

# Evaluation of High Density Air Traffic Operations with Automation for Separation Assurance, Weather Avoidance and Schedule Conformance

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**In this paper we discuss the development and evaluation of our prototype technologies and procedures for far-term air traffic control operations with automation for separation assurance, weather avoidance and schedule conformance. Controller-in-the-loop simulations in the Airspace Operations Laboratory at the NASA Ames Research Center in 2010 have shown very promising results. We found the operations to provide high airspace throughput, excellent efficiency and schedule conformance. The simulation also highlighted areas for improvements: Short-term conflict situations sometimes resulted in separation violations, particularly for transitioning aircraft in complex traffic flows. The combination of heavy metering and growing weather resulted in an increased number of aircraft penetrating convective weather cells. To address these shortcomings technologies and procedures have been improved and the operations are being re-evaluated with the same scenarios. In this paper we will first describe the concept and technologies for automating separation assurance, weather avoidance, and schedule conformance. Second, the results from the 2010 simulation will be reviewed. We report human-systems integration aspects, safety and efficiency results as well as airspace throughput, workload, and operational acceptability. Next, improvements will be discussed that were made to address identified shortcomings. We conclude that, with further refinements, air traffic control operations with ground-based automated separation assurance can routinely provide currently unachievable levels of traffic throughput in the en route airspace.**

## Nomenclature

<i>AAC</i>	=	Advanced Airspace Concept
<i>ADS-A/B</i>	=	Automatic Dependent Surveillance-Addressed/Broadcast
<i>ANSP</i>	=	Air Navigation Service Provider
<i>AOL</i>	=	Airspace Operations Laboratory at NASA Ames
<i>ATM</i>	=	Air Traffic Management
<i>CD&amp;R</i>	=	Conflict Detection and Resolution
<i>CPDLC</i>	=	Controller Pilot Data Link Communication
<i>CPC</i>	=	Certified Professional Controller
<i>CTAS</i>	=	Center/TRACON Automation System
<i>DSR</i>	=	Display System Replacement (Center Controller Workstation in the NAS)
<i>DST</i>	=	Decision Support Tool
<i>ERAM</i>	=	En Route Automation Modernization
<i>ETA</i>	=	Estimated Time of Arrival

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- FAA = Federal Aviation Administration
- FMS = Flight Management System
- JPDO = Joint Planning and Development Office
- LOS = Loss of Separation
- MACS = Multi Aircraft Control System
- NAS = National Airspace System
- NASA = National Aeronautics and Space Administration
- NextGen = Next Generation Air Transportation System
- TBO = Trajectory-Based Operations
- TMA = Traffic Management Advisor
- SA = Separation Assurance
- STA = Scheduled Time of Arrival
- VSCS = Voice Switching and Communication System

### I. Motivation

Separating aircraft is the most important task for a current day air traffic controller, and it is one of the main components of their workload. In today's very safe system, air traffic controllers take active control over each aircraft in their airspace and issue clearances to separate each one from other traffic. The main factor limiting en route capacity, therefore, is exactly this – controller workload associated with providing safe separation between aircraft – as this manual separation process can only be performed for a limited number of aircraft. As a consequence, each airspace sector today has a defined maximum number of aircraft that are allowed to enter. This constraint is a way of ensuring that the demands on the cognitive resources of the air traffic controller(s) working any particular sector are not exceeded [1].

The FAA currently predicts increases in IFR aircraft handled at FAA Air Route Traffic Control Centers of 25% by 2020 and over 50% by 2030 [2]. However, separating aircraft using current day techniques remains inherently limited by controller workload and will not be able to support this expected long term traffic growth. To illustrate the problem, Fig. 1 indicates how an air traffic controller display might look if more than twice as many aircraft were allowed into this airspace without additional modifications. Clearly, keeping track of each individual aircraft in this environment exceeds the cognitive resources of human operators.

