Concept and Laboratory Analysis of Trajectory-Based Automation for Separation Assurance

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An operating concept and a laboratory analysis methodology were developed and tested to examine how four-dimensional trajectory analysis methods could support higher levels of automation for separation assurance in the National Airspace System. Real-time simulations were conducted in which a human controller generated conflict resolution trajectories using an automated trial plan trajectory generation and analysis function, but only in response to conflicts detected and displayed by an automatic conflict detection function. Objective metrics were developed to compare aircraft separation characteristics and flying time efficiency under automated operations with that of today's operations using common airspace and common traffic scenarios. Simulations were based on recorded air traffic data from the Fort Worth Air Route Traffic Control Center and were conducted using today's and nearly two-times today's traffic levels. The results suggest that a single controller using trajectory-based automation and data link communication of control clearances to aircraft could manage substantially more traffic than under today's conditions, and with improved route efficiency while maintaining separation. The simulation and analysis capability provides a basis for further analysis of semi-automated, or fully automated, separation assurance concepts.

INTRODUCTION

In its Next Generation Air Transportation System (NGATS) report the multi-agency Joint Planning and Development Office (JPDO) de-

scribes an expected two- to threefold increase in air traffic demand by the year 2025 and the need for new automation technologies and operating procedures for the National Airspace System (NAS) [JPDO, 2004]. Under today's operations air traffic controller workload, severe weather, capacity-constrained airports and other factors limit airspace capacity and efficiency. In the absence of severe weather, controller workload is probably the single most important factor limiting airspace capacity. An air traffic controller's primary task is to ensure safe separation by visual and cognitive analysis of a traffic display and voice communication of control clearances to pilots. The Decision Support Tools (DSTs) developed and deployed in recent years provide trajectory-based information and automation that assists controllers with conflict detection and resolution and with arrival flow management. However, the controller still holds primary responsibility for safe separation. Though DSTs are providing measurable improvement in today's NAS [Federal Aviation Administration, 2003], DST-based concepts and technologies alone are not expected to support a two- to threefold increase in airspace capacity. Under the NGATS vision, the use of four-dimensional (4D) aircraft trajectory analysis with higher levels of automation for separation assurance and data link communication are expected to be core components of future airspace operations.

Recently, airspace operating concepts have been proposed for increasing airspace capacity through higher levels of automation and/or delegation of some separation assurance responsibility to the cockpit. The Advanced Airspace Concept proposes highly automated separation assurance for equipped aircraft using air/ground data link communication and an independent safety assurance function [Erzberger, 2004]. Concepts for delegation of separation assurance to the cockpit through airborne automation and Cockpit Display of Traffic Information (CDTI) have been proposed [Wing et al., 2004; Barmore et al., 2004; Battiste et al., 2000], as have concepts that employ a mix of controller-managed and airborne separation assurance methods [Prevot et al., 2005]. The objective of this paper is to make an initial determination as to whether or not existing 4D trajectory analysis methods and trajectory-based conflict detection and resolution functions have promise as a point of departure for development of the next-generation separation assurance automation for the NAS.

The concept and laboratory analysis described herein centers on the following questions: If automated 4D trajectory-based strategic conflict detection and resolution functions could be trusted, could a controller use them as their primary means to maintain safe separation? If so, are there resulting benefits in terms of capacity and flying-time efficiency that could be exploited to increase the amount of traffic managed by the controller? And, should the primary strategic conflict detection function fail, could a backup tactical conflict

detection function [Erzberger, 2004; Paielli and Erzberger, 2005] detect an imminent conflict in time to prevent a loss of separation? For the purposes of this experiment the operating concept and simulation methodology assume that aircraft are deviated from their nominal route of flight or vertical profile only when a traffic conflict is detected by the automation. We refer to this concept as "Control by Exception." Experimental studies have been previously conducted to investigate the controller cognitive workload associated with Control (or "Management") by Exception operations in air traffic control [Dekker and Woods, 1999]. In the simulations described herein, following a detected conflict, the controller uses an automated conflict resolution function to generate a flight plan amendment that results in a conflict-free resolution trajectory. Route or altitude restrictions, inter-sector coordination requirements, or sector boundary considerations common in today's operations are not considered when generating resolution trajectories or any trajectory changes. Flight plan amendments are transmitted to the aircraft via simulated data link communication.

The paper begins with a description of the simulation methodology that makes use of existing 4D trajectory analysis methods and Federal Aviation Administration (FAA) en route Center radar track and flight plan data as a basis for higher levels of automation for separation assurance. The use of actual Center data exposes automation algorithms and software to a rich variety of real-world traffic conditions. The implementation of the Control by Exception concept in human-in-the-loop simulation is described, and objective metrics are defined that provide the basis for a comparative analysis of Control by Exception operations with today's operations. The Analysis and Results section describes the various simulation runs that were conducted during the study and presents objective comparison of simulation operations with today's operations using common traffic samples. Simulation runs include conditions where a single controller maintains separation in five sectors under nominal and two-times nominal traffic levels using Fort Worth Center traffic data. The paper closes with some concluding remarks. The original, and expanded, version of this paper includes conditions where the controller maintains separation in more than five sectors and includes analysis with Cleveland Center traffic data [McNally and Gong, 2006].

SIMULATION METHODOLOGY

The simulation methodology is based on an operating philosophy where all traffic conflicts are assumed to be detected by trajectory-based automation and all trajectory changes, including conflict reso-

lution trajectories and pilot-requested route or altitude changes, are generated and implemented using trajectory-based automation. Mature trajectory analysis methodologies and software previously developed for DSTs are configured to run such that they automatically detect and provide the necessary automation to resolve all traffic conflicts. We refer to this integrated capability for automatic detection and automated resolution as trajectory-based automation (TBA). The human controller relies on the automation to detect and resolve conflicts, but does not scan traffic for conflicts as in today's operations. Traffic flow and separation characteristics are then measured and compared to those of today's operations. This is expected to help determine the suitability of current trajectory analysis methods for higher levels of automation. It is also expected to help uncover shortcomings in trajectory analysis methods that will need to be overcome to achieve the research objectives of two- to three-times traffic density with safety and user-preferred trajectories.

The Center/TRACON Automation System (CTAS) trajectory analysis methodology and software are the basis for this analysis [Erzberger et al., 1993; Slattery and Zhao, 1995; Paielli and Erzberger, 1997; Erzberger et al., 1997; Isaacson and Erzberger, 1997; Erzberger et al., 1999; Swenson et al., 1997]. The CTAS, developed at the NASA Ames Research Center, includes mature capabilities for 4D trajectory prediction, time-based metering, conflict detection, conflict resolution, flying time analysis of direct routes accounting for winds, and other functions. The CTAS trajectory analysis and conflict prediction capabilities are based on real-time analysis of FAA en route Center radar track (12 s updates) and flight plan amendment (periodic updates) data from the Center Host computer, hourly updates of wind predictions from National Oceanic and Atmospheric Administration (NOAA) Rapid Update Cycle (RUC) model, and a database of aircraft performance models. The CTAS conflict detection, trial planning, and direct route advisory functions have been tested extensively under operational conditions at FAA Center facilities [McNally et al., 1998, 1999, 2001]. A tactical conflict detection function is being analyzed as a potential enhancement to the legacy Host Conflict Alert function [Paielli and Erzberger, 2005] and is the basis for the backup tactical conflict alerting function in this analysis.

A fundamental requirement of the simulation methodology was a means for the TBA to provide separation assurance in a simulation derived from actual Center traffic data. To make use of Center traffic data, a methodology was needed to "undo" the effects of actual controller clearances from the traffic data and replace them with trajectory changes generated by the simulation controller using the automation to resolve detected conflicts.

The methodology used for this experiment was adapted from a

previous CTAS simulation experiment [Robinson and Isaacson, 2002]. Consider the notional airspace shown in Figure 1, which is defined by a single airspace sector or any number of adjoining sectors. CTAS automation receives a live or recorded feed of actual Host track and flight plan data as described above. Host radar track messages (received every 12 s) are monitored to identify aircraft that are entering the simulation airspace. The radar track update at which a given aircraft's Host sector ID (an element of the radar track message) changes to one of the simulation airspace sectors (i.e., a transfer of separation responsibility from a non-simulation sector to a simulation sector) defines the initialization point (IP) for that aircraft in the simulation. At this point, the actual aircraft data source (live or recorded) is replaced by a simulated aircraft instantiated and controlled by the Pseudo Aircraft Simulator [Weske and Danek, 1993]. Following the IP, the aircraft simulator generates all subsequent radar track updates based on the initial conditions at the IP (position, altitude, speed, and flight plan intent) and the NOAA RUC wind data. All subsequent flight plan amendments (route or altitude) are generated by the TBA system. Actual Host radar track and flight plan amendments received for the simulated aircraft are ignored once the aircraft has passed the IP. Using this methodology, the automation can be tested using realistic traffic flows derived from an authentic source of track and flight plan data from any Center for which a CTAS adaptation is available.

