

# AUTOMATED SEPARATION ASSURANCE IN THE PRESENCE OF UNCERTAINTY

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## Abstract

*A trajectory-based automation system originally designed for decision support tool applications is configured to investigate trajectory uncertainty factors that could lead to loss of separation (LoS) under higher levels of automation for separation assurance. Laboratory simulations using fully automated conflict detection and resolution functions and en route Center traffic data are conducted. LoS cases are examined to uncover key uncertainty factors that need to be addressed such that trajectory-based automation could be made suitable for automated separation assurance operations. A simple LoS performance metric is defined. Results show 90% performance when trajectory prediction errors are present, and 99% performance when trajectory prediction errors are removed. Late conflict detections due to climb trajectory prediction uncertainty are the largest contributor to LoS.*

## 1 Introduction

Air traffic controller workload is a major factor limiting airspace capacity under today's operations. Controllers using visual and cognitive analysis of radar traffic displays and decision support tool automation can ensure safe separation for no more than about fifteen aircraft, plus or minus a few, depending on traffic conditions. It is expected that higher levels of automation and/or some transfer of separation assurance responsibility to the cockpit are needed to substantially increase airspace capacity while maintaining safety [1]. The specifics of these automation systems have yet to be determined.

NASA is conducting research to identify trajectory-based automation technology and operations that could safely support a 2-3x increase in airspace capacity. Automatic conflict resolution algorithms have been developed, modeled in software, and tested in fast-time simulation using en route Center traffic to 3x-nominal levels [2,3,4]. Results show a marginal increase in flying time delay associated with conflict resolution maneuvers as traffic levels increase, suggesting that airspace capacity is not limited by airspace volume to 3x levels. Real-time laboratory simulations with en route Center traffic at 1-2x levels were conducted assuming reliable conflict detection and conflict resolutions generated by a human operator, a pseudo controller, using interactive conflict resolution automation [5,6]. Results suggest that a single controller could work 5-times the traffic levels they work today without LoS. Tactical (0-3 min) trajectory modeling and conflict detection methods, deemed a critical safety net for higher levels of automation [7], have shown a substantial improvement in missed alert and false alert performance compared to today's Conflict Alert function [8,9]. Airborne separation methods based on resolution trajectories generated by cockpit automation using Automatic Dependent Surveillance broadcast are also being investigated [10]. Trajectory-based automation research has yet to sufficiently account for the effects of uncertainty on an automated separation assurance concept.

This research investigates the effects of uncertainty on the performance of an automated conflict detection and resolution system. It is anticipated that any future automated separation assurance capability will be required to detect

and resolve a large percentage of traffic conflicts, probably well over 95%, on a strategic time horizon, up to 20 min prior to LoS, well before they become tactical. Simulation experiments using an automatic conflict resolution algorithm incorporated into a real-time conflict detection and resolution system are used in this study to uncover and investigate uncertainty factors that could lead to LoS. Uncertainty factors that affect trajectory and conflict analysis include climb and descent speed profile, aircraft weight, wind, flight plan route intent, particularly the next waypoint, and datalink delay [11-13].

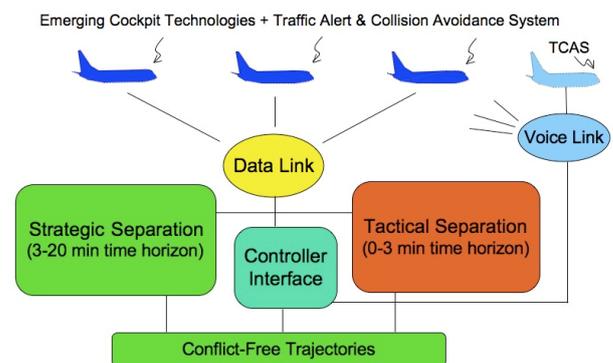
The analysis herein focuses on LoS performance. LoS is the critical factor in airspace operations and is affected by both conflict detection and conflict resolution functions. The use of a state-of-the-art trajectory-based automation system, the Center/TRACON Automation System (CTAS) [14,15], serves to uncover trajectory automation functions that must be improved relative to today's technology to support higher levels of automation for separation assurance. Uncertainty factors that may be acceptable, or at least tolerable, for decision support tool operations in today's environment where controllers maintain full responsibility for separation, may be unacceptable under higher levels of automation for separation assurance.

The paper is organized as follows. A trajectory-based automation concept, which could potentially serve the Next Generation Air Transportation System (NextGen), is outlined. The simulation methodology, including the use of en route Center traffic data to drive the simulation, and the conflict detection and automatic resolution approach are described. This analysis focuses on en route and transition airspace operations involving level, climbing, and descending aircraft in Fort Worth Center high altitude airspace, i.e., at or above Flight Level (FL) 240. The Analysis and Results section describes the LoS analysis methodology and the simulation runs. Specific LoS cases are analyzed to uncover uncertainty factors affecting separation assurance, and a LoS performance metric is defined. A Trajectory Uncertainty section compares prediction errors

based on actual Center Host traffic to that of simulated traffic which is initialized by Center Host traffic, and compares LoS performance of a system with trajectory uncertainty to that of a system with near-zero trajectory uncertainty. The paper closes with conclusions.

## 2 Operating Concept

An operating concept for a trajectory-based automated separation assurance system that could potentially serve NextGen is illustrated in Fig. 1 [7]. Three primary components work together with datalink communication to ensure safe separation and prevent collisions. These are Strategic Separation, Tactical Separation, and the Traffic Alert and Collision Avoidance System (TCAS).



**Figure 1. A trajectory-based automation system concept for NextGen.**

The primary function of the Strategic Separation component is to maintain conflict free, fuel-efficient, user preferred trajectories in the airspace. Strategic Separation provides conflict detection and resolution on a 3-20 min time horizon and is expected to detect and resolve most traffic conflicts, i.e., well in excess of 95%. Strategic resolution trajectories are continuous [7,16] in that a single trajectory includes an initial maneuver segment that resolves a traffic, metering, or severe weather conflict, and final segment that rejoins the aircraft with its preferred route or altitude profile. This allows the resolution trajectory to be probed like any other trajectory to protect against a previously undetected conflict that may arise, due to a pop-up aircraft for example, while the aircraft is flying the resolution

trajectory. Strategic Separation also provides conflict probing for a trial trajectory change initiated by a controller or downlinked by a pilot.

The Tactical Separation component serves as a back up to the Strategic Separation component. It is intended to catch any potential losses of separation missed by Strategic Separation due to trajectory uncertainty, aircraft deviating from their route or altitude profile, and other factors. Tactical Separation operates on a 30 sec to 3 min time horizon and is relatively independent of Strategic Separation. Its primary function is to detect imminent LoS and to compute tactical resolution maneuvers that keep aircraft conflict-free for a few minutes [17,18]. Though some efficiency factors are considered in the tactical maneuver selection, Tactical Separation generally does not attempt to compute efficient continuous resolution trajectories. Once the aircraft is on a safe tactical trajectory following a tactical resolution, Strategic Separation takes over and builds a trajectory that rejoins the aircraft with its nominal route or altitude profile.