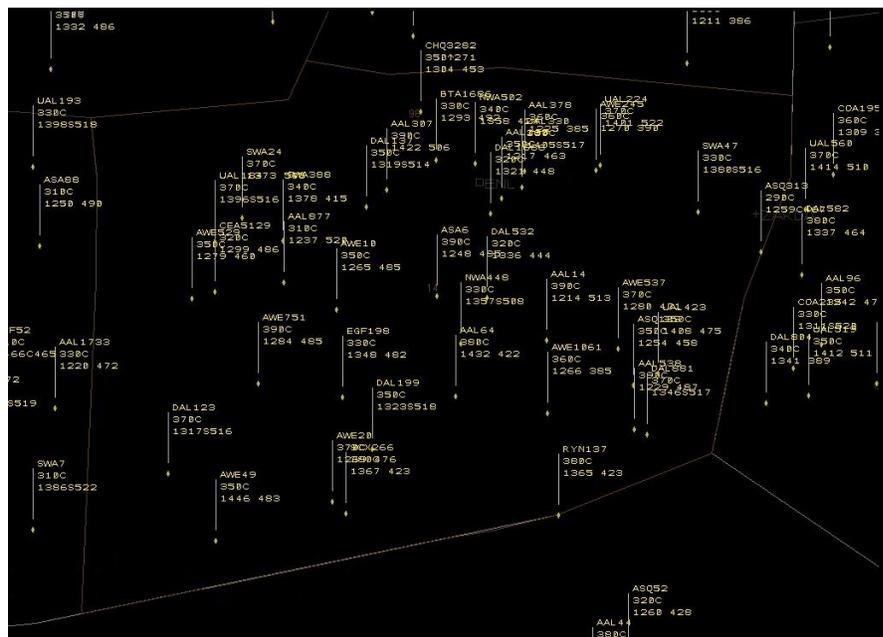
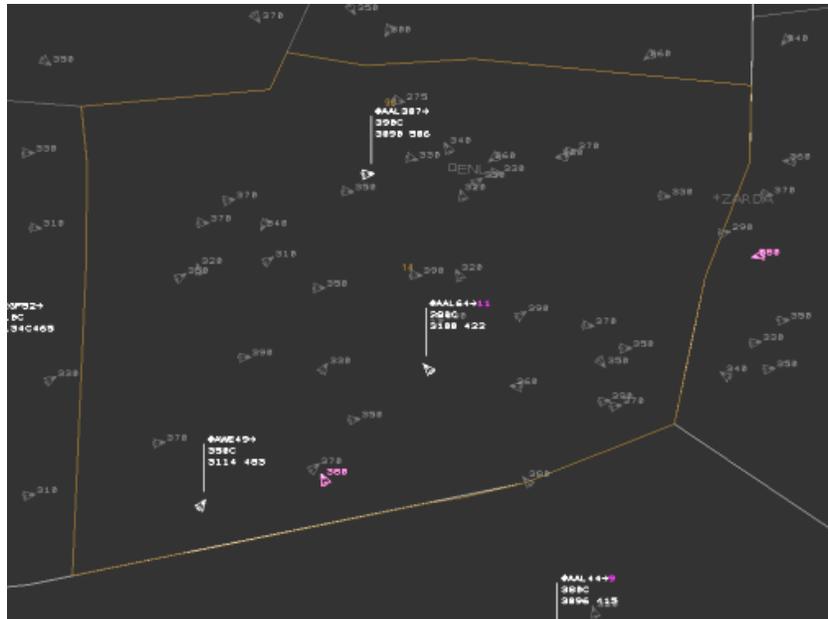


Figure 1. Current day controller display at more than 2x traffic density.

One approach to augment human resources is to use automation. The primary purpose of automating separation assurance is to enable air traffic controllers to manage much higher traffic densities than today. Within the ground-based concept discussed in this paper, the controller and the automation work together to enable levels of safety and

efficiency equal to or greater than today in spite of much higher traffic demands. Fig. 2 illustrates how the ground-based automated separation assurance approach can impact the design of the controller display, as it presents the same high-density traffic problem as depicted in Fig. 1. In the example in Fig.2 the automation manages most aircraft and highlights only those that require the human operators' attention.



