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Human-in-the-Loop Evaluation of Ground-Based Automated Separation Assurance for NextGen

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Summary

This paper describes human-in-the-loop research at NASA Ames Research Center on service provider-based automated separation assurance for the Next Generation Air Transportation System (NextGen). Key human/automation integration aspects such as levels of automation and roles and responsibilities of automated separation management are investigated in the Airspace Operations Laboratory. A trilogy of part-task studies was designed to examine efficiency, safety, workload impact and acceptability of central aspects of the concept. Findings from a 2007 study on strategic trajectory-based automated separation assurance with data link-equipped aircraft are discussed in detail. Preliminary results on mixed operations with data link and conventional aircraft gathered in spring 2008 are included. The experiment design for investigating tactical safety assurance and off-nominal situations in summer 2008 is outlined. This research was funded by the Separation Assurance element of NASA's Next Generation Air Transportation System – Airspace Project.

Nomenclature

AAC = Advanced Airspace Concept
ACES = Airspace Concept Evaluation System
ADS-A/B = Automatic Dependent Surveillance-Addressed/Broadcast
ADRS = Aeronautical Data Link and Radar Simulator
AOL = Airspace Operations Laboratory (at NASA Ames Research Center)
ASAS = Airborne Separation Assistance System
ATM = Air Traffic Management
ATSP = Air Traffic Service Providers
CDTI = Cockpit Display of Traffic Information
CPDLC = Controller Pilot Data Link Communication
CTAS = Center/TRACON Automation System
DAG-TM = Distributed Air Ground Traffic Management
DAC = Dynamic Airspace Configuration
DSR = Display System Replacement (En Route Controller Workstation in the NAS)
DST = Decision Support Tool
FAA = Federal Aviation Administration
FMS = Flight Management System
IFR = Instrument Flight Rules
MACS = Multi Aircraft Control System
NAS = National Airspace System
NASA = National Aeronautics and Space Administration
NextGen = Next Generation Air Transportation System
TFR = Trajectory-based Flight Rules
TMA = Traffic Management Advisor
TRACON = Terminal RADAR Approach Control
TSAFE = Tactical Separation Assisted Flight Environment
RNP = Required Navigation Performance
RVSM = Reduced Vertical Separation Minima

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SA = Separation Assurance
SESAR = Single European Sky ATM Research program

I. Problem

Air traffic demand is anticipated to grow substantially in the coming decades[1]. The Federal Aviation Administration (FAA) and industry forecast that air traffic operations are expected to increase 150 to 250 percent over the next two decades. Analyses of even the most conservative growth estimates show a significant lack of existing and planned capacity.[2]

The primary purpose of the research discussed in this paper is to gather more insight into the fundamental problem of human/automation integration and allocation of roles and responsibilities required to achieve the significant capacity increases targeted for NextGen. Initial part-task studies with controllers in the loop have been conducted in the Airspace Operations Laboratory since August 2007. These studies specifically begin to investigate the future role of air traffic controllers and automation in a service provider-based automated separation assurance environment. The focus is on trajectory-based operations at substantially higher traffic densities than in today's airspace system.

It is assumed that managing 2 or 3 times today's traffic density requires a fundamental change from today's operations in how separation between aircraft is assured. In today's very safe system, air traffic controllers take active control over each aircraft in their airspace and issue clearances to keep it separate from other traffic, expedite traffic flows, and provide additional services, workload permitting. Being actively involved with each individual aircraft provides the awareness required to detect and resolve potential losses of separation independent of automated aids. However, this manual process can only be performed for a very limited number of aircraft. In recognition of this fact, each airspace sector today has a defined maximum number of aircraft that are allowed to enter. This constraint exists as a way of ensuring that the demands on the cognitive resources of the air traffic controller(s) controlling this sector are not exceeded. Figure 1 below depicts an air traffic controller display contrasting a typical current day high traffic density to twice and three times this density. Assuming that the display on the left represents the limit of the sustained traffic load a controller can comfortably manage today, operations need to change significantly for the move to the traffic levels depicted in the center and on the right to be realized.

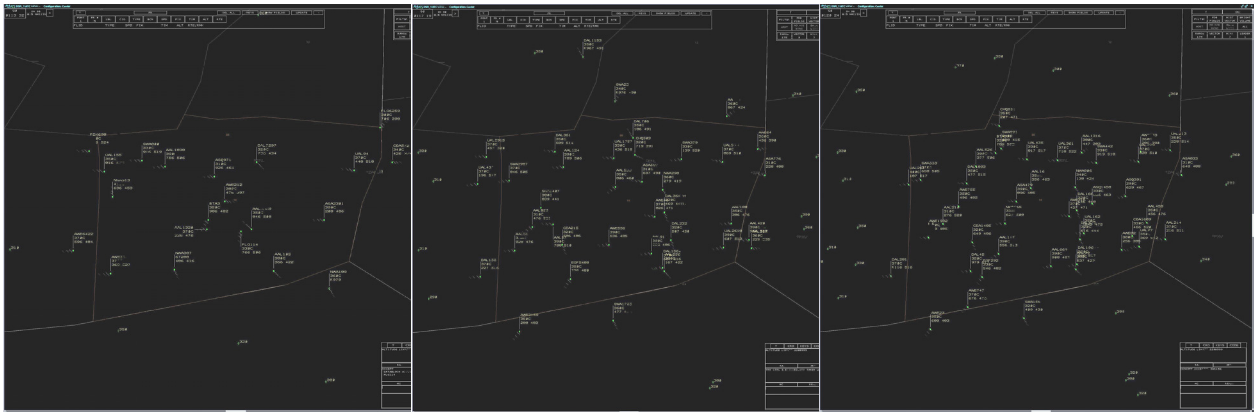


Figure 1: Current day controller display with 1x, 2x and 3x traffic

NextGen envisions trajectory-based operations (TBO) to replace clearance-based operations in many parts of the airspace. New automated separation assurance functions are intended to help overcome the aforementioned limitations of controllers in manually maintaining safe separation between aircraft. The two primary new separation assurance concepts are airborne self-separation and ground-based automated separation assurance. Research is ongoing in both areas. NASA researchers, including the authors of this paper were part of prior human-in-the-loop assessments of mixed operations with airborne self-separation at more than two times today's traffic density.[10] Various evolutionary concepts aimed at achieving incremental benefits over the next ten years, including the use of new decision support technologies, new data communication capabilities, new airborne spacing capabilities, and changes in the air traffic control team structure, have also been simulated with humans in the loop at various research institutions including NASA and MITRE CAASD.[11-17] Initial laboratory demonstrations and closed-loop automated evaluations of the enabling technologies for service-provider based automated separation assurance have now progressed to technology prototypes that start looking at the actual operations as envisioned under the far-term concept of automated separation assurance.[18, 19, 20, 21]

The research described in this paper, initial part-task controller-in-the-loop simulations with ground-based separation assurance automation in double and triple traffic densities, is therefore breaking new ground. It should be viewed only as a first step towards understanding the complexities of human/automation interaction in the airspace system of 2025 and beyond.

II. Approach

The approach to ground-based automated separation assurance in NextGen can be described in a two layered system using the diagram depicted in Figure 1. It is composed of a "strategic" separation layer for trajectory management and de-confliction and a "tactical separation" layer for safety assurance. The goal of the trajectory management function is to ensure that aircraft trajectories do not intersect to create a potential loss of separation (LOS) within the next two to twenty minutes. If a potential LOS is predicted, a trajectory change is planned and communicated to the aircraft that will separate the flight paths without needing tactical intervention. The goal of the tactical safety assurance function is to avoid a LOS, even if it is predicted to occur within the next one or two minutes. Generally, such a near-term conflict does not leave enough time for a strategic trajectory change. The most likely cause for near-term conflicts is a faulty prediction of the aircraft trajectory due to a drastic mismatch between the actual and the expected aircraft performance, non-conformance to the cleared trajectory, or different trajectories stored in the air and the ground system. Additionally, less frequent off-nominal situations may occur that lead to detecting potential conflicts late. While a primary goal of trajectory de-confliction is to never have to use the tactical layer, the goal of the safety assurance function is to provide a safety net in case the trajectory management layer fails. Both layers -trajectory-based SA and safety assurance- apply to all aircraft, whether through a data link or a voice link to Air Traffic Control.

Operationally, communicating complex trajectory changes via voice is difficult and the primary communication means used for strategic separation assurance is envisioned to be data link. Nonetheless, the question of mixed operations with data link equipped and unequipped aircraft is important for transitional stages to NextGen and airspace design considerations.

