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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 planning resolution 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 to that of today's operations using common airspace and traffic scenarios. Simulations were based on recorded air traffic data from Fort Worth and Cleveland Centers and conducted using today's and nearly two-times today's traffic levels. 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 they do now 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.

I. Introduction

In its Next Generation Air Transportation System (NGATS) report [1] the multi-agency Joint Planning and Development Office describes an expected two- to threefold increase in air traffic demand by the year 2025 and describes new automation technologies and operating procedures needed for the National Airspace System (NAS). 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. Decision Support Tools (DST) developed and deployed in recent years provide trajectory-based automation and information that assist 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, DST-based concepts and technologies alone are not expected to support a two- to threefold increases 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 [2]. Concepts for delegation of separation assurance to the cockpit through airborne automation and cockpit display of traffic information [3-5] have been proposed, as have concepts that employ a mix of controller-managed and airborne separation assurance methods [6]. 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.

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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 [2,7] 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 [8]. In the simulations described herein, following a detected conflict, the controller uses the trajectory-based automation 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 FAA en route Center radar track and flight plan data augmented with 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 simulations is described, and objective metrics are defined which 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 or more sectors under nominal and two-times nominal traffic levels using Fort Worth and Cleveland Center traffic data. The paper closes with some concluding remarks. Since uncertainty is an important consideration in trajectory-based operations, the results of any analysis of trajectory-based automation should be considered in light of the trajectory prediction uncertainty inherent to the analysis. The Appendix describes the application of a trajectory prediction accuracy methodology [9] that was used to compare trajectory predictions based *fully* on Center track and flight plan data to the trajectory predictions used in this simulation that were only *initialized* with Center track and flight plan data.

II. Simulation Methodology

The simulation methodology is based on an operating philosophy where all traffic conflicts are assumed to be detected by the trajectory-based automation and all trajectory changes, including conflict resolution trajectories and pilot-requested route or altitude changes, are generated and implemented using the trajectory-based automation. Mature trajectory analysis methodologies and software previously developed for decision support tools are configured to run such that they automatically detect and provide the necessary automation to resolve all traffic conflicts. 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 be needed 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 [10-16]. 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 sec updates) and flight plan amendment data from the Center Host computer, hourly updates of wind predictions from National Oceanic and Atmospheric Administration (NOAA) Rapid Update Cycle 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 [17-19]. A tactical conflict detection function (TSAFE) is being analyzed as a potential enhancement to the legacy Host Conflict Alert function [7] and is the basis for the backup tactical conflict alerting function in this analysis.

A fundamental requirement of the simulation methodology was to develop a means for the trajectory-based automation (CTAS conflict prediction and trial planning functions) 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 amendments 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 [20]. Consider the notional airspace shown in Fig. 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, which are received every 12 sec, 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 handoff 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 [21]. 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 wind data. All subsequent flight plan amendments (route or altitude) are generated by the trajectory-based automation 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, because the conflict resolution automation was not well configured to solve conflicts between arrivals merging to a common metering fix.

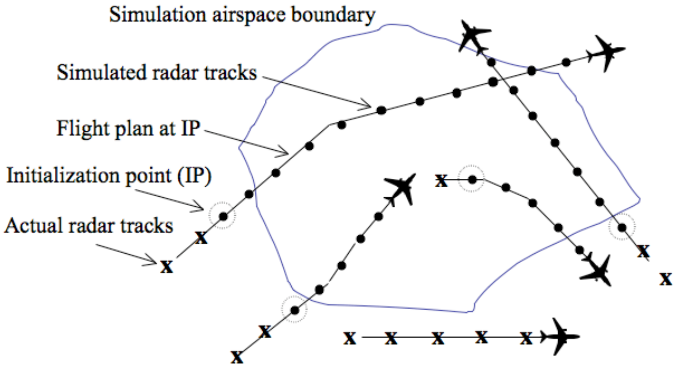

Figure 1. Simulation methodology

This study defines the open-loop traffic flow as that which results when all simulated aircraft in the simulation airspace fly an un-interrupted (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 trajectory-based automation provides separation assurance in the simulation airspace. Closed-loop simulation operations were conducted according to the feedback control diagram in Fig. 2. The trajectory-based automation (TBA) includes the CTAS 4D trajectory analysis, conflict prediction, trial planning, and graphical user interface functions. A human controller monitors a list of traffic conflicts predicted by the TBA. The controller uses the TBA trial planner automation to manually generate flight plan amendments (FP AM) that resolve all traffic conflicts. When the controller inputs the flight plan amendment, it is sent to the aircraft simulator without voice communication. The pilot is modeled as a simple "wilco" time delay. A fixed wilco delay of 24 seconds was used for all the simulation runs in this analysis. Following the time delay, the flight plan amendment is sent to the simulated aircraft and the TBA. The TBA updates the trajectory database with the flight plan amendment, and the aircraft simulator flies the aircraft and generates subsequent radar track updates consistent with the flight plan amendment. This process simulates data link communication of control clearances to aircraft. Requiring a wilco from the aircraft before the TBA updates the flight plan is expected to be an important aspect of the coordination process in automated airspace operations with

