DEVELOPMENT AND TESTING OF AUTOMATION FOR EFFICIENT ARRIVALS IN CONSTRAINED AIRSPACE

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Abstract

The paper presents an overview of development and testing of ground-based automation for accommodating fuel-efficient arrivals in heavy traffic. The Efficient Descent Advisor (EDA) is an emerging decision-support tool for air-traffic controllers managing arrival airspace in en-route facilities. It generates trajectory-based clearance advisories that allow a continuous, descent at low engine power while avoiding conflicts and maximizing arrival throughput. Findings from several human-in-the-loop simulations and a field test are presented and discussed, which pertain to controller use and acceptance of EDA as a near-term capability for the Next-Generation Air Transportation System (NextGen).

1 Introduction

Improving the efficiency of flight operations is a defining objective of the Next-Generation Air Transportation System (NextGen). To reduce fuel consumption, emissions, and noise during arrival operations, a continuous descent at low engine power is desired – preferably at idle throttle setting from cruise altitude to the final approach fix – that can be planned and executed through the airplane's Flight Management System (FMS). Such an arrival profile is referred to as an Optimized Profile Descent (OPD).

The challenge is to perform OPD operations during busy traffic conditions where airspace and runway capacity are limited. Indeed, NextGen must respond to a traffic demand that is projected to double by the year 2025 [1]. Today, OPDs are typically prevented or disrupted during busy traffic conditions by controller actions taken to separate, schedule and sequence aircraft for terminal airspace entry and landing. These frequent, tactical control actions include temporary altitude assignments, speed changes, lateral vectoring, and airborne holding. While such actions serve well to manage throughput and separation, they impede an otherwise continuous, low-power descent to the runway. These tactical control actions not only create inefficient flight profiles, but they also prevent a shared understanding of intended arrival trajectories between controllers and pilots.

Over the past decade, numerous initiatives have been launched in the U.S. and abroad to study the benefits and implementation of OPDs. Although some activities – such as the early continuous-descent-approach trials at London's Heathrow airport [2] – have relied upon conventional aircraft equipage, most have leveraged modern FMS guidance, navigation and control technologies. Examples include flight trials conducted at Lousiville in 2004 and Amsterdam in 2006 [3,4]. In these studies, area navigation (RNAV) routes were combined with vertical profile constraints to create a set fixed, published procedures. Due to the inflexible nature of these procedures, however, they could not be adapted to account for dynamic separation and throughput constraints. As a result, they were mostly restricted to periods of low traffic density, which limited their full benefits potential.

In recent years, OPD initiatives such as those in daily use at Los Angeles have sought to address the high-density traffic problem by coupling RNAV procedures with redesigned airspace. These techniques segregate arrival flows to avoid conflicts with over flights, and they rely on legacy controller decision making to establish inter-arrival spacing at designated control points. While beneficial, the application of these procedural techniques tends to be limited to specific arrival directions, atmospheric conditions, and runway configurations. Furthermore, without predictive automation, controllers must apply conservative spacing buffers at control points, which can limit runway throughput. To mitigate this problem, Ren and Clarke [5] have developed a stochastic technique that calculates the minimum inter-arrival spacing required at a control point along the descent profile to allow OPD operations in heavier traffic. This capability, however, is limited to off-line processing due to its computational complexity and relies on controllers upstream to precisely deliver aircraft to the control point without compromising the OPD. Without additional automation, the ability of controllers to precisely deliver airplanes to control points will vary largely with skill level, resulting in indeterminate benefits.

Other approaches for allowing OPD operations in busy traffic have focused primarily on flight-deck automation. Flight trials at Stockholm demonstrated the ability of FMS-equipped aircraft with Required-Time-of-Arrival (RTA) capabilities to meet assigned landing times while performing OPDs [6]. Tailored Arrivals at San Francisco, Los Angeles and Miami have proven the feasibility of issuing fixed 3D profile clearances over data link for automated guidance and control through the FMS [7]. Without accompanying ground automation to strategically tailor trajectories for separation and throughput, however, the chances of an uninterrupted OPD in busy traffic using airborne capabilities alone are limited.

To better accommodate efficient arrivals during busy traffic, NASA, in collaboration with the FAA and Boeing, is developing the Efficient Descent Advisor (EDA) as a near-term technology for NextGen. EDA provides controllers with strategic maneuver advisories that allow aircraft to fly idle-thrust descents while maximizing throughput and avoiding conflicts, even during periods of peak demand.

The paper first describes the concept and technology behind EDA as near-term controller tool. An overview of recent simulations and field tests is then provided, followed by key results from those activities pertaining to EDA concept validation and prototype design.

2 Automation Overview

2.1 Operational Concept

The concept behind EDA as a near-term (2015 to 2018) capability for NextGen is referred to as Three-Dimensional Path Arrival Management (3D-PAM). Under 3D-PAM, EDA provides controllers in the Air Route Traffic Control Center (ARTCC) with comprehensive clearance advisories that can be issued by voice, which satisfy a time-based metering schedule computed by the currently deployed Traffic Management Advisor (TMA). TMA specifies the time required for each airplane to cross a meter fix located at the TRACON boundary for optimal arrival throughput [8]. To compute solutions, EDA models descent trajectories that can be flown at idle thrust through the FMS, thereby enabling a fuel-efficient OPD. In the process of computing maneuver advisories that meet the TMA schedule, EDA checks for and attempts to avoid conflicts with other traffic along the arrival trajectory to the meter fix.

3D-PAM is a *trajectory-based* concept, since it relies on predictions computed over strategic time horizons of up to 25 minutes. Over these time horizons, EDA solutions affect multiple airspace sectors within the ARTCC. This is markedly different from today's *sector-based* arrival operations where each controller develops a solution that primarily affects only the portion of flight within their own sector boundaries.

By attempting to avoid conflicts in a strategic manner while solving the meet-time problem, EDA decreases the chance that a controller will have to interrupt an OPD trajectory to manage separation downstream. In looking for conflict-free solutions, EDA only considers adjusting the trajectory of the arrival aircraft for which a meet-time solution is being generated. Because of this inherent constraint and the requirement to meet a precise arrival time at the meter fix, EDA cannot always compute a conflict-free solution. In such cases, EDA provides controllers with an advisory that minimizes the number and severity of predicted downstream conflicts.

Its important to note that when using EDA for 3D-PAM, the controller retains full responsibility for separation assurance. Furthermore, EDA is intended to work with, rather than replace, automation for general conflict detection and resolution, such as that described in [9] and [10].