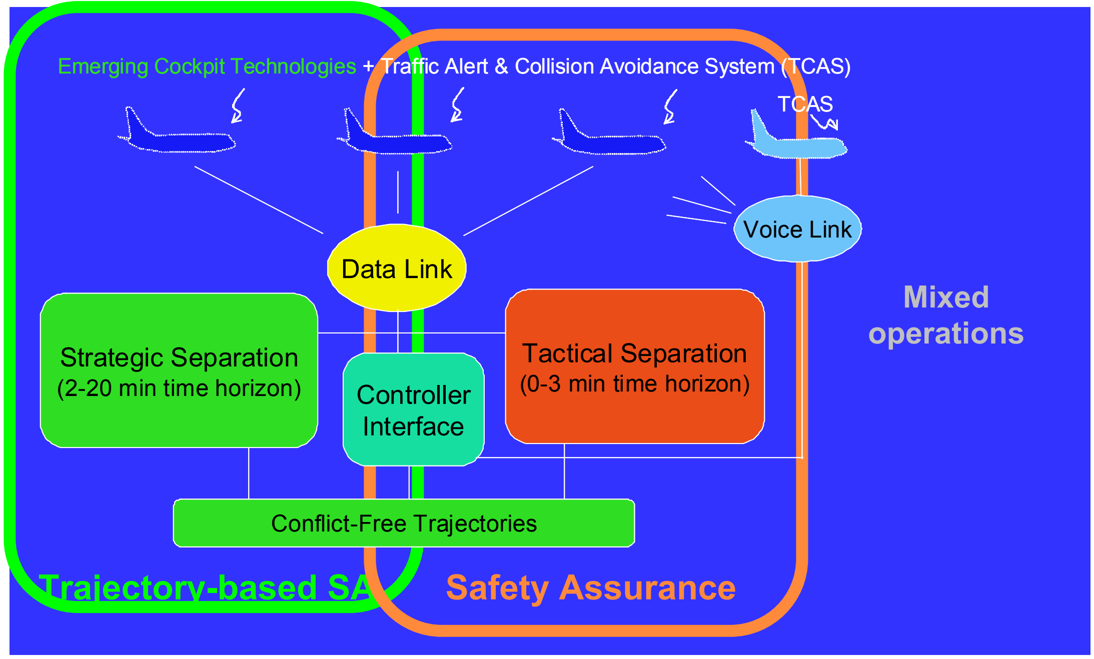


Figure 2: Simplified schematic of ground-based automated separation assurance

In order to get an initial handle on the key questions regarding roles and responsibilities, level of automation, and human automation integration, three part-task experiments were initiated by the Separation Assurance and the Dynamic Airspace Configuration research focus areas to be conducted between August 2007 and August 2008. These three experiments are designed to give initial insight into each of the three main components described above:

1. Initial Study of Trajectory-Based Separation Assurance (August 2007)
2. Initial Study of Mixed Operations with automated SA (March 2008)
3. Initial Study of Tactical Separation Assurance (July 2008)

The studies are conducted in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center using the Multi Aircraft Control System (MACS) to simulate the operations. Additional flight deck aspects are investigated in the Flight Deck Display Research laboratory at NASA Ames. This paper will briefly describe the simulated NextGen environment including the concept of operations, equipage requirements and automation capabilities. This will be followed by a description of the experimental apparatus and a discussion of each part-task study. Data analysis of the trajectory-based SA study is complete and key results are included. Data analysis of the mixed operations simulation is underway and preliminary findings are presented. The tactical separation assurance study is in preparation and the experimental design will be outlined.

III. Simulated NextGen Environment

This section will give a brief overview over the key elements of the NextGen environment that is simulated commonly for each of the experiments. While this environment is by no means comprehensive, it includes some of the key assumptions necessary to understand the results.

A. Narrative of the simulated NextGen environment

The following is a narrative of the simulated environment. Some specifics such as minimum altitudes or performance requirements should be seen as illustration aids rather than conceptual decisions.

The year could be 2025. Data link has been integrated into air traffic control facilities and many routine tasks such as transfer of control and communication are handled by the automation. Airspace is still divided into sectors, and includes trajectory-based airspace above flight level 240. Traffic levels range from current day density (1x) to double (2x), triple (3x) and in some cases even more than three times today's traffic density. The mix of aircraft types is similar to today's mix. All aircraft entering trajectory-based airspace are equipped with flight management systems and broadcast position and speed information via ADS-B. Aircraft meeting minimum equipage requirements can conduct their flights according to trajectory-based flight rules (TFR). TFR aircraft can always enter trajectory-based airspace, and are cleared to proceed, climb, cruise and descend via their uplinked trajectory. Flight crews of TFR aircraft monitor uplinked frequencies and do not verbally communicate with air traffic controllers unless by exception. TFR operations require data link capabilities to receive basic (FANS-like) data link messages including frequency changes, cruise altitudes, climb, cruise, descent speeds, and route modifications, and need to meet a required navigation performance (RNP) value of 1. Aircraft without the appropriate equipage follow current day Instrument Flight Rules (IFR). They receive clearances and instructions like today, and are only permitted into trajectory-based airspace on an "as available" basis.

B. Roles and Responsibilities

The ground automation generates and maintains a trajectory data base for all aircraft. It is responsible for detecting "strategic" medium-term conflicts (typically up to 20 minutes) between all trajectories and for monitoring the compliance status of all aircraft relative to their reference trajectory. The ground automation is also responsible for detecting "tactical" short-term conflicts (typically 0 to 3 minutes) between all aircraft.

Flight crews are responsible for following their uplinked (or initially preferred) trajectory within defined tolerances and for the safe conduct of their flight (just like today).

Air traffic controllers are responsible for issuing control instructions to IFR aircraft. Their roles and responsibilities with regard to TFR aircraft, the interactions between IFR and TFR aircraft and their interaction with the ground automation are key questions to be initially investigated by the human-in-the-loop research reported in this paper. The initial findings will be presented in the subsequent results section.

C. Controller workstation

A new design of the controller workstation can be implemented in light of the fundamental paradigm shift that is entailed by the redefined roles and responsibilities described above. Responsibility for monitoring trajectories for conflicts as well as each individual aircraft's conformance to those trajectories is assigned to the automation. Routine tasks, such as transfer of control and communication are also conducted by the automation. The controller is no longer expected to maintain awareness of each individual flight. Therefore, the controller workstation can be drastically re-designed. The goal is to provide efficient task sharing between the controller and the automation. If, for example, the automation is responsible for conflict detection and the controller is responsible for conflict resolution, the display focuses on aircraft that are already in conflict, while other aircraft are low-lighted. If the controller is not responsible for monitoring or managing certain aircraft, there is no need to display all the details about those aircraft all the time. This approach was pursued for the initial set of studies on automated separation assurance. Figure 3 gives one example of a display prototype (right) showing the same traffic that was used to illustrate the 3x display shown in figure1.

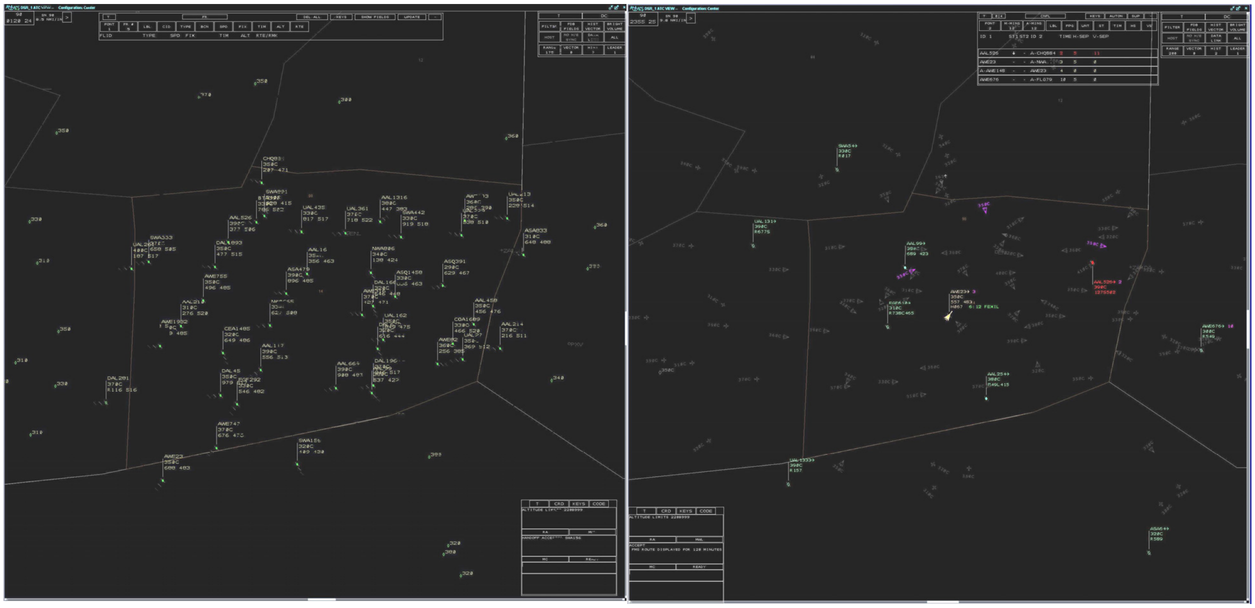


Figure 3: Current day display at 3x traffic and display prototype

A cursory look at the prototype on the right shows several "unequipped" IFR aircraft with current day data tags. It also highlights conflicts between unequipped IFR and equipped TFR aircraft (in magenta). The controller issues clearances to the IFR aircraft and is responsible for managing conflicts between IFR and TFR aircraft. All other TFR traffic is managed by the automation. Those aircraft are depicted with low-lighted directional symbols and altitudes to provide a general picture of traffic clusters. The controller can easily access additional information using the track ball or keyboard.