**Figure 2. Controller display designed for advanced automation with the same traffic as Fig. 1**

While it is unclear whether the entire NAS airspace will ever need to accommodate two or three times as many aircraft as today, enabling much higher capacity -even locally- can provide substantial benefits. By eliminating airspace capacity constraints resulting from controller workload limitations, automation for separation management can reduce the need for costly traffic management initiatives. Today, whenever air traffic demand exceeds capacity, traffic management initiatives are put in place to reduce the number of aircraft entering congested sectors. In many cases demand is reduced by holding aircraft at their departure airports. These ground stops avoid burning extra fuel and polluting the environment unnecessarily. However, ground delay programs often have a severe impact on airline schedules and inconvenience many passengers. When delays are taken in flight, the aircraft fly longer routes than necessary, which increases the cost and the environmental impact of each flight. The weather impact on airspace throughput often ripples through the National Airspace System (NAS) and results in inefficiencies, long delays, and increased cost.

Automation for separation assurance has been developed and studied in laboratory analyses and fast-time and part-task settings [3-9]. However, there has been little research on operational issues that may arise when automated operations are used as a standard operating mode for a larger air traffic control area. A human-in-the-loop simulation in the Airspace Operations Laboratory at the NASA Ames Research Center in 2010 began exploring the feasibility, issues, potential benefits and shortcomings of controllers interacting with each other and high levels of automation to control much higher traffic densities than today. A challenging environment was developed for this exploration that included complex traffic and weather problems and time-based metering situations. The simulation enacted the operational concept of ground-based automated separation assurance and did not include transferring separation responsibility to the flight crew. Alternate allocations of separation assurance functions between the air/ground including airborne self separation are pursued in complimentary research [e.g. 10], but this aspect is not discussed in this paper.

The paper is organized as follows: In the next section we will review the operational concept, enabling technologies and function allocation between automation, controllers and flight crews. In section III we will describe the prototype system that we developed for this research in some detail. Section IV presents the method of the current study, followed by the results in section V. Section VI highlights technical improvements that we implemented to address some of the shortcomings that were recognized during the study. Section VII presents the conclusions based on the research to date.

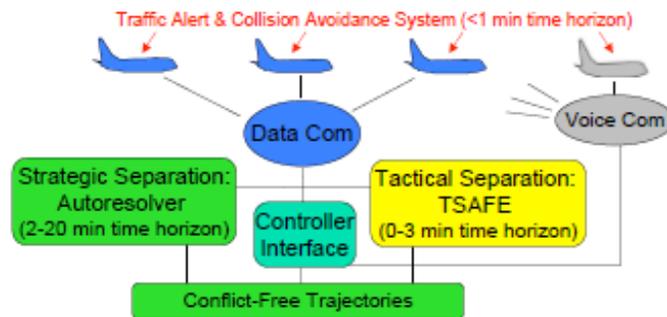
## II. Operational Concept

### A. Ground-based Automated Separation Assurance Premise and Concept

In the concept of ground-based automated separation assurance, air traffic control automation supports and enables the controller to manage more aircraft within the same airspace than today by having the automation -not the air traffic controller- monitor traffic for potential conflicts. Additionally, the automation conducts many workload-intensive routine tasks such as transferring ownership and communication frequencies between air traffic control sectors. Relieved of these tasks, controllers can concentrate on managing the non-routine operations that often require human intelligence, ingenuity, and experience. As a result of this functional allocation, more aircraft can be controlled within a given airspace. Airspace saturation occurs at higher traffic levels than today resulting in fewer aircraft reroutes and ground-stops. More aircraft get their most efficient, user-preferred 'green' trajectories. Passengers experience less delay on busy travel and/or bad weather days.

The original concept of ground-based automated separation was developed by Erzberger and is detailed in [3-5]. In this concept, technologies are utilized to shift the workload-intensive tasks of monitoring and separating traffic from the controller to the automation. A critical element of this centralized concept is that the ground-side automation, not the controller, is responsible for conflict detection. The automation is also responsible for monitoring the compliance status of all aircraft relative to their reference trajectory. In many cases, the automation, not the controller, is responsible for resolving conflicts as well.

