FIELD EVALUATION OF DESCENT ADVISOR TRAJECTORY PREDICTION ACCURACY

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Abstract

The Descent Advisor (DA) automation tool has undergone a series of field tests at the Denver Air Route Traffic Control Center to study the feasibility of DA-based clearances and procedures. The latest evaluation, conducted in the fall of 1995, expanded the operational nature of DA testing to include a wider variety of test conditions. A total of 197 commercial flights from three airlines participated in the study over twenty-three days of testing. Aircraft included large and heavy jet transports, both conventional- and flight-management-system-equipped, and turboprop commuter types. The primary objective was to measure DA trajectory prediction accuracy for use in validating DA metering advisories and developing conflict-probe error models. Previous evaluations, involving large jet types only, demonstrated an arrival time prediction accuracy within 20 sec. The 1995 test results indicate a mean error of 0.5 sec late with a standard deviation of 14.3 sec. The least variation was found for flight-management-system-equipped jets with a standard deviation of 11.9 sec compared to 15.2 and 15.4 sec for conventional-equipped jets and turboprop types respectively. This paper describes the test and presents an analysis of the descent trajectory prediction accuracy in terms of errors in the horizontal profile, altitude profile, and arrival time.

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Introduction

The quest to achieve "free-flight" benefits for airspace users is a driving force in the development of new automation systems for both aircraft operations and Air Traffic Control (ATC)[1]. Substantial benefits, in the form of reduced operating costs (time and fuel), will require new tools and procedures to increase the realization of user preferences (route, altitude, speed, and/or time) while maintaining system safety and robustness. One area with a large potential for benefit gains is the extended terminal area wherein aircraft transition from relatively “unconstrained” en route airspace to high-density terminal airspace. In the extended terminal area, ATC procedural constraints (routes, altitudes, and speeds) are needed to facilitate the safe and orderly handling of aircraft in the en route, arrival, and departure phases of flight. In addition, traffic management constraints (e.g., miles-in-trail or metering) related to terminal area capacity limitations have a significant impact on the cost of flight operations. In this environment, both ATC procedural and traffic management constraints must be addressed simultaneously to improve flight efficiency. The economic benefit of flying an optimized trajectory (e.g., best wind route, speed, and altitude) into a high density terminal area may be negated if the optimization does not account for constraints such as metering delays and separation.

The Center TRACON Automation System (CTAS) is a set of ATC automation tools designed to assist controllers in maximizing the efficiency of the extended terminal area airspace.[2] The Descent Advisor (DA) is the CTAS element designed to assist Air Route Traffic Control Center (Center) controllers with an emphasis on achieving an efficient transition from the en route to the arrival phase of flight. DA assists controllers by generating accurate, fuel-efficient clearance advisories for the merging, sequencing, and separation of high-density arrival traffic while providing automation assistance for the prediction and resolution of conflicts between aircraft in all phases of flight (i.e., departure, en route, and arrival). These advisories will enable user-preferred trajectories to be extended farther into the terminal area, for example, by reducing the need for merging arrivals on standard routes.

The key to this technology is the accurate prediction of aircraft trajectories, particularly when the trajectories will include large changes in course, altitude, and speed typically associated with the extended terminal area. For metering purposes, a reduction in arrival time prediction error (2-sigma) from 180 sec (the approximate value in today's system) to 30 sec will save approximately $14 per arrival at high density hub airports.[3] Improvements in trajectory prediction accuracy will also extend the effective time horizon of conflict prediction and resolution advisories leading to fewer, and more efficient, resolution actions.

The Descent Advisor (DA) automation tool has undergone a series of field tests at the Denver Air Route Traffic Control Center (Center) to study the feasibility of DA-based clearances and procedures.[4,5,6] Previous evaluations, involving large jet types only, demonstrated an arrival time prediction accuracy (mean + standard deviation) within approximately 20 sec.[4,5] These data were for en route descents (from cruise altitude to Terminal Radar Approach Control (TRACON) entry) of 15–20 min duration and based on a single descent clearance without corrective updates.

The latest evaluation, conducted at the Denver Center in the fall of 1995, expanded the operational nature of DA testing to include (1) controller interaction with DA, (2) a published descent procedure, (3) a greater variety of aircraft types including large and heavy jet transports, both conventional- and flight-management-system (FMS)-equipped, as well as three turboprop commuter types, and (4) an expanded set of delay conditions requiring changes in cruise speed, altitude, and routing in addition to top-of-descent location and descent speed. The primary objective was to measure DA trajectory prediction accuracy for validating DA metering advisories and for use in developing error models for analysis of conflict-probe probability. Additional objectives included the evaluation of the published descent procedure and DA clearance phraseology, an initial evaluation of a prototype DA display and interface, and an exploratory first look at the use of DA conflict prediction tools in the field. These additional objectives will be addressed in a separate report. This paper describes the test and presents an analysis of the descent trajectory prediction accuracy in terms of errors in the horizontal profile, altitude profile, and arrival time.

Test Description

Approach

The test was conducted at the Denver Center over two calendar periods including September 13–29 and October 1 through November 8, 1995. The test focused on arrivals to Denver from the northwest and included the participation of three airlines: United Airlines (UAL), Mesa Airlines (Air Shuttle (ASH)), and Mark Air (MRK). Traffic periods were selected for moderate arrival traffic conditions and typically occurred in the late morning and early afternoon.

An experimental version of the DA descent procedure and related phraseology were developed in concert with the FAA and participating airlines. The test procedure and phraseology were published by Jeppesen and distributed to the flight crews of the participating airlines. This approach allowed the test to be conducted during any traffic period and involve any flight of a participating airline. The DA procedures and phraseology were observed from both the cockpit and sector position. Participating controllers, and the majority of participating pilots, were either debriefed by an observer or completed questionnaires.

