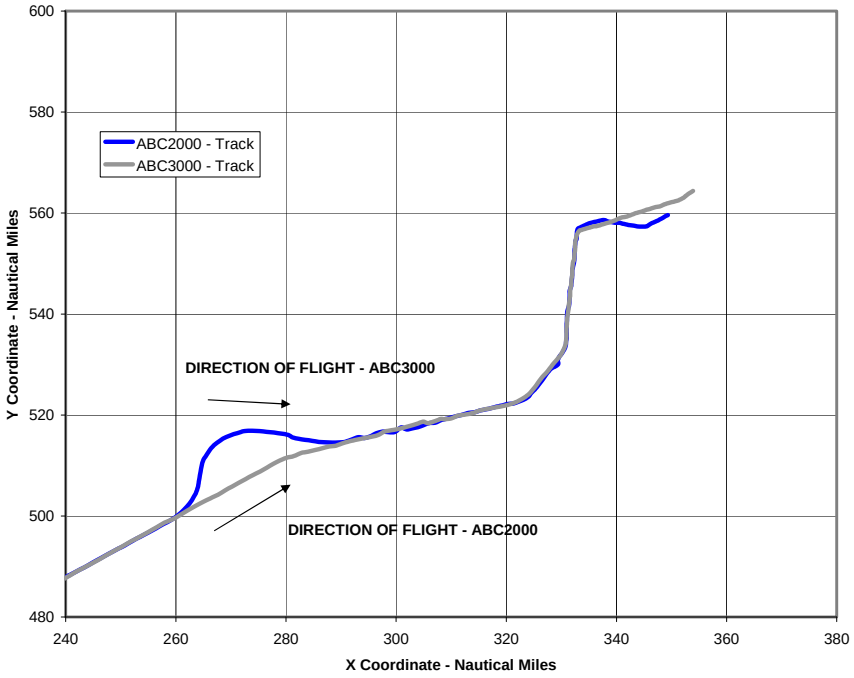


Figure 5: Example Flights - Possible Conflicts – Tracks

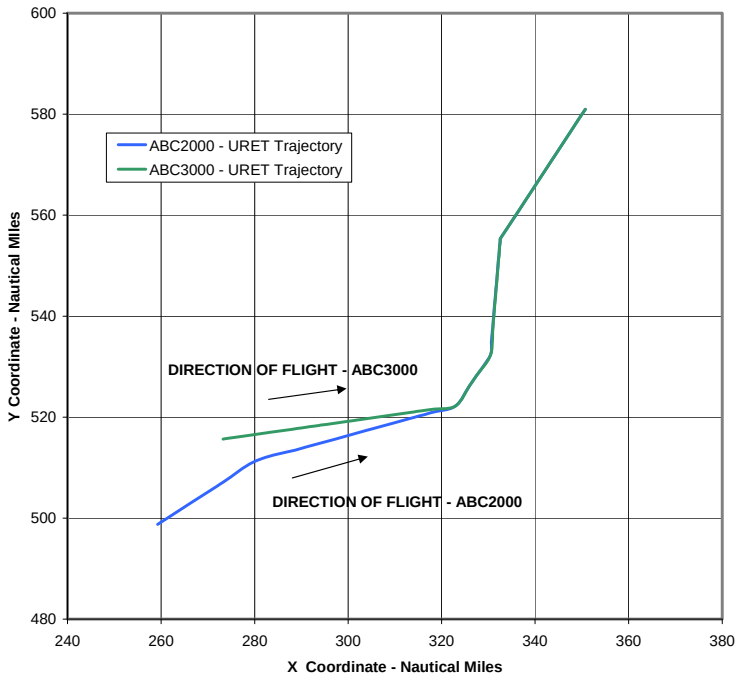


Figure 6: Example Flights - Possible Conflict - URET Trajectories