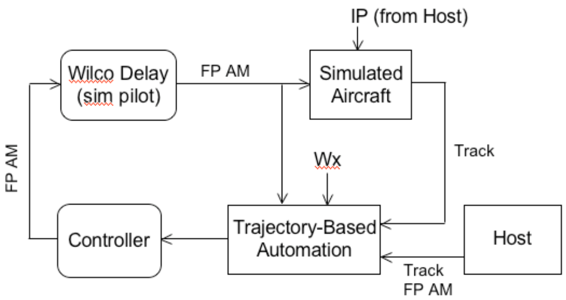

Figure 2. Closed-loop simulation architecture

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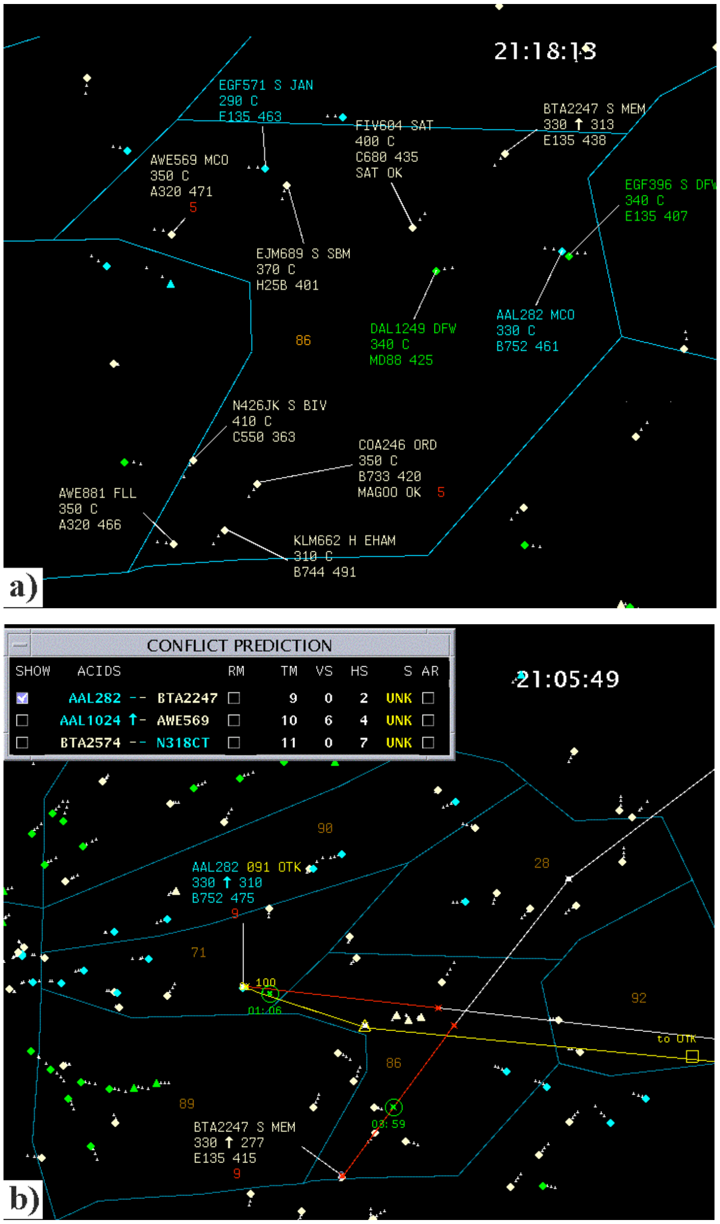
data link communications. In this analysis, flight plan amendments are generated by a human controller operating the trial planner, but the methodology should be suitable for the analysis any trajectory-based automation concept.

III. Operating Concept

Figure 3 illustrates the difference between today's operations and the Control by Exception operations being investigated in this study. Under today's operations (Fig. 3a), the controller monitors a radar display showing radar track positions and flight data block information for all aircraft in their 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 trajectory-based automation detects traffic conflicts and displays them to the controller through a conflict list or other suitable user interface mechanism as shown in Fig. 3b. Because the controller was not asked to identify potential conflicts as in today's operations, the information traditionally presented in the flight data block was not needed. Therefore, flight data blocks were not displayed by default. When two aircraft were predicted in conflict by the automation, the controller could display 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 [17-19] to resolve the conflict.

As shown in Fig. 3b, the controller used 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 Fig. 3b was a workable nominal display format.

Two operating modes were used during the simulations. Under the 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 trajectory-based automation. 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,



SHOW	ACIDS	RM	TM	VS	HS	S	AR
☑	AAL282 -- BTA2247	☐	9	0	2	UNK	☐
☐	AAL1024 ↑- AWE569	☐	10	6	4	UNK	☐
☐	BTA2574 -- N318CT	☐	11	0	7	UNK	☐

Figure 3. Controller's radar display: a) today's single sector operations, b) five-sector Control by Exception operations.

and 3) vector to an auxiliary waypoint followed by a direct route to a downstream flight plan fix (shown in Fig 3b). 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 criteria. As an example, the aircraft pair of BTA2574 and N318CT in Fig. 3b 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 criteria remained at the legal vertical separation criteria of 1000 ft. To provide an additional safety margin when changing trajectories, the separation criteria for trial planning was set higher than that for alerting. The separation criteria for trial planning was set to 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 [15]. 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.

IV. Metrics

A. 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 laterally or 1000 ft vertically) 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 Fig. 3b. 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 minutes, 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.

B. 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 trajectory-based automation 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 Fig. 4 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 (described later). 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 Fig. 4 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 shortcuts, which generally improve efficiency, and vectors for traffic, which generally reduce efficiency.

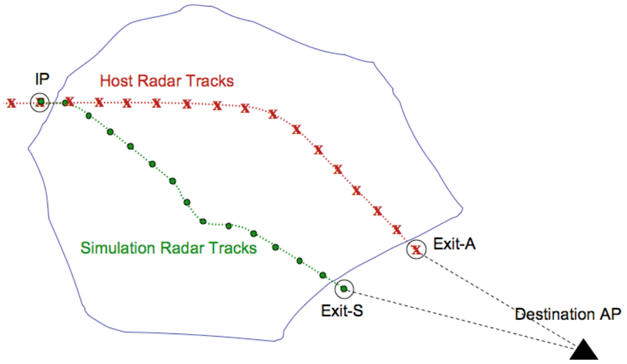


Figure 4. Route efficiency metric

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 wind field.

Flying time was calculated by integrating ground speed (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 a standardized 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 standardized 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) wind at each track point. Standardized ground speed is then calculated from the standardized true airspeed and wind. The flying time resulting from the integration of the standardized groundspeed of each aircraft were then compared, allowing differences to be 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 equivalent flying time from the IP to the actual exit point (Exit-A) were computed using Host radar track data. The path distance and equivalent 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 equivalent 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 total path distance and equivalent flying time for each set of routes were differenced to compare actual route efficiency with simulated route efficiency.

C. Flight Plan Amendment Metric

The number of flight plan amendments a controller implements while controlling traffic is one objective measure of controller workload. 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 comparison, 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.

V. Analysis and Results

A. 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 for the first series of runs. The combined five-sector airspace is shown in Fig. 5 and includes flight levels from FL240 and above. This airspace was chosen because it includes a good mix of climbing Eastbound departures from the Dallas/Ft Worth International 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 6a shows a time history of the total traffic count in the five-sector region. Figure 6b shows the minimum separation 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 Fig. 6b. This baseline minimum separation analysis reflects the actions of actual controllers working the traffic under today's operations. 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 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.

