AIAA's 3rd Annual Aviation Technology, Integration, and Operations (ATIO) Tech
17 - 19 November 2003, Denver, Colorado

AIAA 2003-6794

DEVELOPMENT OF CONFLICT-FREE, UNRESTRICTED CLIMBS FOR A TERMINAL AREA DEPARTURE TOOL

Yoon C. Jung* and Douglas R. Isaacson†
NASA Ames Research Center, Moffett Field, California

Abstract

The Expedite Departure Path (EDP) is a decision support tool being developed at NASA Ames Research Center aimed at providing Terminal Area Radar Approach Control (TRACON) Traffic Management Coordinators (TMCs) with pertinent departure traffic loading and scheduling information and radar controllers with advisories for tactical control of terminal area departure traffic. One of the proposed features of EDP is to provide departure controllers with the ability to perform unrestricted climbs where procedures typically restrict departures below incoming arrival traffic streams. The potential benefits of this feature include reductions in time-to-climb, fuel burn, and aircraft noise impact to the surrounding communities. This paper focuses on the issue of unrestricted climb in congested terminal areas and describes the modeling and simulation of such climbs. First, flight data of departures in TRACON airspace were analyzed to estimate the level of uncertainties in climb trajectory prediction. Second, the existing Trajectory Synthesizer (TS) module of the Center-TRACON Automation System (CTAS) was modified to generate trajectories that closely model actual aircraft climb profiles and terminal airspace procedures. Third, an algorithm was applied to predict conflicts between trajectories of departure and arrival aircraft and to determine if an unrestricted climb is advisable. Controller-in-the-loop simulations were performed to validate the feasibility of the algorithm and evaluate human factors. Lastly, a future application of a conflict probability estimation method for EDP was examined.

Introduction

NASA Ames Research Center (ARC) has been involved in research and development of air traffic control (ATC) decision support tools (DSTs) for more than twenty years. NASA ARC, in cooperation with the Federal Aviation Administration (FAA), developed the Center-TRACON Automation System (CTAS) to assist traffic management coordinators (TMCs) and air traffic controllers in the efficient management and control of air traffic. CTAS is a suite of decision support tools aimed at the terminal and en route domains and is comprised of the following tools: the Traffic Management Advisor (TMA), the Final Approach Spacing Tool (FAST), the Direct-To (D2) tool, and the Expedite Departure Path (EDP) tool.[1] Each CTAS tool consists of software processes running on networked workstations.

EDP is a DST aimed at providing Terminal Radar Approach Control (TRACON) Traffic Management Coordinators (TMCs) with pertinent departure traffic loading and scheduling information and radar controllers with advisories for tactical control of TRACON departure traffic. EDP employs the CTAS trajectory synthesis routine to provide conflict-free altitude, heading, and speed advisories. These advisories will assist the TRACON controllers in sequencing, spacing, and merging departure aircraft into the en route traffic flow. The anticipated benefits of EDP include a reduction in airborne and departure delay, reduced fuel burn, and reduced noise impact and emissions due to expedited climb trajectories.[2] To provide TRACON controllers with advisories that allow departure aircraft to perform conflict-free, expedited climbs in congested terminal airspace, accurate prediction of climb trajectories is essential. The accuracy requirement of climb trajectories for terminal airspace DSTs such as EDP is likely more stringent than for en route DSTs in both spatial and temporal respects due to the traffic density within TRACON airspace and the frequency of merging/crossing scenarios.

This paper discusses the issues related to accurately predicting climb trajectories and unrestricted climbs of departure aircraft in terminal airspace where the altitude range spans approximately 1,500 ft to 17,000 ft. First, a brief description of EDP is presented; algorithms for departure route generation, sequencing and merging among aircraft are explained, and the display of controller advisories is briefly discussed. Next, the trajectory synthesis method employed by CTAS to integrate climb trajectories is described. The existing TS module was modified to generate trajectories that closely model actual aircraft climb profiles and terminal airspace procedures. Next,

* Aerospace Engineer, Member AIAA
† Research Scientist, Member AIAA

results from data analysis performed on actual air traffic data from Dallas/Fort Worth TRACON airspace are presented and the sources for climb trajectory prediction error are discussed. Of particular interest is the typical variance of climb trajectories among aircraft of the same type; this variance plays a vital role in determining when an unrestricted climb can be safely advised. In the following section, the unrestricted climb of departure aircraft in the presence of arrival traffic is addressed and the algorithm to achieve this in EDP is described. A brief description of the controller-in-the-loop simulations performed to validate the feasibility of the algorithm and evaluate human factors is also presented. Lastly, a plan for the future development of EDP is presented.

Overview of EDP

The primary purpose of EDP is to provide TRACON departure controllers with tactical advisories to schedule and merge departing aircraft into en route traffic streams while meeting constraints for flow control and ensuring safe flow of outbound traffic. EDP software is composed of nine software modules running on networked workstations. These modules are categorized into five major functions: communication among processes, processing and distribution of surveillance and weather data, route generation, scheduling, and a user interface for displaying information, including advisories. This section briefly describes the route generation and scheduling algorithms of EDP. Detailed descriptions of each module and the software architecture can be found in Reference 2.

Departure Route Generation

Given weather data and position information for a departed aircraft, the Route Analyzer (RA) module builds a complete set of two-dimensional routes for the aircraft. A route is composed of a series of waypoints along the aircraft's departure path. A typical departure path begins at the current position of the aircraft and ends at a departure metering fix. To separate and sequence aircraft in compliance with the departure procedures, controllers vector aircraft along a series of trajectory segments. Figure 1 depicts a sample departure trajectory consisting of the following segments: INITIAL (or UPWIND), CROSSWIND, DOWNWIND (or RADIAL_INTERCEPT), and RADIAL.