A field-test version of CTAS, including both the DA and Traffic Management Advisor (TMA) tools, was temporarily installed at the Denver Center and activated during discrete test periods. A prototype version of TMA normally supports the Denver Center Traffic Management Unit (TMU) with real-time analysis of arrival traffic conditions. For the test, TMA was operated by a CTAS engineer to provide DA with conflict-free meter-fix scheduled times of arrival (STAs) based on traffic demand and airspace capacity. Although TMA was operated in a shadow-mode (i.e., controllers were not working to meet TMA STAs), this approach provided an effective means to generate reasonable STA targets for DA. A cadre of three full-performance-level controllers (test controllers) interacted with DA and coordinated clearances with the controllers working at the appropriate sectors. To be as conservative as possible, DA-based clearances were issued without corrective updates to lengthen the time duration of the trajectory predictions and magnify errors. A DA test engineer monitored the use of DA advisories to facilitate the collection of trajectory prediction data. DA trajectory predictions and radar data were recorded for later comparison to determine prediction accuracy.

Test Set-up

Airspace

Figure 1 illustrates the field test airspace and depicts the general boundaries for sectors 13 and 14, the primary test sectors that issued DA-based clearances. Sector 14 is responsible for high-altitude traffic, at or above flight level (FL) 270, and sector 13 is responsible for low-altitude traffic, below FL270. Typically, sector 14 performs the initial sequencing of high-altitude arrivals, initiates descents to FL270, and then hands-off to sector 13. Sector 13 merges the high and low altitude arrivals for hand-off to the TRACON at the TOMSN and RAMMS meter fixes. The meter-fix crossing restrictions required jets to cross RAMMS at or below 250 knots indicated airspeed (KIAS) and at 17,000 feet, and TOMSN at or below 250 KIAS and at FL190. The crossing restriction for turboprops at both meter fixes was 16,000 feet with no restriction on speed.

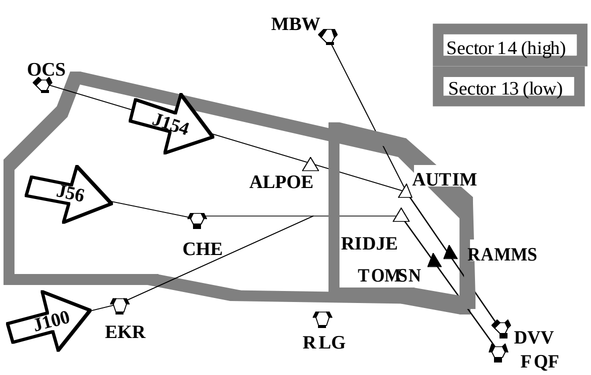

Figure 1. Field-test airspace.

Participating jet flights typically arrived on one of three routes: J154 from the northwest (Seattle and Portland) via ALPOE and the RAMMS1 standard terminal arrival route (STAR); J56 from the west (Salt Lake City and Boise) via Hayden (CHE) and the TOMSN1 STAR; and J100 from the southwest (Northern California) via Meeker (EKR) and the TOMSN1 STAR. The majority of participating turboprop flights arrived from satellite airports in Montana and Wyoming via Medicine Bow (MBW) and the RAMMS1 STAR.

CTAS System

The system set-up is illustrated in figure 2. The CTAS system included a DA station, located next to the participating sectors, and a TMA station, located adjacent to the TMU (approximately 75 feet from the participating sector positions). The DA station included an alphanumeric auxiliary display/interface (ADI) for the test controllers and a full DA color graphical user interface for the test engineer. The ADI was designed to emulate a simple meter-list display concept that may be possible to implement on the current Plan View Display hardware. The full DA interface was used for data collection and conflict prediction.[7] The TMA station included the normal complement of TMA displays for displaying arrival traffic demand and delay in plan view, timeline, and load graph formats.[8] For this test, the TMA station also included a display of DA data for monitoring the test activities, as well as a data link communications terminal for accessing the UAL dispatch database and facilitating two-way data link communications with UAL flight crews via the ARINC [Aeronautical Radio, Inc.] Communications Addressing and Reporting System (ACARS).

The CTAS test system was configured on a distributed network of Sun Microsystems workstations including five 19" color monitors, nine Sparc 10 processors, and one Britelite portable computer. This configuration represents the baseline system required for TMA with the addition of two processors, two displays, and one portable computer to support DA functions and data collection.

CTAS received real-time updates of radar track and flight plan data for arrivals from the Center's Host computer via a one-way (Host-to-CTAS) interface. CTAS also received predictions of the winds and temperatures aloft based on the Rapid Update Cycle (RUC) 3-hour forecast.[9] The data link communications terminal was used to coordinate special delay/expedite cases as well as two-way data exchange with participating flight crews. The data exchange included the downlink of aircraft weight, for input to CTAS, and aircraft/atmospheric state (Mach/IAS, temperature, and wind) for cross-checking Host track and RUC atmospheric data. For several cases, winds from the CTAS descent profile were uplinked to FMS-equipped aircraft for use in the airborne descent calculations.

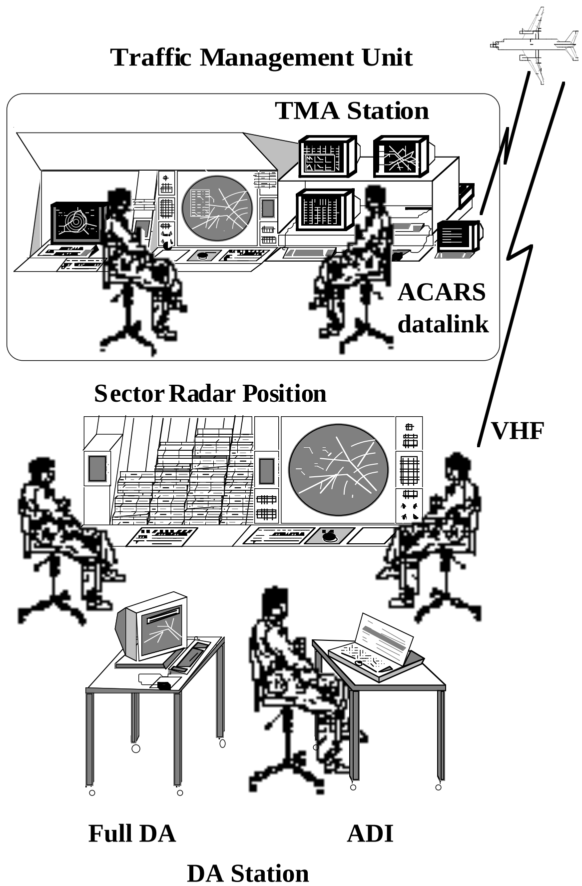

Figure 2. DA test setup.