The technical system that enables automated conflict resolutions incorporates two independent separation assurance layers, each of which is designed to detect and resolve conflicts over different time ranges. In the first layer, an algorithm, referred to as the Autoresolver, can be invoked to handle conflicts with times to loss of separation (LOS) in the range of two to 20 minutes. This algorithm is intended to resolve non-urgent conflicts and is the mainstay of automated separation assurance. The Autoresolver aims to compute a complete trajectory that clears all traffic and weather conflicts and returns the aircraft to its original flight path. Since it takes time to communicate these trajectories to the flight deck, have them reviewed, loaded and executed by the flight crew, the



**Figure 3. Components of the Advanced Airspace System [3]**

Autoresolver is inappropriate to solve urgent traffic conflicts. Therefore a second layer is realized through the Tactical Separation Assured Flight Environment (TSAFE), which contains the algorithm designed to handle urgent conflicts. Its main purpose is to provide a safety net for conflicts that were not detected and/or resolved by the first layer. TSAFE is designed to create an initial conflict avoidance maneuver that can be quickly communicated to and executed by the flight crew. The maneuver is intended to avoid a LOS and keep the aircraft clear of traffic for a few minutes, so that a trajectory-based solution can be found. Operational implementation of a system for automated separation assurance requires an air-ground data link that allows ground-based systems to uplink resolution trajectories to systems onboard aircraft.

However, it is envisioned that the controller will use a conventional voice link to maintain separation of unequipped aircraft and handle certain off-nominal situations. Thus, under automated separation assurance, the air traffic controllers' roles will involve providing service and performing decision-making activities in certain nominal and off-nominal situations while the roles of monitoring, providing the majority of nominal separation functions, and being the safety net in dire situations, will be allocated to the automation.

### B. Enabling Environment

The concept of automated separation assurance is enabled by integrating controller workstations, ground-based automation, data link, Flight Management System (FMS) automation and flight deck interfaces. The ground automation creates, maintains, and communicates trajectories for each flight. Data link is the primary means of communication, and all aircraft are cleared to proceed, climb, cruise and descend via their nominal or uplinked trajectories. High accuracy surveillance information for position and speed is provided via Automatic Dependent Surveillance Broadcast (ADS-B) or a comparable source. 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. Automated trajectory-

based conflict resolutions are generated for conflicts with more than three minutes to initial loss of separation (LOS). When conflicts are detected with less time before LOS, an automated tactical conflict avoidance function generates heading changes and sends them to the flight deck via a separate high-priority data link connection (e.g., Mode-S).

### C. Function Allocation

The Air Navigation Service Provider (ANSP) is responsible for maintaining safe separation between aircraft. The ground automation is responsible for detecting ‘strategic’ medium-term conflicts (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 (less than 3 minutes) between all aircraft. The automation sends conflict resolutions automatically via data link to the aircraft whenever predefined tolerances on delay, lateral path, and altitude change are not exceeded. Whenever the ground automation cannot resolve a conflict without controller involvement, it must alert the controller with enough time to make an informed decision and keep the aircraft safely separated. Likewise, the ground automation is also responsible for alerting controllers to other problems and exceptional situations.

Flight crews are responsible for following their uplinked (or initially preferred) trajectory within defined tolerances and for the safe conduct of their flight (like today). Flight crews can downlink trajectory-change requests at any time. The ground automation probes requested trajectories for conflicts without involving the controller. If the requested trajectory is conflict free, the automation uplinks an approval message. Otherwise, it alerts the controller that there is a trajectory request to be reviewed.

Controllers supervise the automation and are responsible for making decisions on all situations that the automation, flight crews, or other ANSP operators (i.e., other controllers or traffic managers) present to them. Additionally, they provide service in time-based metering and weather avoidance operations. Issuing control instructions to non data-link-equipped aircraft is also the responsibility of the controller. The controller can use conflict detection and resolution automation to generate new trajectories for any aircraft. Controllers use data link to communicate with equipped aircraft and voice to communicate with non-data-link-equipped aircraft.