The RA constructs the route beginning with the determination of an aircraft's analysis and route segment categories based on the aircraft's flight plan and current state. Each category defines a detailed route-building instruction for the particular scenario. In addition, each category definition prescribes a set of degrees-of-freedom (DOFs) which define the set of all likely trajectories for the aircraft based on vectors commonly employed by the departure controllers. Lastly, the CTAS TS computes four-dimensional trajectories for the set of all likely routes. Reference 2 provides detailed information on DOFs currently available in route building and examples of the variation from the nominal route by applying such DOFs.

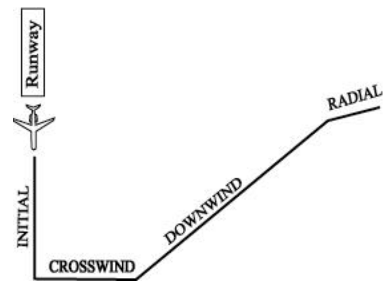

Figure 1. Example Departure Flight Segments

EDP Scheduling Algorithm

The purpose of the scheduling algorithm is to sequence departure aircraft on the trajectory segments and to resolve future conflicts among them. Sequencing is performed in two steps: ordering and merging. Ordering is achieved by applying predefined criteria that dictate relative order among aircraft flying on a particular trajectory segment. This portion of sequencing attempts to determine the order in which aircraft should fly over a specified scheduling constraint (i.e., end point of a trajectory segment). The second step is to merge 'ordered' flight trajectory segments which converge into a common trajectory segment. During the ordering and merging process, the conflict resolution algorithm predicts future conflicts among aircraft in the ordering and merging processes and adjusts trajectories via additional application of the aforementioned DOFs to meet the proposed sequence. If the resolution of a sequence incurs unacceptable delay (or a conflict-free resolution does not exist), the relative order is abandoned, and a new sequence solution is attempted. EDP employs the same concurrent sequencing and conflict resolution algorithm developed as FAST; this algorithm is detailed in Reference 3.

In addition to sequencing and conflict resolution among departure aircraft, EDP resolves conflicts between departure and arrival aircraft, thus allowing for the removal of procedural restrictions between departures and arrivals when warranted. A spatial constraint shared between aircraft not on the same trajectory segment has been added to the EDP's concurrent scheduling algorithm to allow for conflict resolution between aircraft that do not share scheduling (temporal) constraints, but which could come into conflict spatially. This crossing constraint allows unrestricted climbs in the presence of inbound traffic. A crossing constraint consists of a special three-dimensional region in the terminal airspace where arrival and departure streams are crossing. The conflict prediction algorithm searches for departure aircraft that will fly through the region in future time and investigates any possible conflict against arrival traffic. If a conflict is predicted, the departure aircraft's trajectory (in most cases) is adjusted by altering its DOFs in accordance with rules for resolving these types of conflicts within the specified airspace (derived from common controller tactics).[4] A detailed description of this process is presented in a later section of this paper. The final outcome of the concurrent sequencing and deconfliction algorithm is a set of efficient, conflict-free trajectories for all aircraft constrained to the scheduling needs of the airspace operators. From this set of trajectories, EDP extracts the Scheduled Time of Arrival (STA) for each aircraft at the scheduling constraint (e.g., departure metering fix), and presents controllers with tactical advisories to assist in meeting this STA without conflict or excessive workload.

EDP Graphical User Interface

EDP provides TRACON departure controllers with tactical advisories to assist in issuing vectors and clearances to pilots in a timely manner. Heading, speed, and altitude advisories in textual format are displayed in the Full Data Block (FDB) for each aircraft. In addition, graphical markers are displayed at the location where the aircraft should initiate the advised maneuver. As a development tool, the Planview GUI (PGUI) module of EDP provides flexibility in choosing colors, symbology, and time horizons for these advisories, allowing researchers to determine the appropriate presentation through a series of experiments. The FDB advisories, as well as graphical symbology, will be displayed on controllers' workstations. Figure 2 shows an example of the EDP graphical user interface on the controller display. Figure 10 shows an example of advisories for three departure aircraft with heading, speed, and altitude advisories. For example, the controller is directed to issue a direct climb advisory for COA557 to ascend and maintain 17,000 ft. Similarly, the same aircraft will be advised to change the heading to 80 degrees when the aircraft's targets reach the triangle (blue) symbol. The color scheme and shapes of the advisories are consistent with those of the FAST tool, which were determined through a series of human factors evaluations focused on system interaction and advisory presentation.[5]

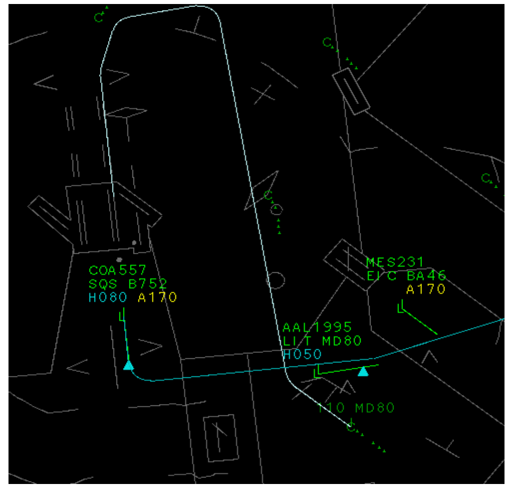

Figure 2. EDP Graphical User Interface

CTAS Climb Trajectory Prediction

Accurate climb trajectory prediction is essential to the acceptability of EDP. The CTAS TS module integrates simplified aircraft equations of motion to generate four-dimensional trajectories. The aircraft is represented as a point mass in solving the equations of motion and weight is held constant throughout the computation. The complete set of equations is found in Reference 6. CTAS employs airframe drag and engine thrust models supplied, in most cases, by the manufacturer. The aircraft model database also includes parameters key to climb trajectory prediction such as max takeoff weight, default ascent calibrated airspeed (CAS), and wing area.