Descent Advisor

Trajectory Synthesis

The cornerstone of DA is a trajectory synthesis algorithm which generates FMS-like 4D trajectory predictions.[10] Trajectory prediction accuracy is achieved through the use of detailed models of aircraft performance, pilot procedures, operator preferences, and atmospheric characteristics (winds and temperatures aloft). DA uses the trajectory prediction process to generate ATC clearance advisories to meet traffic management constraints such as a TMA-generated meter-fix STA. The advisories are generated by iteration on clearance "degrees-of-freedom" (e.g., speed profile, altitude, and routing) until the predicted trajectory meets the traffic management and airspace constraints. These trajectory solutions are then used to predict separation between flights and to support DA conflict detection and resolution functions.

The trajectory solutions are continually updated to reflect changes in aircraft state (position, altitude, and velocity) and controller intent. Nominally, the predicted path is based on the flight plan route. DA monitors the aircraft to determine if it is tracking the flight plan route. If not, DA generates a path to re-join the flight plan route or join another route designated by the controller. The controller may also constrain the trajectory solutions in terms of cruise altitude, cruise speed, descent speed profile (Mach/IAS), and top-of-descent location (TOD). These constraints enable DA to complement individual controller technique and to adapt to pilot-imposed constraints such as speed changes for turbulence penetration, or path changes for weather avoidance. In addition, the controller may also direct DA to generate provisional trajectory solutions to help the controller visualize the effect of a clearance before it is issued.

Vertical profiles are generated within ATC constraints to be fuel-conservative (i.e., minimum flight at lower altitude), and to be as close as possible to the operator's (pilot or airline operational control) preference. Preferences may be defined in a database or input in real-time. Currently, a database is used to define default descent speed preferences as a function of aircraft type and operator. The descent speed and other preferences (e.g., route, altitude, cruise speed, or an entire 4D trajectory) may be defined by the operator for individual flights and input to DA manually or via datalink.[11,12]

DA Advisories

The trajectory solutions are translated into ATC clearance advisories which include cruise speed, TOD, descent speed profile (Mach/IAS), and vectors. The vectoring advisories include direct-headings and pathstretch. Direct-headings provide the magnetic heading to the next fix, corrected for wind drift, for aircraft that are not area-navigation equipped. The pathstretch advisory is based on projecting the aircraft's current velocity vector forward until a turn back to the next planned fix would result in meeting the STA. The pathstretch advisory is displayed in terms of a distance (or time) to go until the turn back. DA monitors each aircraft's progress to provide feedback on the aircraft's conformance to the cleared route, vertical profile (speed and altitude), and traffic management constraints (e.g., STA).

In addition to the clearance advisory functions, DA contains spacing and conflict detection/resolution functions. The spacing function predicts the spacing between two or more aircraft when the first aircraft passes abeam a selected reference fix. The predicted spacing is then reported to the controller in terms of either the relative separation, or equivalent miles-in-trail distance, depending on controller preference. The conflict functions probe the predicted trajectories to determine if the relative separation between two aircraft will fall below a minimum (specified by the controller). This analysis is automatically updated to include the latest DA trajectory predictions. Predicted conflicts are then displayed in terms of the aircraft involved, the time (min:sec) until first loss of separation, and the predicted position of each aircraft at the first loss of separation. If a conflict is predicted, controllers may use DA to evaluate their own resolution strategies via manual inputs. Automated functions for resolving conflicts with arrivals have been developed and evaluated in earlier versions of DA[7] but were not included in the system for this test. The conflict probe and spacing tools were available at the engineering station for this test for use in setting up test conditions for conflict-free descents.

DA Auxiliary Display and Interface

The ADI included a keyboard and mouse for inputs and an alphanumeric meter-list display. Controller inputs to DA were supported via keyboard function keys and dwell options. To invoke a DA function (e.g., pathstretch mode) for a particular flight, the controller would use the mouse to dwell the cursor on the aircraft identifier within the meter list and depress the appropriate function key. Inputs were entered the same way with the addition of an alphanumeric string (e.g., descent speed) followed by a carriage return.

The alphanumeric meter list is illustrated in figure 3. The list displays the current Greenwich mean time (GMT) and the sequence of arrivals for each STAR. Aircraft are displayed in order of meter-fix arrival, from the bottom to top. The sequence list contains eleven fields for each flight. The first field displays the aircraft identifier preceded by a "+" symbol if the aircraft is a Heavy type (e.g., DC10), and a "#" symbol if the flight's STA has been frozen by TMA. The second and third fields indicate the STA (hrmin:sec GMT) and the delay remaining to be absorbed (min:sec). Field four presents the current speed in Mach number and KIAS for jets, or KIAS for propeller aircraft. Field five displays the cruise speed advisory status which indicates whether the controller has suppressed cruise speed advisories ("S"), issued the advisory as a clearance ("C"), or input their own cruise speed choice ("I"). The cruise speed advisory, or controller's choice, is displayed in field six in Mach number or KIAS depending on aircraft type, altitude, and speed. Field seven indicates the distance to TOD (n.mi.) from the reference fix displayed in field eight. The reference fix is automatically chosen by DA based on the flight plan route and may be modified by the controller. When an aircraft is within a parameter distance from the TOD (e.g., 5 n.mi.), the TOD advisory switches to a countdown of distance (n.mi.) from the aircraft's present position (PP). Field nine displays the descent speed advisory status which indicates whether the controller has suppressed descent speed advisories ("S"), issued the advisory as a clearance ("D"), or input their own descent speed profile choice ("I"). The descent speed advisory, or controller's choice, is displayed in field ten as a Mach/IAS profile for jets, or an IAS profile for propeller aircraft. Field eleven displays navigational advisory data. If the aircraft is tracking its flight plan route, an "R" is displayed. Otherwise, DA displays the magnetic heading to intercept the next fix along with the fix identifier. For pathstretch cases, this field displays the distance-to-go (n.mi.) until the turn-back point followed by the magnetic heading for that turn. The final field indicates the predicted crossing conditions (flight level and speed) at the meter fix. If the controller locks the trajectory for conformance tracking, this column indicates the error in the vertical profile. This is analogous to the feedback a pilot receives from an FMS regarding the aircraft's state relative to the FMS vertical navigation (VNAV) path.