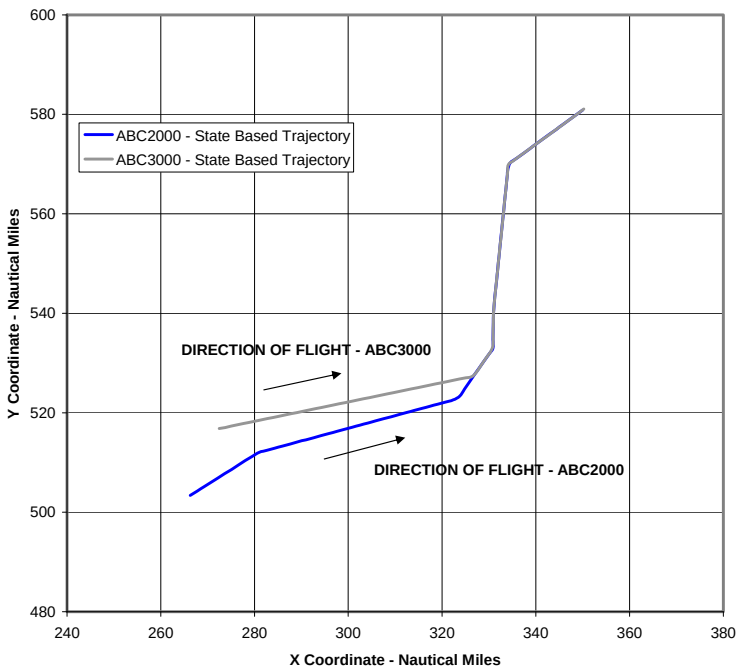


Figure 7: Example Flights - Possible Conflict - State Based Trajectories

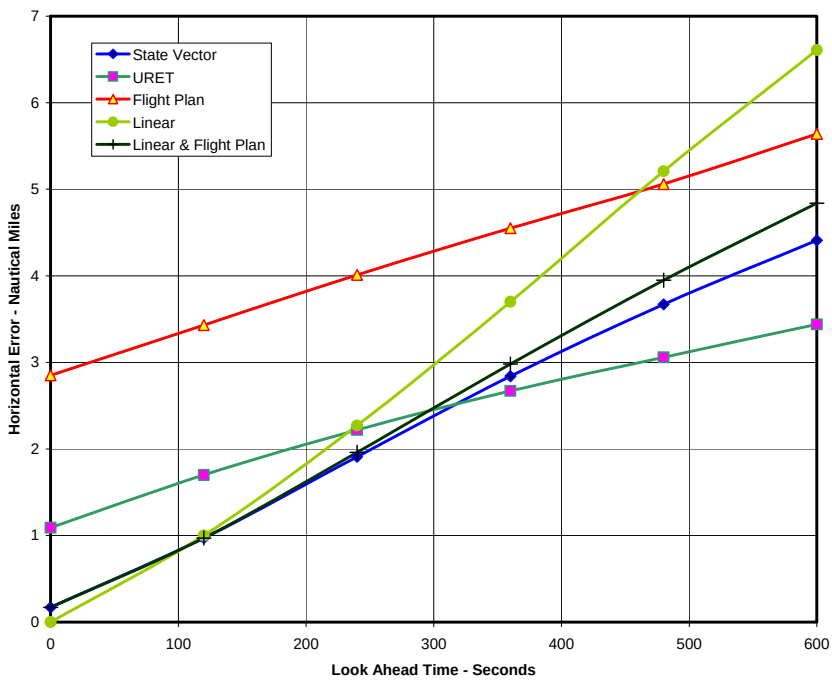
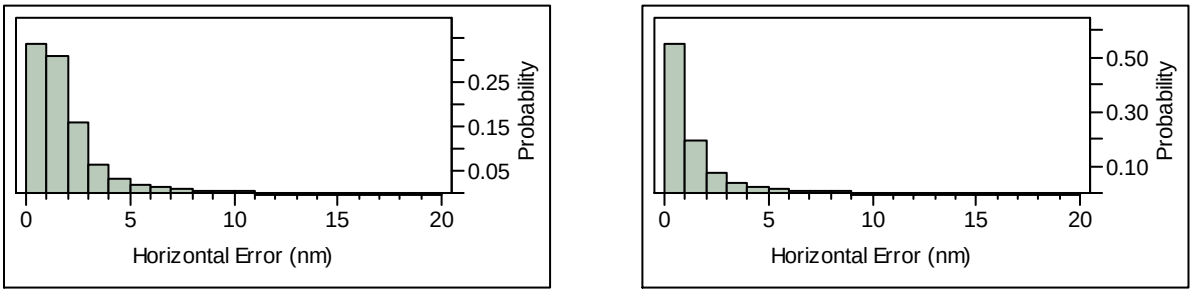