Table 1 summarizes the allocation of functions between controllers and automation as it was simulated in the study described in this paper. Some of these tasks were assigned to the controller during this study simply to learn about the acceptability of certain task assignments and to gather requirements for future automation. We will present the prototype system that was developed for this function allocation and used during the study in the next section.

**Table 1 . Allocation of functions between automation and controllers in the 2010 study**

Automation	Controller
<ul style="list-style-type: none"> <li>•Detect Separation and weather Conflicts</li> <li>•Resolve trajectory-based conflicts (if within tolerances)</li> <li>•Resolve all time-critical traffic conflicts</li> <li>•Alert controller to urgent problems</li> <li>•Provide trajectory planning assistance</li> <li>•Use data comm. to communicate</li> </ul>	<ul style="list-style-type: none"> <li>•Supervise the automation</li> <li>•Resolve trajectory conflicts flagged by the automation</li> <li>•Monitor and maintain schedule compliance</li> <li>•Implement weather reroutes with automation support</li> <li>•Place aircraft back on trajectory following automated tactical maneuvers</li> </ul>

## III. Prototype System

### A. Overview

A prototype system for ground-based automated separation assurance was implemented in the Multi Aircraft Control System (MACS). MACS is developed by the AOL for human-in-the-loop simulations and rapid prototyping of advanced air traffic concepts and operations [11, 12]. While many functions had to be realized within MACS, the following functional components will be described in more detail:

- Controller workstation
- Trajectory planning
- Data communication

- Conflict probing
- Trajectory-based conflict resolution
- Short-term conflict alert and resolution
- Weather avoidance
- Scheduling and time-based metering

## B. Controller Workstation

Figs. 4 and 5 depict the air traffic controller workstation prototype that was developed for the human-in-the-loop research on automated separation assurance. Fig. 4 shows the workstation hardware, Fig. 5 an example of the screen contents. The new functions are built into the framework of the operational en route air traffic control workstations in the NAS. The workstation utilizes the operational keyboard and trackball and extends the Computer Human Interaction (CHI) principles built into this system. The current prototype is integrated with MACS's emulation of the Display System Replacement (DSR). As soon as the new En Route Automation Modernization (ERAM) is widely integrated into the operational facilities, the MACS prototype will be integrated with an ERAM emulation. This way certified professional controllers (CPC) are already familiar with the existing workstation and can more quickly learn the