In this analysis, arrivals to major hub airports in, or near, the simulated airspace were not converted to simulated aircraft. Instead they were allowed to proceed according to their live or recorded track data. This simplification was made due to the fact that the conflict
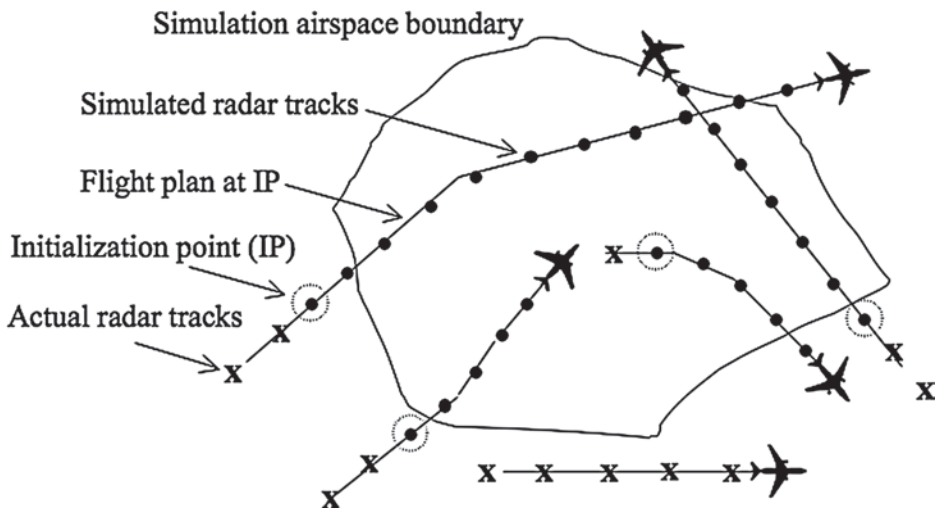

Figure 1. Simulation methodology.

resolution automation was not well configured to solve conflicts between arrivals merging to a common metering fix. Analysis of merging arrival traffic, though an important element of air traffic control operations near capacity constrained airports, was beyond the scope of this study. Furthermore, analysis of automation concepts for future airspace should first be assessed in terms of their ability to accommodate basic separation assurance problems, i.e., conflict detection and resolution problems that do not include arrival metering, before they are extended to problems that require concurrent separation and metering.

Given that trajectory prediction uncertainties can be on the same order of magnitude as safe separation criteria (5 nmi and 1000 ft in en route airspace), uncertainty is an important consideration in the analysis of TBA concepts. A typical 5–7 m/s (10–14 kn) wind speed error [Schwartz et al., 2000] can result in about a 2 nmi along-track prediction error over a 10 min time horizon. A similar error in cruise speed intent can have the same effect. A typical 20% error in the weight estimate for a Boeing 757 aircraft can result in a 3 nmi error in predicted along-track distance to top of climb over a 10 min time horizon [Coppenbarger, 1999]. These errors can result in faulty, late, or missed conflict detections and generally require that trajectory and conflict analysis methods are robust to uncertainty. Aggregate CTAS trajectory prediction errors based on analysis of hundreds of actual en route trajectories can be on the order of 2–3 nmi (1-sigma) for 10 min level flight trajectory predictions, and 1000–2000 ft (1-sigma) for 5 min climbing flight trajectory predictions [Gong and McNally, 2004]. A number of methods are employed in CTAS to mitigate the effects of uncertainty including updating trajectory predictions at every radar track update, employing expanded separation criteria for conflict detection (e.g., 7 nmi horizontal and 1500 ft vertical for climbing or descending aircraft), and the use of uncertainty-based conflict probability analysis to filter low probability conflicts [Erzberger et al., 1997].

Detailed uncertainty modeling is beyond the scope of this study. However, the methodology in [Gong and McNally, 2004] is applied to compare the aggregate uncertainty of trajectory predictions based fully on actual traffic data with those based on simulated traffic data that is only initialized with actual traffic. The results, presented in the Appendix, show that the trajectory uncertainty inherent to the simulation methodology applied in this study is roughly on the same order of magnitude as the trajectory uncertainty present under actual traffic conditions. This makes the results more meaningful, since uncertainty is an unavoidable aspect of trajectory-based operations.

This study defines the open-loop traffic flow as that which results when all simulated aircraft in the simulation airspace fly an uninterrupted (i.e., no controller inputs) nominal trajectory along the

flight plan and vertical profile (e.g., climb profile) that was current when they entered the airspace at the IP. The open-loop simulation provides a baseline traffic flow in the simulation airspace region to which metrics can be applied. As shown later, analysis of the open-loop traffic flows provides a quantitative measure of the traffic conflicts that must be resolved by the separation assurance automation to maintain safe separation in the airspace.

This study defines the closed-loop traffic flow as that which results when the human controller using TBA provides all trajectory changes needed to maintain separation in the simulation airspace. The TBA includes the CTAS 4D trajectory modeling, conflict prediction, trial planning, and graphical user interface functions, and a simple data link communication model. A human controller monitors a list of predicted traffic conflicts. The controller uses the trial planner automation to manually (and interactively) generate flight plan amendments that resolve all traffic conflicts. When the controller inputs a flight plan amendment, a fixed time delay count down begins. Following the time delay count down, the amendment is automatically transmitted to the aircraft simulator and to the TBA's flight plan database. The trajectory database is updated with the flight plan amendment, and the aircraft simulator starts flying the aircraft and generating subsequent radar track updates consistent with the flight plan amendment.

The fixed time delay simulates the time required for a pilot to review a flight plan change and indicate compliance or non-compliance. A 24 s time delay seemed plausible for future operations and was used for all simulation runs in this analysis. In reality this delay would vary from a few seconds to a minute or two depending on the data link. Additionally, a small percentage of flight plan amendments would be rejected by the pilot due to aircraft performance limitations (e.g., too heavy to climb), severe weather avoidance, or other operational factors. A better model could include a random time delay characterized by a mean and standard deviation and include a percentage of unable responses from pilots requiring that an alternative resolution trajectory be generated. Requiring a compliance message (e.g., will comply, or "wilco") from the aircraft before the TBA updates the flight plan is expected to be an important aspect of the coordination process in trajectory-based operations with data link communications.

The automatic transmittal of a flight plan amendment to the aircraft simulator combined with the time delay associated with the pilot's compliance simulates a simple model of data link communication for TBA. This model assumes that consistency in flight plan intent (route and altitude) between the aircraft and the TBA system will yield adequate consistency between predicted trajectories and actual trajectories. This seemed like a reasonable starting point for

this study. In the future, data link communication could require more complete trajectory information to improve consistency between predicted and actual trajectories. Such information could include time and speed at selected waypoints, speed during certain flight legs (e.g., climb, cruise, descent) and other information. An aircraft's complete preferred fuel-efficient descent trajectory could possibly be transmitted to the TBA system for conflict analysis. Future research towards the NGATS vision will determine the information content and the aircraft conformance requirements for data link communication in trajectory-based operations.

In this analysis, flight plan amendments are generated by a human controller operating the trial planner, but the methodology should be suitable for the analysis of any TBA concept.

OPERATING CONCEPT

Figure 2 illustrates the difference between today's operations and the Control by Exception operations being investigated in this study. Under today's operations (Figure 2a), the controller monitors a radar display showing radar track positions and flight data block information for all aircraft in the sector. Though DSTs are available to aid conflict detection and resolution, the controller is ultimately responsible for detecting traffic conflicts and issuing clearances to maintain safe separation. Under Control by Exception operations as defined in this experiment, the TBA detects traffic conflicts and displays them to the controller through a conflict list or other suitable user interface mechanism as shown in Figure 2b. Because the controller is not asked to identify potential conflicts as in today's operations, the information traditionally presented in the flight data block is not needed. Therefore, flight data blocks are not displayed by default. When two aircraft are predicted in conflict by the automation, the controller displays their flight data blocks and additional graphical information by a click on the conflict list. Additional pertinent graphical information is displayed when the controller activates the trial planner functions [McNally et al., 1998, 1999, 2001] to resolve the conflict.

As shown in Figure 2b, the controller uses the trial planner to interactively generate and conflict-probe a trajectory defined by a shallow right turn to an auxiliary waypoint followed by a direct route to a downstream fix to resolve the conflict. An analysis of the user interface requirements for Control by Exception was beyond the scope of this study, but the configuration shown in Figure 2b was a workable nominal display format.