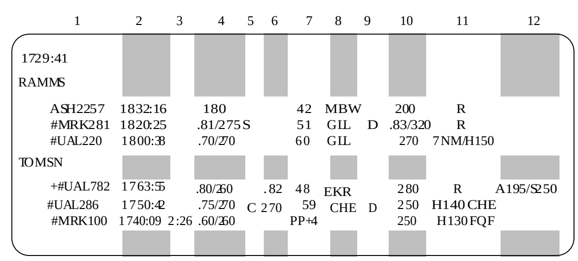

Figure 3. Alphanumeric meter-list display.

Descent Procedures

The DA descent procedure and related phraseology were based on the procedures and lessons learned from previous field testing.[5,6] The most significant refinement involved the issuance of TOD clearances to FMS-equipped types. The previous test allowed FMS-equipped types to initiate descent at the pilot's discretion based on the use of VNAV. Although DA had been able to consistently predict the VNAV TOD within a few miles, the pilot discretionary nature of that procedure did not protect the controller against the possibility of an unpredictable TOD resulting from a VNAV input error. The new procedure still allowed the pilot to descend along the VNAV path as long as the descent was initiated within 5 n.mi. of the TOD clearance.

Turboprop descents, evaluated for the first time in a DA test, were based on an inertial flight path ratio of 4:1 (four miles for every thousand ft of altitude). This procedure was developed with ASH and evaluated over two days of piloted-cab (Phase III) simulation prior to the test. Turboprop operators favor the power-on descents for decreasing block time and increasing passenger comfort. The 4:1 ratio results in a predictable altitude profile over the range of possible speeds and atmospheric conditions.

In all cases, the descent procedure calls for the pilot to monitor the descent and make corrections, if necessary, to achieve the meter-fix crossing restrictions while maintaining the descent speed profile. This is relatively simple for the pilot of an FMS-equipped aircraft who uses VNAV to monitor the descent progress. The procedure is also relatively simple for turboprop types because of the predictable altitude profile and the relative ease with which pilots can control the altitude profile, with power, over the entire range of possible descent speeds. For conventional-equipped jets, the procedure is more challenging because of the difficulty associated with monitoring descent progress along profiles that vary from flight to flight as a function of descent speed, atmosphere, and weight.

Airline operators have indicated the strong desire for fuel-conservative idle-thrust descents. Although the CTAS models (for four types) had been validated in simulation and worked well in previous field testing[5,6] (i.e., achieving fuel conservative descents), flight crews of conventional-equipped jets indicated that they were uncomfortable in descending without a small buffer to allow for errors. To address this issue, the performance models for conventional-equipped jet types were modified by the introduction of a drag scaling factor. These drag model data were modified by 10% in descent to force a slightly earlier TOD. Compared to a fixed-flight-path-ratio approach, the drag factor represents a compromise which provides a buffer for pilots while still providing for TOD optimization (as a function of descent speed and atmospheric conditions) for the airlines.

Phraseology

Due to the random mix of participating and non-participating flights during test periods, all participating flights received notification to expect a DA clearance 10–15 minutes prior to TOD. The meter-fix crossing conditions for the STARs were published on the Jeppesen chart. The DA descent clearance was generally issued 2–4 minutes prior to TOD. If the aircraft was cruising in the high altitude airspace (sector 14), the DA-based clearance was issued as:

"Company123, maintain FL___ until ___ miles E/W/N/S of (*fix*), descend and maintain FL270, maintain ___Mach/___ knots in the descent."

After hand off to the low altitude sector (13), the descent was continued as:

"Company123, continue descent at ____knots, cross TOMSN at and maintain FL190 and 250 knots (or RAMMS at 17,000 ft and 250 knots)."

For turboprops cruising in the low altitude airspace, a single descent clearance was issued as:

"Company123, maintain FL___until ____miles E/W/N/S of (*fix*), cross TOMSN (or RAMMS) at and maintain 16,000 ft, maintain ___ knots in descent."

Training

Logistical limitations severely limited the training options for participating controllers and flight crews. Two test controllers were selected by the FAA and received training during the week prior to the test. The training included shadow operation of the DA system and several dress rehearsal periods at the test sectors. A third controller joined the test team for the last eight days of testing and received one day of training. Participating controllers at the test sectors were not selected ahead of time, but were asked to participate in the test if they were on duty during a test period. Sector staffing practices, and the randomness of traffic conditions, excluded the option of identifying participating controllers and flight crews in advance. Instead, a training approach was required to prepare any sector 13/14 controller and any pilot arriving from the northwest. All the sector 13/14 controllers received a one-hour briefing.

Training materials were distributed to all potential participating flight crews. Each pilot received a two page Jeppesen chart which included a one page description of the descent procedure and phraseology, and a one page description of the test. Jet pilots also received a one page update to their flight manual bulletins which complemented the Jeppesen chart in areas that were unique to their equipment, particularly VNAV operations.