The RA or the scheduling process specifies the horizontal route, speed and altitude restrictions, and then the TS module uses them to build both horizontal and vertical segments of a trajectory. The horizontal segments of a trajectory consist of straight line and curved line segments, which specify the end points, radius, altitude and ground speed for each turn. The existing TS module was modified to generate trajectories that closely model actual climb profiles and airspace procedures. This section provides a description of the TS climb trajectory integration method.

Altitude and Speed Restrictions

Once the horizontal segments are specified, the vertical segments are computed by numerical integration (both Euler and Runge-Kutta integration methods are employed). The TS builds the climb trajectory from the aircraft's current position to the specified trajectory end point (e.g., departure metering fix). The TS performs trajectory integration in multiple stages, to satisfy one or more specified capture conditions along the trajectory (e.g., speed increases/reductions or altitude restrictions). The capture conditions are defined mainly by altitude and speed restrictions as well as initial and final conditions that are imposed by the RA or scheduler. Table 1 presents sample altitude and speed restrictions imposed on the trajectory of a jet aircraft.

Table 1. Altitude and Speed Restrictions Example

Restriction type	Syntax
Altitude	GO HIGHER TO 10,000 AT CURRENT LOCATION
	GO HIGHER TO 17,000 AT CROSSWIND TURN
Speed	DEFAULT_ASCENT ACCEL ALLOWED AT CURRENT LOCATION

In this example, the aircraft is prescribed to climb to an altitude of 10,000 ft from its current position (radar track location), and will be cleared to climb to 17,000 ft when the aircraft reaches the turn to the crosswind route segment. The speed restriction dictates to the integration scheme that the aircraft is allowed to speed up to its default ascent airspeed specified in the aircraft model database. This speed restriction is further augmented by the rule that limits an aircraft's airspeed to 250 Kts below 10,000 ft altitude. Table 2 shows an example of altitude and speed restrictions for a MD80 jet aircraft (Table 3 shows some of the model data) in Dallas/Fort Worth TRACON airspace. (The negative sign in path distance denotes the distance measured from trajectory end point.) Table 2 also includes both initial and final constraints. The initial constraint includes the current position and speed of the aircraft, and the final constraint specifies the required position and speed of the aircraft at the departure metering fix.

Table 2. Sample Constraints Used for TS Trajectory Prediction

Cnstrt type	Altitude (ft)	CAS (Kts)	Path distance (ft)
Initial condition	2,142	176	Current (-254,667)
Speed 1	-	280	Current
Altitude 1	10,000	-	Current
Altitude 2	17,000	-	Crosswind turn wpt (-225,817)
Final condition	-	-	Departure metering fix

Table 3. An Example Aircraft's Model Data

Aircraft name	MD-80
Gross wing area	1209.3 ft^2
Max. takeoff weight	147,000 lbs
Airframe drag model	MD80
Engine thrust model	JT8D-217
Engine type	JET
Effective number of engines	2.3
Default ascent CAS	280 Kts

TRACON Vertical Segment Strategy

The TS employs the altitude and speed restrictions along with the horizontal segment information to form a strategy to integrate the vertical profile as a series of stages that meet each restriction in succession. In each integration stage, when one of the specified capture conditions is met, the integration is stopped and the next integration stage proceeds with appropriately updated initial condition and capture conditions. Table 4 shows an example of integration stages for a TRACON vertical segment strategy as well as the capture conditions for each stage. The last column of the table shows which capture condition was first met during the integration.

Table 4. TS Integration Stages and Capture Conditions

Integration stage	Constant	Capture cond.	Converged
PATH DISTANCE THEN SPEEDUP	d(TAS)/dt (1.8)	DIST (-254,667) CAS (250)	DIST (-254,667)
PATH DISTANCE THEN CLIMB	RC (25)	DIST (-225,817) CAS (250) ALT (10,000)	CAS (250)
PATH DISTANCE THEN CLIMB	CAS (250)	DIST (-225,817) ALT (10,000)	DIST (-225,817)
PATH DISTANCE THE CLIMB	CAS (250)	DIST (0) ALT (10,000)	ALT (10,000)
PATH DISTANCE THEN CLIMB	RC (25)	DIST (0) ALT (17,000) CAS (280)	CAS (280)
PATH DISTANCE THEN CLIMB	CAS (280)	DIST (0) ALT (17,000)	ALT (17,000)
PATH DISTANCE	CAS (280)	DIST (0)	DIST (0)

(Units: RC (ft/sec), CAS (Kts), DIST (ft), ALT (ft), d(TAS)/dt (ft/sec^2))

The purpose of having a TRACON strategy divided into stages is to integrate climb trajectories of aircraft so that the computed trajectories resemble the actual speed and altitude profiles flown by airlines. Under normal circumstances, a departure aircraft (jet) speeds up to 250 Kts CAS with maximum takeoff thrust and maintains the airspeed until the aircraft reaches 10,000 ft. For this normal profile, the TS integrates the profile while climbing and accelerating until either the speed or altitude is achieved, or until the next constraint's path distance is reached. At this point, the integration reaches a new stage and is reevaluated to determine the proper integration method. This is repeated until the last constraint (final condition) is met. The two methods of integration for departure profiles will now be discussed briefly.

The CTAS TS integrates the equations of motion in two different ways based on the assumptions made for airspeed and rate of climb (RC). Rate of climb and true airspeed are computed in TS as follows:

For constant CAS condition:

$$\frac{dh}{dt} = V_t \sin\gamma$$

$$\gamma \cong \arcsin\left(\frac{T-D}{W}\right)$$

$$\frac{dV_t}{dt} = \frac{dV_t}{dh}\frac{dh}{dt}$$

$$\frac{dV_t}{dh} = \frac{V_t(h+\Delta h) - V_t(h)}{\Delta h}.$$

For constant climb rate condition:

$$\frac{dh}{dt} = const$$

$$\frac{dV_t}{dt} \cong \frac{(T-D)g}{W} - g\sin\gamma$$

$$\gamma = \arcsin\left(\frac{dh/dt}{V_t}\right).$$

For both sets of equations, h is altitude, V_t is true airspeed (TAS), T is total engine thrust, D is aerodynamic drag force, W is aircraft weight, and γ is the flight path angle. The result of TS trajectory integration is a collection of state vectors and their rates of change. Figures 3-5 illustrate an example horizontal path and climb profile for a departure aircraft generated by TS.