TCAS, which is operational today, is the backup to Tactical Separation. TCAS is an implementation of the Airborne Collision Avoidance System, which is mandated by the International Civil Aviation Organization for all aircraft that carry over 19 passengers [19]. TCAS monitors the airspace surrounding an aircraft and warns the pilot of other aircraft that may present a threat of mid-air collision. TCAS is also installed on many general aviation and military aircraft.

An important characteristic of the operating concept depicted in Fig. 1 is that a common trajectory-based automation system serves all aircraft regardless of their equipage. Highly equipped aircraft exchange trajectory information (desired routes, altitudes, speed profiles) via datalink, and trajectories are automatically computed and analyzed for conflict, with potentially little or no controller intervention. Trajectory clearances, whether they be conflict resolution clearances or responses to downlinked pilot-initiated trajectory change requests, are sent to the aircraft via datalink. The pilot then views,

loads, and executes the clearance using interactive Flight Management System (FMS) display functions. For unequipped aircraft, a controller issues a voice clearance for a resolution that is generated either automatically or semi-automatically, but likely tailored for voice communication. A controller manually enters a trial plan in response to a pilot's voice request for a reroute.

Regardless of equipage, a common trajectory analysis engine processes all trajectories to ensure coordination among all aircraft. In high demand, high density airspace, traffic density and complexity require that more aircraft, maybe all aircraft, are equipped for datalink communication. In low demand, low density airspace, a mix of aircraft equipage is acceptable. The common trajectory automation system can handle any level of aircraft equipage and any level of controller interaction with the automation. Future research will determine the appropriate level of automation as a function of traffic demand, safety, and cost/benefit.

### **3 Simulation Methodology**

The CTAS trajectory analysis methodology and software are the basis for this analysis. CTAS, developed at NASA Ames Research Center, includes mature capabilities for 4D trajectory prediction, conflict detection, conflict resolution, time-based metering, and other functions [14,15,20-26]. The primary inputs to CTAS (for en route Center airspace) are radar track and flight plan messages from an FAA Air Route Traffic Control Center (ARTCC, or Center) Host computer, hourly updates of atmospheric model forecasts (wind, temperature, pressure) from the National Oceanic and Atmospheric Administration (NOAA) Rapid Update Cycle (RUC) model [27], and a database of aircraft performance models. Center Host radar track data update every 12 sec for each flight, and Host flight plans update whenever controllers enter amendments in response to conflicts, pilot requests, or other factors. The CTAS Trajectory Synthesizer (TS) [20] updates 4D trajectory predictions for all aircraft every 12 sec using the most recent radar track, flight plan, and

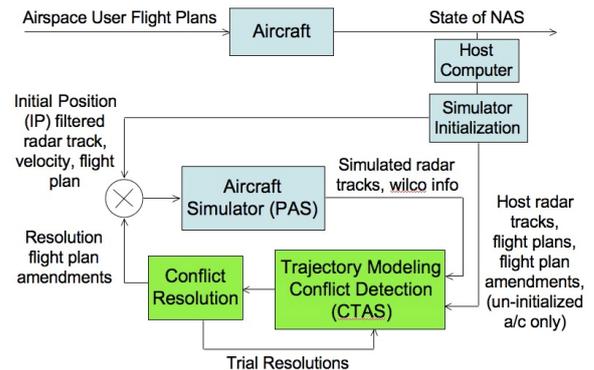
atmospheric model data. A recently upgraded conflict detection module in CTAS [28] updates predicted traffic conflicts every 12 sec by comparing the most recent trajectory updates. The conflict detection module also supports rapid-feedback conflict analysis of trial resolution trajectories whether they be generated manually by a controller using an interactive trial planning function, or automatically by an automatic conflict resolution function as in this analysis.

The simulation methodology, extended from [5,6], is shown in Fig. 2. Center Host radar track and flight plan data initialize trajectories in the simulation airspace. All track updates downstream of the initialization point (IP) are generated by an aircraft simulator (Pseudo Aircraft Simulator [29]) based on the aircraft position and velocity, which are filtered by CTAS, and the Host flight plan intent (route and altitude) at the IP. All flight plan amendments downstream of the IP are generated by the automatic conflict resolution function (described later). Any aircraft inside the simulation airspace on simulation start up are initialized at their current position. The aircraft simulator flies according to flight plan amendments automatically. No air traffic controllers (or pseudo controllers) participated in this simulation.

The simulation airspace includes all high altitude sectors in Fort Worth Center airspace (FL240 and above). Airspace sector boundaries that are internal to the simulation airspace are not modeled and in no way influence the simulation. This design and methodology provides realistic traffic scenarios that include a variety of routings and climb and descent profiles, but with the effect of vectors, altitude changes and other controller clearances removed. Note that in Fig. 2 the traffic simulation elements (top of figure) are shaded differently than the Strategic Separation elements, i.e., trajectory modeling, conflict detection, conflict resolution (bottom of figure).

For climbing aircraft approaching high altitude airspace from below, the first radar track update at which the Mode-C transponder altitude is 14,000 ft or greater defines the IP. Fourteen-thousand ft was selected because it is

more likely that the aircraft has reached a steady climb following the 250 kt speed restriction at 10,000 ft, and nominally allows 5 min of climbing flight (assuming 2,000 ft/min) before the aircraft reaches the lower boundary of high altitude airspace. Any temporary altitudes that are active for climbing aircraft at the IP are automatically removed. This prevents aircraft from flying level through the airspace at a temporary altitude and keeps all climbing aircraft nominally on steady climbs to their flight plan altitude. For aircraft approaching the Fort Worth Center boundary from neighboring Centers, the 5<sup>th</sup> radar track update defines the IP. Initializing at the 5<sup>th</sup> track update allows the CTAS ground speed filter to stabilize and thus produces a more accurate airspeed estimate for the track simulator. Aircraft landing in or near Fort Worth Center airspace are automatically descended at their minimum-fuel top-of-descent point as computed by the CTAS TS.



**Figure 2. Simulation methodology.**

Uncertainty in the simulation methodology depicted in Fig. 2 is due to differences between the CTAS trajectory model predictions, and the PAS aircraft simulator models. These include differences in climb and decent speed profiles, turn dynamics, waypoint capture logic, thrust models, and aircraft weight. Wind errors were not modeled since the same RUC wind data files were input to both CTAS and PAS for this analysis. Later, in the Trajectory Uncertainty Analysis section, the uncertainty characteristics of the CTAS predictions versus the PAS aircraft model, and the CTAS predictions versus Host track data are compared to gain insight as to how well the LoS performance in these simulations might compare to actual loss

performance. In this analysis the radar track data, whether they be Host or simulated, are defined as truth.