Figure 4. Air traffic controller station

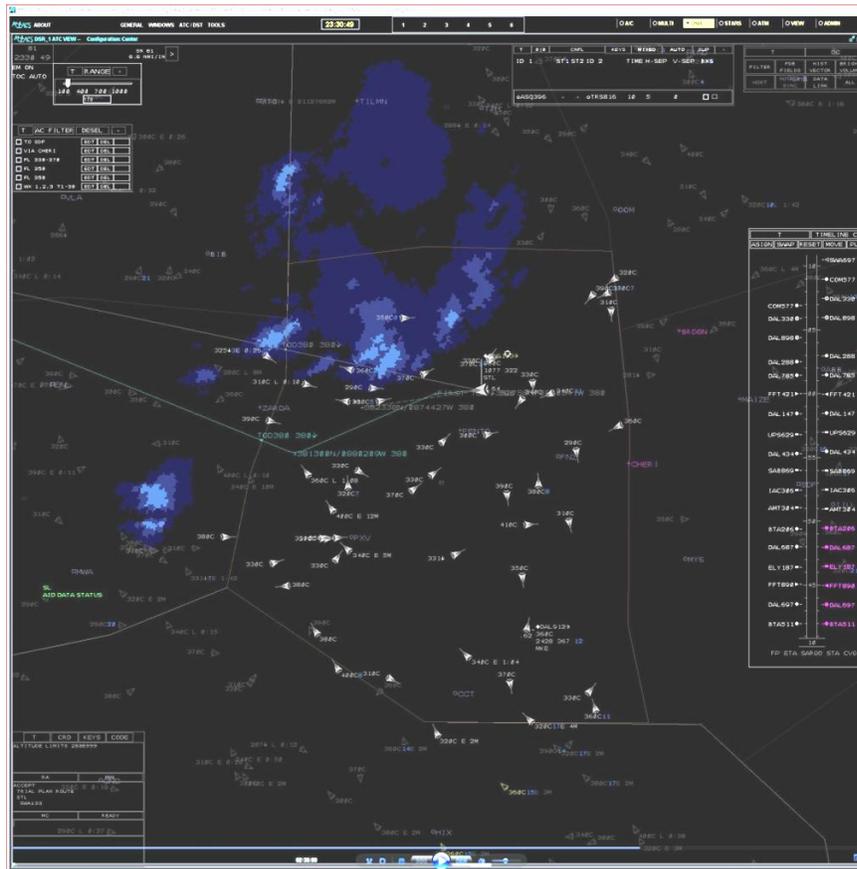


Figure 5. Controller display designed for automated separation assurance.

new features that were designed for this specific concept.

As shown in Fig. 5, the display is designed for general situation awareness and management by exception rather than controlling all aircraft individually. Aircraft that are managed by the automation within the controller's sector have a brighter icon than the aircraft outside that area, which are dimmed.

Additional information in data tags and colors are used to draw the controller's attention to specific problems. The sector displayed in Fig. 5 contains approximately three times as many aircraft as can be controlled within this sector in current day operations.

Weather is shown in blue with different intensities. The controllers can use additional views to control the display contents and invoke automated functions. In addition to the

standard DSR views, the display in Fig. 5 includes an aircraft-filter view that can be used to highlight specific flows, a conflict list view that can be used to review pending conflicts and their status and invoke resolutions, and a timeline view (shown on the right side of the controller display in Fig. 5), used to monitor schedule compliance and invoke trajectory changes to meet the schedule. Trajectory planning functions can be accessed from data tags, conflict lists and timelines. The cyan line in Fig. 5 represents a trajectory generated to avoid the convective weather area and other traffic while meeting the scheduled time of arrival (STA). Semi-automated functions are provided to easily create trajectories that, if possible, provide a conflict-free trajectory that does not penetrate weather cells and meets time constraints.

The controller can request trajectories to avoid traffic conflicts and weather hazards and to meet time-constraints via various easy-to-use mechanisms: keyboard entries, data tag items, the conflict list, or the timeline. The automated trajectory-based conflict resolutions are generated by the Autoresolver [5]. When initiated by the controller, the automatically generated trajectory becomes a provisional trial-plan trajectory (e.g., the cyan line in Fig. 5). The controller can then modify and/or uplink the trajectory constraints to the aircraft. The automation immediately probes all proposed trajectory changes for conflicts and provides real-time conflict feedback when used interactively. Weather penetration probes and schedule conformance functions are integrated into the toolset to alert the controllers and automation to potential problems.

### C. Trajectory Planning

Trajectory planning can be conducted at different levels of automation: (1) manual (2) semi-automated and (3) fully automated [9]. The system tested in 2010 used fully automated trajectory planning to resolve most traffic conflicts. Semi-automated trajectory planning was used for traffic conflicts and scheduling. Manual trajectory planning was used for weather conflicts and could be used any time at the controller's discretion to create a new trajectory or to modify an automation proposed trajectory. Manual trial planning can be accessed from the full data tag or via keyboard entries. When initiated through the trial planning portal (arrow to the right of the callsign in Fig. 7) a route trial plan is started. As shown in Fig. 6 the automation inserts a "FIRST TURN" point in front of the aircraft along its current trajectory at a defined time (2 minutes for the current study). This point is necessary to make sure that the new trajectory can be communicated to and executed by the flight crew without 'overshooting' the first turn, thereby stabilizing the trajectory during the trajectory change. After the first turn point controllers can insert, move and delete as many trajectory points as necessary to create the desired flight path. The automation provides integrated real-time feedback on potential conflicts with other aircraft or the predicted weather and any time constraints downstream. The fourth line of the full data tag in Fig. 6 shows the example aircraft ASQ428 en route to JFK. It is originally predicted to arrive 35 seconds early (E 0:35 in white). The cyan trial plan trajectory that routes the aircraft to the south would delay this aircraft so much, that it would arrive 2 minutes late (L 2M in the data tag).