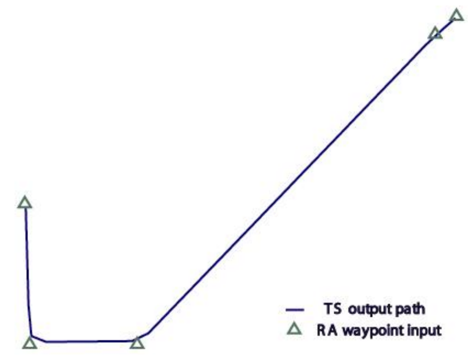

Figure 3. TS generated Horizontal Path

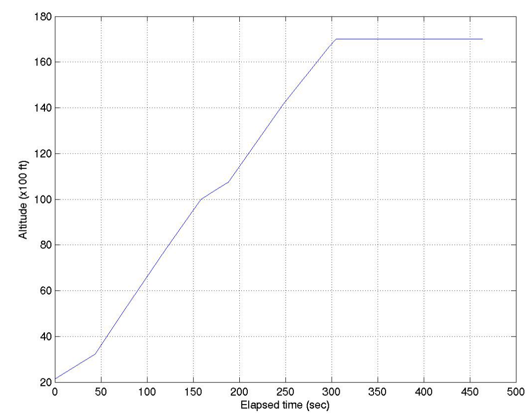

Figure 4. TS Generated Altitude Profile (MD80)

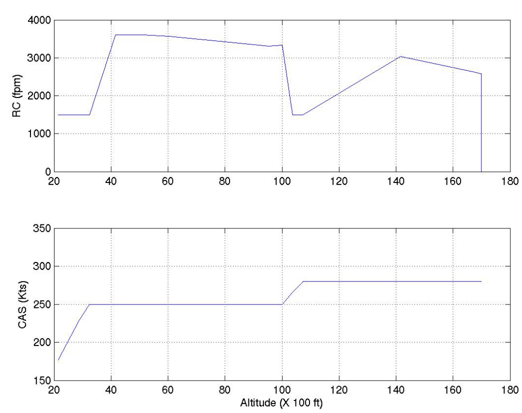

Figure 5. TS Generated Rate of Climb and CAS Profile (MD80)

Uncertainties in Trajectory Prediction

The reliability of the scheduling and conflict resolution capabilities of EDP is dependent on the accuracy of the trajectory prediction. The accuracy of climb trajectory prediction depends on several key factors: accuracies in aircraft weight estimation, engine thrust computation, drag force computation, wind prediction, and a priori knowledge of pilot intent and airline procedures. Consequently, a lack of accuracy in estimating these parameters contributes to errors in TS trajectory prediction. There have been efforts to enhance climb trajectory prediction and some of the results have been reported.[7,8,9,10] For example, flight-planning data from Airline Operations Centers (AOCs) such as takeoff weight, speed profile, and engine type specification offer some improvement in en route climb prediction accuracy.[7] In this section of the paper, the focus is on the uncertainties inherent to climb trajectory prediction in TRACON airspace, where aircraft flight paths are actively controlled (i.e., by human controllers) under various restrictions on altitude and speed. First, TRACON climb profile data of departure traffic obtained from a statistical analysis are presented to quantify the variance among like aircraft climb profiles. Next, sources of uncertainty in trajectory prediction are addressed.

DFW TRACON Climb Trajectories

Dallas/Fort Worth (DFW) TRACON departure air traffic data from late May to mid June of 2003 was recorded and analyzed to quantify variances in the climb profiles of common jet aircraft. The data were also used to compare with CTAS TS climb trajectory prediction for an error analysis. Data was recorded from live traffic feeds from the DFW TRACON facility (D10). Additionally, one-hour Rapid Update Cycle (RUC) weather forecasts from the National Oceanic and Atmospheric Administration (NOAA) were recorded to log winds aloft, temperature and barometric pressure for each traffic recording. A total of 4,240 departure operations were recorded and the data were sorted by aircraft type. The recorded data included time, position, altitude, rate of climb, CAS, TAS, and ground speed of each aircraft at every radar track update. In post processing, aircraft whose climb profiles revealed any indication of leveling off were eliminated from the data. This was performed to remove aircraft adhering to procedural restrictions from the desired variance analysis of unrestricted climb profiles. An aircraft was regarded as leveling off if the altitude remained unchanged within a specified tolerance (50 ft) for at least five track updates (about 25 seconds). Table 5 shows a list of the six most common jet aircraft types in D10 airspace and number of departure operations used for analysis.

Table 5. Refined Dataset for D10 Climb Profile Analysis

Aircraft type	Number of operations recorded	Number of operations used for analysis
MD80	946	764 (80.76%)
B737-800	204	176 (86.27%)
B757-200	387	283 (73.12%)
CRJ2	581	384 (66%)
E145	252	177 (70.8%)
F100	220	196 (89.09%)

Figures 6 and 7 show average climb profiles (with standard deviations) of two jet aircraft types listed in the above table. The average climb performance can serve as a baseline when TS climb trajectories are validated.