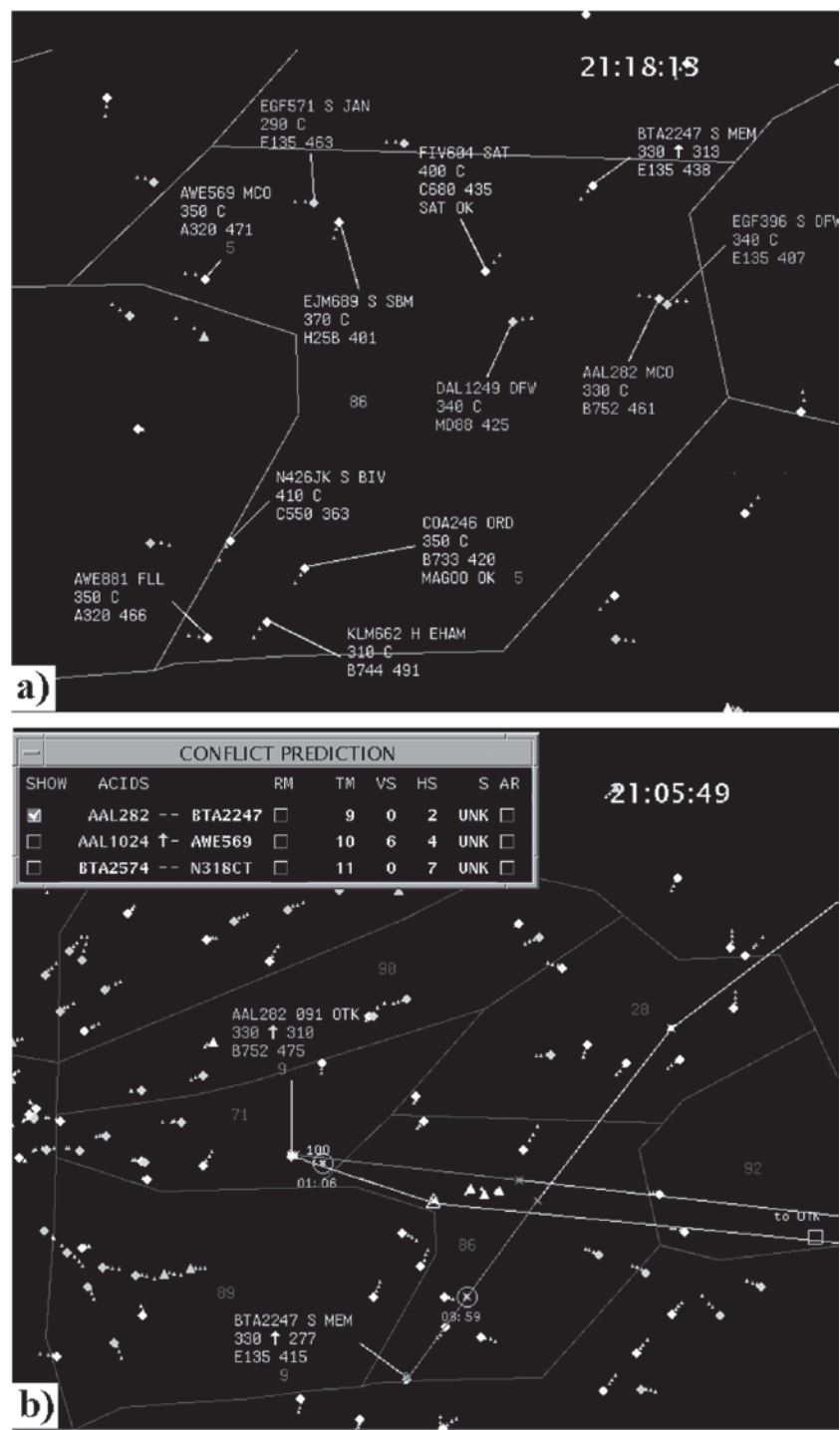Two operating modes were used during the simulations. Under the

Figure 2. Controller's radar display: a) today's single sector operations, b) five-sector Control by Exception operations.

first, the "Conflict Resolution" mode, a human controller (here, a NASA engineer) used the trial planner to resolve only those conflicts that were displayed on the conflict list. The controller did not scan and analyze flight data blocks for potential conflicts as in today's operations. Instead, the controller reacted only to conflicts detected by the TBA. The controller's tasks were to: 1) monitor the conflict list, 2) use the trial planner to generate route and altitude flight plan amendments that would resolve displayed conflicts, and then 3) issue flight plan amendments to aircraft via the simulated data link. These tasks were chosen to emulate an automated conflict resolution function, albeit with a human closing the resolution loop. Resolution maneuvers were limited to three types: 1) altitude change, 2) direct route to a downstream flight plan fix, and 3) vector to an auxiliary waypoint followed by a direct route to a downstream flight plan fix (shown in Figure 2b). These are common clearances in today's air traffic operations. Speed changes were not used in this experiment. Route or altitude restrictions, or restrictions associated with sector boundaries or procedural routings, were not considered in the generation of the conflict resolution trajectories.

Expanded separation criteria were used for conflict alerting and for generating conflict-free resolution trajectories with the trial planner. Expanded separation criteria provide a safety buffer to guard against missed alerts in the presence of trajectory prediction uncertainties. The horizontal separation criterion for conflict alerting was 8 nmi as opposed to the 5 nmi legal horizontal criterion. As an example, the aircraft pair of BTA2574 and N318CT in Figure 2b was listed as a conflict because the minimum horizontal separation was predicted to be 7 nmi. The vertical separation criterion for alerting was 1500 ft if at least one aircraft in the conflict pair was climbing or descending at the point of first loss of separation. If both aircraft were flying level at the point where horizontal separation was lost, the vertical separation criterion remained at the legal vertical separation criterion of 1000 ft. To provide an additional safety margin when changing trajectories, the separation criteria for trial planning were set higher than that for alerting. The separation criteria for trial planning were 12 nmi horizontal for all cases and 2000 ft vertical when one or more aircraft was climbing or descending.

Under the second operating mode, the "Conflict Resolution & Direct-To" mode, the controller resolved all conflicts using the trial planner as described above and issued all conflict-free direct route advisories that were displayed on the Direct-To route advisory list [Erzberger et al., 1999]. The CTAS Direct-To algorithm automatically performs a wind-route analysis on all aircraft routings to identify those aircraft that could save at least one min of flying time by flying direct to a downstream fix on their route of flight. Direct-To route advisories are limited so as not to propose a route amendment

that would substantially deviate an aircraft from its nominal route of flight. All direct route advisories are automatically probed for conflict using the trial plan separation criteria. In the context of this analysis, the Direct-To list could be considered to emulate pilot requests a controller might receive during normal operations. While operating in this mode, all conflict-free Direct-To route advisories were issued immediately without regard for sector boundary or coordination considerations common in today's operations.

METRICS

Minimum Separation Metric

An important objective of this analysis was to develop and apply objective metrics to compare trajectory-based operations with today's (baseline) operations. An objective measure of airspace separation characteristics was needed to compare the safety and complexity of traffic under automated operations during the simulations versus that of today's operations using a common airspace and a common traffic sample. In any airspace, the frequency and number of aircraft pairs that pass with a minimum separation that is at, or near, the legal separation standard (5 nmi or 1000 ft) is one measure of controller workload, traffic complexity, and safety. Consider the traffic in any finite airspace, e.g., the five-sector airspace shown in Figure 2b. The radar track data for all aircraft that pass through the airspace over a given time interval are analyzed to determine the minimum separation distance for each unique pair of aircraft that are not legally separated by altitude (i.e., those aircraft pairs separated by less than 1000 ft). The minimum separation metric is the number and frequency of unique aircraft pairs that pass at or near the legal separation criteria. Plots of this metric for the various simulation runs are shown later in the Analysis and Results section. For an aircraft pair to be considered in the analysis, at least one of the aircraft had to pass through the airspace during the selected time interval (this covers cases where one aircraft was in the airspace and the other was not). For example, over a given interval, say five min, some unique pairs pass with a minimum separation of 10 nmi while other unique pairs pass with a minimum separation of 50 or 100 nmi. Any unique pair that passes with less than 5 nmi minimum separation while not separated by altitude would reflect a loss of legal separation and a serious safety violation. The minimum separation metric is calculated throughout the duration of each traffic scenario. Since this method is based purely on analysis of current-time radar track data (i.e., predictions are not used), it provides for a simple objective comparison of today's operations with automated operations.

Route Efficiency Metric

The flying time and path distance required for an aircraft to pass through a given region of airspace is a measure of route efficiency. Measuring route efficiency by path distance alone is not adequate because of the effect of wind. Apparent route efficiency gains due to shorter, more direct, routing may not be realized if the TBA does not account for potentially unfavorable winds. For this reason, flying time is the primary measure of route efficiency. As with the separation metric, a common airspace and traffic sample are used to achieve a direct comparison of today's operations with operations that include higher levels of automation.

Shown in Figure 3 is an aircraft entering a notional simulation airspace region at the initialization point, IP. The Host radar track history reflects the actual aircraft path through the airspace based on Host radar track recordings. The simulated radar tracks reflect the simulated aircraft's path through the airspace when the aircraft was being controlled under Control by Exception operations as described above. In this example, the actual radar tracks show the aircraft following a standard departure routing though the airspace. The simulated tracks show the aircraft flying a shortcut that skips the departure routing but, in this case, includes vectoring for traffic. Both actual and simulated track histories in Figure 3 are notional but are representative of actual operations. The shortcut and the vector were included in this example to illustrate the point that the efficiency metric uses a common methodology to account for short-cuts, which generally improve efficiency, and vectors for traffic, which generally reduce efficiency.
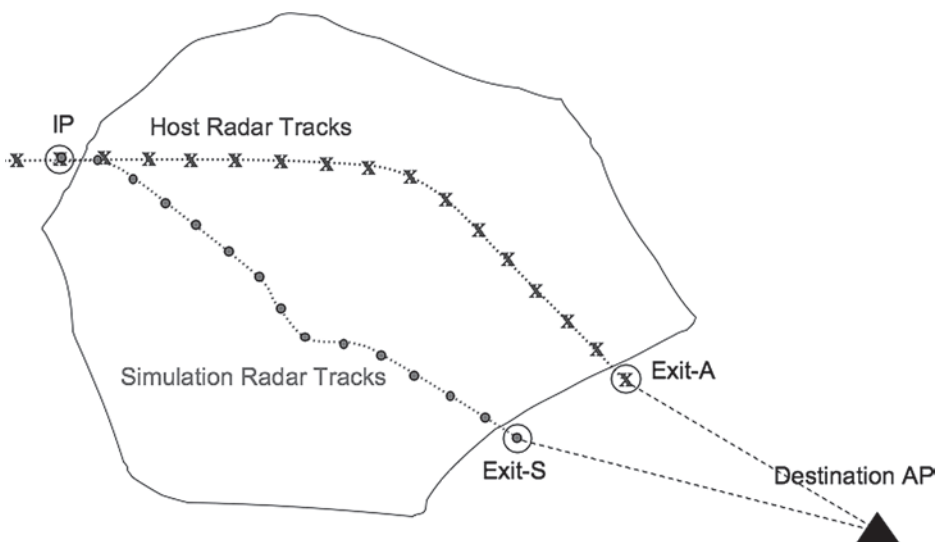

Figure 3. Route efficiency metric.