Automatic conflict resolutions are attempted for all detected conflicts that meet the following conflict detection criteria:

- Predicted time to LoS is between 3 min and 12 min, inclusive,
- Separation criteria: 8 nmi or 1,000 ft when both aircraft are in level flight at LoS,
- Separation criteria: 8 nmi or 1,500 ft when one or both aircraft are climbing or descending at LoS,
- Conflict not between two aircraft merging to a common arrival metering fix, and
- Predicted LoS is at or above FL240 and inside Forth Worth Center airspace.

It should be noted that conflicts are detected out to a 20 min time horizon, but automatic conflict resolutions are not attempted until the predicted time to LoS is 12 min or less. (The conflict detection function increases vertical separation criteria for aircraft not equipped for Reduced Vertical Separation Minima, but not many of those aircraft were present in these simulations.)

The 3 min lower bound for automatic resolution is deemed a reasonable lower limit for acceptability of a strategic automated resolution function in en route Center airspace. It is anticipated that future automated separation assurance operations will require that well over 95% of conflicts are detected and resolved prior to 3 min to LoS. The 12 min upper bound was a somewhat arbitrary selection but within the bounds of what other researchers are using. The expanded separation criteria, 8 nmi or 1,500 ft for transitioning aircraft, helps account for higher trajectory prediction uncertainty for climbing and descending aircraft. (The expanded vertical criteria applies only to aircraft that are on converging trajectories. Once an aircraft pair that was originally converging begins diverging, the vertical criteria drops back to the legal separation criteria.) Conflict resolutions for arrivals merging to a common meter fix are being explored in fast-time

simulation [3,4], but are beyond the scope of this paper. This analysis was limited to conflict detections and losses of separation that occur in high altitude airspace, i.e., FL240 and above. However, many climbing aircraft below FL240 are included in the simulation since conflicts with predicted LoS above FL240 often involve aircraft climbing from below FL240.

The automatic conflict resolution algorithm that is being developed and tested at NASA Ames [2,3,4,30] has been integrated with CTAS. The auto-resolution algorithm handles the complete spectrum of conflict types found in en route airspace including those involving ascents to cruise altitude and descents to arrival fixes. Resolution trajectories are patterned after changes to flight plans, altitudes, and speed profiles that controllers customarily issue to pilots in today's operations. Each conflict is first assigned a type category that determines the set of acceptable trial resolution maneuvers and the preferred aircraft to maneuver. The trajectory modeling and conflict detection model generates a 4D trajectory for each trial resolution maneuver and determines if it is conflict-free. If it is not, the algorithm computes an alternative maneuver which is then analyzed for conflict.

Automatic resolution trajectories are selected based on the following conflict resolution criteria:

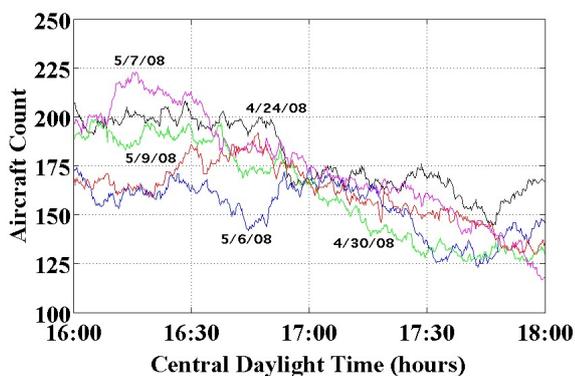
- Separation criteria: 10 nmi or 1,000 ft when both aircraft are in level flight at first LoS,
- Separation criteria: 10 nmi or 2,000 ft when one or both aircraft are climbing or descending at first LoS,
- 20 min conflict free resolution trajectory from the time the resolution amendment is entered.
- 3 min tactical resolution minimum (the auto-resolver will not attempt resolution if predicted LoS is less than 3 min),
- 45 deg maximum turn angle for auxiliary waypoint route amendment resolution trajectories,

- 350 nmi maximum range to downstream capture fix for auxiliary waypoint resolutions, and
- 1,000 ft increments of climb and descent resolution trajectories.

The auto-resolution algorithm employs the Multiple Resolver extension [2] which attempts to calculate as many as three types of resolutions for each aircraft in a conflict pair. The three types consist of horizontal, vertical, and speed maneuvers (though speed was not used in this study). The Multiple Resolver selects the resolution and corresponding aircraft that results in the least amount of delay. Delay is defined as the time to fly the resolution trajectory minus the time to fly the nominal trajectory. Note that in some instances delay can be negative, and reflect a flying time savings, for example when the resolution includes a direct route to a downstream fix. The auto resolution algorithm has been implemented in a Java applet which is called from CTAS as illustrated in Fig. 2.

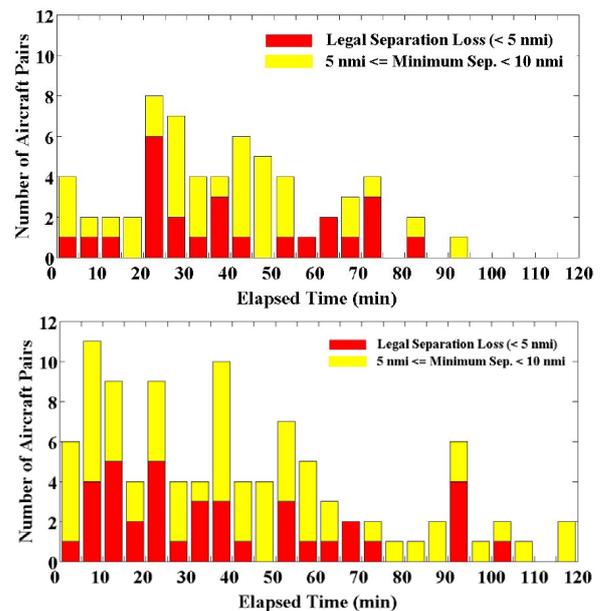
#### 4 Analysis and Results

Five simulation runs were conducted using Fort Worth Center traffic recorded during a relatively busy 2-hour period of the day (4-6 PM local time) on five weekdays (24 April 2008, 30 April 2008, 06 May 2008, 07 May 2008, and 09 May 2008). Figure 3 shows the total traffic count in high altitude airspace (FL240 and above) for each of the five days during the 2-hour period selected for analysis.