For 3D-PAM operations, the majority of control actions required for an uninterrupted OPD to the runway are assumed to occur in ARTCC airspace with the assistance of EDA. With EDA enabling precise delivery of aircraft to the meter fix, TMA can potentially compute schedules that depend on little or no further delay absorption in the TRACON, thereby allowing aircraft to continue along uninterrupted glide paths to the runway. In 3D-PAM operations, it is assumed that after crossing the meter fix, aircraft can continue to the runway along a pre-defined RNAV path, flown using the FMS with Required Navigation Performance (RNP) criterion for lateral containment. This general concept is illustrated in Fig. 1, showing an airplane that has received an EDA speed and path-stretch clearance to the meter fix.

The initial 3D-PAM concept is focused towards commercial air carrier operations in which airplanes are equipped with a "3D FMS", i.e., one that provides both lateral (LNAV) and vertical (VNAV) guidance and control. Pilots enter EDA clearances into the FMS, which then guides and controls the airplane along its computed arrival path. With the assumption of an idle-thrust descent, EDA speed and path clearances, together with meter-fix crossing restrictions built into the Standard Terminal Arrival Route (STAR), are sufficient for the FMS to compute the location of Top-of-Descent (TOD).

Although 3D-PAM relies on voice-based communications for near term application, the concept and automation can be readily adapted to accommodate data-link communications in the future. With data link, more intricate clearances can be issued, resulting in potentially more efficient arrival solutions in the presence of complex traffic, airspace and weather constraints.

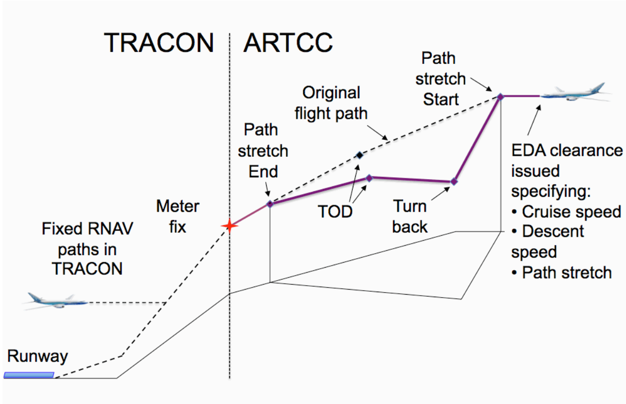


Fig. 1. 3D-PAM Concept

2.2 Functional Description

The primary elements of EDA are shown in Fig. 2. At its core, EDA relies upon a Trajectory Synthesizer (TS) to generate accurate 4D predictions for each aircraft in the airspace. For a more complete description of EDA functions and algorithms, refer to Coppenbarger, et al. [11].

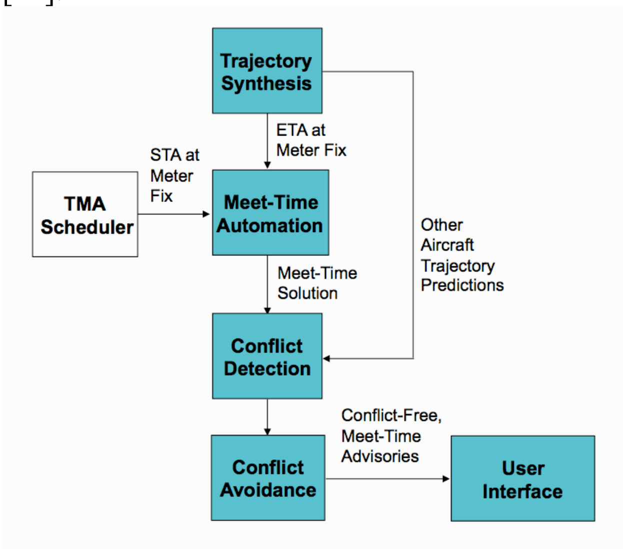


Fig. 2. EDA Functional Elements

Before computing an advisory for an arriving flight, EDA first calls the TS to compute the airplane's Estimated Time of Arrival (ETA) at the meter fix. To compute the ETA, the TS uses the airplane's active flight plan together with stored information specifying its nominal descent speed. If the absolute difference between the airplane's ETA and Scheduled Time of Arrival (STA) computed by TMA differs by more than a set tolerance (currently set to 20 sec) EDA computes a meet-time maneuver advisory. This computation process relies upon repeated calls to the TS while iterating on speed and path degrees of freedom to absorb any required delay. EDA only invokes path stretching for delays that are too large to be absorbed with changes to cruise and descent speed alone [11].

Having solved the meet-time problem, EDA then checks for any traffic or airspace-boundary conflicts along the trajectory to the meter fix. In the event of a conflict, EDA further iterates on speed and path in its attempt to generate a conflict-free solution that satisfies all spatial and temporal constraints. In resolving conflicts, changes to the path geometry alone are considered prior to changes to both speed and path.

Upon finding a successful trajectory solution, EDA displays the required speed and path parameters in the form of a clearance advisory to the controller. Since the user interface represents a key result of recent simulations, it is described in detail in the "results" section of this paper.

3 Development and Testing Approach

EDA research and development has proceeded incrementally through a combination of simulations and field tests. Over the past two years, efforts have focused on developing a prototype as a basis for transferring technology to the FAA in support of 3D-PAM. Recent efforts have relied on a series of high fidelity, human-in-the-loop simulations to iterate on the concept and design of EDA as decision-support tool for the radar (R-side) ARTCC controller. The objective is to produce a working prototype upon which design and performance specifications can be based. By relying on high-fidelity simulations with traffic scenarios and airspace conditions that represent end-state operations, the EDA concept and prototype can be matured to the greatest extent possible prior to pursuing more costly and intrusive field evaluations.

The remainder of this section describes the simulations used to study and develop the EDA prototype. The field test recently completed at the Denver ARTCC to collect data for modeling trajectory-prediction uncertainty for use in future simulations is also described. Key findings from these activities are discussed in Section 4.

3.1 Simulations

Fort Worth ARTCC Simulations

A series of simulation experiments involving Fort Worth ARTCC (ZFW) were completed in 2005 to demonstrate EDA automation and potential benefits. Results from these early 'proof-of-concept' simulations showed the potential of EDA to substantially improve flight efficiency and reduce controller workload. These benefit findings were used to launch the current 3D-PAM development effort.