Since the actual aircraft and the simulated aircraft were influenced by different wind fields and airspeeds, a method was needed to determine the equivalent flying time of each aircraft if the winds and airspeeds were the same along their respective routes. Comparing flying times derived by integrating track histories of a given aircraft from two different sources is greatly influenced by both airspeed and wind the aircraft is flying through. For example, a simulated aircraft flies through a predicted wind field. The resulting flying time could vary significantly from the actual aircraft's flying time, because the actual aircraft was affected by real winds, which likely differed from the predicted winds.

Flying time was calculated by integrating groundspeed (true airspeed + wind speed) with respect to path distance along a given route. By assuming each aircraft was flying in the same wind field with the same true airspeed profile, any difference in the resulting flying time could then be attributed to the difference in the routing of each aircraft. For each track point of a given aircraft, true airspeed was set to a value determined from the CTAS aircraft model database based on aircraft type and phase of flight. The corresponding wind speed was determined from the modeled (NOAA RUC) wind at each track point. Groundspeed is then calculated from the modeled true airspeed and wind. The flying times resulting from the integration of the groundspeed of each aircraft were then compared. Differences are attributed to operational factors affecting routing, e.g., direct route and/or vectors.

Since irregularities in the geometry of the airspace region could cause errors in flying-time comparisons, a method was needed to obtain a fair comparison of flying time while considering only the differences in operations within the airspace region of interest. The initialization point (IP) and the destination airport were the only two points assuredly on both actual and simulated trajectories. Route changes affecting the aircraft while it flew through the simulation airspace were reflected in the track data. The path distance and flying time from the IP to the actual exit point (Exit-A) were computed using Host radar track data. The path distance and flying time from the IP to the simulated exit point (Exit-S) were computed using simulated track data. Once the aircraft exited the simulation airspace, it was assumed the aircraft would continue direct to the destination. The specific routes the aircraft took after exiting the simulation airspace are irrelevant to this analysis. Therefore, the remaining path distance and flying time from the exit point to the destination airport were calculated for a direct route between the two points. The total path distance and flying time, i.e., from IP to Destination AP, were the sum of the components inside and outside of the simulation airspace. The flight time efficiency metric is the difference between the flying time for the actual route vs. that of the

simulated route. The path distance efficiency metric is the difference
between the path distance for the actual route vs. that of the simu-
lated route.

Flight Plan Amendment Metric

The number of flight plan amendments a controller implements
while controlling traffic is one objective measure of controller work-
load. Using a common airspace and a common traffic sample, the
number of route and altitude amendments issued while aircraft were
in the airspace was compared for simulation operations and actual
operations. Altitude amendments include changes to the planned
flight altitude as well as temporary altitudes. To obtain a fair com-
parison, only amendments to aircraft common to both simulated and
actual traffic samples were counted. Because descents to satellite
airports within the Center and near-by adjacent Center airports were
not simulated in this analysis, amendments to those aircraft were not
counted.

ANALYSIS AND RESULTS

Conflict Resolution Mode—Today's Fort Worth
Center Traffic

Five adjoining high altitude sectors in Fort Worth Center (ZFW)
airspace (28, 71, 86, 89, and 90) were selected as the simulation
airspace. This airspace was chosen because it includes a good mix of
climbing Eastbound departures from the Dallas/Fort Worth Interna-
tional Airport (DFW), climbing North-East-bound departures from
airports in Houston, two arrival streams to DFW, and level over-
flight traffic. The simulation and analysis were based on ZFW Host
radar track and flight plan data recorded over a 90-minute period
starting at 1525 Central Standard Time (CST) on May 26, 2005.

   The Host radar track data were first analyzed to establish the
baseline characteristics of the actual recorded traffic flow in the five-
sector airspace. Figure 4a shows a time history of the total traffic
count in the five-sector region. Figure 4b shows the minimum sepa-
ration metric computed at 5 min intervals over the 90 min recording.
Only aircraft pairs not separated by altitude and that passed with a
minimum horizontal separation of 10 nmi or less are reflected in
Figure 4b. This baseline minimum separation analysis reflects the
actions of actual controllers working the traffic under today's opera-
tions. In all of the five-sector airspace, only one unique pair had a
minimum separation between 5 and 10 nmi during the 20–25 min
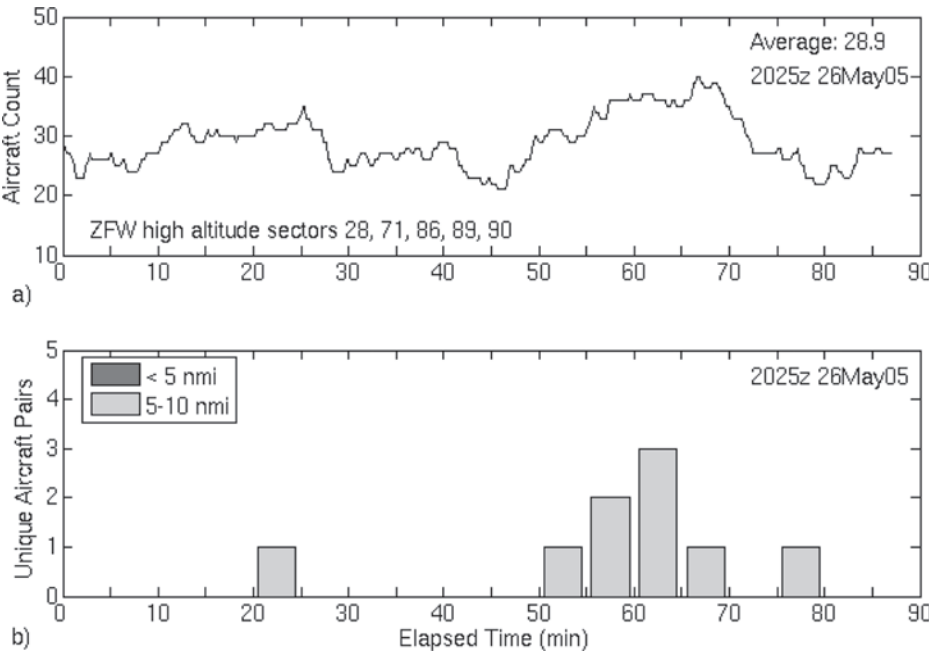
Figure 4. Separation characteristics, today's live traffic baseline, five sectors: a) aircraft count, b) minimum separation metric.

elapsed time period. Later, during the 60–65 min elapsed time period, 3 unique pairs had a minimum horizontal separation between 5 and 10 nmi. For much of the time, aircraft not separated by altitude remained horizontally separated by more than 10 nmi. Under today's operations, the number of controllers working this airspace likely ranged from 4 radar (R-Side) controllers when sectors 71 and 90 were combined (as they often are), to as many as ten controllers when both R-Side and a D-Side controllers were assigned to each of the 5 sectors.