**Figure 3. Fort Worth Center high altitude traffic, 4-6 PM local time.**

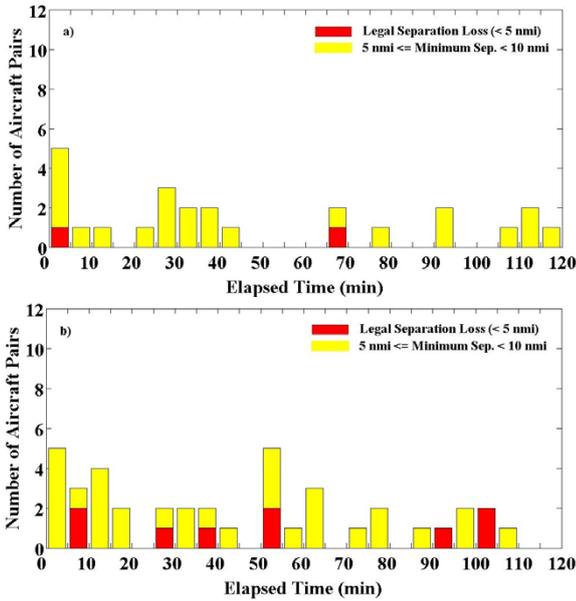
The first step is to run each simulation in open-loop mode where all aircraft fly unimpeded, without conflict resolution, along the route and altitude profiles upon which they were initialized. The open-loop runs provide a measure of the number and frequency of traffic conflicts that need to be detected and resolved by the automation to maintain separation in the airspace. The open-loop runs also provide input data for a performance metric described later.



**Figure 4. Open-loop minimum separation metric, a) 4/30/08 and b) 5/7/08 traffic.**

The histograms in Fig. 4 show the open-loop minimum separation metric [5] for the 2-hour traffic samples on April 30 and May 7, 2008. As described later in this section, the two days shown in Fig 4 are the best and worst days respectively in terms of the automatic conflict resolution performance. The simulated open-loop radar track data are analyzed to determine the number of unique aircraft pairs that pass with less than legal separation (5 nmi or 1,000 ft), plus those pairs that are legally separated, but pass with a minimum separation that is close to legal separation (10 nmi or 1,000 ft), but not less than legal separation. For example, Fig. 4a shows that during the 20-25 min period 6 unique aircraft pairs pass with less than legal separation (darker bars) and 2 additional pairs pass with a minimum separation that is close to legal separation (lighter bars). During the 75-80 min period all unique aircraft pairs pass with a

minimum separation that is greater than 10 nmi or 1,000 ft (no bars shown). Since the minimum separation metric is computed based purely on analysis of current-time radar track data, it provides a simple objective measure of separation in the airspace.



**Figure 5. Minimum separation metric for closed-loop simulations using a) 4/30/08 traffic, best case, and b) 5/7/08 traffic, worst case.**

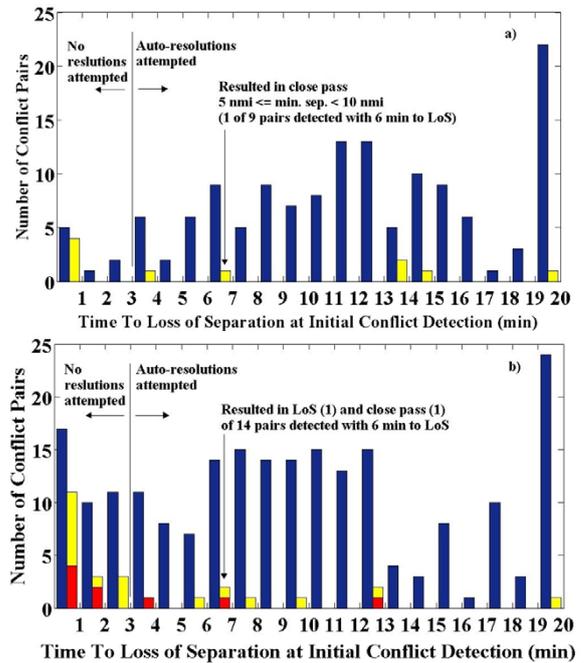
### 4.2 Closed-Loop Simulations

The next step is to run the simulations in closed-loop mode where automatic conflict resolutions are computed and implemented as illustrated in Fig. 2. Following each run the minimum separation metric is computed to identify losses of separation that occurred during the closed-loop run. Shown in Figures 5a and 5b are the minimum separation metrics for the best case (April 30, 2008) and worst case closed-loop simulation runs (May 7, 2008).

### 4.3 Loss of Separation Analysis

Early in this study it was clear that many of the LoS cases were due to late conflict detections. This led to an examination of the first conflict detection for any given conflict pair as a function of the predicted time to LoS for that pair. Shown in Figures 6a and 6b is a conflict detection metric that groups conflicts in

histogram format in terms of the time to LoS at which the conflicts are first detected. For example, Fig. 6a shows that there were nine unique conflicts pairs first detected with between 8 and 9 min to predicted LoS, and there were two unique conflicts pairs first detected with between 4 and 5 min to predicted LoS. Note the wide variation in predicted time to LoS at first detection. This wide variation is clearly evident in all of the runs and due in large part to climb prediction uncertainty and to a lesser extent limited surveillance coverage for aircraft approaching Center airspace from neighboring Centers.



**Figure 6. Conflict detection metric for closed-loop simulations using a) 4/30/08 traffic, and b) 5/7/08 traffic.**

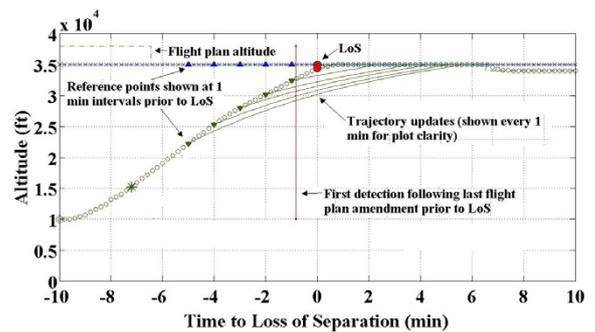
The actual LoS and close pass data from the closed-loop minimum separation analysis are also shown on Figs. 6a and 6b for those conflict detections that ultimately resulted in an actual LoS (in simulation). For example, Fig. 6b shows that one of the conflict pairs which was first detected at 12-13 min to predicted LoS actually resulted in a LoS, and another of the conflict pairs first detected at 12-13 min to LoS resulted in a minimum separation that was close to legal separation. Of the 11 conflicts first detected at 3-4 min to predicted LoS, one resulted in a LoS. Note the large number of

false detections in the 0-3 min range, i.e., cases where a conflict was detected, but no LoS occurred. It should be noted that a close case, where minimum separation is between 5 and 10 nmi, does not necessarily reflect poorly on system performance. However, since the detection criteria is 8 nmi and the resolution criteria is 10 nmi, the close cases are included in the graphs. Note from Fig. 6b that conflict detections for 6 of 9 losses of separation were first detected with less than 3 min to first LoS. As described later, the data show that most of the late detections are due to climb prediction uncertainty.