Figure 8: Variation of Horizontal Error with Look Ahead Time



URET Horizontal Trajectory Errors

State Vector Horizontal Errors

Figure 9: Histograms of Trajectory Horizontal Errors

The horizontal error rates start out at low values for near term predictions (for small values of the look ahead times) and gradually increase as the look ahead times increase, for all of the methods shown. The State Vector trace shows the accuracy of the method presented in this paper and the URET trace shows the accuracy of the current method used in the field. For near term predictions of less than five minutes the State Vector method is more accurate than the URET method. For longer term predictions the URET method is better.

The State Vector based method combines the three methods described previously - linear prediction, flight plan following, and linear prediction followed by flight plan following when there is an intersection with the planned route. The three other traces show how accurate each of these three methods are individually. The combination of the three methods, the state base method, is more accurate than any of the three methods individually.

The trajectory error rates (averages) are presented in Table 2 for the different methods. The State Vector method is a combination of the Linear, Flight Plan, and Linear & Flight Plan methods. The table shows that, as expected, the cross track and along track error rates for the State Vector method are also better than the URET predictions for short term predictions.

Table 2: Trajectory Error Rates

Prediction Method	Error Type	Look Ahead Times – Seconds					
		0	120	240	360	480	600
State Vector	Horizontal Error	0.17	0.97	1.91	2.84	3.67	4.41
	Cross Track Error	0.17	0.52	1.01	1.49	1.86	2.12
	Along Track Error	0.00	0.67	1.31	1.97	2.58	3.12
URET	Horizontal Error	1.09	1.70	2.22	2.67	3.06	3.44
	Cross Track Error	0.62	0.93	1.12	1.23	1.29	1.34
	Along Track Error	0.74	1.15	1.60	2.00	2.38	2.76
Flight Plan	Horizontal Error	2.85	3.43	4.01	4.55	5.06	5.64
	Cross Track Error	2.85	2.36	2.03	1.88	1.78	1.71
	Along Track Error	0.00	1.46	2.52	3.29	3.95	4.65
Linear	Horizontal Error	0.00	1.00	2.27	3.70	5.21	6.61
	Cross Track Error	0.00	0.59	1.56	2.72	3.96	5.10
	Along Track Error	0.00	0.64	1.24	1.85	2.46	3.02
Linear & Flight Plan	Horizontal Error	0.17	0.97	1.96	2.98	3.95	4.84
	Cross Track Error	0.17	0.54	1.15	1.79	2.38	2.87
	Along Track Error	0.00	0.64	1.24	1.85	2.42	2.96

The linear trajectories are built every 10 second sample time and the first point of the trajectory is the current track point. Therefore the horizontal, cross track, and along track trajectory errors at a look ahead time of 0 seconds are 0.

B. Comparison of Conflict Prediction Error Rates

Trajectories are used by the air traffic automation systems to predict future aircraft to aircraft conflicts or loss of minimum acceptable separation. An improvement in trajectory accuracy is expected to lead to better conflict alert performance. A comparison of the missed and false alert rates between the URET trajectories and the state vector trajectories was made. Some improvement is noted as is shown in Table 3.

Table 3: Comparison of Conflict Alerts

URET Action	State Vector Action	Count
Missed Alert	Valid Alert	8
Valid Alert	Missed Alert	6
False Alert	No Call	77
No Call	False Alert	12

IX. Summary and Conclusions

It was hypothesized that a linear trajectory prediction method would be more accurate than the traditional return to route method because of the common practice of vectoring aircraft off route to add a time delay. If an aircraft is not following its route the best one can do is dead reckoning. To apply this technique required determining whether or not an aircraft was following its route. The method chosen, illustrated in Figure 1, combined the distance the aircraft was from its route with a check on its heading to see if it was heading away from its route. The threshold values used in this determination were selected empirically. In addition, if the linear extrapolation predicted that the aircraft would return to its route, it was assumed that the aircraft would follow its route once it was back on it. The study has shown that the hypothesis is true, but only, as expected, for short term predictions.

X. Acknowledgements

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