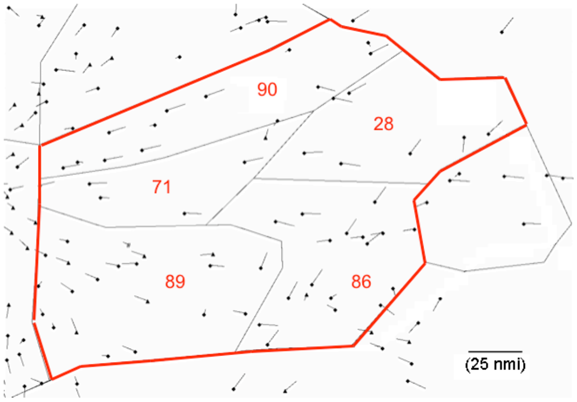


Figure 5. Fort Worth Center five-sector simulation airspace

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 7a 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 7b shows the minimum separation metric for the open-loop run. Note that Fig. 7b shows numerous instances where aircraft violated the vertical and horizontal separation standards (red bars). This was not surprising, given that the traffic flow was effectively uncontrolled. Fig. 7b illustrates the fundamental reason for the air traffic control system – to maintain safe separation. The amount of red showing in Fig. 7b directly reflects the number of control actions that are required to maintain safe separation in the airspace.

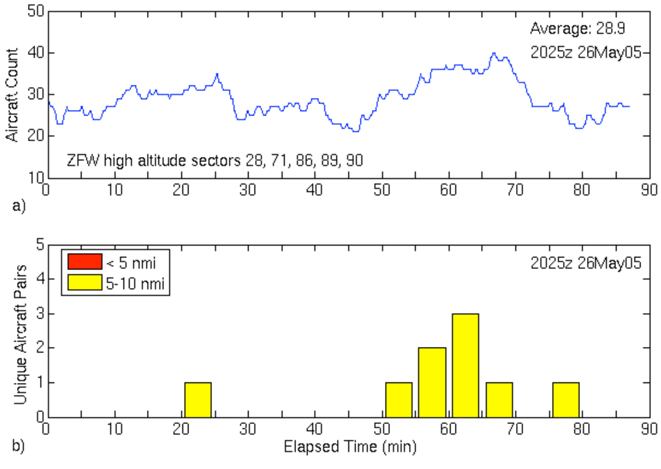


Figure 6. Separation characteristics, today's live traffic baseline, five sectors: a) aircraft count, b) minimum separation metric.

A closed-loop simulation was conducted in Conflict Resolution mode using the 90 min recording in the five-sector ZFW airspace. As described above, in Conflict Resolution mode one controller (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 was simulated by applying a fixed 24 sec delay between the time a data link clearance was issued and the time the simulated aircraft responded.

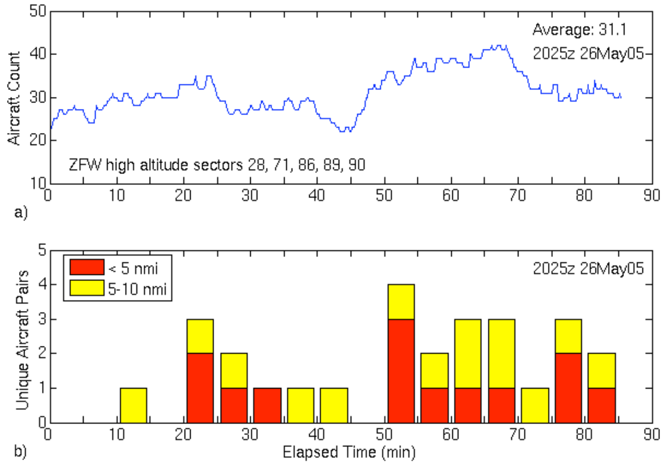


Figure 7. Separation characteristics, open-loop, five sectors: a) aircraft count, b) minimum separation metric.

Sectors 86 and 89 (Fig. 5) include two streams of DFW arrivals approaching the metering fix where they enter the DFW TRACON. Since the trial planner was not well suited for solving conflicts between arrival aircraft approaching a common metering fix, these arrival flows 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 8 shows a time history of the closed-loop traffic count and the minimum separation metric for the closed-loop five-sector run. Note that the minimum separation metric for closed-loop five-sector operations (Fig. 8b) is very consistent, arguably a little better, than the minimum separation metric for the baseline run (Fig. 6b). These data suggest that one controller operating with trajectory based automation and data link communications in a simulation environment can keep a nominal flow of aircraft in a five-sector region safely separated.

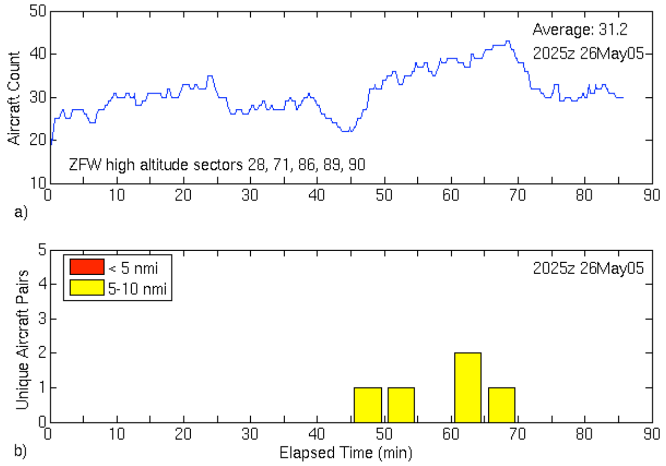


Figure 8. Separation characteristics, closed-loop, Conflict Resolution mode, five sectors: a) aircraft count, b) minimum separation metric.