A more in depth examination of the individual LoS cases sheds light on the uncertainty factors that affect performance of the conflict detection and resolution system. A few cases are described here and the rest are summarized in the Appendix. The LoS indicated in Fig. 6b, which was first detected at 12-13 min to LoS, is a typical example where climb prediction uncertainty leads to a LoS. The case involved a Raytheon Premier 1 business jet (PRM1) climbing west bound out of the Dallas area for a cruise altitude of FL380, and an east bound Airbus A320 cruising level at FL350. Shown in Fig. 7 are altitude versus time plots for both aircraft where the time axis is biased such that its zero point occurs at first LoS. The graph shows every other 12 sec track update (to reduce plot clutter) for each aircraft. The trajectory prediction updates for each track are displayed starting at 5 min to LoS. The dark triangles are added for reference and denote points at 1, 2, 3, 4, and 5 min to LoS. The dashed lines represent the flight plan altitude for each aircraft. The asterisk at 15,000 ft for the climbing aircraft denotes the IP point where the track simulator starts flying that aircraft and generating track updates.

The conflict is first detected at 12-13 min to LoS when the business jet is climbing out of 10,000 ft. (A conflict is detected between two aircraft even if both are not yet initialized by the aircraft simulator. However, a resolution is not issued to any aircraft not initialized by the simulator.) But, the conflict quickly falls off the conflict list (list of detected conflicts displayed on the CTAS graphical user interface) after a

few track updates as the trajectory and conflict analysis update and predict the A320 to pass over the business jet with greater than 1,500 ft of vertical separation. In this case an auto resolution was not issued to the climbing business jet. This was because it had not yet been initialized by the target simulator and, therefore, could not take a resolution flight plan amendment. (In climb/cruise cases such as this one, the auto-resolution favors an interim altitude for the climbing aircraft.)



**Figure 7. Sample LoS due to climb uncertainty.**

A subsequent conflict involving the business jet and an MD11 cruising level at FL380 resulted in the auto-resolution algorithm issuing a temporary altitude amendment stopping the business jet at FL350. The trial resolution trajectory for the business jet was determined to be conflict-free for a level-off at FL350 due to the fact that the predicted climb profile was shallower than the actual climb profile. Note from Fig. 7 that there is a 5,000 ft error in predicted altitude at a 5 min time horizon, and a roughly 5 min error in time to top of climb. The shallow climb prediction for the business jet ultimately results in a late detection (1 min to LoS) and a LoS.

The example in Fig. 7, and others like it, illustrate the need for automatic resolution logic that is more robust to climb prediction uncertainty. In most instances a long-time-horizon (e.g., more than 10 min) conflict detected between a climbing aircraft at a relatively low altitude (e.g., less than 20,000 ft) and a level aircraft at cruise altitude, needs to be filtered from auto-resolution processing until a point where the conflict detection is more certain, and it is more certain that the conflict resolution trajectory will remain conflict-free.

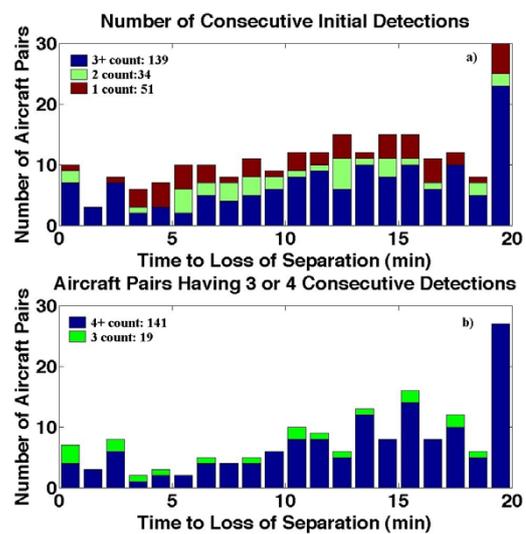
This is especially true since interim altitude resolutions are relatively easy to implement even when climbing aircraft are a few flight levels below level flight traffic. Air traffic controllers know to wait on these cases, but an automated system must include logic to account for such uncertainties. Future research will determine the time to predicted LoS at which an automatic resolution should be called for as a function of conflict geometry, conflict certainty, ease of resolution implementation and other factors.

A means to improve conflict detection performance for climbing aircraft is needed, particularly the time to LoS at which the conflict is first detected. One approach would be to compute and analyze high performance and low performance climb trajectories for all climbing aircraft. A case similar to that shown in Fig. 7 involved a B767 climbing out of Dallas which lost separation (in simulation) with a B737 level at FL350. The cause was late detection (2.1 min prior to LoS) due to climb prediction uncertainty. The case was rerun using 5 different climb trajectories for the 767 aircraft, assuming aircraft weights ranging from 75% to 95% of max gross take-off weight in 5% increments. Table 1 shows the time to LoS at first detection for each weight case and the variation in time to top of climb starting from a point at 7.5 min to LoS. The boundaries of the low performance and high performance climb trajectories define a vertical region of airspace that could be protected to account for uncertainty in climb performance.

Weight Ratio	Time to LoS at conflict detection (min)	Time to Top of Climb at 7.5 min to LoS (min)
75%	7.5	9.0
80%	7.1	10.1
85%	4.5	11.5
90%	2.1	13.5
95%	1.5	16.5

**Table 1. Conflict detection time and time to top of climb for variable aircraft weight.**

It was noted during the analysis that occasionally a conflict pair would appear on the list momentarily and then drop off. This could be due to transients associated with maneuvering aircraft, trajectory update anomalies, or other factors. This was the case with the initial 12 min detection for the business jet and the A320 discussed above. Controllers know to wait a few update cycles before considering action on a conflict detected with more than a few minutes to LoS. However, for an automated system, logic must determine at what point a conflict is actionable.



**Figure 8. Conflict detection stability.**

Figure 8a shows conflict detections in terms of their time to first LoS and the number of consecutive detections that follow the first detection. It was found that 23% of first detections (51 out of 224) were not followed by a consecutive detection of the same conflict pair. Fifteen percent of first detections (34 out of 224) had two consecutive detections, and the remaining 62% of first detections had three or more consecutive detections. Also note that a large percentage of detections below the 12 min to first loss point, where auto-resolutions are requested, have only one or two consecutive detections. The relatively large number of conflicts and high stability for conflicts first detected in the 19-20 min range is due to the fact that some of these conflicts include those that were detected, but not sent to the display list until predicted time to LoS dropped to  $\leq 20$  min.