An open-loop simulation of the 90 min, five-sector traffic sample was conducted to measure the minimum separation metrics that would result without any control actions. Recall that the open-loop simulation methodology, where aircraft fly the flight plan and vertical profile as intended upon entering the airspace, effectively removes the effects of actual controller actions (e.g., vectors or altitude changes) from aircraft trajectories in the simulation airspace. Figure 5a shows a time history of the open-loop total traffic count. Average traffic count varied slightly from run to run (and from baseline to open-loop), because aircraft exited the simulation region at different times. However, the total number of aircraft entering the simulation region remained the same for each run. Figure 5b shows the minimum separation metric for the open-loop run. Note that Figure 5b shows numerous instances where aircraft violated the vertical and
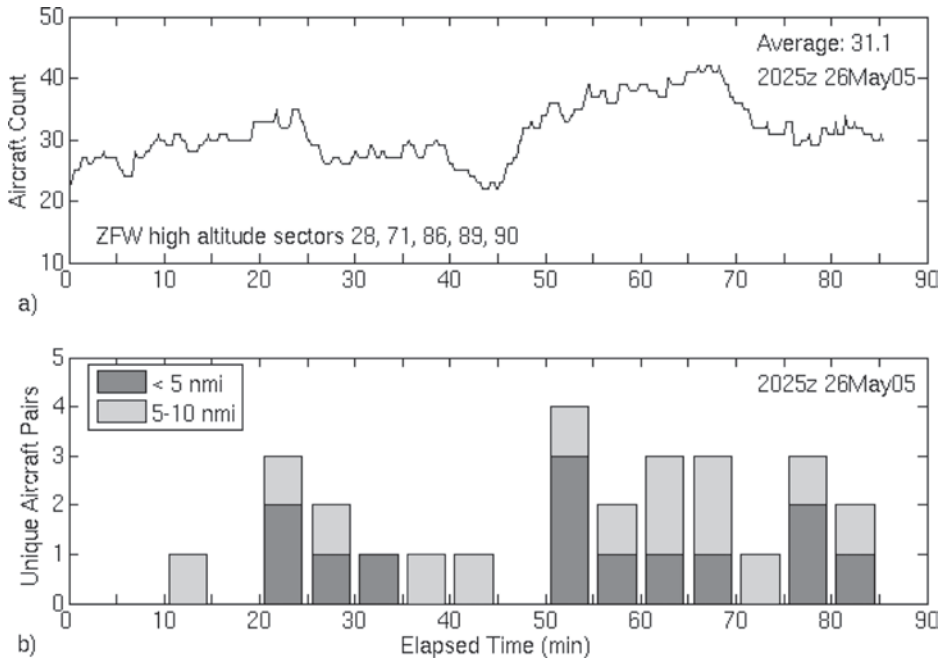
Figure 5. Separation characteristics, open-loop, five sectors: a) aircraft count, b) minimum separation metric.

horizontal separation standards (dark bars). This was not surprising, given that the traffic flow was effectively uncontrolled. Figure 5b illustrates the fundamental reason for the air traffic control system—to maintain safe separation. The number of open-loop loss of separation cases in Figure 5b is directly related to the number of control actions required to maintain safe separation in the airspace.

A closed-loop simulation was conducted in Conflict Resolution mode using the 90 min recording in the five-sector ZFW airspace. As described above, one controller (a NASA engineer) resolved all conflicts using the conflict list for alerting, the trial planner for resolutions, and a simulated data link for communication of control clearances to the aircraft. A pilot's wilco response was simulated by applying a fixed 24 s delay between the time a data link clearance was issued and the time the simulated aircraft responded.

Sectors 86 and 89 (see Figure 2) include two streams of DFW arrivals approaching the metering fix where they enter the DFW TRACON. All DFW arrivals were allowed to run live through the simulation airspace. In the case of conflicts that were displayed between a DFW arrival aircraft and a non-arrival aircraft, i.e., any other aircraft in the simulation airspace, the controller resolved the conflict by moving the non-arrival aircraft. This in effect removed the arrival merging and spacing problem from the simulation.

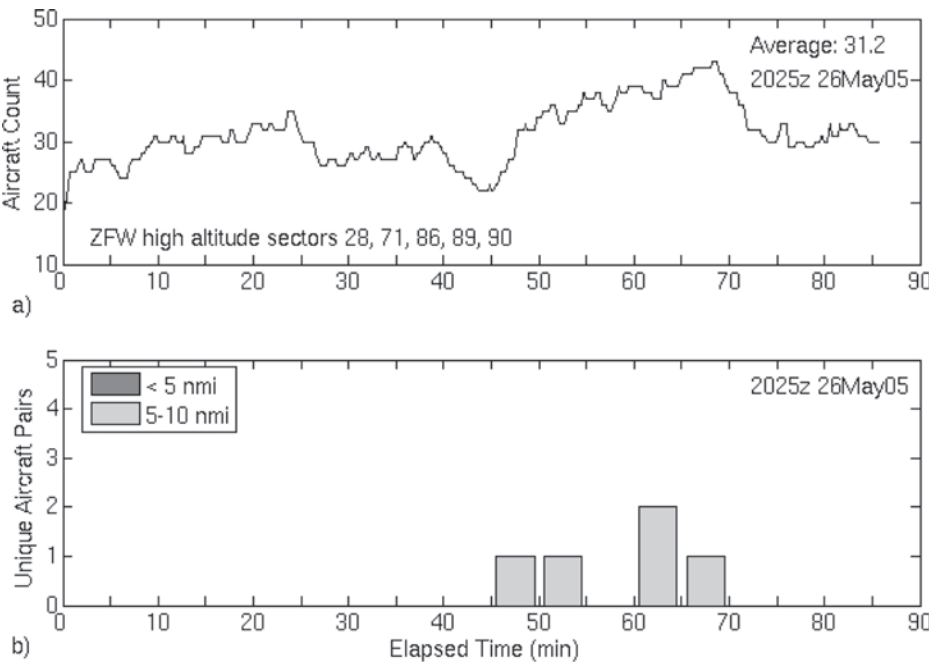Figure 6 shows a time history of the closed-loop traffic count and

Figure 6. Separation characteristics, closed-loop, Conflict Resolution mode, five sectors: a) aircraft count, b) minimum separation metric.

the minimum separation metric for the closed-loop five-sector run. Note that the minimum separation metric for closed-loop five-sector operations (Figure 6b) is very consistent, arguably a little better, than the minimum separation metric for the baseline run (Figure 4b). These data suggest that one controller operating with TBA and data link communications in a simulation environment can keep a nominal flow of aircraft in a five-sector region safely separated.

Actual route and altitude flight plan amendments issued to the departure and over-flight aircraft in the five-sector live traffic baseline are shown in Figure 7. It was assumed that flight plan amendments issued during the live traffic baseline were to maintain safe separation or to accommodate pilot requests. On average, approximately seven amendments were issued during each five-min interval. There were nearly twice as many altitude amendments as there were route amendments. Moreover, temporary altitude amendments accounted for 69 of the 84 altitude amendments (82%). Further analysis showed controllers issued multiple temporary altitude amendments, as many as four, to a given departure aircraft. Occurrences of multiple temporary altitude amendments may be attributed to the uncertainty associated with conflict detection and resolution for climbing aircraft under today's operations. It is common under today's operations for controllers to issue a temporary altitude clearance, and input an associated temporary altitude amendment,
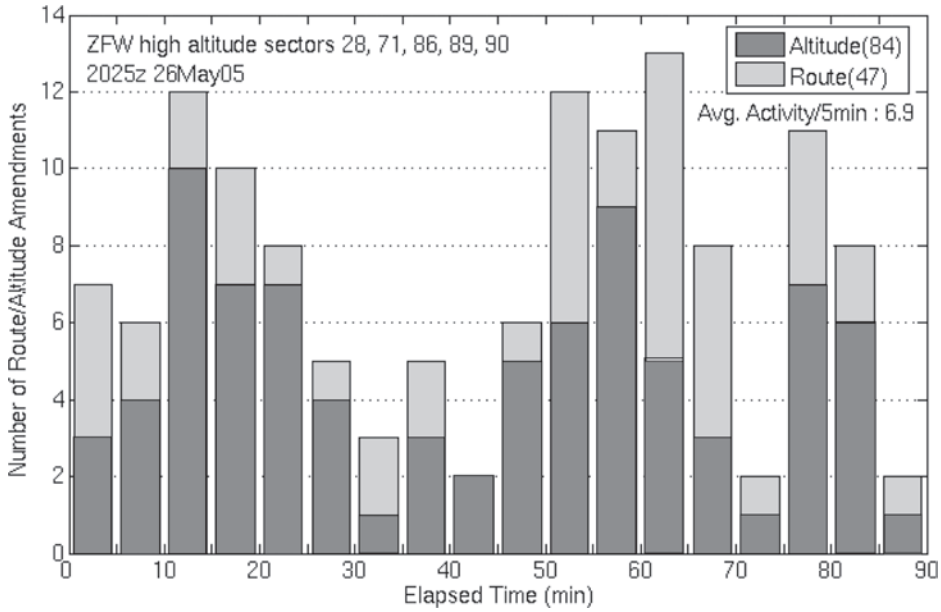
Figure 7. Flight plan amendment metric, five sectors, live traffic baseline.

to a climbing aircraft as an added safety measure only to cancel it and allow the aircraft to continue climbing uninterrupted through the temporary altitude.