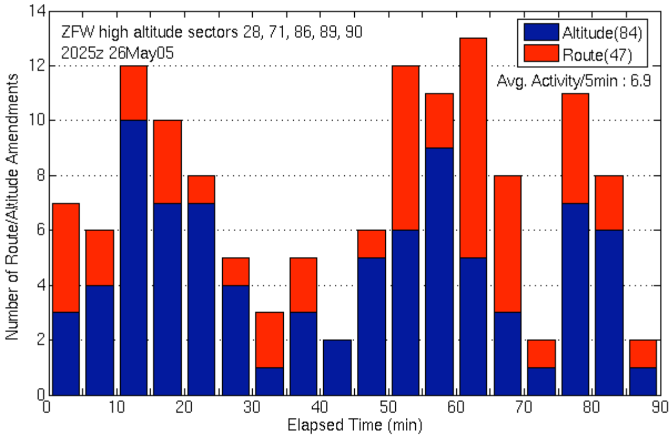


Figure 9. Flight plan amendment metric, five sectors, live traffic baseline

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 Fig. 9. 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, 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 Fig. 10. 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 solve a conflict, amendment activity shown in Fig. 10 can be viewed as a measure of the minimum number of amendments needed to maintain safe separation. The amendment activity in Fig. 10 shows some correlation with the open-loop separation characteristics shown in Fig. 7. There were no more than 3 amendments issued during any five min time interval, nor were there more than 3 aircraft with a minimum separation of less than 5 nmi. The substantial decrease in amendments under Control by Exception (Fig. 10) compared to today's operations (Fig. 9) 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.

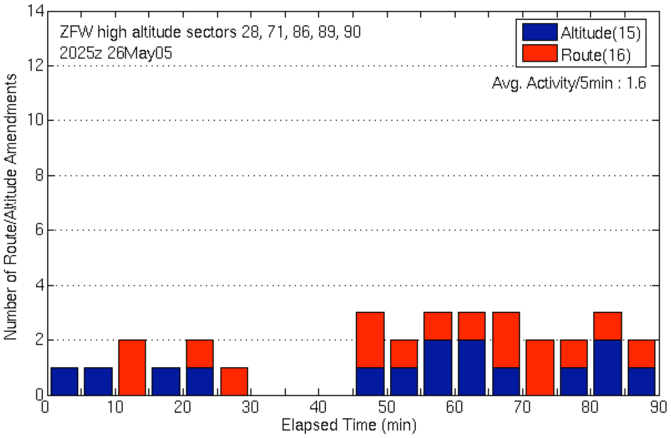


Figure 10. Flight plan amendment metric, five sectors, closed-loop, Conflict Resolution mode

B. Conflict Resolution & 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. A typical example of a departure routing is shown in Fig. 11. Under trajectory-based operations we might speculate that the more direct routing in Fig. 11 could be the nominal trajectory and the aircraft could be deviated only when the 4D trajectory analysis determines that such a deviation is necessary, perhaps due the to presence of a busy arrival stream.

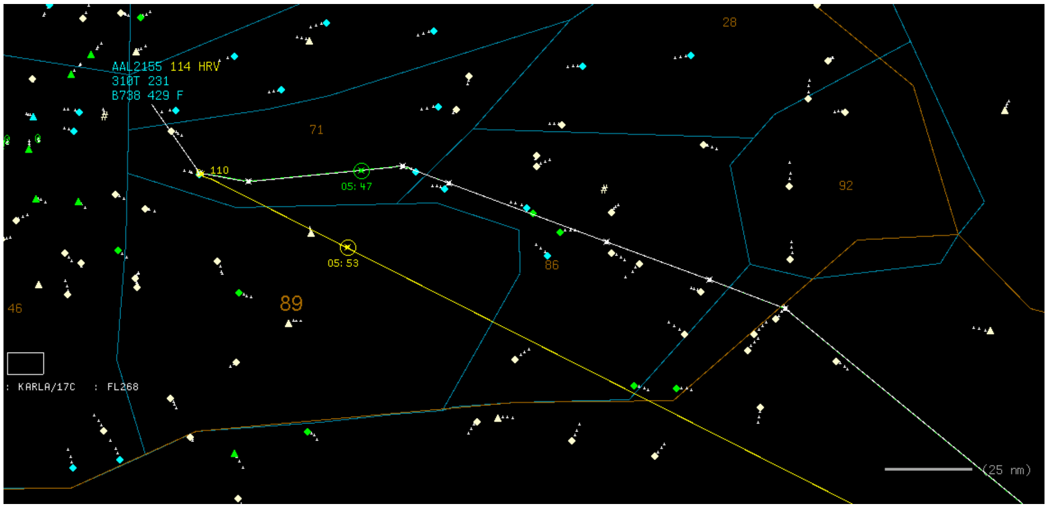


Figure 11. Example of procedural delay due to standard departure routing

In this section, the CTAS Direct-To function [15] is used in the simulation to analyze the separation characteristics and trajectory efficiency improvements that could be achieved if standard routings, such as that shown in Fig. 11, could be eliminated or reduced. Analysis of ZFW traffic has shown that the savings for the shortcut shown in Fig. 11 is typically about 2 min of flying time depending on wind conditions. It is common for the Direct-To function to identify direct route shortcuts such as that shown in Fig. 11. The DFW departure (AAL2155) was flying a flight plan represented by the white line that takes a less direct route around the arrival sector 89. The yellow line represents a time saving Direct-To route through sector 89. In the Fig. 11 example the direct route was conflict free and the traffic count in Sector 89 was low enough to not be adversely affected by additional aircraft flying through the sector.

A closed-loop simulation was conducted using the five-sector ZFW airspace and the 90 min traffic sample described in the Section V-A. The simulation was run in Conflict Resolution & Direct-To mode, where as described above, one controller (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 sec wilco time delay was applied. The resulting traffic count and minimum separation metric are shown in Fig. 12. Figure 12b clearly shows that the separation characteristics for this run are comparable to that of the baseline operations (Fig. 6) and the Conflict Resolution simulation (Fig. 8). During this run, Direct-To route amendments were issued to 43 of the 167 simulated aircraft (26%) that flew through the airspace.

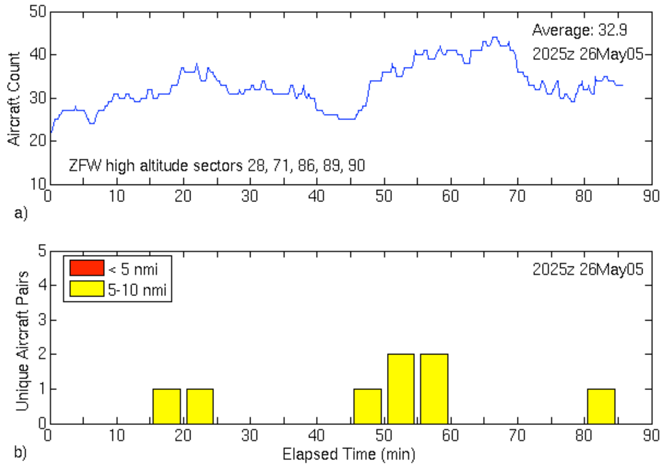


Figure 12. Separation characteristics, closed-loop, Conflict Resolution & Direct-To mode, five sectors: a) aircraft count, b) minimum separation metric.