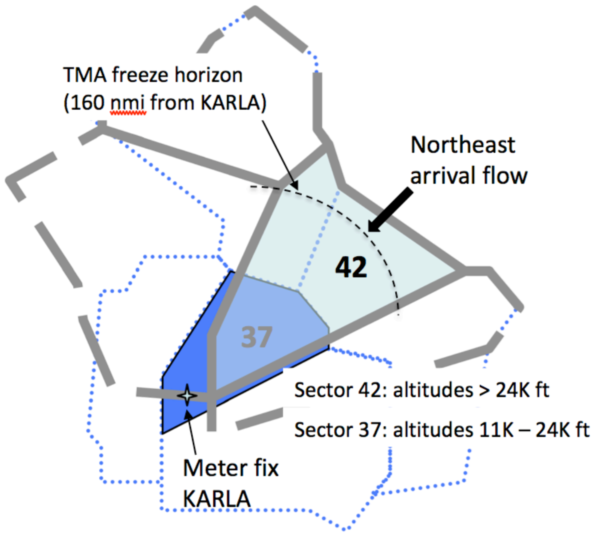


Fig. 3. Airspace Used for ZFW Simulations

The simulations involved the high-altitude and low-altitude arrival sectors in northeast ZFW airspace, illustrated in Fig. 3. Controller participants were presented with traffic scenarios initialized with aircraft track and flight plan data captured during actual ZFW arrival rushes. Scenarios with TMA and EDA were compared against baseline scenarios in which controllers were provided with TMA only. In all scenarios, TMA schedules and metering delays were presented to controllers using both graphical timelines and metering lists. In EDA scenarios, only the controller working the high-altitude airspace (sector 42) was provided with automation for meeting TMA arrival times. EDA provided controllers with metering solutions involving combinations of cruise speed, descent speed and path stretching.

Denver ARTCC Simulations

More recently, in 2009, simulations were conducted with controllers and subject-matter experts from Denver ARTCC (ZDV) to develop EDA for 3D-PAM. The purpose of these activities was to validate the 3D-PAM concept, assess controller workload distribution, and obtain end-user design feedback for improving EDA functions and user interface. Controllers were provided with a high-fidelity display (pictured in Fig. 4), simulating an end-state implementation of EDA on the FAA's Display System Replacement (DSR).

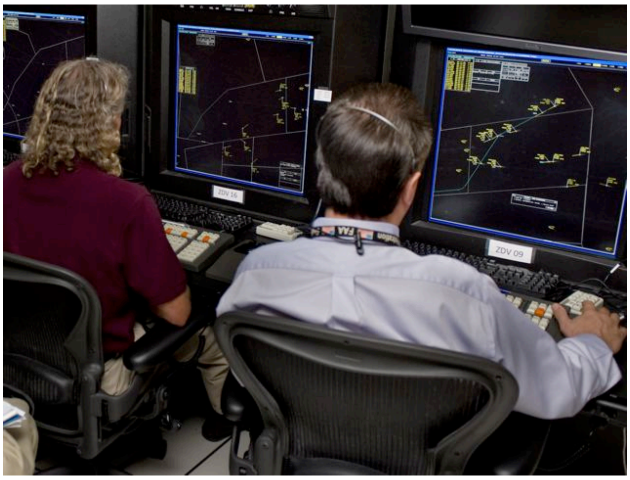


Fig. 4. Controllers Using EDA in ZDV Simulation

Simulations involved three adjacent arrival sectors in the northeast Denver ARTCC, as illustrated in Fig. 5. EDA was available to the controller working the initial high-altitude sector (sector 9), adjacent to the Minneapolis ARTCC. Upon crossing the TMA freeze horizon, Denver arrivals were issued EDA clearances to conform to their TMA-scheduled arrival time at the meter fix SAYGE. Aircraft were required to cross SAYGE at 19,000 ft with airspeed of 250 kt.

Controllers were rotated through each of the three arrival sectors to maximize their exposure to EDA operations. Numerous traffic scenarios – representing busy arrival operations of between 24 and 42 aircraft per hour over the meter fix – were studied over the course of two separate simulation activities in April and December 2009. Results from these simulations, described in Section 4, showed the feasibility of using EDA with existing FAA automation, display and communication infrastructure.

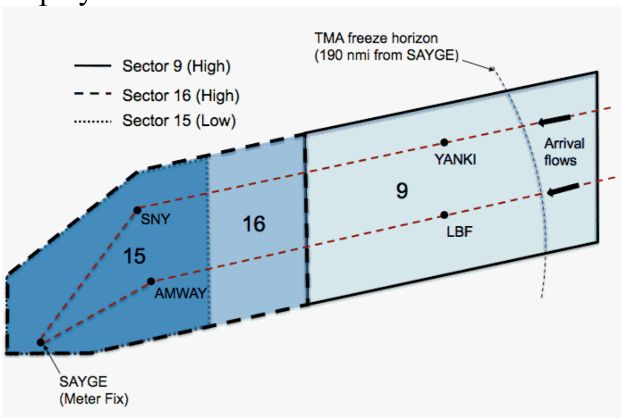


Fig. 5. Airspace Used for ZDV Simulations

3.2 Field Testing

To assess the accuracy of current EDA trajectory predictions and to provide a basis for modeling real-world prediction uncertainty in upcoming simulations, a field test was conducted at Denver ARTCC in September 2009. Pre-scripted (i.e., non automated) EDA speed-profile clearances were issued to revenue flights operated by United and Continental airlines that approached Denver along published STARs from the northeast and northwest. Eligible aircraft types were the Boeing 737-300 and -800, Boeing 757-200, and Airbus 319/320, all of which were equipped with a 3D FMS.

Pilots were issued bulletins describing the test procedures prior to flight. Their participation, however, was entirely voluntary. If they chose to participate, pilots completed a data sheet to record aircraft weight and wind forecasts used for FMS input. FMS-estimated arrival times at waypoints and TOD were also recorded on the data sheet.

Over a three-week period, approximately 400 flights participated in the trials. After discarding flights that had either interrupted

OPDs or incomplete pilot-recorded data, 270 flights remained for post-test data analysis. Selection wasGround-based predictions using intent data derived from flight plans and EDA clearances were compared against flown trajectories. Initial results from this analysis are presented in Section 4.4.

In addition to the commercial flights, a single FAA Global-5000 business jet participated in the field test. This airplane was issued both speed and path-stretch clearances. Since the Global-5000 FMS does not compute a performance-based VNAV path based on idle thrust, a fixed inertial flight-path angle of -2.5° was chosen to specify its descent trajectory from TOD to the meter fix.