D. Flight deck

While the ground-side undergoes significant changes in many aspects, including technology, team configuration, and operational procedures, changes on the flight decks are primarily procedural. The minimally required technologies for accepting data link messages and broadcasting position information via ADS-B already exist in various airplanes. However, with only few exceptions, data link is currently used primarily in the oceanic airspace. Flight crews will have to get used to a "silent" ATC environment, and to respond quickly to data link messages. Procedurally they will have to set their flight control system to follow their trajectory without receiving a clearance for each altitude change. Emerging flight deck technologies for airborne separation assistance may change the roles on the flight decks as well. These technologies may be beneficial for other purposes, but are not required for the concept of ground-based automated separation assurance.

E. Automation

The concept of automated SA is enabled through a seamless integration of controller workstations, ground-based automation, data link, flight management automation and flight deck interfaces. The ground automation creates and maintains accurate trajectories for each flight. The conflict detection is highly reliable and able to detect trajectory-based conflicts with more than eight minutes before initial loss of separation. A conformance monitoring function detects off-trajectory operations and triggers an off-trajectory conflict probe. The trajectory generation function used for conflict resolution and all trajectory planning provides FMS compatible and loadable trajectories. These trajectories account for the nominal transmission and execution delays associated with data link messaging.

Automated trajectory-based conflict resolutions are generated for conflicts with more than three minutes to initial LOS. Short-term conflict avoidance maneuvers are generated in the tactical separation arena of zero to three minutes to LOS. These technologies enable human operators to manage significantly higher traffic densities than today. Whether and when the operators simply supervise the automation or frequently interact with specific tools is a primary research question asked in the experiments described in this paper.

IV. Method

A. Experimental Apparatus: Airspace Operations Laboratory and Multi Aircraft Control System

The NextGen operations described in the previous section were simulated in the Airspace Operations Laboratory[8] (AOL) at NASA Ames Research Center using the Multi Aircraft Control System (MACS)[22, 23]. The AOL and MACS have been used frequently to investigate new operational concepts, procedures, decision support tools and automated systems. The hardware and software can be configured to accurately emulate current day ATC operator stations as well as flight decks with full flight management and data link capabilities. On the ground side, controller positions as they exist in Air Route Traffic Control Centers, TRACON and Oceanic facilities can be accurately emulated. Figure 4 shows some of the controller and pilot positions in the AOL. All operator stations are provided by MACS, a JAVA program created at NASA Ames Research Center for air traffic operations research.

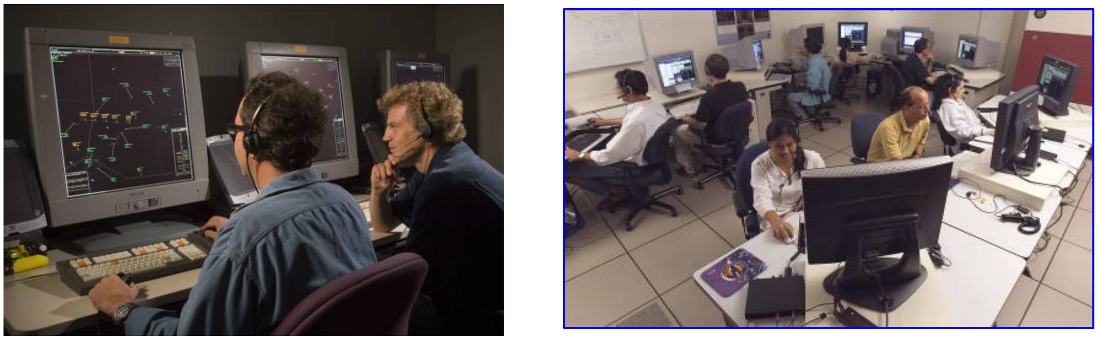


Figure 4: Scenes from the Airspace Operations Laboratory. Controller and support pilot workstations

Numerous advanced automated functions and operator stations have been prototyped in MACS from prior research on near-, medium- and far-term concepts. Some of the standard functions available in MACS are a very fast and effective trajectory generator, ARINC 702 data link capabilities, ADS-B emulation, highly configurable conflict detection and conflict alert functions and highly configurable displays. New capabilities are prototyped within MACS as the research progresses into new territory and are added to the available suite of tools. Since conflict detection and resolution are among the central elements of separation assurance the following gives a brief introduction into how these functions are implemented into the experimental environment.

B. Conflict detection

The MACS conflict detection logic conducts a deterministic conflict search along the flight plan-based trajectories stored in the ground-based system as long as aircraft are in compliance with their trajectories. Once out of conformance, MACS generates flight state based trajectories for 5 minutes and uses those for conflict probing. A potential separation violation is flagged when level-flight aircraft are predicted to get closer than 5.5 NM and 1000 feet of each other, and when transitioning aircraft are predicted to get closer than 5.5 NM and 1500 feet. The MACS trajectory engine uses aircraft performance models and real-time information to predict up to 12 different flight deck and ground-based trajectories for each aircraft. Atmospheric conditions, such as winds, can be varied between environment, ground-based forecast and flight deck forecast. Different surveillance models can also be selected to model additional uncertainties impacting the trajectory prediction errors in addition to flight technical and actual navigation performance errors. For the initial set of experiments it was decided not to introduce wind errors and use the best surveillance source available. Thus, primarily trajectory modeling and flight technical errors remained, making the conflict detection fairly reliable. However, it was particularly climbing aircraft causing late, false and missed alerts. The overall trajectory-based conflict detection accuracy rate in this configuration is approximately between 95% and 98 % depending on the time to LOS.

In addition to the trajectory-based conflict detection a state-based conflict alert function is independently evaluating the traffic situation for near-term conflicts. This function is typically configured to look at zero to three minutes to LOS and is highly reliable (close to 100 %). During the experiments on trajectory-based separation this function was only used for data collection purposes and not presented to the controllers.

C. Conflict Resolution

Where appropriate, MACS can host and integrate externally developed prototypes. For the separation assurance research discussed in this paper, two "external" components were integrated into MACS, both developed by Heinz Erzberger and his team at NASA Ames Research Center:

1. The "auto-resolver": A trajectory-based conflict resolution algorithm that provides efficient flight path changes to solve medium term conflicts [24]
2. The TSAFE near-term conflict resolution logic that provides heading maneuvers to solve time-critical tactical conflicts

The auto-resolver was used during all experiments described in this paper. The TSAFE component is used for the first time in the summer 2008 study. The software of both components was directly integrated into MACS by accessing the original JAVA software through the given programming interfaces. This enables MACS to run the exact same software that is also integrated into the Airspace Concept Evaluation System ACES for fast-time simulation purposes[19, 25] and into the Center TRACON Automation System CTAS for analysis and testing under all the uncertainties of a live data-driven environment[26].

The auto-resolver is integrated into its hosts, such as MACS, ACES, or CTAS, in an iterative manner. For the implementation used in the AOL, MACS is responsible for conflict detection and provides a conflict description to the auto-resolver. The auto-resolver uses its carefully designed logic and a selected prioritization scheme to determine viable solutions and evaluate each candidate trajectory change. Each candidate trajectory that passed an initial test is evaluated using MACS' trajectory generator and conflict detection logic. All successful solutions are compared with regard to the additional flight time or magnitude of change that they impose on the individual flight and the best solution is selected. Data generated during the conflict resolution cycles are stored in a MySQL data base that can be uploaded to a web-based server for detailed analysis and inspection of each iteration cycle [25].

D. Controller interface

Within MACS, conflict resolutions can be initiated by the controller or automatically based on the selected configuration. The controller can request a conflict resolution by selecting the time to conflict or the altitude field in the data tag of conflicting aircraft or by clicking on a conflict in the conflict list. Selecting the altitude gives preference to altitude solutions; otherwise lateral solutions have a small preference. In the current software version, resolution trajectories are generated within few milliseconds. Controller initiated resolutions are presented as trial plans. Trial plans are provisional trajectories that can be modified with click and drag operations, and are continuously probed for conflicts. Figure 5 depicts such a trial plan resulting from a conflict resolution request.

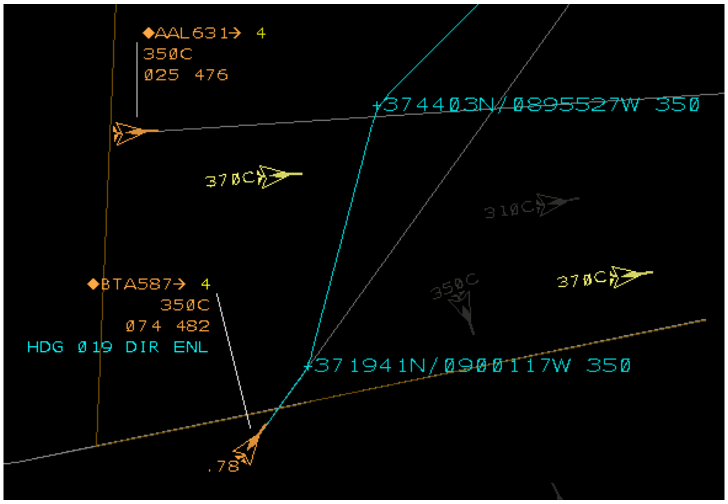


Figure 5: Auto-resolution presented as trial plan

Controllers can start manual trial plans on any aircraft at any time using the click and drag functionality. Trial plan trajectories can be data linked to equipped aircraft or sent to the ground automation as flight plan amendments and issued by voice. Automation initiated conflict resolutions can also be data linked directly to the aircraft without presenting them to the controller.