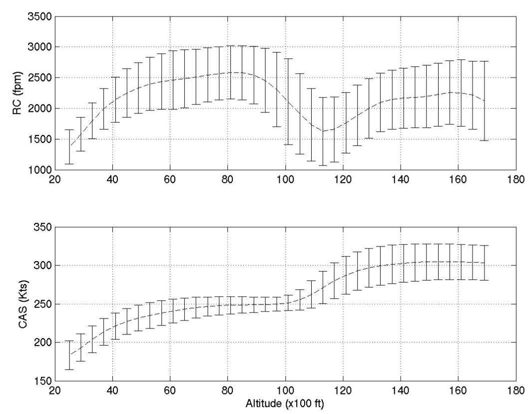

Figure 6. Average Climb Profile of MD80 Aircraft

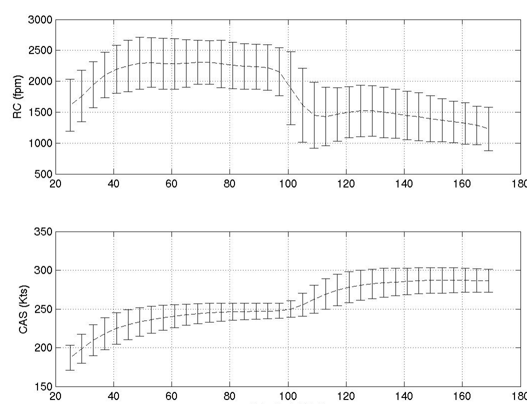

Figure 7. Average Climb Profile of CRJ2 Aircraft

Figures 8 and 9 show comparisons of average rate of climb and CAS profiles for all aircraft types analyzed. As expected, the average climb performance, especially the rate of climb, varies widely among different aircraft types.

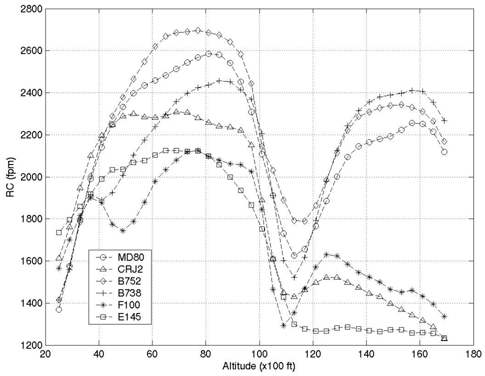

Figure 8. Average Rate of Climb Data of Six Jet Aircraft Types in DFW TRACON

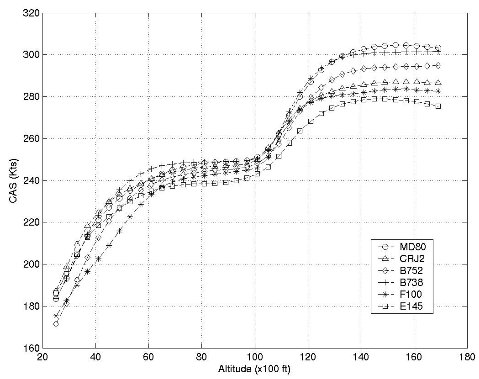

Figure 9. Average CAS Data of Six Jet Aircraft Types in DFW TRACON

<u>Aero-propulsive Model Data</u>

As previously shown in the equations of motion, the difference between engine thrust and aerodynamic drag force for a given aircraft weight determines the climb rate and true airspeed. The CTAS aircraft model database provides the TS with aero-propulsive model data for over 400 distinguishable aircraft types. The model data include aircraft weight, wing area, drag coefficient tables, engine thrust tables, minimum and maximum CAS, etc. Among these data, weight and engine thrust are more susceptible to error than other parameters due to a number of factors. First, CTAS models a limited number of engines, and actual aircraft engine equipage may vary significantly from that assumed. Furthermore, aircraft takeoff weight can vary substantially based on the stage length and load. For example, the average takeoff weight of MD80 aircraft type may vary from 115,000 lbs (estimated takeoff weight of MD81 aircraft with 30% loading and 500 n.mi. stage length) to 160,000 lbs (published maximum takeoff weight of MD83 aircraft). In contrast, the maximum takeoff weight described in the CTAS aircraft model database for the MD80 aircraft was 147,000 lbs. Figure 10 demonstrates the sensitivity of trajectory prediction to takeoff weight variation. The TS generated climb trajectories of a MD80 aircraft for three takeoff weights (147,000 lbs, 160,000 lbs, and 115,000 lbs) were compared. Figure 11 shows a comparison of actual average climb performance data between long-haul (i.e., stage length greater than 1,000 n.mi,) and short-haul (i.e., stage length less than 500 n.mi.) MD80 aircraft collected on May 30, 2003. Short-haul aircraft show higher average rates of climb than long-haul aircraft throughout entire flight segments in the TRACON. It is likely that short-haul aircraft are much lighter than long-haul aircraft because short-haul aircraft normally carry less fuel than those of long-haul aircraft.

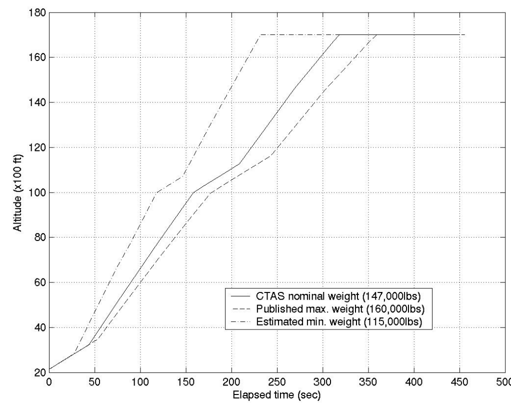

Figure 10. TS Generated Climb Trajectories of MD80 Aircraft For Different Takeoff Weights

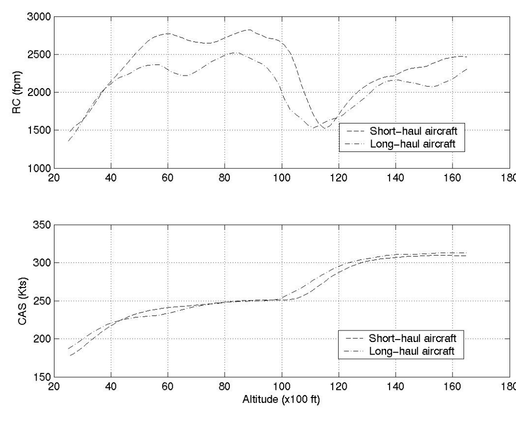

Figure 11. Comparison of Climb Performance Between Short-haul and Long-haul MD80 Aircraft