4 Results and Discussion

Key results gathered across the aforementioned simulation and field experiments are now categorized and presented. These general findings are accompanied by a discussion of their significance to the evolution of EDA.

4.1 User Interface

EDA's user-interface design was continuously improved upon with feedback from controllers, and therefore represents a key result of the human-in-the-loop simulations. The state of the Graphical User Interface (GUI), procedures and phraseology described below is that resulting from the December 2009 3D-PAM simulation.

GUI

The primary elements of the EDA GUI are illustrated in Fig. 6. Airplanes crossing the TMA freeze horizon that required a delay to meet their scheduled arrival time at the meter fix were presented with the symbol "EDA" at the bottom of their data block. This symbol – referred to as the EDA portal – was displayed in a cyan color to allow it to stand out from other information in the data block. EDA portals were displayed whenever the required delay for an airplane exceeded a preset tolerance of 20 seconds. Numerical data showing scheduled arrival times and delay values were presented in a meter list similar to that used in today's TMA operations. Because of the added functions and GUI provided by the EDA tool, controllers seldom needed to refer to TMA-timeline information during the 3D-PAM simulations.

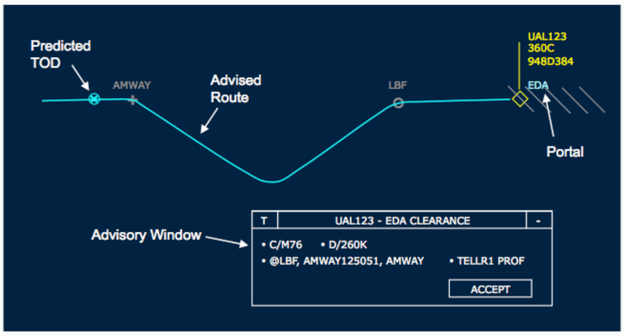


Fig. 6. Example of EDA CHI Upon Advisory Request

When ready for an advisory, controllers simply clicked on the EDA portal. Upon clicking, a window containing the advisory opened up, as shown in Fig. 6. The horizontal trajectory prediction associated with the advisory – including the predicted location of the airplane's TOD – was presented on the controller's display along with the advisory window. The controller could adjust the location of the advisory window to minimize display clutter, thereby establishing the future default location of the window. For simplicity, only a single EDA advisory window could be opened at any one time. Furthermore, to minimize workload during busy conditions, controllers asked that only a single, ready-to-issue clearance advisory be presented in the window at any one time, representing the best solution that EDA could find within traffic and airspace constraints. In this way, no manual manipulation was needed by the controller to generate a viable solution, and no choosing from among multiple options was required.

The controller could leave the advisory window open for as long as necessary to evaluate the suitability of the solution. However, if the window was left open for more than 60 sec (an adjustable parameter) a 'refresh' button within the window appeared, allowing for an update at the controller's discretion. Any advisory updates were based on trajectory predictions using the latest surveillance data available for that airplane. Controllers insisted that no advisory updates occur without their request, since they might be in the process of issuing a verbal clearance based on the previous advisory.

If satisfied with the EDA advisory, the controller issued it as a clearance. After receiving acknowledge from the pilot, the controller pressed the 'Accept' button, which closed the advisory window and updated the flight plan for the airplane. Because the active trajectory prediction now incorporated the EDA-based flight intent, the predicted arrival time at the meter fix would conform to its scheduled arrival time assigned by TMA. This resulted in the EDA portal changing color from cyan to gray. If at any time the controller wished to see the advisory that was issued, they simply clicked on the gray EDA portal.

If the controller chose not to issue the EDA advisory as a clearance – for example due to other traffic duties, radio interruptions, or unresolved conflicts – they simply closed the advisory window. In such event, the color of the EDA portal would remain cyan, indicating that a meet-time problem remained for that airplane. Any subsequent click on the portal resulted in a new EDA advisory.

Controllers tended to reject advisories that relied on auxiliary control actions or traffic assumptions. For example, controllers often rejected an EDA advisory that was predicted to result in a downstream separation violation without compensating control action. In the event that controllers chose to accept such an advisory, they were alerted to the potential conflict situation by a red 'Accept' button in the advisory window, accompanied by information identifying the conflicts. The controller then had the option of accepting the conflicted EDA advisory – perhaps with the intent of resolving conflicts by moving other aircraft – or rejecting it by closing the window. If rejecting an initial advisory, controllers often reopened the advisory window after resolving traffic conflicts using legacy control techniques.

If an advisory was accepted with a conflict, controllers requested that an indicator (e.g., framing the EDA portal with a red box) be presented in the data block to enhance their awareness. A revision of the EDA GUI to better manage unresolved conflicts is in progress, based on controller feedback obtained from the latest simulation.

Phraseology and Procedures

A major challenge for enabling EDA to support 3D-PAM operations was designing the phraseology and procedures to allow trajectory-based clearances to be communicated by voice and managed largely in accordance with today's Federal Aviation Regulations (FARs). Although designed for voice-based communications, advisories were formatted in a manner that could support clearance delivery by data link in future.

Clearance phraseology resulting from the latest EDA simulation – with validation from additional, pilot-oriented 3D-PAM simulations conducted by Boeing – is represented in the example below. Here, the sequence of communications between the controller and pilot correspond to the GUI example shown in Fig. 6. In this example, it is assumed that 'UAL 123' is flying its filed STAR, designated as TELLR1, which specifies the nominal arrival route and the speed/altitude crossing restrictions at the meter fix SAYGE. The EDA clearance consists of a cruise Mach number of 0.76, a descent calibrated airspeed of 250 kt, and a dogleg path stretch between the waypoints LBF (a.k.a. North Platte) and AMWAY, which has a turn-back point located 51 nmi from AMWAY along a magnetic bearing of 125°.

Controller: "United 123, EDA clearance, maintain mach point seven-six, slash two-five-zero knots, revised routing when ready to copy"

Pilot: "EDA clearance, maintain mach point seven-six, slash two-five-zero knots, ready to copy revised routing, United 123"

Controller: "United 123, at North Platte proceed direct to the AMWAY one-two-five slash five-one then direct AMWAY, descend via the TELLR ONE profile"

Pilot: "At North Platte proceed direct to the AMWAY one-two-five slash five-one, then direct AMWAY, descend via the TELLR ONE profile, UAL123"

Once cleared via the TELLR1 profile, no further air/ground communications are typically required other than for radio frequency changes as the airplane transitions from sector to sector en route to the meter fix. The airplane simply flies the FMS-computed trajectory and TOD based on the pilot-entered EDA clearance. Controllers in downstream sectors are informed that the airplane is flying an EDA profile by the presence of the unlit EDA portal in the data block. In addition, once an EDA advisory is accepted, the letter "P" is displayed next to the altitude field in the second line of the data block, indicating that the airplane is flying a profile descent with TOD managed through the FMS.