E. Aircraft Operations

For experimental purposes, MACS can be configured to fully automate aircraft operations. For these purposes automated aircraft follow their FMS trajectories using lateral and vertical navigation modes (LNAV/VNAV). They change altitude settings when the aircraft approaches bottom of climb, top of descent and any other altitude restrictions. Automated aircraft process data link messages with pre-determined delays. This automated aircraft feature was used extensively during the simulations for TFR aircraft, since it provides a deterministic and repeatable behavior. Experimental staff were monitoring the operations to record and intervene in unexpected events.

F. Test Airspace

The airspace used for the simulations consists of two adjacent enroute sectors from the Kansas City Air Route Traffic Control Center (ZKC) and the Indianapolis Air Route Traffic Control Center (ZID). The two sectors are shown in Figure 6. The traffic through the test sector included in the scenarios involved a mixture of overflights with transitioning aircraft from the Lambert-Saint Louis International Airport (STL) and Standiford Field (SDF) International Airport. Sector ZKC 90 was simulated with approximately 20% transitioning traffic while ZID 91 has about 35% transitioning traffic.

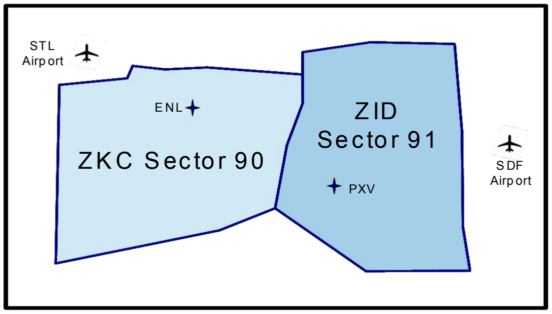


Figure 6: Test airspace

G. Data collection

The primary study metrics were recorded using the comprehensive MACS integrated data collection system. This data collection system logs all relevant parameters for predicted and actual trajectories, flight state information for all aircraft as well as all operator inputs. These logs can be processed with standard spreadsheet software or with custom tools built for post-processing data gathered in AOL simulations[27]. The objective data are then used to analyze the operational effectiveness of the simulated operations, including efficiency and safety aspects. Controller workload is recorded via a workload assessment keypad (WAK) that appears every five minutes in the menu bar of the MACS controller workstation and prompts participants to asses their current workload on a scale of 1 to 7. Additional logs tailored specifically towards complexity analysis were also integrated for this research. These complexity logs, in conjunction with the workload ratings, were used to start analyzing complexity parameters for NextGen environments.[28] Post-run questionnaires as well as post-simulation debriefings are used to gather additional subjective data from the participants.

H. Experiments

As mentioned before, three experiments are conducted to gain initial insight into key aspects of automated separation assurance.

1. Initial Study of Trajectory-Based Separation Assurance (August 2007)
   “Which level of automation is acceptable, appropriate, and manageable for trajectory-based separation assurance with full equipage at 1x, 2x and 3x traffic levels?”
2. Initial Study of Mixed Operations with automated SA (March 2008)
   “Should operations be segregated or integrated? Are mixed-equipage operations feasible in the same airspace under varying traffic densities and to what extent can unequipped aircraft be accommodated?”
3. Initial Study of Tactical Separation Assurance (July 2008)
   “How do controllers, pilots and the automation interact in off-nominal situations and how can the system be safe under uncertainties and resulting imperfections in trajectory-based separation assurance?”

These three studies are discussed subsequently.

V. Initial Study of Trajectory-based Separation Assurance

The initial part-task study with controllers in the loop was conducted in the Airspace Operations Laboratory in August 2007. Envisioned trajectory-based operations for the Next Generation Air Transportation System (NextGen) were simulated, in which conflict detection between aircraft was automated. Four recently retired air traffic controllers and five aviation knowledgeable students participated and were responsible for resolving potential conflicts between aircraft with varying levels of automation. Participants managed two combined high altitude and transition airspace sectors with traffic densities varying from today's density (1x), to double density (2x) and triple density (3x). This section provides an initial overview of the study and its key findings. More detailed explanations and analyses of this study and its findings are available in other publications[28, 29, 30]

Table 1: Scenario characteristics

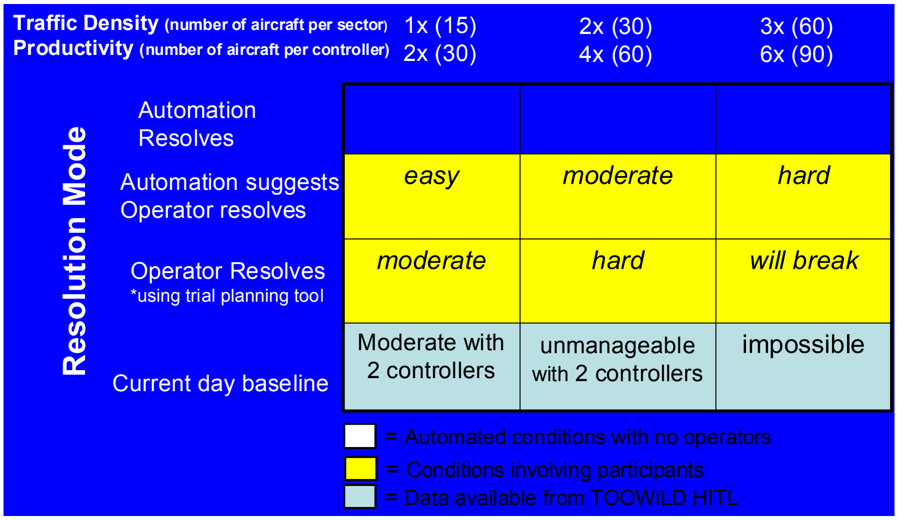
	1x	2x	3x
Average number of aircraft in test sectors	30	60	90
Total Number of aircraft in test sectors *(Both scenarios combined, approximates per hour rate)*	144	284	424
Total Number of scripted conflicts *(Both scenarios combined, approximates per hour rate)*	11	68	134
Level/Level conflicts	8 73%	53 78%	104 78%
Level/Climb conflicts	0 0%	5 7%	11 8%
Level/Descend conflicts	3 27%	10 15%	19 14%

The two combined sectors with these traffic densities engaged participants in solving conflicts between an average of 30 (1x), 60 (2x), and 90 (3x) aircraft during the 30 minute simulation runs. Table 1 presents the number and characteristics of the scripted conflicts during the runs.

A. Experimental Design

The approach to addressing the problem of controller/automation interaction in strategic trajectory-based separation assurance in this study was to compare operations with trajectory-based separation assurance at different levels of automation to each other. In all experimental conditions responsibility for conflict detection was assigned to the automation and controllers did not have to conduct any other tasks than conflict resolution. The first level of automation had automated conflict detection and manual conflict resolution with a highly responsive trial planning tool that was integrated with data link and the conflict detection function. The second level of automation involved the same tools with the addition of the autoresolver, which the controller could use interactively. The final level of automation for comparison was a fully automated, closed-loop system in which all conflicts were resolved by the autoresolver without controller involvement. Baseline data from current day operations had been gathered during previous experiments. For the initial ground-side study it was decided to simulate human/automation interactions only for the relevant aspects of NextGen operations with trajectory-based automated separation assurance and to automate all flight deck operations with reasonable assumptions about flight crew response times and aircraft tracking accuracies. Flight deck aspects were initially addressed separately by the Flight Deck Display Research Group at NASA Ames.

The within subjects design of this initial study gave operators access to the fast manual trial planning function in half the human-in-the-loop runs. During the other half of the runs participants could also interact with the autoresolver. The controllers could use the algorithm to request a conflict resolution trajectory and uplink it unchanged, modify the resolution trajectory using the trial planner and then uplink it, or cancel the modification. This study design can be represented as a multi-part study that varied the *level of automation* over the *traffic density*



Resolution Mode	**Traffic Density** (number of aircraft per sector) **Productivity** (number of aircraft per controller)	1x (15) 2x (30)	2x (30) 4x (60)	3x (60) 6x (90)
	Automation Resolves			
	Automation suggests Operator resolves	*easy*	*moderate*	*hard*
	Operator Resolves *using trial planning tool	*moderate*	*hard*	*will break*
	Current day baseline	Moderate with 2 controllers	unmanageable with 2 controllers	impossible

⬜ = Automated conditions with no operators
🟨 = Conditions involving participants
🟦 = Data available from TOOWiLD HITL

Figure 7: Test Matrix and initial hypotheses about workload

B. Data Collection:

Data collection occurred during three two day sessions over the course of two weeks. Each group had three participants who worked the same scenarios and conditions in independent “worlds” simultaneously. They received half a day of training and then conducted 12 runs of 30 minutes each. Each combination of traffic density and level of automation was run twice for each participant. Aircraft operations and ATC operations in the surrounding sectors were automated and supervised by experiment staff.