Figure 8b shows detection data where three consecutive detections are required to qualify as a “first” detection. Note that the total conflict count drops from 224 to 160, a 29% reduction, and a relatively small percentage of detections at or below the 12 min to LoS point have fewer than four consecutive detections. The May 7, 2008 traffic was rerun in closed-loop auto-resolution mode where three consecutive conflict detections were required before an automatic resolution was requested. The loss performance was virtually identical indicating that requiring three consecutive updates reduces the calls to automatic resolution and does not impact performance. This is likely because many of the detections with only one or two consecutive updates were false alerts.

#### 4.4 Performance Metric

A simple metric was formulated to characterize the overall loss of separation performance of any closed-loop simulation run. The metric accounts for closed-loop losses of separation plus losses that occurred during the corresponding open-loop simulation run. One loss of separation in a dense traffic environment where many open-loop losses of separation occurred, while not acceptable, reflects better performance than one loss of separation in a light traffic environment with fewer open-loop losses of separation. The loss of separation performance metric (LoS Metric) is defined as follows, where  $N_C$  is the number of closed-loop losses of separation, and  $N_O$  is the number of open-loop losses of separation:

$$\text{LoS Metric} = 1 - (N_C/N_O).$$

For every closed-loop simulation run each LoS is examined to determine if it is due to a) a trajectory-based automation error (trajectory modeling, conflict detection, or conflict resolution) or b) a simulation error. For example, if climb uncertainty causes a conflict to be first detected with less than 3 min to LoS, and as a result, a LoS occurs, then the case is classified as due to trajectory-based automation. However, occasionally aircraft are initialized into the simulation late (i.e., when they are near

the airspace boundary), or the aircraft simulator (Fig. 2) does not accept a resolution flight plan amendment (due to a software bug). If either of these cases results in a LoS, then the loss is classified as due to a simulation error. For this analysis, the number of closed-loop losses used in the LoS Metric is the sum of only those losses due to trajectory-based automation errors. The LoS summary tables in the Appendix indicate if the loss is due to a trajectory-based automation error (T) or to a simulation error (S).

Table 2 shows the Loss Performance Metric for the five closed-loop simulation runs. The table includes the total number of open-loop LoS cases for the traffic sample, the total number of closed-loop LoS cases, the corrected number of closed-loop LoS cases, and the Loss Performance Metric. The corrected number of LoS cases reflects only those due to trajectory-based automation errors.

Traffic Day	Losses Open ( $N_O$ )	Losses Closed Un-corrected	Losses Closed Corrected ( $N_C$ )	Metric
4/24/08	33	4	2	94%
4/30/08	25	2	1	96%
5/6/08	22	8	6	73%
5/7/08	38	9	4	89%
5/9/08	25	3	1	96%
Overall	143	26	14	90%

**Table 2. Loss of separation performance metric, closed-loop simulations.**

As the results in the Appendix show, most losses can be traced to climb uncertainty. A few are due to erroneous trajectory predictions caused by an inconsistency in the next downstream fix flown by the aircraft versus that used in the trajectory prediction. Since CTAS does not have perfect intent information, the route building algorithm must determine when the aircraft is turning towards the next downstream fix in its flight plan. Due to this next-fix-selection heuristic, vector resolutions which turn an aircraft away from its flight plan, can also trigger the skipping of downstream waypoints due to that aircraft’s changing heading. These cases could be solved by a

downlink message that ensures consistency between the next fix being flown by the aircraft and the next fix being used by the trajectory-based automation.

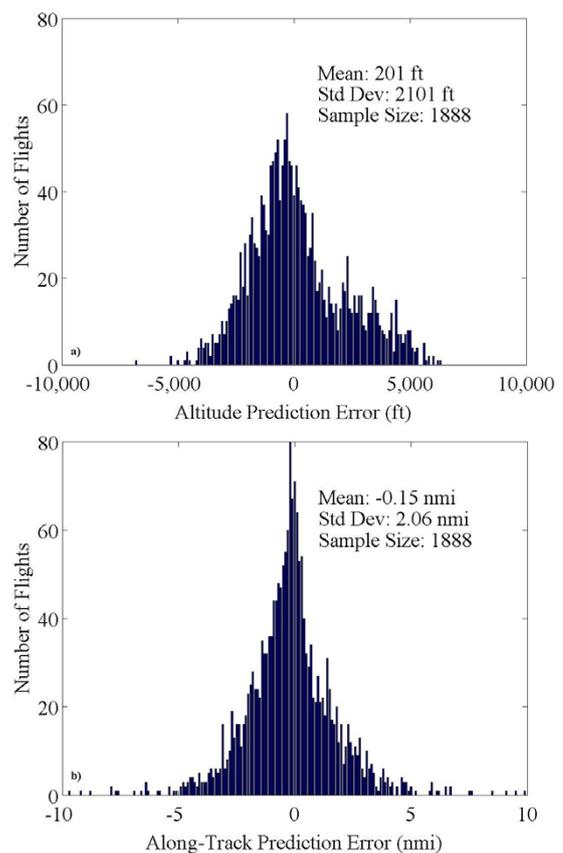
### 5 Trajectory Uncertainty Analysis

Since a large percentage of LoS cases are attributable to climb prediction uncertainty, the climb prediction performance of CTAS is examined. Using methodologies described in [31,32], histograms of the altitude and along-track trajectory prediction errors based on predictions using Center Host traffic data for 1,888 aircraft flying uninterrupted climb trajectories to their cruise altitude are shown in Fig. 9 for a look-ahead time of 5 min. The altitude errors have mean and standard deviation of 201 ft and 2,101 ft, respectively. The along-track errors have a mean of -0.2 nmi and standard deviation of 2.1 nmi. Note that the standard deviation of the altitude errors exceeds twice the legal vertical separation limit of 1,000 ft, while the standard deviation of the along-track errors is not even half of the legal lateral separation limit of 5 nmi. Some of the along-track error is due to CTAS heuristics that attempt to model the aircraft flying off route when turning inside a waypoint.

Histograms of altitude and along-track trajectory prediction errors for aircraft flying uninterrupted climb trajectories to their cruise altitude in the PAS open-loop simulations are shown in Fig. 10 for a look-ahead time of 5 minutes. The altitude errors have mean and standard deviation of -1,198 ft and 1,764 ft, respectively. The along-track errors have a mean of -0.6 nmi and standard deviation of 2.3 nmi, respectively.