4.2 Concept-Related Findings

Trajectory-Based Solutions

Controllers expressed a clear desire for EDA advisories that fully defined the arrival trajectory to the meter fix. As opposed to advising partial solutions, this trajectory-based approach relieved controllers from having to continuously monitor and recall the clearance status of each flight. This not only minimized controller workload, but also provided both airborne and ground-based automation with comprehensive flight-intent information once controllers and pilots accepted the EDA solution. To allow clearance delivery by voice, however, it was necessary to break the trajectory-based solution into a series of individual speed and path instructions, as previously described.

Controllers were encouraged to retrieve an advisory for a flight as early as possible, once the airplane crossed the TMA freeze horizon and an EDA portal appeared in its data block. This allowed cruise-speed adjustments to have the greatest effect on arrival time, thereby minimizing the need for path stretching.

In heavy traffic conditions, however, workload limitations often prevented the controller from retrieving EDA advisories as soon as they became available. For this reason, controllers stressed the need for an operational concept that does *not depend* on EDA clearances being issued right away. Instead, controllers asked that viable, up-to-date solutions be available upon request, i.e., at any time the portal is clicked.

Similarly, controllers stressed that EDA should interoperate with any manual control actions taken to assist with scheduling, sequencing and spacing. For example, controllers might want to initiate delay maneuvers prior to an aircraft reaching the TMA freeze horizon or change an aircraft's cruise altitude to assure separation. Under these circumstances, controllers requested that EDA recognize the flight intent created by these manual control actions in any subsequent advisories. This was shown to be possible in the latest simulation in which controllers used existing DSR functions to enter manual speed and altitude clearances into the ground-based automation to update flight intent. These updated flight-intent data were then incorporated into any future EDA solutions.

Situational Awareness

Although EDA offers to improve the sharing and awareness of intended arrival trajectories between controllers and pilots, human-in-the-loop simulations revealed challenges to the controller's immediate situational awareness. Because EDA takes advantage of all available airspace in generating solutions, aircraft may be assigned trajectories with widely varying path geometries and speed profiles. This is unlike today's operations where controllers tend to create organized flows of traffic through arrival sectors. Although this structure limits flexibility and efficiency, it allows controllers to maintain simple mental models of the traffic to help manage their risk of losing situational awareness. In simulation, controllers commented that EDA compromised their ability to instantly assess the arrival plan, thereby requiring them to place considerable trust in the automation. To address this concern, while preserving the benefits of trajectory-based automation, functions were added to the EDA prototype to allow rapid display of predicted trajectories and review of previously accepted advisories. Concerns about situational awareness decreased over the course of each simulation as controllers gained familiarity and trust in the automation.

Of particular concern to controllers was the awareness and accuracy of the airplane's predicted TOD location, which was calculated independently by airborne and ground automation rather than specified directly in the EDA clearance. Controllers suggested that in future GUI iterations, uncertainty in TOD location – perhaps out to two standard deviations – be presented graphically as a band along the predicted trajectory. Since directly relaying TOD information between the airborne and ground automation is likely impractical using voice communications, TOD awareness might instead be handled through simple procedures, such as pilots reporting when within a certain proximity of the FMS-calculated TOD. Pilots reporting to controllers when within 10 nmi of the FMS-calculated TOD proved effective during the initial EDA simulation for 3D-PAM.

To help address controller concerns regarding the awareness and accuracy of horizontal trajectories, EDA path stretching was anchored between fixed start and end points. For example, in Fig. 6, the path-stretch maneuver is anchored between the published waypoints LBF and AMWAY. This implementation eliminated uncertainty associated with the airplane's turnout to the outbound path-stretch leg and provided a single stream of traffic to the meter fix for each baseline STAR. The fixed start point constraint was relaxed by EDA, however, if required to generate a solution. For example, if the airplane was past the published start point at the time the advisory was generated, the path-stretch maneuver was modeled as an immediate turnout from the nominal route. This provided greater flexibility over when an advisory could be requested for a given flight. The fixed start point was also relaxed if needed for lateral conflict avoidance. Similarly, the anchor point for path stretching was moved to the meter fix itself rather than a point upstream if needed for conflict avoidance.

Traffic and Airspace Conflicts

In every simulation, controllers stressed the importance of avoiding traffic conflicts in any advised EDA solution. Although EDA advisories were generated only in response to a meet-time problem, it was important for the EDA solution to strategically avoid conflicts in order to prevent trajectory interruptions downstream. Controllers requested that conflict avoidance in EDA be fully automated, producing conflict-free advisories prior to display. In the event that a conflict-free solution could not be found, controllers suggested that a meet-time solution that minimized the number of conflicts be presented. In such cases, however, controllers insisted on a clear indication that a downstream conflict will occur pending issuance of the EDA solution with no future, compensating control action.

In addition to avoiding conflicts, controllers stressed the importance of constraining EDA trajectories to avoid penetrating adjacent lateral sector boundaries, thereby preventing the need for point-outs and other inter-sector coordination measures. The acknowledgement of airspace-boundary constraints has now been incorporated into the current EDA prototype.

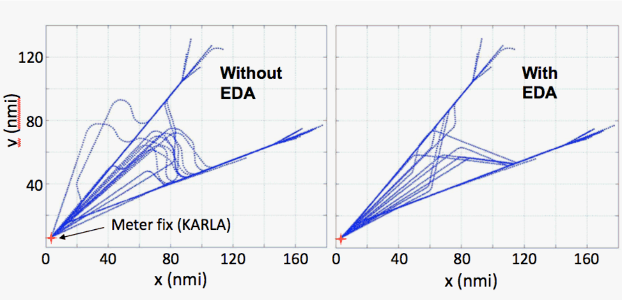
Operations in All Traffic and Weather

Although EDA is currently designed for high-density traffic conditions where arrival demand exceeds airport capacity, controllers expressed a desire to extend EDA to support all traffic levels. In addition to harmonizing procedures, this capability would allow the sharing of comprehensive arrival intent between controllers and pilots at all times of day. When no metering is required, EDA could simply advise pilots to fly their preferred arrival profile. Concepts and designs for this '24/7' capability are being investigated for study in future simulations.