The controller displays were configured to support conflict resolution of equipped aircraft in the respective mode of operations (Figure 8).

All aircraft are displayed with a limited data block unless the operator is viewing or resolving the conflict manually or with the auto-resolver, a data link message is pending, or the operator has manually selected the full data tag for the aircraft. The color coding depends on the conflict status: Dark grey is used to low-light aircraft that are not currently in conflict. If a conflict is detected between 9 and 12 minutes to LOS, the data tag is displayed in white, conflicting aircraft with 5 and 8 minutes to LOS are shown in yellow, and if a LOS is predicted to occur in less than 5 minutes, the aircraft are displayed in orange.

With the aircraft in conflict highlighted, the controller could then easily access that aircraft’s full data block by clicking on the aircraft symbol.Controllers could also access a conflict list sorted by time to LOS to organize their conflict resolution task.

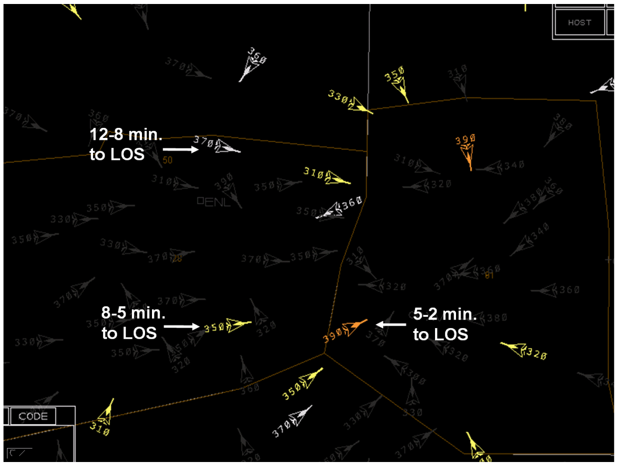


Figure 8: Display design for conflict resolution

C. Results summary

In summary, the simulated part-task setting at the 2x density was very manageable and adequate for the interactive mode and was somewhat manageable with a manual trial planner. 3x density was somewhat manageable interactively, but would not pass the “spill your coffee” test. 3x density was unmanageable using the trial planning function alone. The automated resolutions suggested to the participants in the interactive mode were rated as highly acceptable. Across the various metrics that were included in this study, differences between the air traffic controllers and the student participants were observed.

D. Automation Usage and Acceptability

The differences between the air traffic controller group and the student group are most obvious in how they operated in the interactive mode. The retired air traffic controllers consistently requested the automated resolution advisories in the vast majority of all conflicts with an average of 95% (1x), 98% (2x) and 98% (3x) of the conflicts encountered. The controllers modified very few of the resolution advisories, and "tweaked" only approximately 4% (1x), 1% (2x) and 1% (3x) of all resolution advisories. The students showed a much more diverse behavior and requested the automation advisories on average only for 56% (1x), 80% (2x) and for 95% (3x) of the conflicts. They also modified more resolutions with averages of 17% (1x), 11% (2x) and 5% (3x). Figure 9 depicts these results.

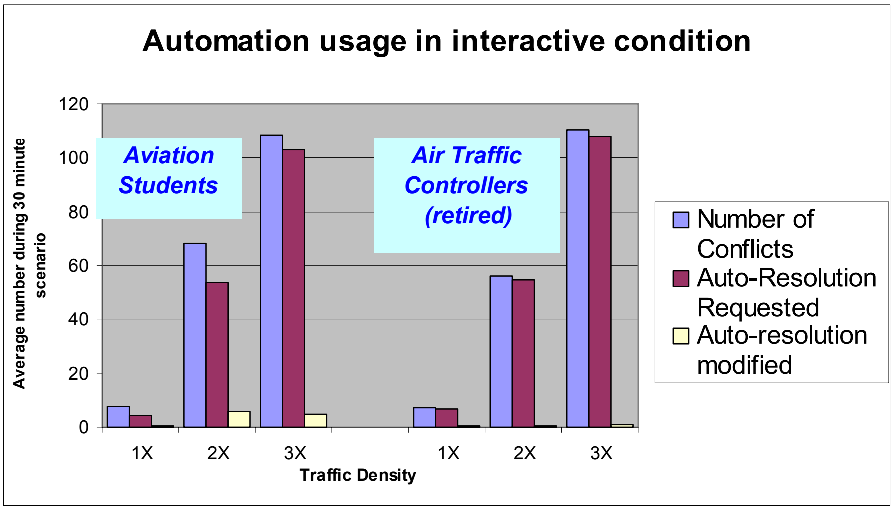


Figure 9: Automation usage in interactive condition

In post-run questionnaires participants also rated the acceptability of the suggested conflict resolutions by answering the question" ***"How acceptable do you feel the suggested conflict resolutions from the automation were?"*** on a scale of 1 = completely unacceptable to 7 = completely acceptable. The results are depicted in Figure 10 below:

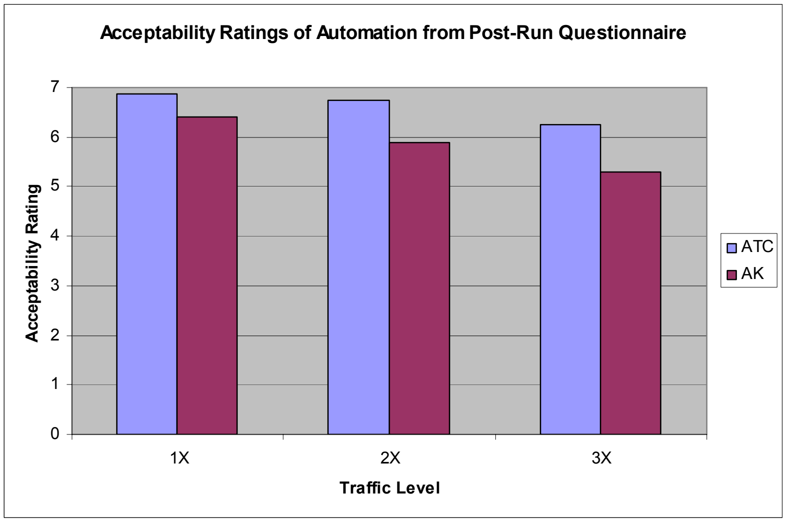


Figure 10: Acceptability ratings of individual conflict resolutions

The results indicate that the resolutions were generally very acceptable with a slight degradation as the traffic density increases. This is likely due to the fact that higher density results in fewer conflict resolution options and the automation generated less efficient trajectory changes than when the density was lower. In general, the retired air traffic controllers found the automated resolutions more acceptable than the aviation knowledgeable students.

E. Workload

Analysis of the controllers' workload ratings on a scale of 1 to 7 taken during and after the runs suggest that peak workload during the 1x case with two sectors was very low (~1). The 2x manual condition was significantly higher than the 2x interactive and the 3x manual was at the maximum (7). The 3x interactive ratings were high (4-6) but consistently less than the manual condition. With conflict detection being automated, the air traffic controller workload related to conflict resolution appears to correlate with the task load involved in the mechanical process of planning a resolution. The monitoring workload and routine task pattern required to achieve the necessary situation awareness to work traffic in the current day environment has disappeared with automating the conflict detection process. This eliminates controller workload as the primary bottleneck in increasing sector capacity. Figure 11 show the workload averages and peaks by participant group, operating mode and traffic density.

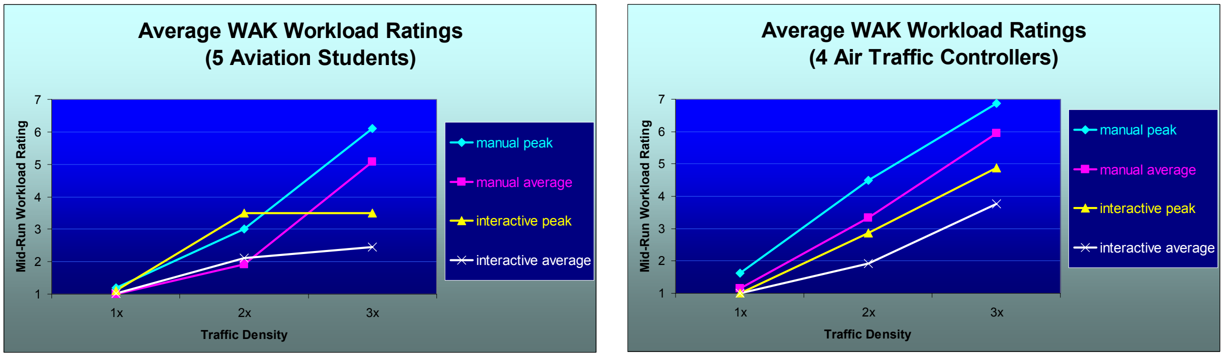


Figure 11: Workload ratings of aviation students and air traffic controllers

F. Maneuver Selection

In order to resolve conflicts participants could use vertical and lateral flight path changes and express preferences when requesting resolution advisories from the automation. The automation used a scheme, in which lateral maneuvers were preferred to vertical maneuvers until the delay imposed was too excessive. Figure 12 below compares the maneuver selection of the air traffic controllers in the manual and semi-automatic (interactive) mode to the fully automated maneuver selection. The results show that in the manual mode, there was a similar preference for lateral maneuvers as with the autoresolver, but that there was a shift to preferring vertical maneuvers at the 3X level. The results for the interactive mode were similar to those for the fully automated mode, with the one exception of the interactive mode showing that a larger number of resolutions were implemented.