Overall many of the uncertainty characteristics of the Host-based predictions (Fig. 9) are reasonably similar to that of the simulation-based predictions (Fig. 10). However, there are some important differences that could affect these results. First, note the substantial mean error (-1,198 ft) in the simulation-based altitude trajectory predictions (Fig. 10). This is primarily due to the fact that the thrust multipliers are higher in the performance models of the PAS database than

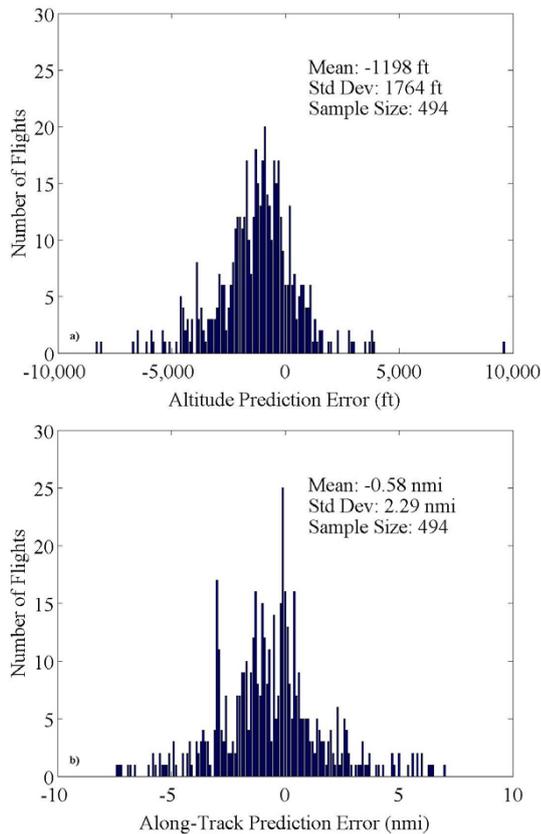
the corresponding performance models used by the TS module of CTAS. Since altitude errors are defined as the predicted altitude minus the actual altitude of the aircraft, the trajectory predictions generated by CTAS will predict aircraft to climb slower than PAS actually flies them in most cases (e.g., Fig. 7). Secondly, notice that there are more cases in the tails of the distribution in the simulation case versus the actual traffic case. This is likely contributing to the loss of separation cases observed in the closed-loop simulation results. Work is ongoing to improve consistency between the CTAS and PAS models, and to build up a simulation capability whereby uncertainty levels can be specified and controlled.



**Figure 9. Climb prediction error relative to Host tracks, 5 min look-ahead, uninterrupted climb to cruise altitude.**

A secondary objective of the uncertainty analysis was to confirm that the automatic resolution performance was near 100% when trajectory prediction uncertainty was removed from the simulation environment. The simulation methodology described in Fig. 2 was modified to achieve a zero, or near zero,

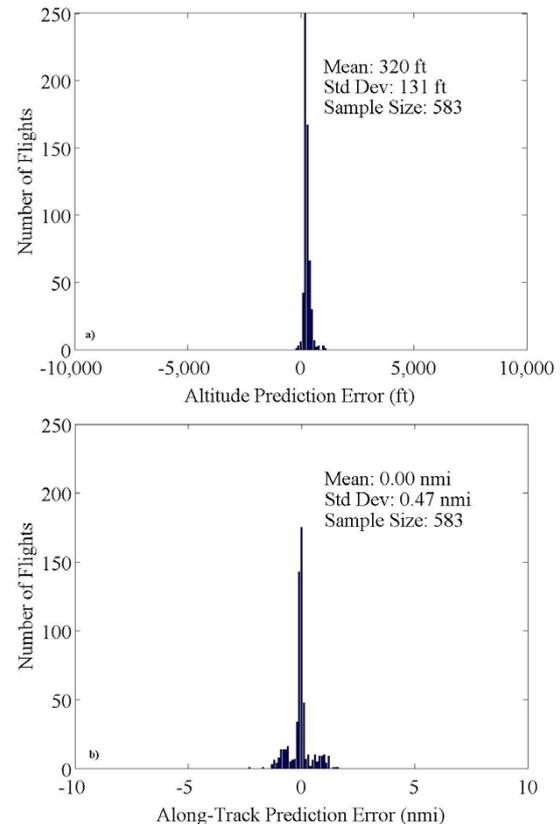
uncertainty simulation environment. It also provides a basis for a future capability where the uncertainty of individual parameters input to the CTAS TS may be specified with selected mean and standard deviation characteristics. In the zero-uncertainty mode (or “feedback” mode) extended from [33], the predicted position 12 sec into the future relative to the current track update is used to compute the simulated radar track for the next track update. So in zero-uncertainty mode the CTAS TS computes all track updates and the Aircraft Simulator (PAS) is not used. With a few exceptions having to do with prediction heuristics (e.g., selection of downstream fix when the aircraft is near a fix) the aircraft flies nearly exactly how the TS predicts it will fly.



**Figure 10. Climb prediction error relative to aircraft simulator tracks, 5 min look-ahead, uninterrupted climbs to altitude.**

Altitude and along-track trajectory prediction error histograms based on analysis of uninterrupted climbing departures run in the open-loop, zero-uncertainty simulation mode are shown in Fig. 11 for a look-ahead time of 5 minutes. The altitude errors have a mean and

standard deviation of 320 ft and 131 ft, respectively. The along-track errors have a mean of 0.0 nmi and standard deviation of 0.5 nmi. The trajectory prediction errors in the CTAS simulation mode are substantially smaller and more tightly clustered around zero compared to those for the Host and PAS simulation runs discussed earlier.



**Figure 11. Climb prediction error for zero uncertainty simulation mode, 5 min look-ahead.**

Open-loop and closed-loop simulation runs were conducted using the zero-uncertainty simulation mode, and the results are shown in Table 3. The loss performance metric is 100% for three out of five runs. The two corrected LoS cases in Table 3 were both due to trajectory failures which resulted in no predicted trajectory being available for the aircraft.

Traffic Day	Losses Open (N <sub>O</sub> )	Losses Closed Un-corrected	Losses Closed Corrected (N <sub>C</sub> )	Metric
4/24/08	44	4	0	100%
4/30/08	31	1	0	100%
5/6/08	29	2	0	100%
5/7/08	23	7	1	96%
5/9/08	25	3	1	96%
Overall	152	17	2	99%

**Table 3. Loss of separation performance metric, closed-loop simulations, zero-uncertainty mode.**

## 6 Concluding Remarks

An automatic conflict resolution algorithm was integrated into the Center/TRACON Automation System trajectory analysis methodology and software, and a study was conducted to examine the effects of trajectory prediction uncertainty on automated conflict detection and resolution in en route Center airspace.

A simulation and analysis methodology was developed whereby examination of loss of separation cases in simulation identified key uncertainty factors relevant to automated separation assurance operations.

The largest percentage of loss of separation cases in the analysis were due to late conflict detections caused by climb trajectory prediction uncertainty. Other factors include an inconsistency in the next downstream fix flown by aircraft versus the next fix used by the trajectory modeler. The distribution of losses of separation due to these factors is:

- Late detection due to climb prediction uncertainty (8 out of 14 total losses)
- Next downstream fix error (3 out of 14 total losses)
- Trajectory not available or not updated (3 out of 14 total losses)

A simple LoS performance metric was defined, which combines losses of separation that occur when aircraft fly unimpeded without conflict resolutions (open-loop), against losses of separation that occur when automatic detection and resolution is activated (closed-

loop). The overall performance metric for closed-loop operations with trajectory uncertainty is 90%, while the overall performance metric for closed-loop operations with near-zero trajectory uncertainty is 99%.