**Figure 6. Graphical Trial Planning**

Manual trajectory planning can also be initiated from the altitude fly-out menu. As shown in Fig. 7 the controller picks the new altitude in the fly out menu and the system will create the appropriate vertical profile and provide the same feedback as during route trial planning. Altitude and route trial planning can be combined in any order.



Figure 7. Trajectory planning starting with the altitude fly out menu.

#### D. Data Communication

The operational environment used in this simulation assumed 100% aircraft equipage, meaning all aircraft had ADS-B, controller-pilot data link communication (CPDLC) for both Transfer-Of-Communication (TOC) and trajectory-change messages, and a Flight Management System (FMS) with integrated data link communication to allow for loadable trajectory clearances.

Using data link for the transfer of communication removed the need for controllers to verbally issue frequency change instructions to aircraft. The controllers did not have to verbally instruct each outgoing aircraft to change to the next frequency. Another assumption within the simulation was that aircraft would not do verbal check-ins, relieving the controllers from having to acknowledge the radio check-ins of each incoming aircraft. In the simulation, this was supported by the use of “monitor” TOC messages, rather than “contact” TOC messages, as shown in Fig. 8. Subject matter experts from previous research indicated this was the preferred mode of operation for full data link equipage.



Figure 8. View of data link Transfer of Communication (TOC) message from the ATC (left) and flight deck (right) perspective.

The trial-planning functions described above allow the controller to construct provisional trajectories. An integrated data link function enables the controllers to send them via data link to the aircraft.



Figure 9. A trial-plan prepared by the controller (left), then sent to the flight deck as an FMS-loadable message (right)

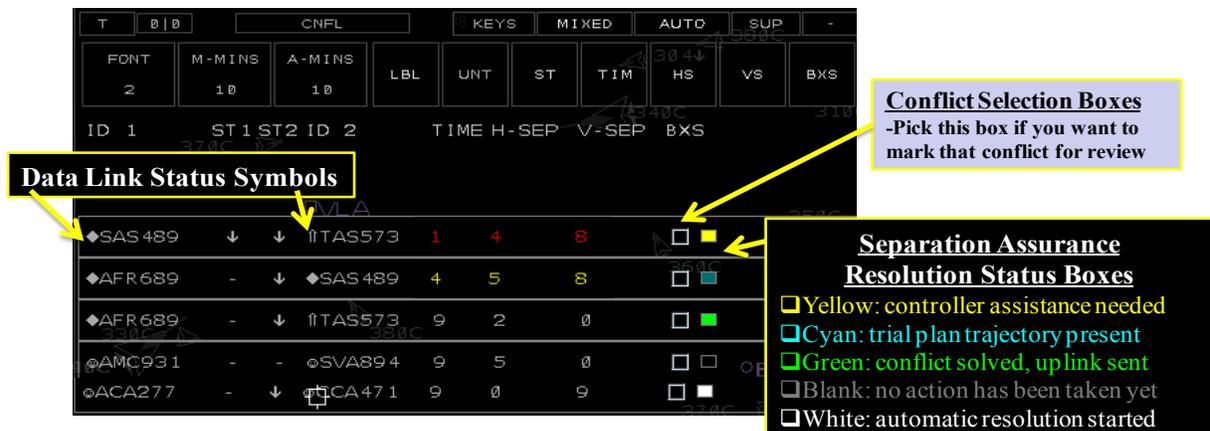
Primarily using the trackball (keyboard commands were also available), the controller starts a trial-plan and can move, insert, and delete points along an aircraft’s trajectory. Points can be dragged with the trackball to any

location, allowing for both named points and latitude/longitude points. With a single command, the controller can then uplink the trial-plan to the aircraft as a packaged route that can be directly loaded into its FMS, as illustrated in Fig. 9. At the same time the trajectory data link message is sent, the ground system’s stored flight plan is amended. This updated flight plan is then used by the ground system for future computation.