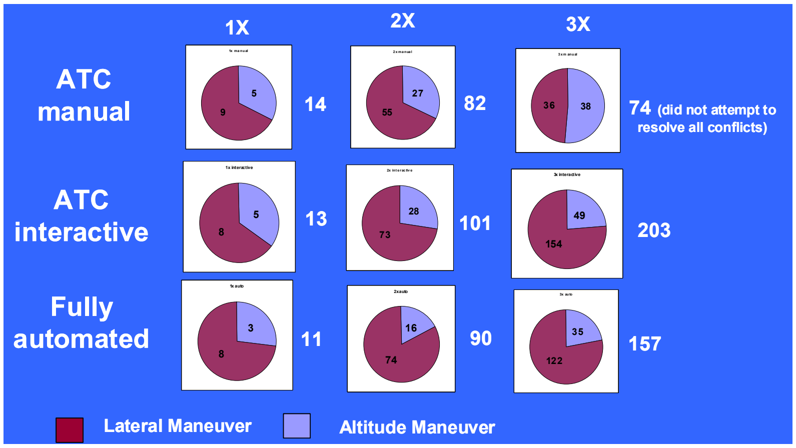


Figure 12: Maneuver selection of air traffic controllers and automation by operating mode and traffic density

G. Safety

The trajectory management function is intended to detect and resolve the medium-term conflicts with strategic trajectory changes. It is expected that short-term conflicts will still occur and that they would have to be resolved using the tactical safety assurance function. Additionally it was expected that managing the 3x density with manual trial planning tools would be impossible and therefore would lead to separation violations. Analysis of the separation violations during the test runs as depicted in Figure 13 confirms both those assumptions. It can be concluded that manual trial planning is an inappropriate operating mode in 3x traffic. The separation violations in the interactive and the automated modes were the result of late conflict detections. Conflicts detected with less than three minutes to LOS were not intended to be resolved by the trajectory-based separation assurance function. Even though the number of such occurrences in this simulation may be more than what would be expected in real operations, their existence confirms the need for the tactical safety layer described earlier in this paper.

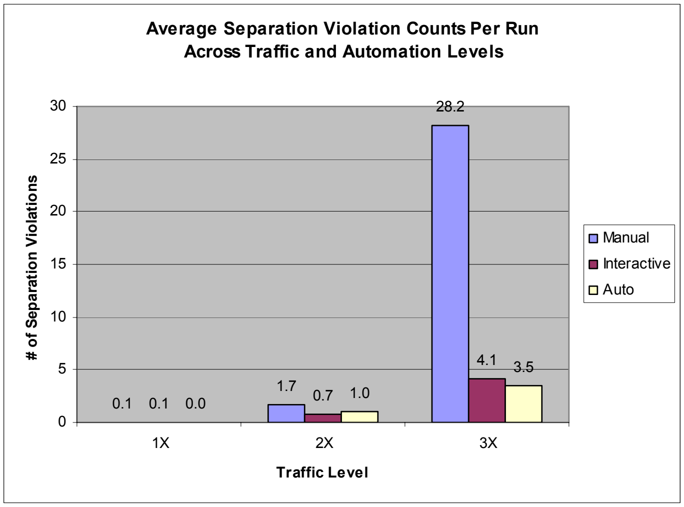


Figure 13: Separation violations per run by operating mode and traffic density

H. Efficiency

As a measure of efficiency the time and delay added to the original trajectories was analyzed for the different conditions. Figure 14 below shows the delay that was added per trajectory change. In the 1x and 2x cases some participants were able to create more efficient routings than the automation at the cost of additional workload (see above). At 3x the participants achieved a similar efficiency in the interactive mode as the automation. The solutions generated in the manual mode imposed significantly more delay than the automated solutions in 3x.

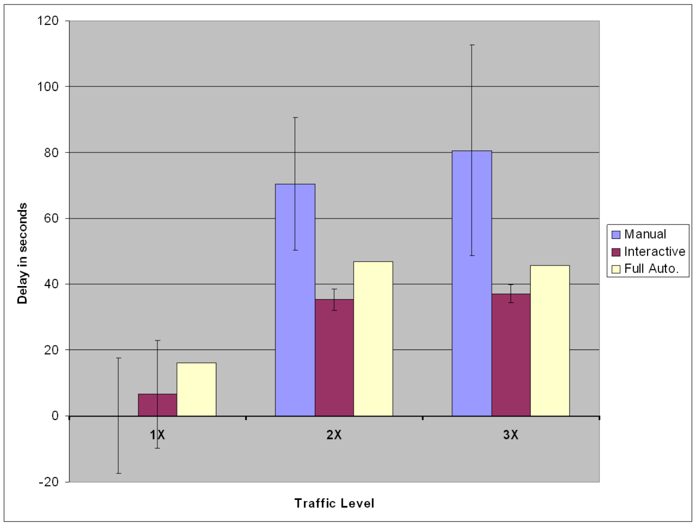


Figure 14: Average flight delay per trajectory change

I. Discussion

The results presented here show that the drastic paradigm shift in making the automation responsible for conflict detection and automating routine tasks pays off. With automated conflict detection and conflict resolution aids traffic densities of equipped aircraft can be raised significantly beyond today's levels. As long as conflict resolution is a manual process the comfortable limit may be less than 2x. However, using the conflict resolution algorithm interactively raised this level even further. This was most apparent at the 3x level of traffic where it was shown that operations are basically unthinkable in a manual trial planning mode. It was also shown, however, that more would need to be done for the transition to 3x traffic as having the controller in the loop on each trajectory change at this level appeared to be exceeding the comfortable workload limit. Overall the automated conflict resolution function was highly acceptable, especially to the air traffic controllers. Through participant feedback and observation of the runs, potential improvements to the auto resolution logic were identified and planned for incorporation. The display design also appeared straightforward, intuitive and in support of the task. This was supported by the fact that after only a few hours of training operators were able to work the positions effectively.

While these results are very encouraging it is also confirmed that with a less than perfect trajectory-based conflict detection function other means of safety assurance need to be in place in order to provide the required level of safety to assign the task of separation monitoring to the automation and move to higher traffic levels.

VI. Initial Study of Mixed Operations with Automated Separation Assurance

The question of whether and how mixed equipage could be accommodated in an automated separation assurance environment is important for separation assurance and airspace design considerations. To begin answering some of the basic questions in this area, an initial study on mixed operations was conducted in the AOL in April 2008. This study was sponsored and led by the dynamic airspace configuration element of NASA's airspace system program. A detailed report on this study will be compiled once the data analysis has been concluded. In this paper the design of the study and a few initial findings are presented.

The objective of the study was to identify the appropriate future airspace configuration in terms of whether or not it should be segregated or integrated to support mixed operations. This means examining if mixed equipage operations are feasible in the same airspace under varying levels of traffic densities (e.g., 1X, 2X, and 3X) and varying levels of equipage mix (i.e., increasing number of non-equipped aircraft).

As discussed earlier 'Equipped' aircraft were those with sufficient data link and navigation performance to participate in trajectory-based automated separation assurance and conduct their flights according to trajectory-based flight rules (TFR). 'Unequipped' aircraft conduct their flights according to instrument flight rules (IFR). In this study equipped aircraft were managed by the ground automation via data link without operator intervention. Unequipped aircraft were managed by the controllers via radio transmission according to current day procedures.

A. Experiment design

The experiment was designed to identify the threshold at which mixed equipage operations are no longer feasible. The experiment design is indicated in Figure 15. The four blocks represent 4 different conditions (or experimental runs each of which lasted for 45 minutes). The count of TFR aircraft in the test airspace is held constant at the following levels: 0 aircraft (0x) 15 aircraft (~ 1x), 30 aircraft (~ 2x) and 45 aircraft (~3x). Over the