The flight plan amendment metric for the closed-loop Conflict Resolution mode simulation is shown in Figure 8. The same filtering was applied to the closed-loop sample as was applied to the live sample to achieve an objective comparison of today's operation versus simulation operations. Since under Control by Exception operations aircraft were not deviated from their nominal route or altitude profile for any reason other than to resolve a conflict, amendment activity shown in Figure 8 can be viewed as a measure of the minimum number of amendments needed to maintain safe separation. The amendment activity in Figure 8 shows some correlation with the open-loop separation characteristics shown in Figure 5. There were no more than three amendments issued during any five min time interval, nor were there more than three aircraft with a minimum separation of less than 5 nmi. The substantial decrease in amendments under Control by Exception (Figure 8) compared with today's operations (Figure 7) is primarily due to the relatively large number of temporary altitude amendments issued under today's operations, and the fact that there were no direct route amendments issued during Conflict Resolution mode simulations. Under today's operations direct route amendments are relatively common in this airspace and are addressed further in the next section.
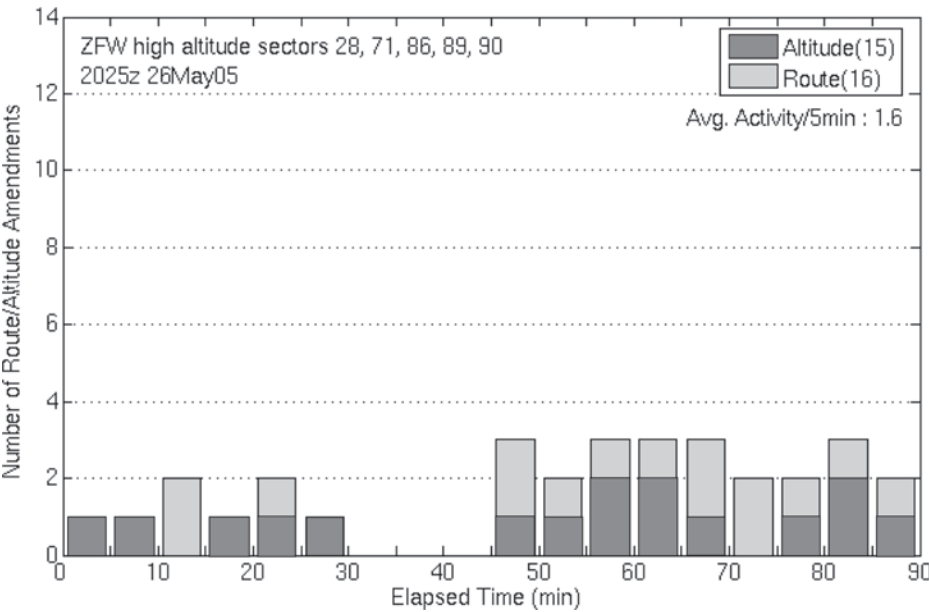
Figure 8. Flight plan amendment metric, five sectors, closed-loop, Conflict Resolution mode.

Conflict Resolution and Direct-To Mode—Today's Fort Worth Center Traffic

In today's operations, standardized routings are used to separate departure and arrival routes serving busy airports. This helps ensure that controller workload does not exceed safe levels during heavy arrival and/or departure flows. These procedures often result in dog-legged routings that may not always be necessary, depending on traffic conditions. In this section, the CTAS Direct-To function [Erzberger et al., 1999] is used in the simulation to analyze the separation characteristics and trajectory efficiency improvements that could be achieved if standard routings could be reduced or eliminated.

A closed-loop simulation was conducted using the five-sector ZFW airspace and the 90 min traffic sample described in the previous section. The simulation was run in Conflict Resolution & Direct-To mode where one controller (a NASA engineer) uses the trial planner to resolve all conflicts *and* issue all conflict-free Direct-To route amendments as soon as they appear on the Direct-To route advisory list. The 24 s wilco time delay was applied. The resulting traffic count and minimum separation metric are shown in Figure 9. Figure 9b clearly shows that the separation characteristics for this run are comparable to that of the baseline operations (Figure 4) and the Conflict Resolution simulation (Figure 6). During this run, Direct-To
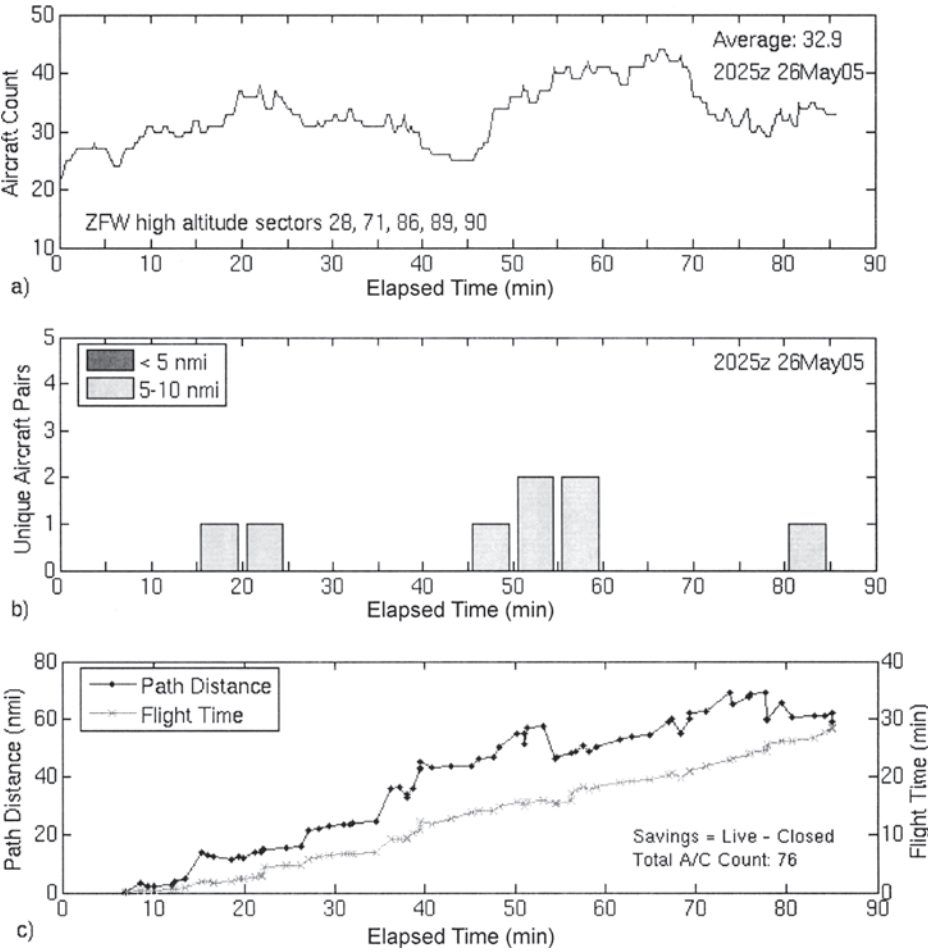
Figure 9. Separation characteristics, closed-loop, Conflict Resolution & Direct-To mode, five sectors: a) aircraft count, b) minimum separation metric, c) route efficiency metric.

route amendments were issued to 43 of the 167 simulated aircraft (26%) that flew through the airspace.

The net improvement in route efficiency was determined by applying the route efficiency metric to the baseline and closed-loop traffic data for this run. The route efficiency metric, as described earlier, measures the aggregate difference in path distance and flight time for a common traffic sample flying in a common airspace but under different operational procedures. In this case, the difference between today's operations (baseline) and the closed-loop Conflict Resolution & Direct-To mode simulation was measured. The difference in path distance and flight time for each aircraft was computed and accumulated as each aircraft exited the simulation airspace. For reference, the cumulative savings were plotted relative to the closed-loop exit time. Figure 9c shows the cumulative results of the route efficiency

analysis of the 76 aircraft that met the initial and exit point conditions defined for the route efficiency metric. As the simulation progressed the path distance and flight time savings increased as the controller issued Direct-To routes. As shown in Figure 9c, the cumulative flight time savings for all aircraft was 28 min. This equates to 1.9 percent of the flight time within the simulation region, e.g., the flight time from IP to Exit-A in Figure 3. For those aircraft that received Direct-To amendments, the flight time savings was 5.2 percent of the flight time within the simulation region. The results show that an efficiency improvement was achieved while maintaining separation assurance characteristics consistent with both today's operations (Figure 4b) and automated operations without improved routing (Figure 6b). The improved route efficiency was attributed to the TBA's ability to identify and safely circumvent the procedural delays inherent to today's sector-based operations.

The flight plan amendment metric for the closed-loop simulation conducted in the Conflict Resolution & Direct-To mode is shown in Figure 10. In this mode, the controller resolved all predicted conflicts and issued all Direct-To routes as described above. The direct route amendments issued in this scenario may be considered a rough approximation of pilot-requested plus controller-initiated direct route amendments under today's operations. Amendment activity in Figure 10 reflects direct route amendments plus amendments issued to maintain separation. The single controller operating with TBA
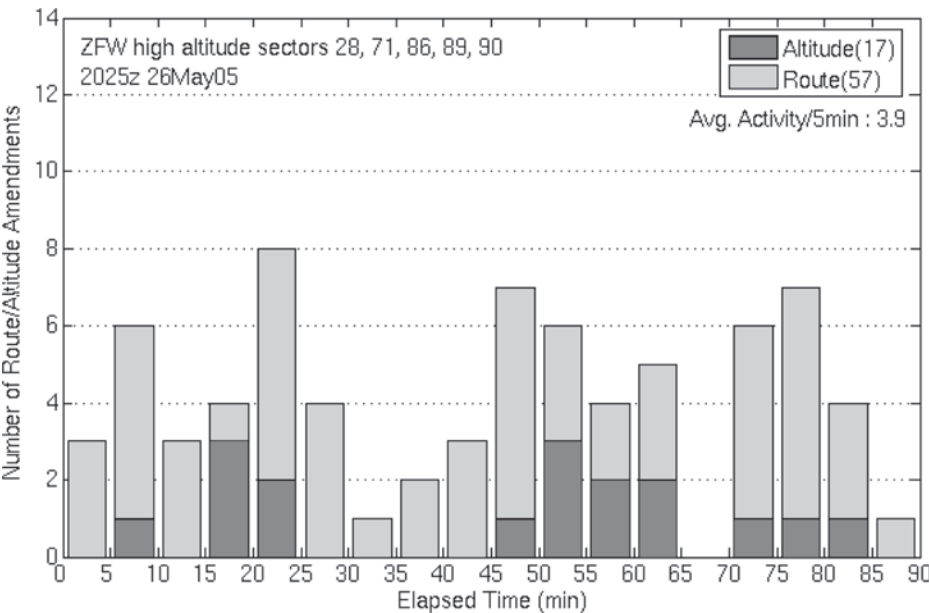