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 13 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 Conflict Resolution & Direct-To mode simulation progressed, the path distance and flight time savings increased as the controller issued Direct-To routes. As shown in Fig. 13, 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 Fig 4. 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 (Fig 6b) and automated operations without improved routing (Fig 8b). The improved route efficiency was attributed to the trajectory-based automation's ability to identify and safely circumvent the procedural delays inherent to today's sector-based operations.

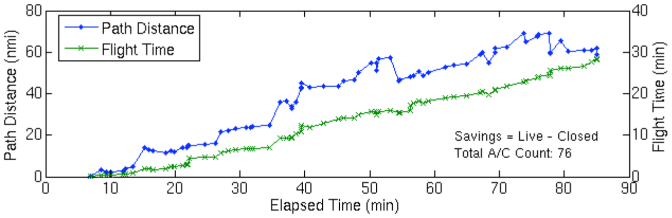


Figure 13. Route efficiency metric, closed-loop, Conflict Resolution & Direct-To mode, five sectors.

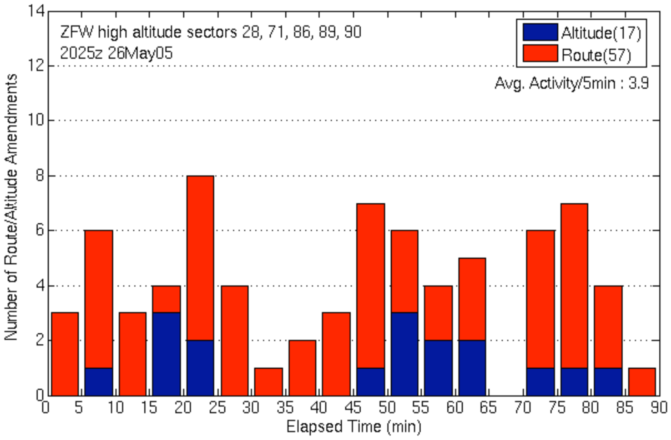


Figure 14. Flight plan amendment metric, five sectors, closed-loop, Conflict Resolution & Direct-To mode.

The flight plan amendment metric for the closed-loop simulation conducted in the Conflict Resolution & Direct-To mode is shown in Fig. 14. 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 Fig. 14 reflects these amendments as well as amendments issued to maintain separation. The single controller operating with trajectory based automation and data link communications issued an average of 4 amendments every 5 minutes, three fewer than the live traffic baseline shown in Fig. 9. 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 were 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.

C. 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 trajectory-based automation to enable improved efficiency *and* increased airspace capacity. The same five-sector ZFW airspace described in Section V-A 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 described in Section V-A. 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 an upstream controller would not hand-off to a downstream airspace sector a pair of aircraft that are nearly in conflict. 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.

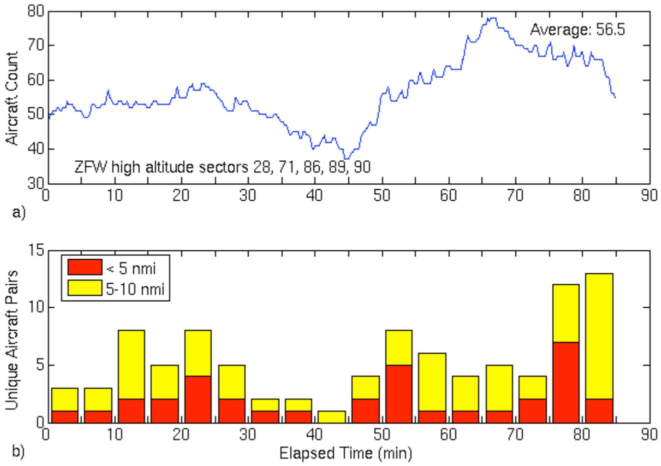


Figure 15. Separation characteristics, two-times nominal traffic, open-loop, five sectors: a) aircraft count, b) minimum separation metric.

The minimum separation metric for the open-loop two-times nominal traffic simulation is shown in Fig. 15. 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 Fig. 7.

A closed-loop simulation was performed using the Conflict Resolution mode. The traffic count and minimum separation metric for the run are shown in Fig. 16. Fig. 16b 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.

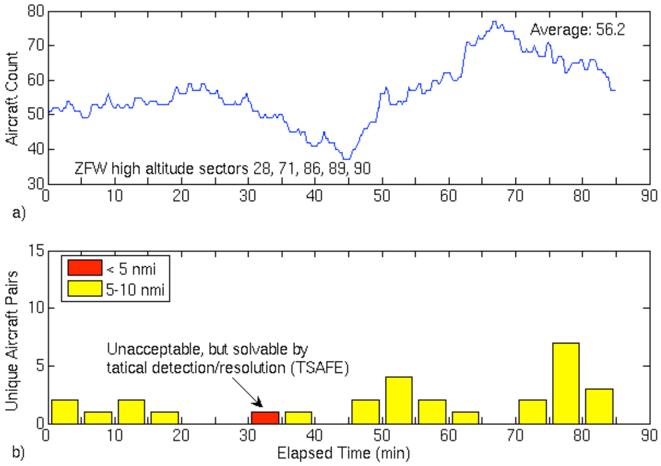


Figure 16. Separation characteristics, two-times nominal traffic, closed-loop, Conflict Resolution mode, five sectors: a) aircraft count, b) minimum separation metric.

Any loss of separation is unacceptable in air traffic operations, so the cause of the loss of separation in Fig. 16b 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. Fig. 17 shows that the nominal strategic climb trajectory under-predicted the actual climb rate of one the aircraft (AAL708). Due to uncertainties in aircraft weight and climb speed, climb predictions are the most challenging for today's 4D trajectory analysis methods.

The encounter was re-played using the TSAFE tactical detection function [7], which simultaneously probes both the strategic trajectory and the tactical trajectory and it was found that the conflict was detected at 3 min before loss of separation. Three minutes would have allowed adequate time for the controller to have resolved the conflict. Figure 17 shows 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 TSAFE 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 [2].