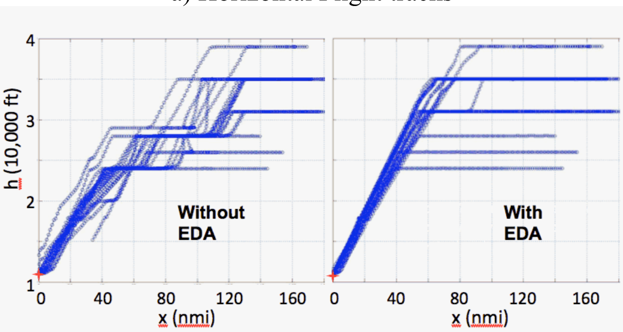
To facilitate '24/7' operations, controllers stressed the importance of avoiding airspace regions impacted by convective weather or other hazardous phenomena. Potential ideas and algorithms for allowing EDA to support '24/7' operations in the presence of convective weather regions can be found in [9].

4.3 Controller Workload

Results from the ZFW simulations identified significant potential workload benefits for controllers using EDA, attributed primarily to a reduction in maneuver-related clearances.



a) Horizontal Flight tracks



b) Vertical Flight Tracks

Fig. 7. Flight Tracks Observed in ZFW Simulation

Shown in Fig. 7 are flight tracks resulting from a busy ZFW traffic scenario, with and without the use of EDA for generating maneuver advisories. In this scenario, aircraft were scheduled by TMA to cross the meter fix with an in-trail spacing of 7 nmi, representative of a heavy arrival rush. Given the traffic demand, the required delay for each airplane induced by the flow constraint ranged from 0 to 6 min. In baseline operations without EDA (i.e., with TMA only), controllers issued frequent maneuver instructions to pilots in their efforts to absorb delay while managing separation. In the horizontal domain, the repeated use of tactical vectoring without EDA is evident by the irregular shaped paths seen in Fig. 7. Similarly, the frequent use of temporary altitude assignments – each requiring the pilot to increase engine power to maintain level flight – can be seen in the vertical tracks without EDA. Corresponding track data with EDA indicate far less maneuvering, with the majority of flights issued a single speed and path instruction near the TMA freeze horizon, resulting in a continuous descent to the meter fix.

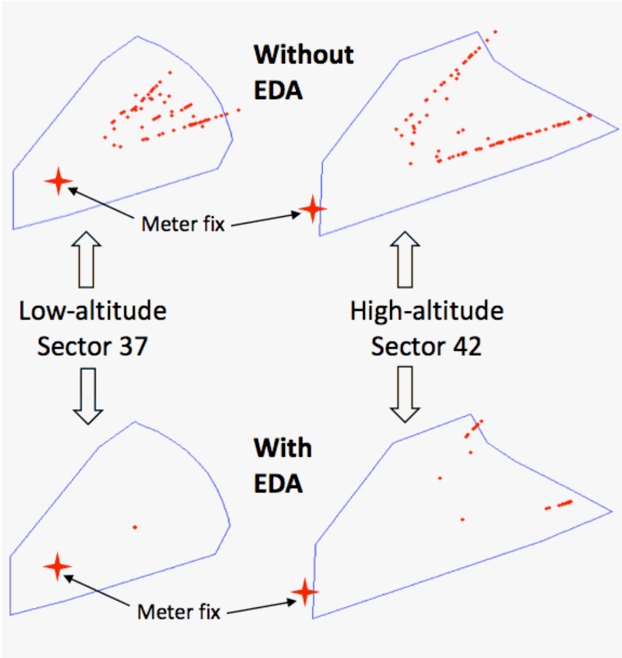


Fig. 8. Location of Aircraft When Issued Maneuver Clearances in ZFW Simulation

Fig. 8 shows the aircraft location within ZFW airspace corresponding to each maneuver instruction issued during a heavy-traffic simulation scenario. As seen here, EDA substantially reduces the required number of maneuver clearances, with most aircraft receiving all necessary arrival instructions shortly after crossing the TMA freeze horizon, near the high-altitude sector boundary. Over all ZFW simulation scenarios, EDA was found to reduce the number of required maneuver instructions by 70%, in comparison with a TMA-only baseline. The number of maneuver instructions required with EDA in the high-altitude and low-altitude arrival sectors was reduced by 55% and 95%, respectively. The histograms shown in Fig. 9 show the majority of aircraft receiving two or less maneuver instructions (depending on whether path-stretching was required) with use of EDA in the high-altitude sector. In the low-altitude sector, all but a few aircraft required any further maneuver instructions following initial EDA clearances upstream.

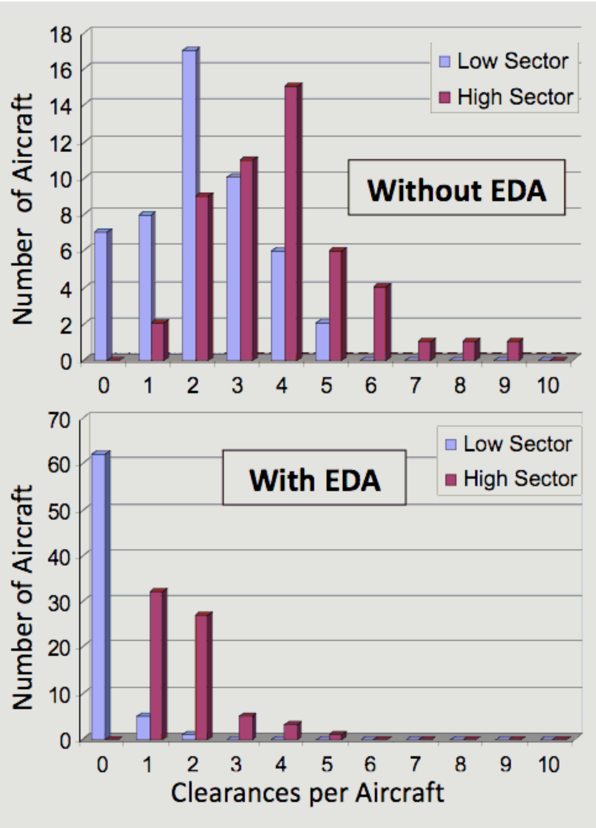


Fig. 9. Number of Maneuver Clearances Issued Per Aircraft in ZFW Simulation

Direct measures of controller workload were obtained from the 2009 3D-PAM simulations. Workload measures were based on the Modified-Bedford scale, which rates the difficulty of completing a task on a scale of 1 to 10, increasing with level of difficulty [12].[1] Controllers were rotated through the three northeast ZDV arrival sectors (9, 16, and 15) previously shown in Fig. 5. After each rotation, each controller provided a rating for their average workload over the duration of the scenario (denoted as *mean* workload) and another rating for their maximum workload at any point in the scenario (denoted as *peak* workload). In the absence of any baseline (non EDA) test conditions, workload ratings were compared only to controller estimates of mean and peak workload for traffic conditions of similar density and complexity during actual operations in the same airspace. The results are shown in Fig. 10, averaged over all traffic scenarios in the two simulations conducted in 2009. Unlike previous simulations, the December 2009 simulation included automated conflict avoidance in the EDA advisories.