Test Conditions

A target set of test cases was identified for evaluating procedures and trajectory prediction accuracy across a representative set of delay situations. The delay situations included delay vectoring but not holding (a special case of delay vectoring). The target cases were based on combinations of clearance advisory type and aircraft type group. The clearance advisory types evaluated in this test included descents (TOD/descent-speed-profile), cruise speed changes, cruise altitude changes, and pathstretch vectors.

The nine participating aircraft types were categorized in three groups (table 1) including FMS-equipped jets, conventional-equipped jets, and turboprops. Participating UAL flights included six aircraft types: Boeing 727 (B727), Boeing 737-200 (B737), McDonnell Douglas DC-10-10 (DC10), Boeing 737-300/500 (B73S/V), Boeing 757-200 (B757), and Airbus A320 (EA32). MRK flights included the Boeing 737-300/400 (B73S/F). Participating ASH flights included three turboprop types: Embraer 120 (E120), Beechcraft 1900 (BE02), and De Havilland DHC-8 (DH8). The B727, B737, DC10, and turboprops are conventional-equipped types that navigate via jet routes defined by VHF Omnidirectional Range (VOR) and Distance Measuring Equipment (DME) navigational aids. Many of the DC10 types were also area-navigation (RNAV) equipped. The B73S, B757, and EA32 are FMS-equipped types with both lateral navigation (LNAV) and VNAV capability. Many of the B73S aircraft also had Required Time of Arrival (RTA) capability. Although integrated RTA/TMA/DA operations have been studied in simulation,[11,12,13] the use of RTA was beyond the scope of this test. Logistical limitations of the test, coupled with the low frequency of EA32 and DH8 flights during the test periods resulted in only a few runs being obtained for these types. For this reason, these two types were removed from the descent data analysis presented in the next section.

Table 1. Participating aircraft types

Jets		Turboprop
FMS	Conventional	
B757	B727	E120
B73S	B737	BE02
EA32	DC10	DH8

The analysis presented in this paper will focus on the descent cases. These descents are divided into three descent speed profile types (table 2). A goal in conducting the test was to obtain at least two descent runs for each combination of aircraft type and descent speed profile type. The intent was to gather data, albeit a limited set, to uncover human factors and modeling issues associated with various types or speed profiles.

Table 2. Descent speed profile types

Aircraft type	Fast	Nominal	Slow
Jets	Mach Accel.	Mach/IAS	IAS Decel.
Turboprops	IAS Accel.	N/A	IAS Decel.

The Fast profile for jets involves a descent acceleration from the cruise Mach to a higher descent Mach, followed by a constant Mach/IAS profile, and a level-off deceleration to 250 KIAS at the meter fix. The choice of descent Mach and IAS (typically 320–340 KIAS) depends on aircraft type and traffic condition. The Fast profile for turboprops involves an acceleration from cruise IAS to a higher descent IAS (typically 220 KIAS). Typical pilot procedures involve an acceleration in descent to a maximum speed (defined by an IAS offset just below the airspeed barber-pole limit) with a transition to the clearance speed when it is achieved at lower altitude. This barber-pole-offset procedure, which is approximated well by a constant Mach descent, is a popular method among turboprop operators for reducing time of flight. The nominal profile type, applied to jets only, involves a descent at the cruise Mach, followed by a constant IAS segment (typically 280–300 KIAS), and a level-off deceleration to 250 KIAS. The slow profile type involves a deceleration, at the TOD, from the cruise IAS to the descent IAS (typically 250–270 KIAS for jets and 160 KIAS for turboprops) followed by a descent at constant IAS to the meter fix.

The majority of jets entered the test at a cruise altitudes ranging from FL290 to FL370, and up to FL410 for the B757. The cruise speeds varied between 0.73–0.76 for the B737, 0.75–0.78 for the B73S, 0.78–0.82 for the B727 and B757, and 0.80–0.85 for the DC10. The turboprop types entered the test between FL210–230, and up to FL250 for the E120. The cruise speeds varied between 165–195 KIAS for the BE02 and 170–200 KIAS for the E120.

Weather conditions varied throughout the test and included several periods of thunderstorm activity, occasional pockets of turbulence, and several frontal passages. The winds aloft were generally out of the west and northwest with velocities at the upper flight levels ranging between 40–120 knots.

Results and Discussion

A total of 185 participating flights received DA-based descent clearances. The results presented here are based on a subset of 89 flights: 38 conventional-equipped jets, 36 FMS-equipped jets and 15 turboprops. Five of the 96 excluded flights were EA32 or DH8 types. Thirty-six of the excluded flights, which will be analyzed in future work, involved conventional-equipped jets on heading vectors. The remaining 55 flights were excluded because they were influenced by factors beyond the scope of this test. The exclusion criteria included: transients in Host groundspeed tracking[‡] due to an immediately preceding test clearance; clearance communication errors (controller issuance or flight crew copy); errors in flight crew's operation of their FMS; interruptions to the clearance due to weather (e.g., storm cell avoidance, turbulence) or ATC (e.g., early TRACON vectors prior to the meter fix).

The descent data are based on a single advisory, issued approximately 30 n.mi. prior to TOD, and a prediction time horizon on the order of 10 min for turboprops and 15 min for jets. The data for conventional-equipped jets and turboprops are based on flights along published routes. The data for FMS-equipped jets are based on flights along both published routes and direct routes to the meter fix. The following sections present descent trajectory prediction accuracy results in terms of errors in the horizontal profile, altitude profile, and arrival time.

Horizontal Profile

Observations indicated that conventional-equipped jets experienced cross-track errors up to 4.6 n.mi. due to errors in VOR course tracking and turn overshoot. Errors associated with turboprop types were similar and slightly smaller in magnitude. The errors associated with FMS-equipped jets were significantly smaller (as would be expected) and typically less than 0.25 n.mi. (generally within the noise of the radar track data). Table 3 summarizes the cross-track error characteristics for each type. A cross-track error was calculated for each radar track (approximately every 12 seconds) along a flight's predicted path. A positive error was defined as left of course. Each flight was then analyzed to determine its average (mean) cross-track error and variation (standard deviation) along its path.