D. Conflict Resolution Mode – All Fort Worth Center High Altitude Sectors

In this section, the airspace region is expanded to include all eighteen high altitude sectors in Fort Worth Center airspace. The simulation and analysis were based on ZFW Host radar track and flight plan data recorded over a 90 min period starting at 1525 CST on May 26, 2005 (same period used in previous nominal traffic five-sector analysis). The baseline minimum separation metric for actual controller operations during the 90 min period is shown in Fig. 18. The average traffic count in the simulation airspace increased from 29 for the five-sector airspace (Fig. 6a) to 122 for the eighteen-sector airspace (Fig. 18a). As expected, Fig. 18b shows that when the entire high altitude airspace was considered, one or more aircraft pairs were nearly always flying with a minimum separation between 5 and 10 nmi.

The minimum separation metric for an open-loop simulation of the eighteen-sector airspace is shown in Fig. 19. When compared to the open-loop separation metric of the five-sector simulation airspace shown in Fig. 7, there was a clear increase in the number of aircraft that needed to be separated by a controller.

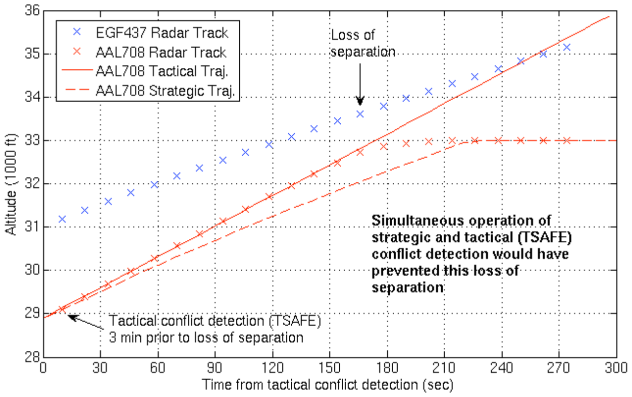


Figure 17. Tactical trajectory analysis predicts loss of separation case in two-times nominal run

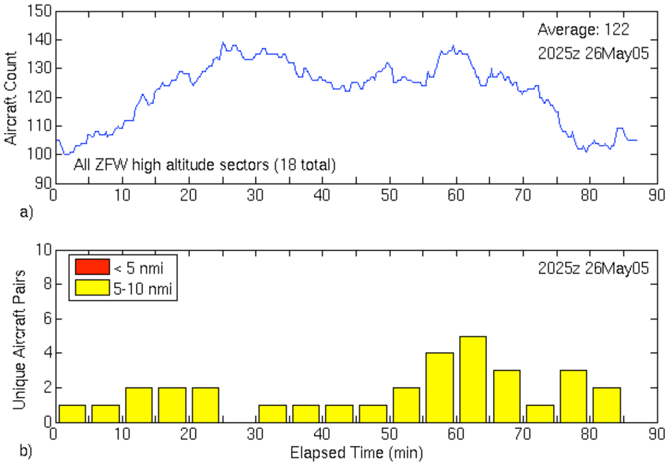


Figure 18. Separation characteristics, live traffic baseline, all ZFW high sectors: a) aircraft count, b) minimum separation metric.

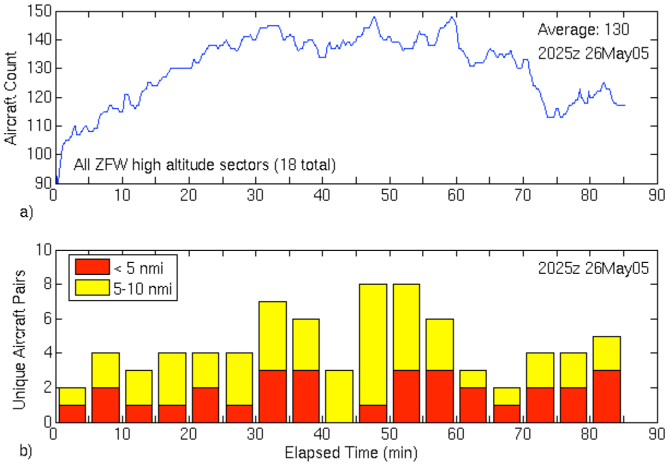


Figure 19. Separation characteristics, open-loop, all ZFW high sectors: a) aircraft count, b) minimum separation metric.

A closed-loop simulation was conducted using the Conflict Resolution mode. As with previous simulations, all arrivals to DAL and DFW remained live (i.e., not simulated). Conflict pairs involving a simulated and a live aircraft were resolved by moving the simulated aircraft. Figure 20 shows the minimum separation metric for the closed-loop simulation. First note that the closed-loop separation characteristics for all high sectors combined indicated a lower level of aircraft pairs near legal separation than in the five-sector two-times-nominal traffic run reflected in Fig. 16b. In this case, two loss of separation cases were observed (Fig. 20b), but the post test analysis showed that both were detected by the TSAFE analysis as described in the previous section.

E. Conflict Resolution Mode – Two-Times Today's Cleveland Center Traffic

In this section a region in the Cleveland Center (ZOB) airspace where traffic is known to be particularly complex is analyzed. Cleveland Center high altitude sectors 45, 47, and 49 were chosen as the simulation airspace. The lower altitude boundary for these sectors is Flight Level 310 (FL310). A traffic scenario made up of two-times the nominal traffic level was created using the techniques described earlier. An evening traffic recording for a 90 min period starting at 1716 CST on December 19, 2005 was combined with a 90 min morning traffic period starting at 0840 CST on December 21, 2005.

The 3-sector ZOB simulation airspace, together with the two-times-today's traffic, was approximately 2.5-times denser than two-times-today's ZFW simulation airspace. The traffic density was calculated by dividing the average number of aircraft in the simulation by the simulation airspace volume. Airspace volume of each simulation region was calculated by arbitrarily setting the upper altitude boundary to a common value of FL450 while the lower altitude boundary remained as defined during the simulation. The average number of aircraft per airspace volume for the two-times-nominal ZOB simulation was 0.277 (1000 sq. nmi x 1000 ft). For the two-times-nominal ZFW simulation, traffic density was calculated to be 0.113 per airspace volume (1000 sq. nmi x 1000 ft). The minimum separation metric for the open-loop simulation is shown in Fig. 21. With the exception of the uncharacteristic first 15 min of the scenario, the number of aircraft pairs that lost separation, or nearly so (yellow), was higher in this run than for the two-times-nominal ZFW simulation shown in Fig. 15.