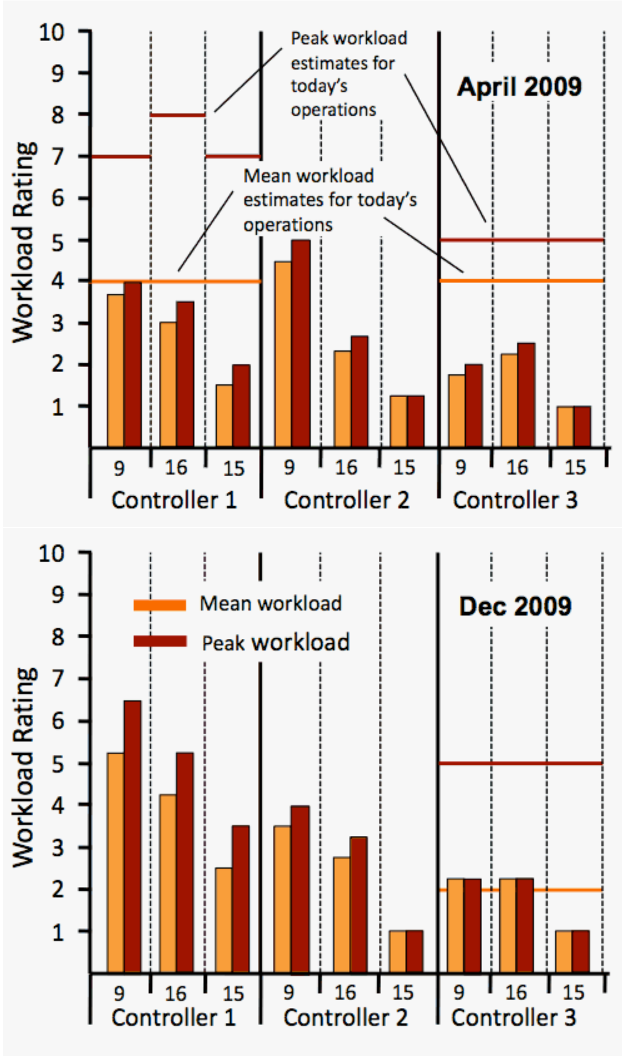


Fig. 10. Workload Measures from ZDV Simulations

As seen in Fig. 10, the mean and peak workload ratings with EDA were lower than estimates of peak workload provided by controllers for the same airspace in current air-traffic operations. As expected, workload was highest in Sector 9, where the EDA clearances were issued. In general, workload was only slightly lower in Sector 16. This was attributed to the difficulty of maintaining situational awareness with airplanes flying disparate path-stretch routes advised by EDA. Workload in the low-altitude airspace (Sector 15) was far below the mean and peak workload levels estimated in current operations. Controllers explained that EDA resulted in high workload occurring

1 Difficulty ratings: easy (1-3), average (4-6), hard (7-9), and impossible (10)

primarily in the initial high-altitude sector, as opposed to current operations where high workload is experienced throughout the arrival airspace during busy traffic conditions.

During simulation debriefs, controllers commented that the 3D-PAM concept with EDA appeared "very workable", and that it generally reduced their workload in comparison to today's operations. Controller trust in EDA increased steadily over the course of the simulations. Furthermore, controllers felt that issuing combined speed and path clearances by voice was feasible, given the phraseology and procedures previously described. Importantly, workload appeared less with EDA despite having only one (R-side) controller handling each arrival sector. Controllers commented that during similar traffic conditions in today's operations, both an R-side and a D-side controller would be assigned to each sector.

Once a mature EDA prototype is available at the end of the 3D-PAM development cycle, additional studies will be conducted to more fully assess the feasibility of voice-based clearance delivery. These studies will compare EDA against a TMA-only baseline, as was done for the ZFW proof-of-concept simulations. Upcoming simulations will include added fidelity such as pilot requests, voice chatter, radio distortion and, most importantly, models of trajectory uncertainty.

4.4 Trajectory Prediction Performance

Accurate and precise trajectory predictions are essential to the success of EDA. Ground-based trajectory predictions must adequately model trajectories resulting from FMS guidance and control, including any compensating pilot inputs. The accuracy of EDA trajectory predictions is limited by uncertainty in inputs such as forecast winds, aircraft weight and aircraft aerodynamic and propulsive performance models.

Data collected during the 2009 Denver field test were used to study the performance of current EDA trajectory predictions. Results were based on a sample size of 270 flights, which were issued pre-scripted EDA clearances. Together with flight plan information, these pre-scripted clearances provided the intent information necessary to allow post-flight comparisons of EDA predictions against radar-derived truth data.