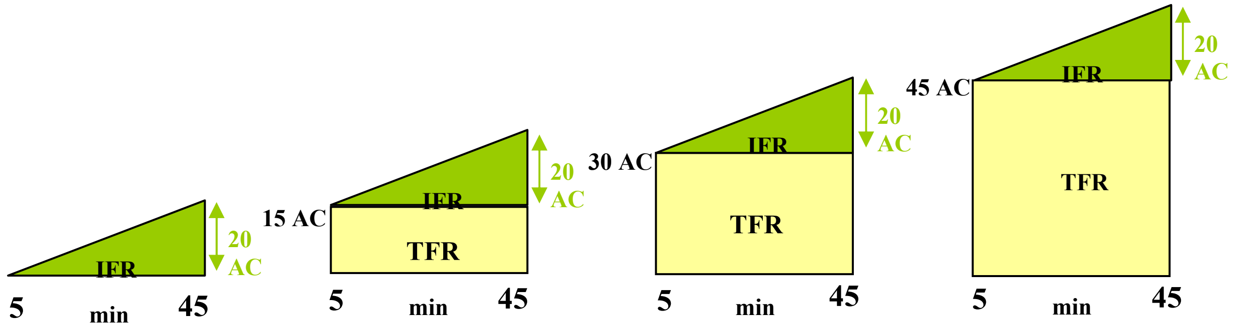


Figure 15: Experimental design for mixed operations study

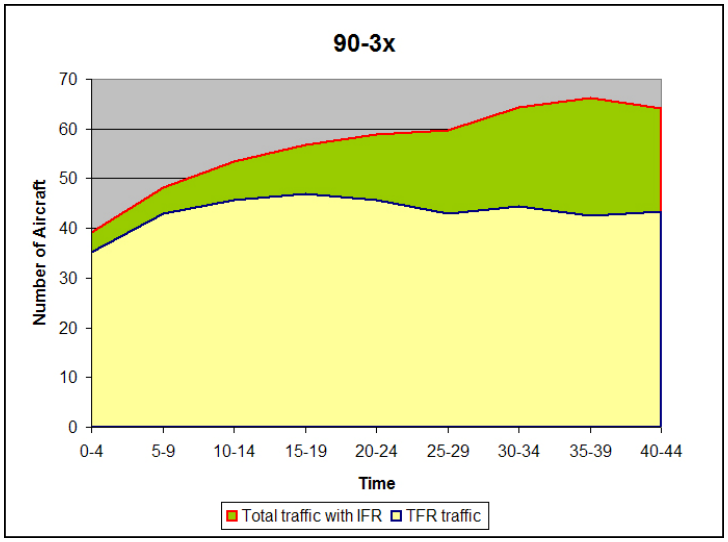


Figure 16: Total number of aircraft in ZKC 90

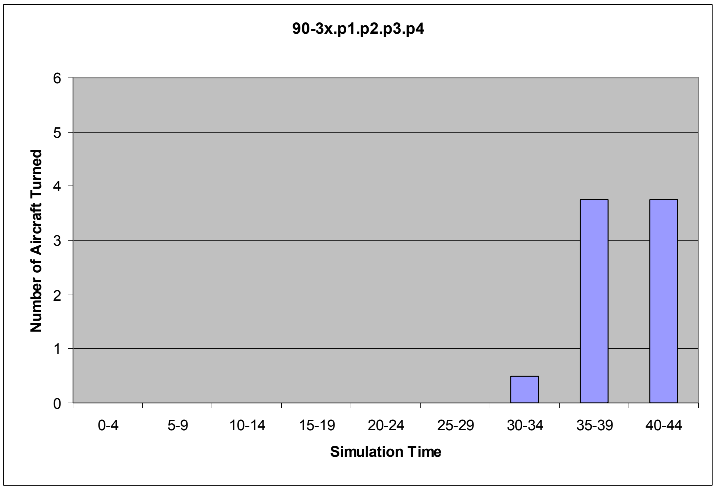


Figure 17: Number of aircraft turned away from ZKC 90

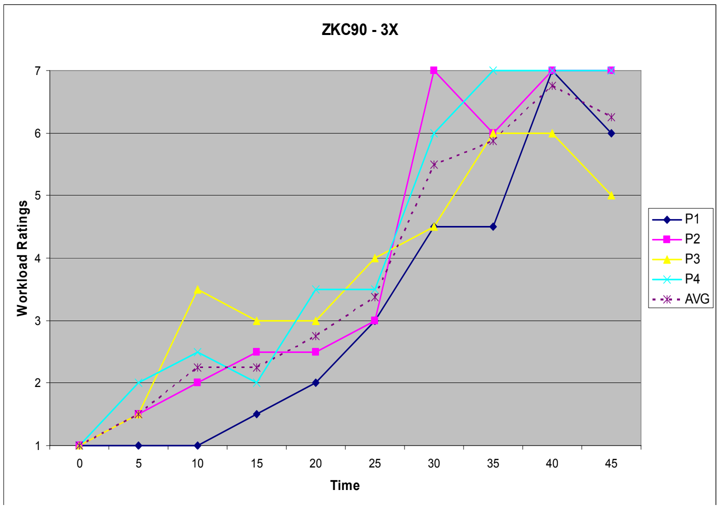


Figure 18: Participant controller workload in ZKC 90

course of each simulation run, an increasing number of IFR aircraft is handed into the test sector by confederate controllers. A confederate supervisor is situated behind the participant observing the controller's actions. When, in the supervisor's judgment, the controller starts to get overloaded, the supervisor instructs the ghost controllers to turn aircraft away from the test sectors.

B. Data Collection

Four full performance level controllers participated in two weeks of data collection. Each week two controllers worked the same scenarios in independent worlds simultaneously. They were trained for one and a half days, followed by two days of data collection and a debriefing with a total of 12 experimental runs. For this study each participant worked both test sectors shown in Figure 6 separately. Sector ZKC 90 was considered less complex than Sector ZID 91 because it has fewer transitioning aircraft and a larger size.

C. Initial findings

The data analysis is still in progress and will be detailed in upcoming publications. Figures 16-19 provide an initial look at some of the data from the study. All graphs are for Sector ZKC 90. Figure 16, 17 and 18 show data for the runs in sector ZKC 90 with the highest traffic load (3x).

Figure 16 shows that the TFR traffic in yellow reaches its near constant state of approximately 45 aircraft in this sector after 5 minutes. The IFR traffic is increased in the course of the run. The total number of aircraft exceeds 65 aircraft at approximately 33 minutes into the run.

Figure 17 indicates that at the same time the supervisor starts to turn aircraft away from this sector. The average number of aircraft turned away per 5 minute interval is shown. So the total aircraft count in sector 90 drops below the peak as the aircraft are turned away.

Figure 18 shows the raw data of the self reported workload of the four controller participants. The controllers were prompted to report their workload every 5 minutes during the run on a scale of 1 to 7, with 1 being very low and 7 being a state where they are just about to lose the picture. The workload curves follow primarily the increase in IFR traffic, which is the traffic that the controller is responsible for. This observation is consistent with findings from research on mixed operations with airborne self separation, in which workload was also related primarily to the number of aircraft for which the controller is responsible. [10]

In sector ZKC 90 the number of automation managed TFR aircraft seems to have a significant but smaller effect on controller workload. Figure 19 shows total number of aircraft, number of aircraft turned away and controller workload for all traffic conditions in ZKC 90.

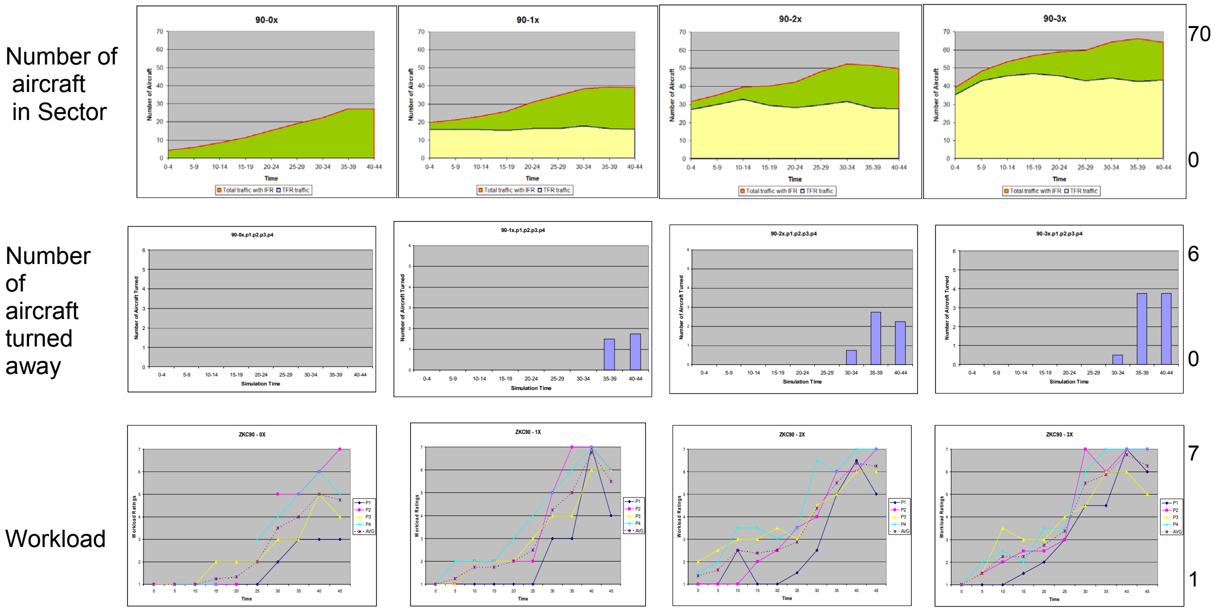


Figure 19: Sector statistics for ZKC 90 for 0x, 1x, 2x, 3x from left to right. Note that the 3x values are depicted in detail in Figures 16 – 18.

When no TFR aircraft were in the sector no IFR aircraft were turned away. However, controller workload reached close to unacceptable levels with 20 IFR aircraft in the sector. Compared to the current day Monitor Alert parameter (MAP) of 18 for this sector this indicates that the baseline simulation resulted in controller workload that is comparable to the workload experienced today at similar traffic levels.