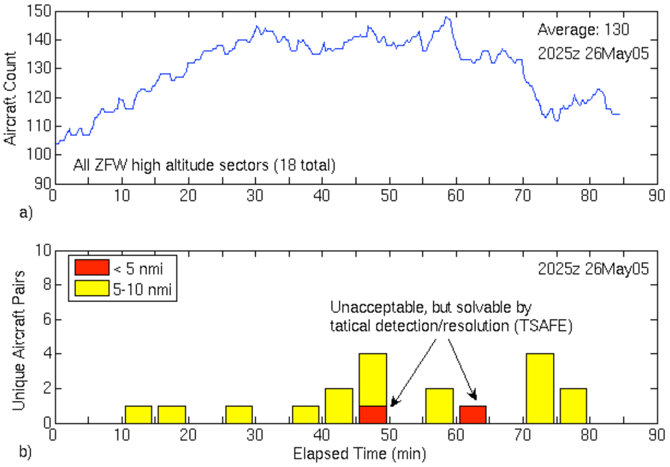


Figure 20. Separation characteristics, closed-loop, Conflict Resolution mode, all ZFW high sectors: a) aircraft count, b) minimum separation metric.

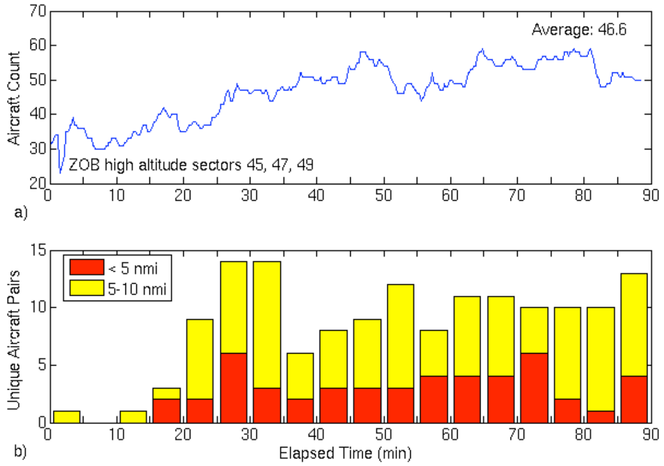


Figure 21. Separation characteristics, two-times nominal traffic, open-loop, three ZOB high sectors: a) aircraft count, b) minimum separation metric.

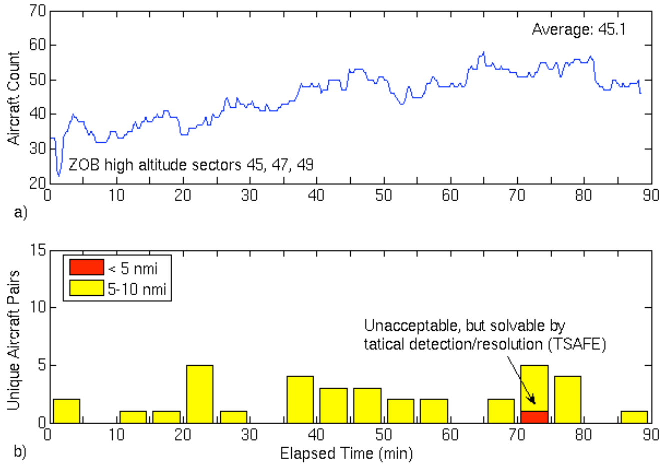


Figure 22. Separation characteristics, two-times nominal traffic, closed-loop, Conflict Resolution mode, three ZOB high sectors: a) aircraft count, b) minimum separation metric.

The minimum separation metric for the corresponding closed-loop, Conflict Resolution mode simulation is shown in Fig. 22. For this simulation, arrivals to Detroit, Cleveland, and Pittsburgh remained live. At the time of this simulation, a standard departure routing from Pittsburgh was not defined in the Cleveland Center database used by CTAS. As a result, Pittsburgh departures remained live as well. As in earlier simulations, conflict resolution maneuvers were applied to only the simulated aircraft if a conflict pair involved a live aircraft. Arguably, this made conflict resolution more difficult, as the number of potential resolution options decreased, because only one of the aircraft was eligible. One controller was able to use trajectory-based automation and data link communications to maintain safe separation for all but one aircraft pair. Again, post simulation analysis confirms the importance of the tactical conflict algorithm (TSAFE) in an integrated trajectory-based automation system. The loss of separation case that was detected late with the strategic conflict detection algorithm was detected by TSAFE with enough time for resolution. Resolving conflicts in the increased traffic density of this scenario proved to be more difficult because there was less airspace to safely maneuver aircraft. The initial resolution maneuver manually created by the human controller often times created another conflict. Subsequent tuning of the initial resolution would be required to resolve these cases. Future development of the Control by Exception concept will investigate automation to improve conflict resolution efficiency by giving the controller an option to query the automation system for the initial resolution maneuver.

VI. 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 (NASA engineer) manually generated conflict resolution trajectories using the 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 sec (wilco) delay. Simulations were based on actual FAA traffic data from Fort Worth and Cleveland Centers. 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 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 5-10 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 improvement 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 where all eighteen high-altitude sectors in Fort Worth Center were combined at traffic levels nearly equivalent to that of today's traffic, a single controller maintained separation in all but two instances. During simulation runs at nearly *two-times* today's traffic levels, in the combined five-sector Fort Worth Center airspace, and in airspace that combined three complex traffic sectors in Cleveland Center, a single controller maintained separation in all but two instances.

In each loss-of-separation instance, a post-simulation analysis showed that a tactical alerting function (TSAFE) detected the conflicts 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 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

The effectiveness of operations with trajectory-based automation will be greatly influenced by the accuracy and robustness of the 4D trajectory prediction methodology. Studies have shown trajectory prediction uncertainties persist even in today's most advanced 4D trajectory prediction methods [9]. Therefore, it is desirable to incorporate trajectory prediction uncertainties into simulation to make a meaningful assessment of operations with a trajectory-based automation.