Airline Procedures and Pilot Interaction with Controllers

The climb speed profile and engine throttle settings are also fundamental to climb trajectory prediction. Although pilots have ultimate authority in determining speed profile and throttle setting for climb, often times, airline procedures provide guidelines under various operating conditions. For example, the Flight Management Computer (FMC) for Boeing 737 aircraft provides reduced climb thrust procedures (approximately 10 – 20% thrust reduction) for some takeoff conditions.[11] The operational use of reduced thrust for climb is to compensate for various environmental conditions during climb as well as to prolong engine life and reduce engine maintenance cost. The TS algorithm, however, does not consider operational variation among individual flights at this time. Other factors that must be considered in estimating deviation of climb trajectories from the TS-predicted trajectory are the behaviors of, and interactions between, pilots and controllers. It was found, through human-in-the-loop simulations of FAST, that there is significant variation in the elapsed time between the display of advisories and when controllers issue the advisories as instructions to pilots.[5] The same is also true for pilots receiving instructions and executing maneuvers.

Accuracy in Wind Prediction

The prediction quality of atmospheric conditions in the terminal area also has a significant impact on the accuracy of trajectory prediction. The ground speed, and thus time-to-fly to points along the route will be affected by the prediction accuracy of winds aloft. Likewise, the predicted altitude of aircraft at points along the path is also affected by the wind prediction and could lead to errors in predicting potential conflicts with crossing traffic streams. Currently, CTAS receives one-hour weather forecasts from NOAA's RUC model to obtain horizontal wind speed, temperature, and pressure with a horizontal resolution of 40 km and vertical resolution of 25 mb pressure altitude. A study of prediction error for this wind model is beyond the scope of this paper. However, a previous study has found that wind vector errors of 7 – 10 m/s (approximately 10 – 15 Kts of headwind error) are significant to CTAS trajectory prediction.[12] As a potential solution, MIT Lincoln Laboratory has developed the Integrated Terminal Weather System (ITWS) and the data from this system can now be used by CTAS. It is anticipated that the new ITWS system will provide better prediction of weather information in terminal areas. The ITWS wind forecasting method uses both RUC weather updates and other sources such as Meteorological Data Collection and Recording System (MDCRS) to provide winds with higher spatial (2 and 10 km grids) and temporal (5 and 30 min update) resolution for the terminal area.[12] Figure 12 illustrates the winds aloft prediction impact on TS climb trajectory prediction by comparing two trajectories: with and without winds aloft for a MD80 aircraft in D10 airspace. Neglecting winds aloft in this case showed a 13 second error in time-to-fly to fly to the departure metering fix and more than 900 ft of difference in altitude.

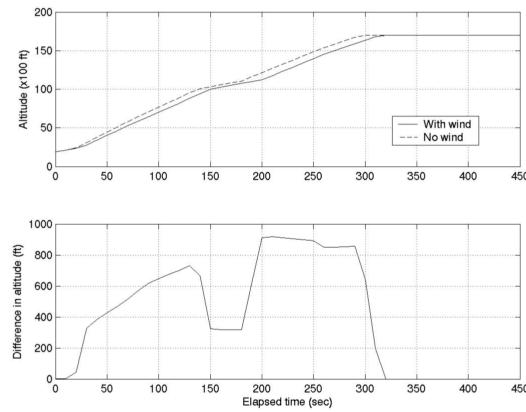

Figure 12. Altitude Predictions of a MD80 Jet With and Without Winds Aloft

Unrestricted Climb Advisories in the Presence of Prediction Uncertainty

In the process of procedurally separating departure and arrival streams in the terminal area, it is often necessary to restrict departure aircraft altitude on climb-out until the departure aircraft is clear of the arrival traffic stream. This type of procedural separation is commonly referred to as tunneling and is in place to manage the workload level of controllers in congested terminal airspace (removing the task of monitoring separation between climbing and descending aircraft). Permitting departures to climb to their cruise altitudes without any intermediate altitude restrictions would be desirable in terms of efficiency, congestion, and in some cases, noise impact. An EDP benefits assessment study performed recently by NASA's Advanced Air Transportation Technologies (AATT) Project Office has identified that direct climb is the primary benefit mechanism of the tool to reduce flight time and, therefore, reduce operating costs of airlines.[13] This section briefly describes the algorithm of EDP that allows departure aircraft to perform unrestricted climbs in the presence of inbound traffic where they would normally be procedurally restricted below the arrival stream. A brief discussion of the controller-in-the-loop EDP simulations performed at NASA

ARC follows, and lastly, the issue of incorporating trajectory prediction uncertainties into the conflict prediction/resolution algorithm is discussed.

Algorithm - Crossing Constraint

In the absence of procedural restrictions separating departures from arrivals, it is necessary to consider conflicts between them when forming the schedule for departure aircraft. For ease of implementation in the concurrent scheduling algorithm, EDP assumes an unrestricted climb profile for each aircraft and adds an altitude restriction where necessary to avoid conflict. To achieve this functionality, a new constraint type (crossing) (defined previously) was added to the existing constraint types. As noted earlier, for EDP, crossing constraints are used for the regions of airspace where unrestricted departures would penetrate arrival controller airspace and potentially conflict with aircraft in the arrival corridor. Typically, this kind of airspace is described as a prearranged coordination area in the FAA TRACON ATC procedures.[14] Figure 13 depicts two of the coordination areas in DFW TRACON airspace. In the scheduling initialization cycle of EDP, if a departure aircraft's or an arrival aircraft's route segments will pass through the region specified in crossing constraint, the aircraft is registered in the constraint. Next, the aircraft's entry to, and exit from, the crossing constraint airspace are determined from the trajectory.