Table 3 presents the mean and standard deviation of the flight cross-track errors (average and variation) across all flights. The absolute value of each flight's average cross-track error was used to prevent errors of opposite sign from canceling.

Table 3. Cross-track error

Aircraft type	Flight average (mean ± SD, n.mi.)	Flight variation (mean ± SD, n.mi.)
FMS	0.12 ± 0.16	0.18 ± 0.10
Conventional	0.78 ± 0.55	0.76 ± 0.30
Turboprop	0.80 ± 0.40	0.62 ± 0.27

For the FMS-equipped jets, the small values for (and small standard deviations about) average mean cross-track and average standard deviation indicate that modeling cross-track errors for these type of equipped aircraft as a scatter of values about a small bias error is appropriate. The relatively large values for conventional-equipped jets and turboprops indicate that the same can not be said for these types. As expected, the cross-track error for these types was observed to vary based on course geometry. The error tended to grow with distance, as aircraft tracked a VOR radial outbound, and to vary across turns due to overshoot.

The most significant effect of cross-track error was to increase (or decrease) the actual distance flown for a given routing. If an aircraft overshot a turn, or entered a turn with cross-track error, the actual distance flown would be greater (or less) than the distance predicted

[‡] A separate effort is underway to study tracking errors and to reduce their effect on trajectory predictions.

along the planned path. Table 4 presents the error in distance flown (actual - predicted) for all flights with a turn of 20 deg or greater. As expected, the greater navigational accuracy of the FMS-equipped jets resulted in significantly smaller errors in the distance prediction than for the conventional-equipped jets and turboprops. Although the distance flown error (mean and variation) for conventional-equipped jets and turboprops was expected to increase with turn size, the mean error results did not. The mean error results were affected by other factors that influence pilot navigation technique. For example, the negative mean error for turboprop types for 20–25 deg turns was due to pilots cutting the corner at the AUTIM fix along the RAMMS1 arrival via MBW.

Table 4. Distance flown error (mean ± SD), n.mi.

Aircraft type	Largest turn in flight, deg		
	20–25	30–35	>40
FMS	NA (0)	-0.01 ± 0.07 (7)	0.13 ± 0.24 (8)
Conventional	-0.41 (1)	0.50 ± 0.32 (10)	0.36 ± 1.24 (26)
Turboprop	-0.27 ± 0.33 (10)	0.47 ± 0.46 (5)	NA (0)

() sample size

Altitude Profile

Figures 4–6 illustrate the altitude profile errors. These figures present the altitude error at common trajectory events defined along the predicted path. Descent events are defined relative to the TOD and bottom-of-descent (BOD) of each flight to facilitate analysis across individual flights with different altitude profiles.

The profile for FMS-equipped jets (fig. 4) is characterized by larger errors (below path) near the TOD compared to smaller errors towards the BOD. The variation in error decreases towards the BOD as the VNAV and DA profiles merge at the crossing restriction. The error (above path) at the BOD event is caused by the pilot’s transition to level flight which is not currently modeled in the DA trajectory prediction.

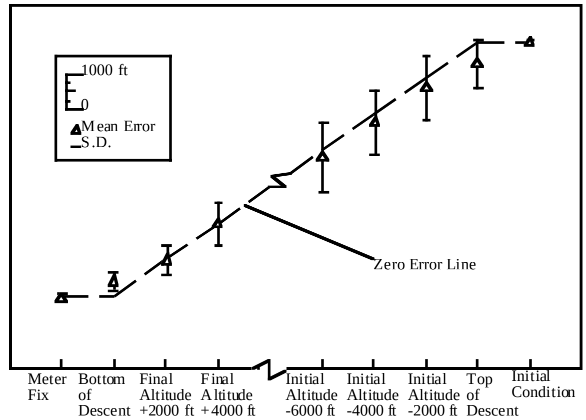

Figure 4. Altitude error profile (FMS).

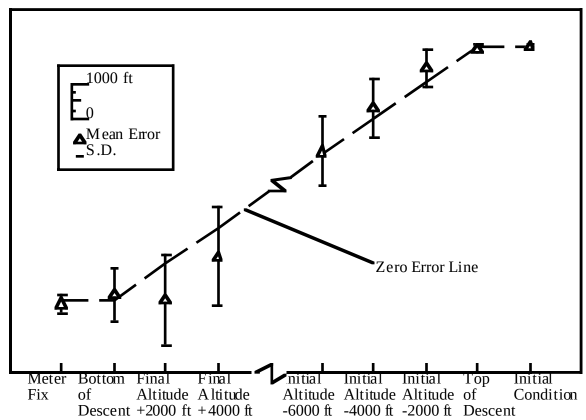

Figure 5. Altitude error profile (Conventional).

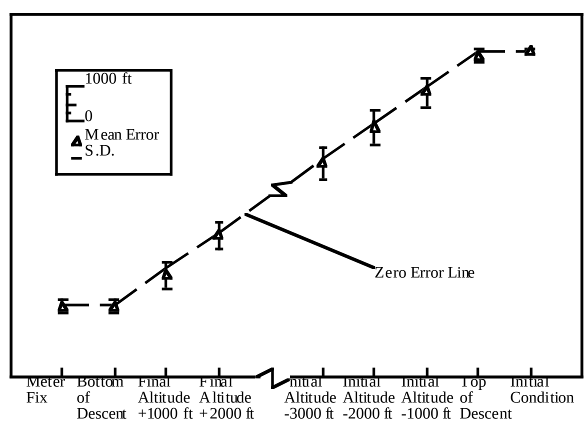

Figure 6. Altitude error profile (Turboprop).