Figure 10. Flight plan amendment metric, five sectors, closed-loop, Conflict Resolution & Direct-To mode.

and data link communications issued an average of 4 amendments every 5 minutes, three fewer than the live traffic baseline shown in Figure 7. This difference may actually be larger since vectors or altitude changes that may have been issued verbally, but not entered into the Host computer, would not have been counted in the live traffic baseline. There were significantly fewer altitude amendments issued during the simulation, 17 compared to 84 for the live traffic baseline. This difference may be attributed to the increased precision and efficiency offered by trajectory-based conflict detection algorithms, minimizing the need to issue temporary altitudes as additional safety precautions as described above. There was approximately the same number of route amendments issued during simulation, indicating the single simulation controller was able to accommodate a comparable number of pilot requests handled by the live traffic controllers and still maintain safe separation between all aircraft.

Conflict Resolution Mode—Two-Times Today's Fort Worth Center Traffic

In this section the traffic load was nearly doubled to evaluate the ability of the TBA to enable improved efficiency *and* increased airspace capacity. The same five-sector ZFW airspace used in the previous simulations of today's traffic was used. The increased traffic level was achieved by combining recordings of two different traffic samples from the same airspace, but at different times of day. A morning traffic recording for a 90 min period starting at 0830 CST on June 2, 2005 was combined with the late afternoon baseline recording used in the previous simulations. A filtering process was used to ensure all aircraft were legally separated for their first two min in the simulation airspace. If an aircraft pair was not initially legally separated, one aircraft of the pair was deleted from the scenario. This filtering is consistent with today's operations, since transfer of separation assurance responsibility for an aircraft from an upstream controller to a downstream controller is typically not initiated when the upstream controller is aware of an impending conflict involving the aircraft in the downstream controller's airspace. In addition, any duplicate aircraft call signs were modified to avoid confusion. This method of increasing traffic load proved to be simple and effective for the purposes of this study. However, it was not based on rigorous projections of future traffic load and routing.

The minimum separation metric for the open-loop two-times nominal traffic simulation is shown in Figure 11. As expected, the number of aircraft pairs that pass with a minimum separation of less than the legal minimum of 5 nmi was substantially higher than in the open-loop nominal traffic simulation shown in Figure 5.
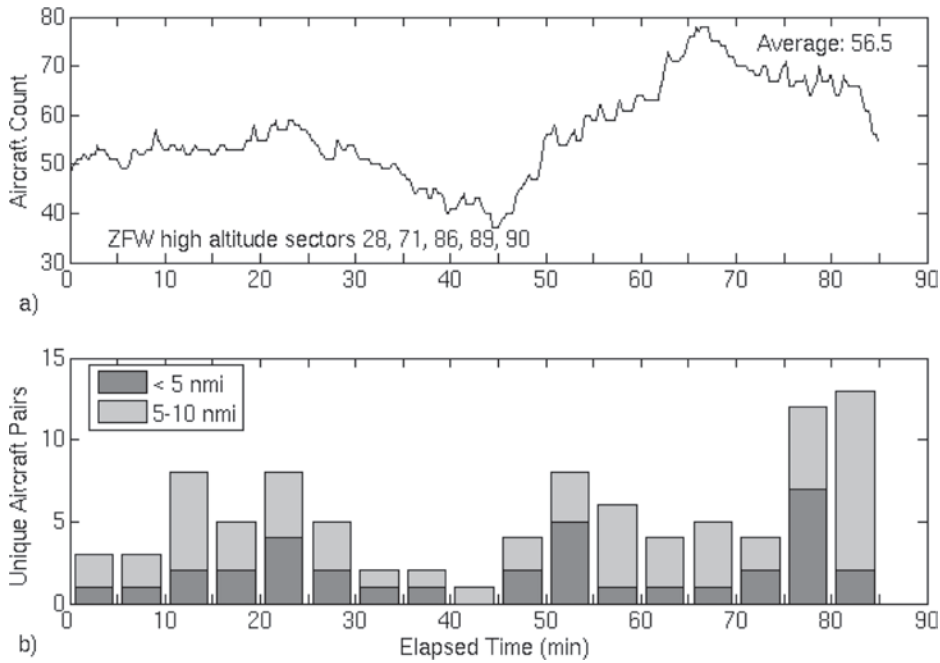
Figure 11. Separation characteristics, two-times nominal traffic, open-loop, five sectors: a) aircraft count, b) minimum separation metric.

A closed-loop simulation was performed using the Conflict Resolution mode. The traffic count and minimum separation metric for the run are shown in Figure 12. Figure 12b shows that under two-times nominal traffic there were usually about 1 or 2 independent aircraft pairs in the five-sector airspace region that were flying near legal separation criteria, i.e., with between 5 and 10 nmi separation. Clearly there were important exceptions to this norm, e.g., 7 aircraft pairs with 5–10 nmi minimum separation in the 75–80 min elapsed time period and one instance where legal separation was lost in the 30–35 min elapsed time period.

Any loss of separation is unacceptable in air traffic operations, so the cause of the loss of separation in Figure 12b was investigated. Post simulation analysis of the encounter revealed that, due to an error in the climb trajectory prediction for one of the aircraft, the conflict was not detected with enough lead time to resolve the conflict and prevent the loss of separation. Figure 13 shows that the nominal strategic climb trajectory under-predicted the actual climb rate of one of the aircraft (AAL708). Due to uncertainties in aircraft weight and climb speed, the climb trajectory predictions are the most challenging for today's 4D trajectory analysis methods.

The encounter was re-played using the tactical detection function [Paielli and Erzberger, 2005], which simultaneously probes both the strategic trajectory and the tactical trajectory and it was found that
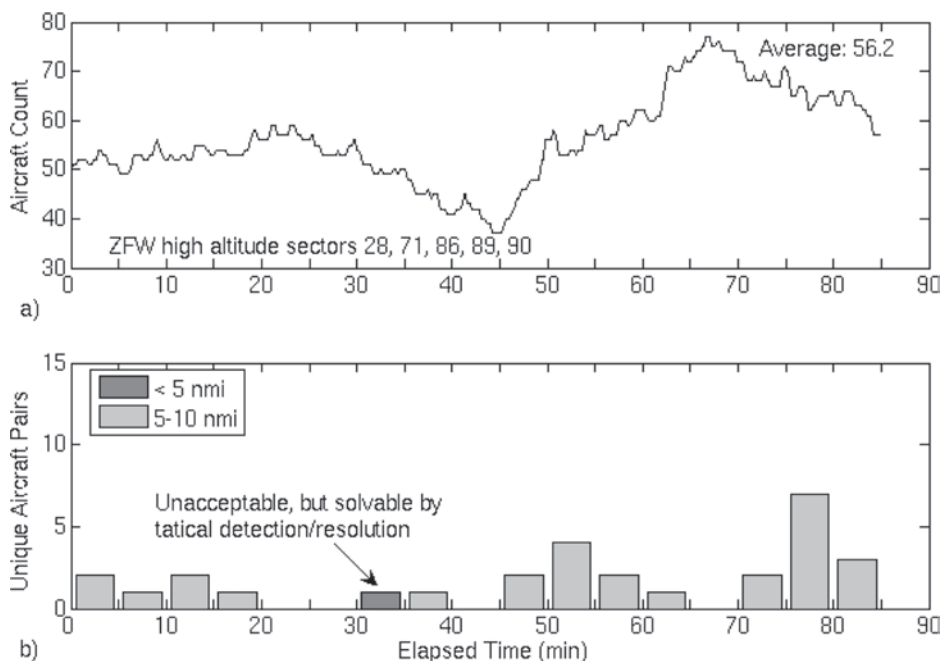
Figure 12. Separation characteristics, two-times nominal traffic, closed-loop, Conflict Resolution mode, five sectors: a) aircraft count, b) minimum separation metric.

the conflict was detected at 3 min before loss of separation. Three min would have allowed adequate time for the controller to have resolved the conflict. Figure 13 shows that the tactical trajectory for AAL708 better estimates the actual climb rate at this instance, resulting in an earlier conflict detection. (At the time of these simulations the tactical detection algorithm was not running simultaneously with the strategic conflict detection algorithms.) This loss of separation example and the post simulation analysis supports the concept of simultaneous analysis of strategic and tactical trajectories for separation assurance in trajectory-based operations with higher levels of automation [Erzberger, 2004].

CONCLUDING REMARKS

The conflict detection and trial planner resolution functions in the Center/TRACON Automation System were configured to examine how four-dimensional trajectory analysis methods could be extended to support higher levels of automation for separation assurance in the National Airspace System.