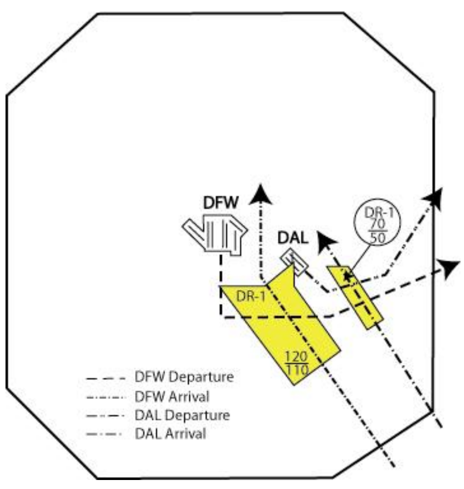

Figure 13. Prearranged Coordination Areas (DR's and Feeders – South Flow)

Next, the conflict prediction algorithm of EDP searches through the list of constraints (including the crossing constraint) to find possible future conflicts among aircraft on each constraint. In particular, future positions of a pair of arrival and departure aircraft are examined against separation criteria. If a conflict is predicted between the two aircraft, a new altitude restriction is imposed on the departure aircraft. In most cases, the altitude restriction imposed on departures for resolution of arrival/departure crossing conflicts is the altitude specified in the Standard Instrument Departure (SID) for the departure aircraft, and no advisory is necessary. While the default assumption for the EDP scheduling algorithm is an unrestricted climb, the default for the aircraft is adherence to the SID and any procedural restrictions it imposes. Table 6 shows two altitude restrictions for a departure aircraft: initial restriction and revised restriction after a conflict is predicted and resolved. The latter restriction limits the aircraft's altitude to 10,000 ft until the aircraft reaches the downwind turn, which is beyond the boundary of the coordination airspace. Figure 14 shows an example of TS climb profile predictions with and without the presence of a conflict.

Table 6. Altitude Restrictions

Initial restriction	Revised after a conflict is resolved
CLIMB NOW TO 17,000 FT	CLIMB NOW TO 10,000 FT
	CLIMB TO 17,000 FT BEGINNING AT THE DOWNWIND TURN

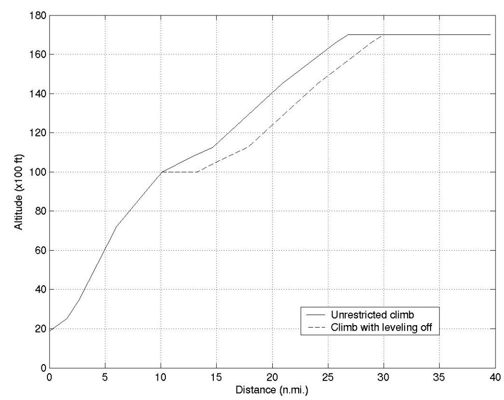

Figure 14. Altitude Predictions With and Without Predicted Conflict

Simulations

A series of simulations was performed at NASA Ames' ATC Simulation Lab during July 2003. The purpose of these simulations was to demonstrate the feasibility of the deconfliction algorithm developed for unrestricted climbs, as well as to conduct a human factors evaluation of advisory presentation to controllers. Eastbound aircraft departing from both DFW and Dallas Love Field (DAL) airports were automatically fed to the EDP system via the Pseudo Aircraft System (PAS) target generator. Retired controllers and pilots acted as controllers and pseudo-pilots who actively controlled departure aircraft. Arrival aircraft were flown automatically by PAS along the flight plan Standard Terminal Arrival Route (STAR) and to the arrival runway. Departure controllers were asked to issue heading and altitude advisories to pseudo-pilots as they were displayed on controllers' workstations. At the end of each simulation, controllers were asked to fill out questionnaires to evaluate the accuracy of the advisories. Questions regarding display of advisories such as symbology (i.e., color and shape), timing, and overall acceptability were also included in the questionnaires. The result showed that the EDP trajectories were more precise than those of baseline (i.e., non-EDP) condition. Overall, the controllers thought the advisories were useful and that the display of advisories was acceptable. The workload associated with integrating advisories into the traffic plan was also rated as acceptable.

A Future Study - Evaluation of Uncertainties in Trajectory Prediction for Unrestricted Climb

Prediction of climb trajectories is known to have errors due to uncertainty in estimation of parameters used in trajectory computation as well as numerical errors in integrating equations of motion. Some of the sources of uncertainties are described in the previous section of this paper, however there are many more with different levels of sensitivity.[15] The challenges are first, to improve the trajectory prediction itself, and second, to estimate the uncertainty of trajectory prediction and use this information in the conflict prediction/resolution process. Improvement of trajectory prediction can be achieved through more accurate aerodynamic and engine thrust model data, better takeoff weight estimation (or actual data from airlines), increased accuracy of wind field prediction, as well as better understanding of airline procedures and human factors.

A conflict prediction methodology using conflict probability has been developed by Paielli, et al. that analytically estimates conflict probability for level and non-level flying aircraft and is applied to en route trajectories.[16] The Conflict Probability Estimation (CPE) method provides the probability of conflict as a function of conflict geometry and predicted time to loss of separation. EDP may utilize this method to assist in determining when an unrestricted climb advisory is acceptable. An initial unrestricted climb clearance can be issued to a departure aircraft if the probabilities of conflict between the aircraft and inbound arrival aircraft are less than a preset value. The EDP conflict prediction algorithm will continuously monitor conflict probability and issue a revised advisory if necessary. The success of this method depends on the accuracy of the error model obtained from statistical analyses of actual flight data and the TS trajectory prediction. The error model produces the root-mean-square (RMS) values of prediction errors in alongside-track, cross-track, and vertical-track dimensions. Figure 15 shows an example of RMS errors in vertical and alongside tracks. The combined data of MD80, B757 and B738 aircraft types from DFW TRACON were used for the analysis. The errors between TS trajectory prediction data and actual flight data were obtained and RMS values at each prediction time were computed. For convenience, the prediction time was measured from when an aircraft's altitude passes 2,000 ft. The RMS error of vertical track shows a strong nonlinear behavior in such that its growth rate is nearly constant for about 140 seconds and then drops to near zero until it increases again at about 240 seconds into prediction. The interval of constant vertical RMS error corresponds to the time interval when aircraft reduce rate of climb while accelerating to default climb airspeed.