Due to the limited scope of this study, trajectory prediction uncertainties were not explicitly added to the simulations. Instead, the simulations were affected by the inherent uncertainties associated with the use of an independent aircraft simulator [21] to generate aircraft tracks. These uncertainties are present, because the aircraft simulator uses aircraft models different than those used by the trajectory based automation to make predictions. A baseline measurement of trajectory prediction accuracy was made by applying the methodology described in Ref. 9 to a live traffic sample from a simulation region comprised all of ZFW high altitude sectors. This method measures accuracy of each trajectory segment as a function of phase of flight and look-ahead time. The baseline live-traffic along-track error for level flight trajectory predictions is shown in Fig. 23. These results were for a look-ahead time of 10 minutes. Average along-track error was -0.7 nmi with a standard deviation of 3.2 nmi. Cross track and altitude error were calculated but not presented in this analysis.

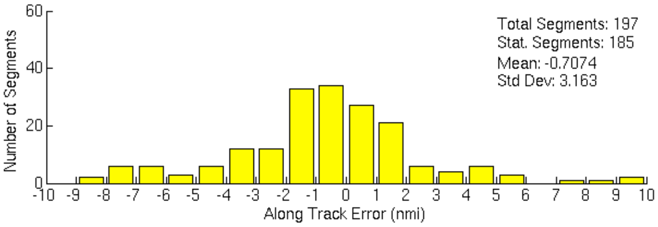


Figure 23. Level flight trajectory accuracy, live traffic baseline, along track error, 10 min. look-ahead.

Along track errors for the level flight trajectory predictions of simulated traffic are shown in Fig. 24. Average along track error for a level flight trajectory prediction with a look-ahead time of 10 minutes was 1.4 nmi in front of the simulated track. In comparison, the average level flight trajectory prediction for the baseline was 0.7 nmi behind the actual track. The standard deviation for the simulated traffic was approximately the same as that of the live traffic baseline.

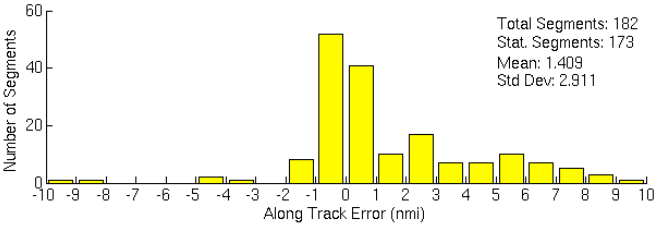


Figure 24. Level flight trajectory accuracy, simulated tracks, along track error, 10 min. look-ahead.

The results of the baseline live traffic climb trajectory prediction accuracy analysis for a look-ahead time of 5 minutes are shown in Fig. 25. The along track errors shown in Fig. 25a were measured in 1 nmi increments with a positive along track error indicating the actual aircraft position was behind the prediction. For this traffic sample, there were 7 climb trajectory segments with an along-track error between 0 and 1 nmi. Altitude errors shown in Fig. 25b are measured in 1000 ft increments with a positive altitude error indicating the actual altitude of the aircraft is below the prediction. Cross-track error was found to be negligible and is not shown.

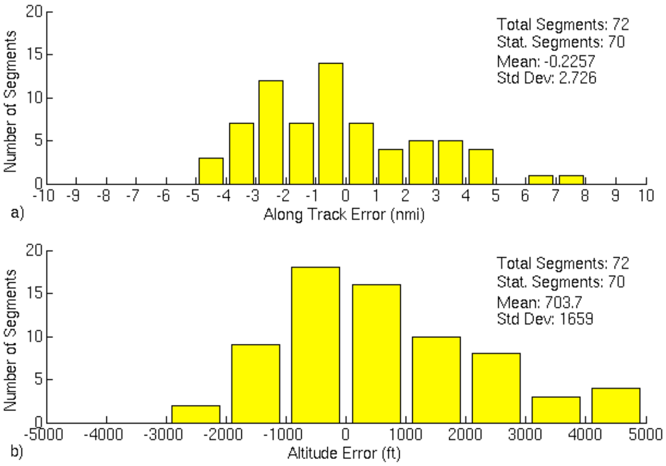


Figure 25. Climb trajectory accuracy, live traffic baseline, 5 min. look-ahead: a) Along track error, b) Altitude error.

Climb trajectory prediction accuracy for the simulated aircraft tracks from the same traffic sample used for the live traffic baseline are shown in Fig. 26. The results clearly show there were uncertainties introduced into the simulations. Along-track errors for the simulated aircraft in Fig. 26a are comparable to the along track error for the live traffic. The mean and standard deviation of along track errors for the simulated track were 0.96 nmi and 2.1 nmi, compared to -0.23 nmi and 2.7 nmi for the live traffic baseline. The average altitude error for the simulated aircraft tracks (Fig. 26b) was notably larger than that of the live traffic baseline. The average trajectory prediction for a look-ahead time of 5 minutes was 1286 ft higher (i.e., greater than one flight level) than the simulated track. For the same look-ahead-time, the average live traffic altitude error was 704 ft lower than the actual track.

Although detailed error modeling is planned for the future, the trajectory prediction uncertainty analysis shows meaningful uncertainties were present in the simulations of this study. The magnitude of the trajectory prediction errors for the simulated traffic was marginally greater than that of live traffic. The presence of these uncertainties creates a more realistic simulation environment in which to assess operations with trajectory-based automation.

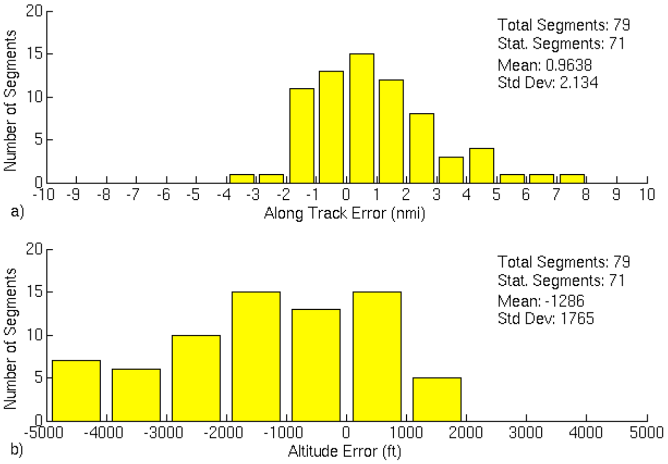


Figure 26. Climb trajectory accuracy, simulated tracks, 5 min. look-ahead: a) Along track error, b) Altitude error.

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