The profile for conventional-equipped jets (fig. 5) is characterized by smaller errors (above path) near the TOD and larger errors (below path) towards the BOD. The mean error initially increases (above path), just after the TOD event, as pilots transition to the descent. As aircraft continue the descent, the mean error tends to fall below the predicted path. Both the mean error and variation tend to grow towards the BOD until the flights begin to level-off near the meter-fix crossing altitude. The steeper descent profiles are attributed to a combination of factors including: the drag-factor bias in the CTAS performance model; additional distance flown due to turn overshoot; and a bias error in the predicted wind data.

The profile for the turboprop types (fig. 6) is characterized by a relatively small error (mean and variation) over the entire profile. These small errors reflect two factors: the robustness of an inertial altitude profile to errors in performance modeling and wind prediction; and the relative ease with which turboprop pilots were able to track an inertial altitude profile.

Table 5 presents the along-track error of the actual TOD and BOD events. The BOD error was computed at the position corresponding to 1000 ft above the BOD altitude to remove the influence of the pilot level-off technique. These data clearly show the differences in TOD and BOD prediction errors between the three groups of aircraft type. BOD errors are smaller for FMS-equipped jets, compared to conventional-equipped jets, whereas the TOD errors are larger. These differences are directly related to the level of cockpit automation and descent procedure. For FMS-equipped jets, the VNAV capability provides pilot guidance to the BOD while the VNAV TOD may differ slightly from the DA TOD. For conventional-equipped jets, the lack of altitude profile guidance leads to a greater mean and variation in BOD error while the procedure calls for the pilot to initiate descent at the DA TOD. For turboprop types, the BOD and TOD errors are both relatively small due to the combination of TOD procedure (same as for conventional-equipped jets) and the relative ease with which pilots track the altitude profile.

Table 5. TOD and BOD errors

Aircraft type	TOD error (mean ± SD), n.mi.	BOD error (mean ± SD), n.mi.
All	-1.28 ± 2.09	-1.60 ± 3.53
All Jets	-1.37 ± 2.23	-1.76 ± 3.80
FMS	-2.41 ± 2.48	0.47 ± 1.33
Conventional	-0.39 ± 1.39	-3.87 ± 4.17
Turboprop	-0.80 ± 1.18	-0.84 ± 1.54

(+/- indicates late/early)

Time Profile

The meter-fix arrival time accuracy is summarized in table 6. The first column of data presents the arrival time error as recorded during data collection. Histograms illustrating the scatter for these data are presented in figures 7–11. Over all flights, the error (mean + SD) is within 15 sec. Only 27% of the flights in table 6 had an arrival time error greater than 15 sec. A greater level of accuracy may be achieved, if desired, by the addition of a mid-descent advisory update or a reduction in the primary sources of trajectory prediction error[14] such as wind prediction and aircraft tracking. These data are consistent with the results from earlier tests[4,5] in that the errors for conventional-equipped jets are characterized by a significantly later mean (approximately 8 sec), and greater variation (4 sec), than for FMS-equipped jets. The use of LNAV and VNAV increases the predictability of FMS-equipped types by reducing the variation in the horizontal and vertical profiles. For turboprop types, the mean error was relatively small while the variation was on par with the conventional-equipped jets.

Table 6. Arrival time errors

Aircraft type	Arrival time error (mean ± SD), sec	Adjusted arrival time error (mean ± SD), sec
All	0.9 ± 14.2	-0.3 ± 12.3
All Jets	1.4 ± 13.9	-0.1 ± 12.5
FMS	-2.9 ± 11.2	-3.1 ± 11.0
Conventional	5.5 ± 15.2	2.7 ± 13.3
Turboprop	-1.6 ± 15.4	-1.3 ± 11.8

(+/- indicates late/early)

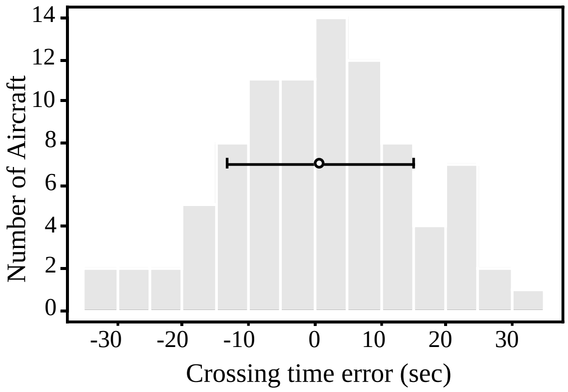

Figure 7. Arrival time error (All).

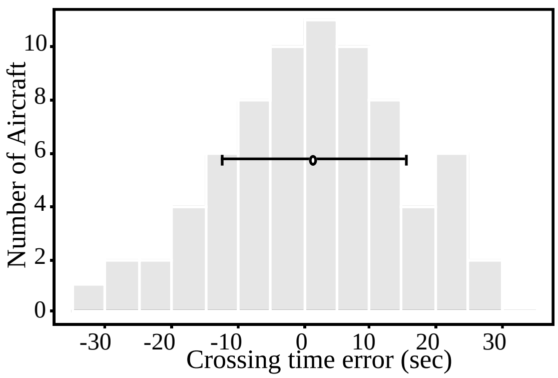

Figure 8. Arrival time error (All Jets).

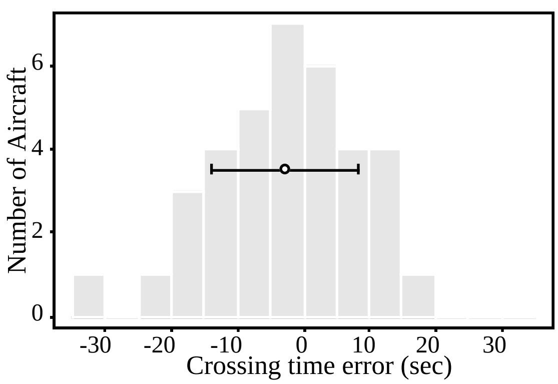

Figure 9. Arrival time error (FMS).