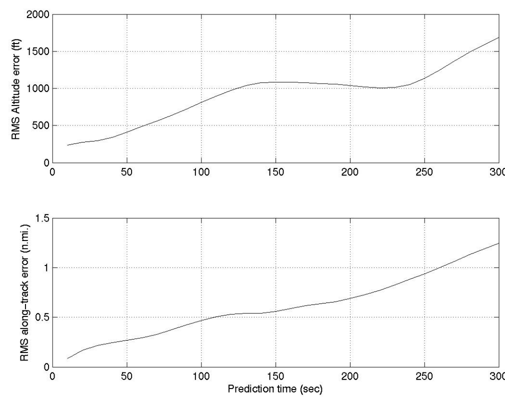

Figure 15. RMS Errors in Vertical and Alongside Tracks

Summary

One of the proposed features of EDP is to provide departure controllers with the ability to perform unrestricted climbs. The potential benefits of this feature include reductions in time-to-climb, fuel burn, and aircraft noise impact to the surrounding communities. In this paper, the methodology for climb trajectory prediction of EDP and its application for unrestricted climbs were presented. DFW TRACON departure traffic data were analyzed and average and standard deviations of climb profiles (i.e., rate of climb and airspeed) of common jet aircraft types were obtained. These data will serve as the basis for future climb trajectory validation for EDP. Sources of uncertainties in climb trajectory prediction were also discussed, and examples obtained from CTAS TS trajectory prediction were provided. Inaccuracies in predicting aircraft weight, aero-propulsive model data, airline procedures/pilot interaction with controllers, and wind prediction were found to be significant. The algorithm developed for unrestricted climbs was described, as well as the method for integrating resolution of crossing conflicts within the EDP concurrent scheduling algorithm. A brief description on the simulations performed at NASA ARC to validate the feasibility of the algorithms as well as human factors evaluations was provided. Controllers participated in simulations reacted positively to the concept of departure advisories and thought the EDP tool could be useful. Lastly, a future application of the Conflict Probability Estimation method developed at NASA ARC to non-level flights in the terminal area was proposed.

References

[1] Anon, CTAS Description and Software Overview, www.ctas.arc.nasa.gov

[2] Jung, Y.C. and Isaacson, D.R., "Design Concept and Development Plan of the Expedite Departure Path," Proc. of the AIAA's Aircraft Technology, Integration, and Operations (ATIO) Forum, Oct 1-3, 2002, Los Angeles, CA.

[3] Robinson, J.E. and Isaacson, D.R., "A Concurrent Sequencing and Deconfliction Algorithm for Terminal Area Air Traffic Control," Proc. of the AIAA Guidance, Navigation, and Control Conference, Denver, CO, August 2000.

[4] Isaacson, D. R., and J. E. Robinson III, "A Knowledge-based Conflict Resolution Algorithm for Terminal Area Air Traffic Control Advisory Generation," AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August 2001.

[5] Quinn, C. and Robinson, J.E., "A Human Factors Evaluation of Active Final Approach Spacing Tool Concepts," 3rd USA/Europe Air Traffic Management R&D Seminar, Napoli, Italy, 13-16 June 2000.

[6] Slattery, R.A., "Terminal Area Trajectory Synthesis for Air Traffic Control Automation," Proc. of the American Control Conference, Seattle, Washington, June 1995.

[7] Coppenbarger, R.A., "Climb Trajectory Prediction Enhancement Using Airline Flight-Planning Information," Proc. of the AIAA Guidance, Navigation, and Control Conference, Portland, Oregon, August 1999.

[8] Chan, W., Bach, R., and Walton J., "Improving and Validating CTAS Performance Models," Proc. of AIAA Guidance, Navigation, and Control Conference, Denver, CO, August 2000.

[9] Gong, C. and Chan, W., "Using Flight Manual Data to Drive Aero-Propulsive Model for Predicting Aircraft Trajectories," Proc. of AIAA's Aircraft Technology, Integration, and Operations (ATIO) Forum, Los Angeles, CA, October 2002.

[10] Slater, G., "Adaptive Improvement of Climb Performance," Unpublished paper.

[11] Boeing 737 Briefings Website, http://www.smartcockpit.com/b737/B737%20CLIMB%20BRIEFING.PDF

[12] Cole, R.E., Richard, C.M., Kim, S., and Bailey, D., "An Assessment of the 60 km Rapid Update Cycle (RUC) with Near Real-Time Aircraft Reports," MIT Lincoln Laboratory, July 1998.

[13] Wang, J.J., Chang, Paul, and Datta, K, "Life-Cycle Cost/Benefit Assessment of Expedite Departure Path (EDP)," Prepared for NASA Ames Research Center, Contract No. NAS2-98074, August 2003.

[14] DFW Air Traffic Control, Department of Transportation, Federal Aviation Administration, Order DFW 7110.65H

[15] Jackson, M.R., Yiyuan, J.Z., and Slattery, R.A., "Sensitivity of Trajectory Prediction in Air Traffic Management," Journal of Guidance, Control, and Dynamics, Vol. 22, No. 2, March-April 1999.

[16] Paielli, R. and Erzberger, H., "Conflict Probability Estimation Generalized to Non-Level Flight," Air Traffic Control Quarterly, vol. 7, no. 3, October 1999.