Figure 19 also seems to indicate that as the number of TFR aircraft in the sector increases controller workload increases earlier in the run and more aircraft have to be turned away.

D. Discussion

The ongoing data analysis promises many more interesting findings related to sector complexity, automation usage, separation management etc. Conclusions will have to wait until all the results are in and will be published soon. Initial findings indicate that a limited number of IFR aircraft may be manually controlled in the same airspace as a potentially large number of aircraft that is controlled by a different entity –the ground automation in this case. At the same time the workload ratings for the IFR only runs indicate that the availability of conflict detection and resolution tools does not seem to enable a significant capacity increase if the controller has to issue verbal control instructions and maintain awareness of the traffic similar to the way it is done today.

VII. Initial Study of Tactical Separation Assurance

The third initial human-in-the-loop part-task study on ground-based automated separation assurance focuses on tactical separation assurance and off-nominal events. The main research question can be stated as "How do controllers, pilots and the automation interact in off-nominal situations and how can the system be safe under uncertainties and resulting imperfections in trajectory-based separation assurance?" This study is conducted jointly by the AOL and the Flight Deck Display Research Lab (FDDRL) at NASA Ames in July/August 2008 with participant pilots and controllers.

In this study the tactical separation assurance layer will be integrated into the ground automation using a near-term conflict alerting function and the TSAFE conflict resolution module. The trajectory-based separation assurance layer will be largely automated. The study will investigate whether and how a certified professional controller can effectively supervise the automation, provide additional services, and resolve near-term conflicts with and without automated aids. The flight deck perspective will be investigated in the same study with airline pilots.

A. Experimental Design

The experiment will investigate the controller/pilot/automation response to "expected off-nominal" situations under different conditions. This means that events that are likely to occur in a realistic NextGen environment, such as altitude and route deviations, trajectory mismatches between air and ground, data link message rejections, communication failures, etc. will be intentionally imbedded into carefully scripted scenarios.

The experimental variables are shown in Figure 20. The experiment will be run at 2x and 3x traffic levels in sector ZID-91, which is the more complex of the two test sectors used in the other part-task studies.

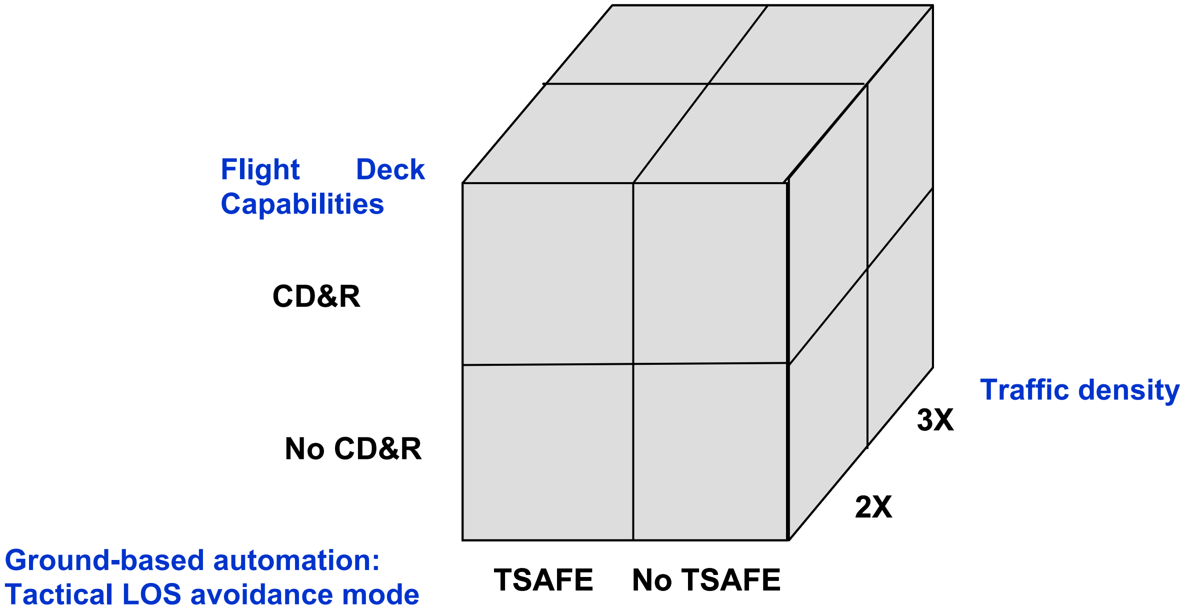


Figure 20: Experimental design for study on Tactical separation assurance

On the ground side, the tactical near-term conflict resolution mode will be varied. In half of the runs, controllers will be asked to resolve near-term conflicts resulting from scripted events without automation support, and in the other half of the runs, the controllers will have the option to issue automated heading advisories generated by TSAFE. In the event that the controller does not deal with an imminent conflict, TSAFE will issue an avoidance maneuver automatically by data link. This manipulation is intended to gather data on how TSAFE resolutions compare to controller-generated resolutions and to further define the appropriate roles and responsibilities of controllers, flight crews and automation. On the flight deck, the availability of independent conflict detection and resolution functions will be varied to investigate the impact of flight deck tools on trajectory exchanges between the air and the ground. To provide an initial framework for the operations, the following roles and responsibilities have been defined for this study:

B. Operating concept and roles and responsibilities for this study

Trajectory-based operations (3 to 15 minute time horizon):

- The ground automation is responsible for all conflict detection and resolves most conflicts automatically.
- The controller is supervising the automation and is responsible for making decisions on all situations that are presented to him or her by the automation, flight crews or other ATSP operators, such as controllers or traffic managers.
- The ground automation generates a resolution trajectory for all conflicts between 3 and 8 minutes to LOS. If the resolution trajectory includes a new conflict or an extreme flight delay the ground automation presents it to the controller for approval, otherwise it sends it automatically to the aircraft.
- The flight crews execute ATC trajectories if acceptable (just like clearances today).
- Flight crews can downlink trajectory change requests at any time. The ground automation will probe the request for conflicts in the background. If it is conflict free the automation will uplink approval without involving the controller. If a conflict is detected, it will present the request to the controller for review. This implies:
    - Flight crews of suitably equipped aircraft may respond to uplinked conflict resolutions with downlinked modified trajectories.
    - Flight crews of suitably equipped aircraft may independently, and optionally, detect conflicts and propose resolutions

Tactical safety assurance:

- TSAFE-type conflict alerting is responsible for short-term conflict detection.
- The operating mode for short-term conflict resolution is a primary independent variable:
    - Condition 1: The controller assesses the situation, determines a resolution and issues a verbal clearance
    - Condition 2: The controller can access a TSAFE resolution and issue it when deemed appropriate. If the controller does not issue it within 60 seconds to LOS, the automation will issue it automatically.
- Flight crews will receive a *verbal instruction or a data link message* with the resolution maneuver and are expected to comply immediately.

C. Data Collection

Data collection will occur over the course of two weeks in July/August 2008. During each week, two certified professional controllers will manage traffic in ZID-91 in two independent worlds simultaneously. Four participant flight decks are assigned to each world. Confederate pilots inject additional events and participate as required. Most aircraft operations and sectors surrounding the test airspace are automated. Scenarios last 30 minutes and include various concentrations of events that are designed to exercise near-term conflicts, trajectory negotiations, off-trajectory operations and emergencies. The controller display is further improved to give controllers tools to quickly assess an unexpected situation and to make an informed decision. Initial findings of this study are expected to be compiled in fall 2008.

VIII. Future work

Once the initial set of part task studies is completed, a better-informed concept and distribution of roles and responsibilities for ground-based automated separation assurance, and NextGen operations in general, can be developed. Operator interfaces and automated functions will then be refined and improved. Future studies planned for 2009 will investigate the integration of separation assurance with arrival and departure management functions, such as sequencing or time-based metering. The interplay of automated separation assurance and flow contingency management will also be addressed in combination with research on multi sector planning.

IX. Concluding Remarks

The initial part-task evaluation of air traffic control operators interacting with ground-based separation assurance automation has yielded very positive results. Automated conflict detection has the potential to eliminate controller workload as the limiting factor in increasing sector capacity. The prototyped conflict resolution algorithm generates highly acceptable and efficient trajectory changes and appears capable of handling the anticipated growth in air traffic for NextGen. The initial study on mixed operations indicates that this traffic growth is only achievable if new trajectories can be uplinked into FMS equipped aircraft and additional controller routine tasks for transfer of control and communication can be automated or eliminated. The simple addition of more advanced decision support tools into current day operations will likely not yield a significant capacity increase, but may be used for transitional stages. A limited number of unequipped aircraft can be handled in the same airspace as equipped aircraft. Equipped aircraft managed by the automation seem to have limited impact on controllers' workload. The second safety layer provided by tactical safety assurance will be evaluated in 2008. Investigating the combination of automated trajectory management and safety assurance with pilots and controllers in the loop is expected to provide more data necessary to determine the operational validity and safety of the concept of service provider/ground-based automated separation assurance.

Acknowledgments

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