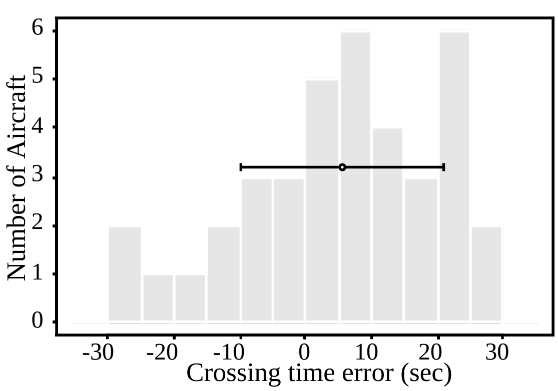

Figure 10. Arrival time error (Conventional).

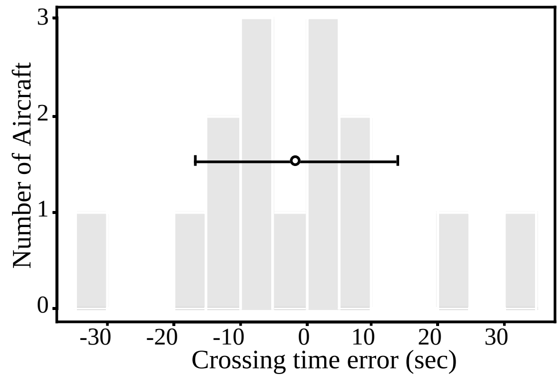

Figure 11. Arrival time error (Turboprop).

Much of the mean error and some of the variation for conventional-equipped jets resulted from distance flown errors. The second column of data in table 6 was adjusted to remove the influence of distance flown errors (table 4). The adjustments were made for each flight by subtracting an equivalent time error, calculated as the ratio of the distance error and average flight groundspeed. The adjustments result in a reduction in the time error for conventional-equipped jets compared to a negligible change in the time error for FMS-equipped jets**.** The remaining differences in arrival time error between conventional- and FMS-equipped jets are primarily due to the differences in the altitude error profiles for these two types (fig. 4,5). For the conventional-equipped jets, the altitude error (below path) at the lower altitudes results in a lower-than-predicted true airspeed (TAS) during a constant IAS descent. For the FMS-equipped jets, the altitude error (below path) at the higher altitudes results in a slightly higher-than-predicted TAS during a constant Mach descent within the troposphere.

It was expected that the arrival time error adjustments would have the same affect on the turboprop data as it did on the conventional-equipped jet data. Although the variation in time error for turboprops was reduced by 3.6 sec, the mean error was relatively unchanged. This unexpected result was attributed to the combination of all turboprop flights which coincidentally resulted in a negligible mean distance-flown error. The 10 flights that averaged 0.27 n.mi. shorter distance than predicted (20–25 deg turns) compensated for the 5 flights that averaged 0.47 n.mi. longer distance than predicted (30–35 deg turns).

Additional insight is gained by separating the data by calendar period. Table 7 presents the arrival time error data, for the jet types, separated by calendar period (period 1: September 13-31, 1995; period 2: October 31 through November 8, 1995). Results from the previous field test (September 27-29, 1994)[5] are also presented. Comparisons between the two 1995 test periods reveal a noticeable shift in mean arrival time prediction error from 5.2 sec late for the first period to 9.6 sec early for the second. First period results are similar to the results from the 1994 test. In particular, the FMS-equipped jets have a significantly smaller mean error and smaller variation. However, the results from the second period differ greatly. Although the relatively small sample of conventional-equipped jet cases may explain some of the differences, the results for the FMS-equipped cases show a distinct shift in mean error with a slight increase in variation. Since the test system and procedures remained constant between the two test periods, the most likely source for this shift in results is atmospheric prediction error.

Table 7. Arrival time error (mean ± SD), sec

Aircraft type	Test period		
	1995 per. 1	1995 per. 2	1994
All Jets	5.2 ± 12.8	-9.6 ± 11.2	2.4 ± 13.1
	(55)	(19)	(24)
FMS	0.4 ± 9.3	-8.7 ± 12.1	-2.5 ± 10.0
	(23)	(13)	(12)
Conventional	8.7 ± 13.9	-11.6 ± 9.6	7.4 ± 14.3
	(32)	(6)	(12)

() sample size

The shift in mean arrival time error indicates a sensitivity of the trajectory prediction accuracy to changes in test conditions over time. The accuracy is expected to vary with atmospheric conditions, traffic composition, and routing. These field test results should be supplemented by a comprehensive sensitivity study to determine the accuracy under the expected range of operational conditions.

Concluding Remarks

Field testing of the Descent Advisor has generated a valuable set of data for validating DA trajectory prediction accuracy. Results indicate that a meter-fix arrival time accuracy of 15 sec is achievable for a single descent advisory in an operational environment. This error may be reduced, if necessary, through the use of additional corrective advisories or system improvements which reduce errors in wind prediction and aircraft tracking.

The trajectory prediction accuracy was found to vary as a function of aircraft type with distinct advantages for FMS-equipped types. The cross-track error for FMS-equipped jets was an order of magnitude smaller than for conventional-equipped types (jets and turboprops) and generally within 0.25 n.mi.. The altitude errors tended to be smaller for FMS-equipped jets, compared to conventional-equipped jets, with progressively less error towards the bottom of descent. In addition, the arrival time errors for FMS-equipped jets were slightly smaller in mean, and 27% smaller in variation, than for conventional-equipped jets. Although the variation in arrival time error for turboprop types was similar to that for conventional-equipped jets, the altitude errors for turboprop types were significantly smaller than the errors for the FMS-equipped jets. These results may be used to develop conflict-probe error models based on aircraft type and trajectory segment.

Additional analysis of the field test data will investigate the remaining trajectory cases, the sources and magnitudes of the trajectory prediction errors, and the human factors issues (both pilot and controller) associated with the DA descents. Follow on studies are recommended to extend the field test results over the expected range of operational conditions and to validate that the CTAS modeling approach may be extended to all types. Future field testing will focus on controller evaluation of conflict detection and resolution tools.

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