Human-in-the-loop laboratory simulations, typically 90 min in duration, were conducted where a human controller (a NASA engineer) manually generated conflict resolution trajectories using the inter-
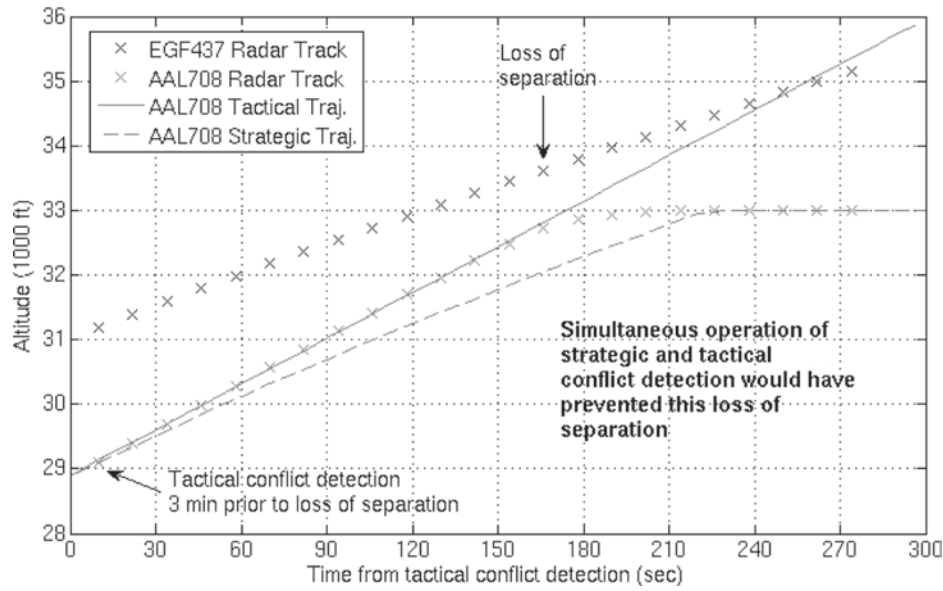
Figure 13. Tactical trajectory analysis predicts loss of separation case in two-times nominal run.

active trial planner resolution function, but only in response to conflicts detected and displayed by the conflict detection function. Resolution trajectories were issued to simulated aircraft via a simulated data link. Simulated aircraft automatically responded to resolution trajectories following a fixed 24 s compliance delay. Simulations were based on actual FAA traffic data from the Fort Worth Center. All conflict resolution trajectories were generated without consideration of routing restrictions or sector boundary considerations common in today's operations.

A single controller maintained legal separation (5 nmi horizontal or 1000 ft vertical) and improved the flying time efficiency by 1.9% while working the combined traffic in five Fort Worth Center high-altitude sectors at traffic levels nearly equivalent to that of today's traffic. Under laboratory conditions, the controller was performing the separation assurance functions that are performed by 4–10 people under today's operations.

During a five-sector simulation at today's traffic levels all aircraft that could save at least 1 min or more of wind-corrected flight time by flying conflict-free direct routes to a downstream fix on their route of flight were immediately given direct route amendments without regard for today's standard departure routings or inter-sector coordination considerations. The controller maintained legal separation and issued conflict-free direct route amendments while working the combined traffic in five Fort Worth Center high-altitude sectors at traffic levels nearly equivalent to that of today's traffic. The improve-

ment in flying time efficiency for the direct route aircraft alone was 5.2%.

The results suggest that the use of trajectory-based automation has the potential to substantially reduce the number of altitude amendments required to ensure separation under today's traffic levels.

During a simulation run at nearly *two-times* today's traffic levels, in the combined five-sector Fort Worth Center airspace, a single controller maintained separation in all but one instance. A post-simulation analysis showed that a tactical alerting function predicted the loss of separation at 3 min prior to loss of separation. Three minutes is generally considered enough time for a controller to resolve a conflict and prevent a loss of separation.

A trajectory uncertainty analysis showed that the trajectory prediction uncertainty associated with the simulations in this study, where traffic flows were initialized with actual FAA traffic data, is roughly consistent with the trajectory prediction uncertainty associated with more realistic conditions, where predictions are based fully on FAA traffic data. This makes the results more meaningful, since uncertainty is an unavoidable aspect of trajectory-based operations.

APPENDIX—TRAJECTORY PREDICTION UNCERTAINTY

A quantitative comparison of the trajectory prediction uncertainty associated with a given actual Center traffic sample with that of a simulated traffic sample initialized with the actual Center traffic sample provides insight as to the applicability of simulation results to the real-world environment. The trajectory accuracy analysis methodology described in [Gong and McNally, 2004] uses large numbers of trajectory predictions to provide an aggregate measure of accuracy, which reflects the combined effect of all errors sources such as wind, speed, and weight. Error characteristics are categorized as a function of flight phase (level, climbing, descending) and look-ahead time. The methodology was applied to the actual traffic sample and to the open-loop simulated traffic sample for one of the 90 min 5-sector Fort Worth Center traffic samples used in this analysis. The histogram in Figure 14 shows the level-flight trajectory error characteristics at a 10 min look-ahead time for the actual traffic sample. Based on analysis of 185 level flight actual traffic trajectory predictions, the mean along-track prediction error is −0.7 nmi and the standard deviation is 3.2 nmi. Figure 15 shows the corresponding along-track error characteristics for the simulated traffic sample that was only initialized with the actual traffic sample (173 level flight trajectory predictions, mean error = 1.4 nmi, standard
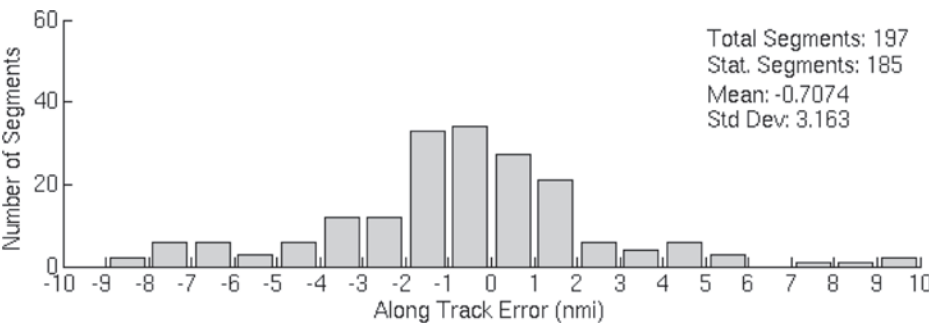
Figure 14. Level flight trajectory accuracy, actual traffic baseline, along track error, 10 min look-ahead.
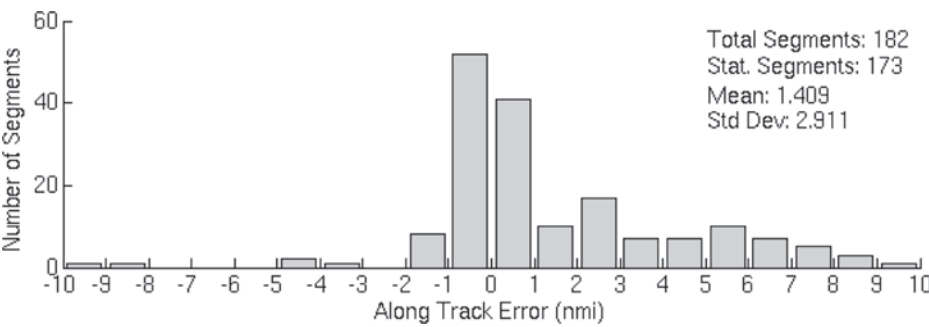

Figure 15. Level flight trajectory accuracy, simulated traffic, along track error, 10 min look-ahead.

deviation = 2.9 nmi). Though the actual traffic errors appear a little more normally distributed than the simulated traffic errors, the overall error characteristics are roughly similar. The climb trajectory error characteristics were analyzed and presented in the original version of this paper [McNally and Gong, 2006].

ACRONYMS

CDTI   Cockpit Display of Traffic Information
CST   Central Standard Time
CTAS   Center/TRACON Automation System
DFW   Dallas/Fort Worth International Airport
DST   Decision Support Tool
FAA   Federal Aviation Administration
IP   Initialization Point
NAS   National Airspace System
NASA   National Aeronautics and Space Administration
NGATS   Next Generation Air Transport System
NOAA   National Oceanic and Atmospheric Administration
RUC   Rapid Update Cycle

TBA   Trajectory-Based Automation
TRACON   Terminal Radar Approach Control
ZFW   Fort Worth Center
4D   Four-Dimensional

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David McNally is a Principal Investigator for air traffic management research at NASA Ames Research Center. He has worked over the past twelve years in laboratory development and analysis, human-in-the-loop simulation evaluation and operational testing of conflict detection and resolution automation for air traffic management. Previously he conducted flight research on the use of satellite navigation for precision landing guidance. He is currently the Associate Principal Investigator for Separation Assurance under NASA's research in support of the Next Generation Air Transportation System. He holds an MS degree in Mechanical Engineering and a BS degree in Mechanical/Aeronautical Engineering, both from the University of California, Davis.

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