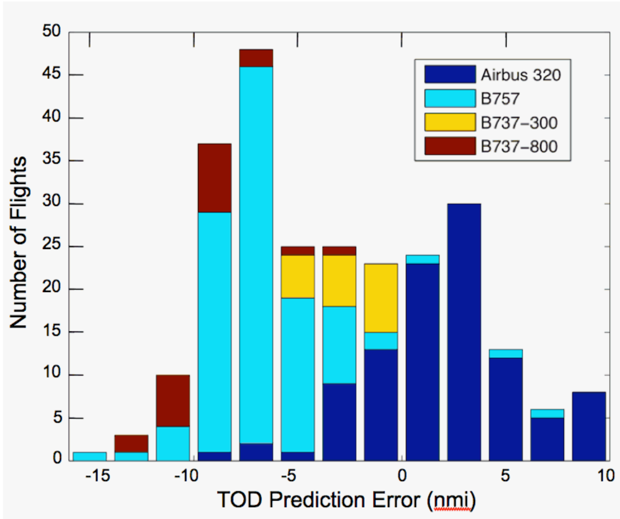


Fig. 11. TOD Prediction Error from ZDV Field Test

Because of its importance, the accuracy and precision of TOD predictions were given priority. A histogram of TOD prediction error – broken down by aircraft type – is shown in Fig. 11. The median absolute error in TOD prediction was found to be 5.4 nmi, with 47% of flights having an absolute TOD prediction error of less than 5 nmi.[2] Because of the dependency on aircraft type seen in these data, it is concluded that TOD prediction error is due largely to errors in modeling aircraft weight, thrust and drag. To investigate the affect of aircraft weight error on TOD prediction, actual weight (obtained from the pilot data sheets described in Section 3.2) was substituted for the nominal weight assumed in EDA predictions for the B-737-800. As shown in Fig. 12, pilot-reported weight values reduced mean TOD prediction error from 9.7 nmi to 6.9 nmi. This analysis illustrates the potential benefit of exchanging parameters between airborne and ground-based automation for improving and harmonizing trajectory predictions. Stell [13] presents more detailed analysis of ground-based TOD prediction error based on the Denver field data.

2 Variance was not represented by standard deviation due to the non-Gaussian distribution of data

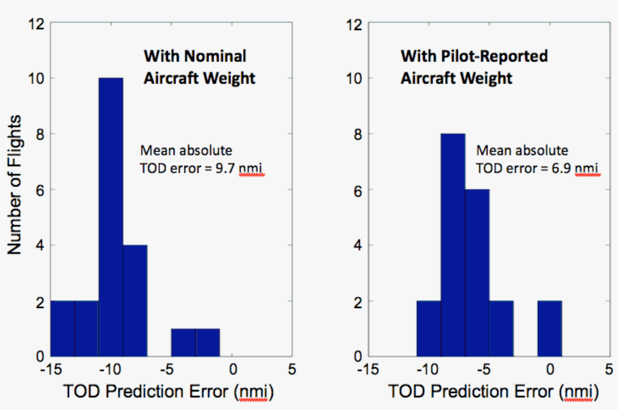


Fig. 12. Improvement in TOD Prediction Using Pilot-Reported Aircraft Weight for the B-737-800

In order to maximize arrival throughput during OPD operations, EDA must effectively deliver aircraft to the meter fix in accordance with the TMA schedule. Using the data collected at Denver, arrival-time predictions generated 20 minutes upstream of the meter fix were compared with actual meter fix crossing times. Results are shown by the histogram in Fig. 13. From these data, mean absolute arrival-time prediction error was found to be 11.5 sec across all aircraft types, with 80% of flights having an absolute error less than 20 sec. Because arrival-time prediction error did not vary significantly across aircraft type, it was concluded that this error was due mainly to errors in modeling winds, which directly affect groundspeed estimates in along-track trajectory predictions.

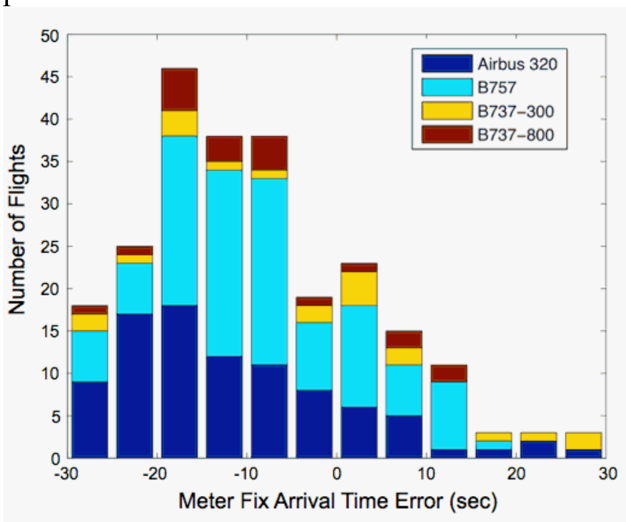


Fig. 13. Meter-Fix Arrival Time Prediction Error

Simulation observations suggest that current EDA along-track prediction accuracy – represented by the arrival-time performance in Fig. 13 – is likely adequate for end-state operations. Current TOD-prediction accuracy, however, is likely not adequate without changes to procedures and/or expansion of conflict-avoidance buffers. In general, the required accuracy of EDA predictions depends on two factors: 1) controller acceptance and trust of the automation, and 2) retention of airspace capacity for accommodating maximum throughput. The former requirement is related to the probability of success desired by controllers in avoiding conflicts with strategic EDA clearances without any further corrective action downstream. To achieve the desired level of performance, buffers can be added to the separation minima used by EDA in its conflict-avoidance solutions. Although resolution buffers can be added to compensate for almost any degree of prediction uncertainty, airspace capacity will be compromised if buffers are made too large. With these considerations in mind, a simulation is planned later this year to quantitatively define the accuracy and precision required in EDA trajectory predictions, with emphasis on TOD.

5 Conclusions

A prototype of the Efficient Descent Advisor (EDA) has been developed as a controller tool for accommodating fuel-efficient descents during high-density operations where traffic and throughput constraints are prevalent. A series of high fidelity, human-in-the-loop simulations were carried out with controller participants to obtain end-user feedback critical for shaping the concept and design of EDA.

Controller reaction was encouraging, suggesting that EDA has the potential to be implemented as a near-term capability with only minor changes to controller roles, responsibilities and procedures. Although EDA provides an obvious application for data link communications, simulations show that trajectory-based clearances involving speed and path can successfully be issued by voice, using the phraseology and user interface described. By providing controllers with a single, comprehensive arrival solution upstream, EDA was shown in simulation to reduce the number of required maneuver clearances by 70%, suggesting a significant potential reduction in controller and pilot workload.

Controller feedback obtained during simulation was incorporated directly into the design of the EDA prototype. At the request of controllers, EDA solutions were provided to strategically avoid downstream traffic conflicts and crossing of lateral sector boundaries. Functions were added to allow controllers to quickly display trajectory information – including Top-of-Descent (TOD) – to preserve situational awareness during trajectory-based operations in which airplanes are flying a variety of route, altitude and speed profiles.

Accurate ground-based trajectory prediction remains a key challenge for EDA implementation. Data collected during live traffic operations at Denver reveal that better predictions of TOD are required to implement EDA without procedurally sharing TOD information between controllers and pilots and/or increasing buffers for conflict avoidance in the vicinity of TOD. Simulations later this year will focus on trajectory-prediction performance in the continued effort to develop EDA for NextGen.

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