The results suggest that in order for most conflicts to be resolved prior to 3 min to loss of separation, improvements in climb trajectory modeling and prediction and/or functionality to probe multiple climb trajectories ranging from low performance to high performance climbs, will be required.

The results are colored by the fact that the trajectory prediction uncertainty characteristics computed based on the aircraft simulator used in this analysis are greater than that computed based on Center Host traffic data. Therefore, it is expected that real-world performance would be somewhat better than the performance indicated in this analysis.

Future work should examine the performance improvement that could be gained by downlink of key aircraft parameters such as speed profile, weight, local winds, and next waypoint.

## Acknowledgments

The authors would like to thank John Robinson and Jim Murphy for their thoughtful contributions to the conflict detection and resolution logic and software, and Jinn-Hwei Cheng, Thien Vu, and Scott Sahlman for their dedicated support and analysis of numerous data runs.

## Appendix

Tables A1 through A5 summarize the LoS cases for all 5 closed-loop simulation runs. The tables include the aircraft type for both conflict aircraft, the flight phase at predicted first loss of separation (climbing, level, or descending), the miss distance at minimum separation, the conflict detection parameters (time to first loss in min, minimum predicted horizontal separation in nmi, minimum predicted vertical separation in ft), the cause of the loss of separation based on post run analysis, and the

category of the loss case, i.e., either due to a trajectory-based automation error (T) or to a simulation error (S) as described earlier.

Each LoS case was post-processed using the TSAFE tactical conflict detection logic [8,9]. The last column in Tables A1-A5 shows the time in minutes before loss of separation at which TSAFE detected the conflict. TSAFE is currently configured for a 2 min look-ahead time, so most TSAFE detections will be 2 min or less before LoS. The 2 min look-ahead was selected because current research is comparing

TSAFE performance to that of today's Conflict Alert function, and Conflict Alert is a tactical alerting tool designed for display to air traffic controllers on a radar display. Research is needed on how best to configure TSAFE for integration with a strategic automated separation assurance function such as that being investigated here. The results show that TSAFE detected all LoS cases with times ranging from 0.8 to 3.0 min to LoS.

	AC1 (type)	AC2 (type)	Flt Ph	Miss Dist. (nmi)	Conflict Detection (min, nmi, ft)	Cause of LoS		TSAFE Detection (min)
1	B738	B733	C/C	0.4	2.9, 1.0, 650	airspace boundary, late detection	S	3.0
2	C25B	B752	C/L	4.7	0.7, 0.8, 580	no trajectory for climbing AC	T	2.2
3	C560	A320	L/L	4.9	3.3, 4.1, 0	next waypoint error	T	3.0
4	E145	E145	L/L	3.3	2.8, 2.3, 0	late sim. init. (2.6 min prior)	S	2.6

**Table A1. 20080424 closed-loop simulation**

	AC1 (type)	AC2 (type)	Flt Ph	Miss Dist. (nmi)	Conflict Detection (min, nmi, ft)	Cause of LoS		TSAFE Detection (min)
1	B737	H25B	L/C	4.4	no detect	late sim. init. (2.7 min prior)	S	2.0
2	C56X	DC10	L/L	4.8	4.6, 4.8, 0	next waypoint error	T	1.6

**Table A2. 20080430 closed-loop simulation**

	AC1 (type)	AC2 (type)	Flt Ph	Miss Dist. (nmi)	Conflict Detection (min, nmi, ft)	Cause of LoS		TSAFE Detection (min)
1	LJ60	B735	C/L	0.9	1.6, 4.9, 1412	late detection, climb uncertainty	T	2.0
2	CRJ7	E145	C/C	0.1	3.0, 2.8, 1417	no resolution	T	2.6
3	B733	B763	L/C	2.8	2.6, 7.9, 1423	late detection, climb uncertainty	T	2.0
4	MD82	GAL X	L/D	4.2	8.8, 6.7, 1076	resolution issued, not resolve, climb uncertainty	T	2.4
5	C550	B752	L/C	2.3	4.2, 6.6, 1436	late detection, climb uncertainty	T	2.2
6	B733	B733	C/L	4.9	8.5, 5.5, 893	AC1 not initialized, Host amendment causes LoS	S	2.0
7	E145	E145	L/C	4.6	2.2, 4.2, 312	late sim init. (1.8 min prior)	S	1.6
8	B752	B737	C/L	2.2	2.7, 7.3, 1390	late detection, climb uncertainty	T	2.4

**Table A3. 20080506 closed-loop simulation**

	AC1 (type)	AC2 (type)	Flt Ph	Miss Dist. (nmi)	Conflict Detection (min, nmi, ft)	Cause of LoS		TSAFE Detection (min)
1	MD83	B733	C/L	4.9	4.4, 0.3, 122	next waypoint error	T	1.0
2	C525	CRJ1	L/L	4.6	0.0, 4.9, 386	AC descends unexpectedly	S	1.0
3	A320	CRJ9	L/C	4.2	2.0, 3.1, 1440	late detection, climb uncertainty	T	1.2
4	E145	B733	L/L	4.8	3.4, 1.9, 0	late sim. init. (3.2 min prior)	S	1.6
5	A320	PRM1	L/C	3.7	12.9, 2.3, 581	missed secondary conflict, climb uncertainty	T	1.8
6	LJ45	CRJ2	C/L	1.2	0.0, 1.1, 930	late detection, climb uncertainty	T	1.4
7	B752	A321	C/L	2.4	3.3, 7.6, 1387	aircraft did not take alt. resolution, climb uncertainty	S	1.4
8	A320	B733	L/C	4.9	6.1, 4.0, 110	AC2 not initialized, Host descent clearance causes LoS	S	1.0
9	B752	B737	L/C	3.3	0.6, 5.3, 1294	AC2 not initialized, Host amendment causes LoS	S	0.8

**Table A4. 20080507 closed-loop simulation**

	AC1 (type)	AC2 (type)	Flt Ph	Miss Dist (nmi)	Conflict Detection (min, nmi, ft)	Cause of LoS		TSAFE Detection (min)
1	MD11	LJ60	C/C	3.6	0.0, 3.5, 653	late sim. init. (2.2 min prior), LoS prior to AC entering sim airspace	S	3.0
2	DC10		C/C	4.9	no detect	no trajectory	T	1.0
3	E145	E45X	L/C	4.7	3.1, 6.4, 887	late sim init. (2.9 min prior)	S	1.0

**Table A5. 20080509 closed-loop simulation**

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