As described above, the trial-planning function can also be used for altitude changes, either as a separate trial-plan or combined with a lateral modification. Data link-enabled trial-plans have the major benefit of reducing a controller’s workload associated with radar vectoring; turn-outs and turn-backs can be replaced with a complete “hand-drawn” trajectory designed by the controller. Flight crews accept the data link clearances electronically as well, which further reduces frequency congestion by replacing the clearance read-backs.

### E. Conflict Probing

The prototype system includes a very fast deterministic conflict probe that allows for the rapid evaluation of trajectories for potential loss of separation (LOS) events with trajectories of other aircraft. The system utilizes a constant time interval scheme that makes sure any conflicts are depicted to the controllers without detectable delay even when the controllers use the graphical trial planning tools. Details of this process are described in [13]. Potential LOS events (i.e. conflicts) are depicted in the data tags and target symbols of the aircraft as well as in a



**Figure 10. Conflict List**

tabularized conflict list. The conflict list shows all potential traffic conflicts sorted by urgency and provides additional information. The time to potential LOS, the minimum horizontal and vertical separation are indicated as well as the resolution status. As shown in Fig. 10 a colored rectangle indicates that the automation is either working on a conflict (cyan), has successfully generated and sent a resolution (green), or controller assistance is needed because no resolution could be found or the generated resolution violated the preset criteria for issuing it automatically to the flight deck (yellow).

Based upon earlier feedback from subject matter experts the conflict list also contains the data link status symbols and the ability to send data link messages directly from the list, if an aircraft in the list has a pending trial plan.

Shown in Fig. 11, the traffic situation display depicts conflicting aircraft with 3 to 5 minutes to LOS in yellow. Conflicts with less than three minutes to LOS are depicted in red. These colors are coordinated between the conflict list and the traffic display.

Also depicted in Fig. 11 is an aircraft with a much bigger chevron than the others. This is intended to draw the controllers’ attention to the fact that this aircraft is currently free-tracking, which means that it is not following the trajectory that



**Figure 11. excerpt from controller display showing a conflict and a free-track aircraft**

the ground-system currently has stored for that aircraft. This is important for conflict probing, as aircraft that are off their trajectory are less predictable than aircraft that conform to their trajectory.

### F. Trajectory-based Conflict Resolution

In order to resolve traffic conflicts the automation invokes the Autoresolver software module that uses a heuristic search through all reasonable resolutions for a given situation and then selects the most preferable one [5].



Figure 12. Activation methods for conflict resolution. Conflict list (left) and data tag items (right)

This conflict resolution function takes into consideration weather and scheduling constraints. The controller can use manual trajectory planning for conflict resolution or also use the Autoresolver to arm the manual trial planner with an initial resolution and then uplink the resulting trajectory or modify it further. The controller can direct the Autoresolver to invoke preferences by activating it in different ways. Table 2 below summarizes these options:

Table 2. Activation methods for conflict resolution

Activation Method (Trackball enter on...)	Preference
Conflict list	No preference – search for best overall resolution
Time to LOS in data tag	Prefer to move this aircraft – no preference for lateral or altitude solution
Portal in data tag	Prefer to move this aircraft – prefer lateral solution
Altitude in data tag	Prefer to move this aircraft – prefer altitude solution

### G. Short-term Conflict Alert and Resolution

When a conflict is predicted to occur within less than three minutes to LOS, a strategic trajectory-based solution becomes impractical and a tactical solution is generated.

A vectoring solution function originally designed for the Tactical Separation Assisted Flight Environment (TSAFE) [14] is activated, which computes heading changes for one or both of the aircraft involved in the conflict and presents it to the controller or issues it directly to the aircraft. Fig. 13 shows a typical complex short-term conflict situation. The data tags of three aircraft that are involved in the short-term conflict are shown in red. Note the vectoring information in the fourth line of the data tags. The aircraft on the lower left (DAL697) started a sudden descent crossing paths with two other aircraft at different altitudes (UAL534 and COA831). In the 2010 study, the automation

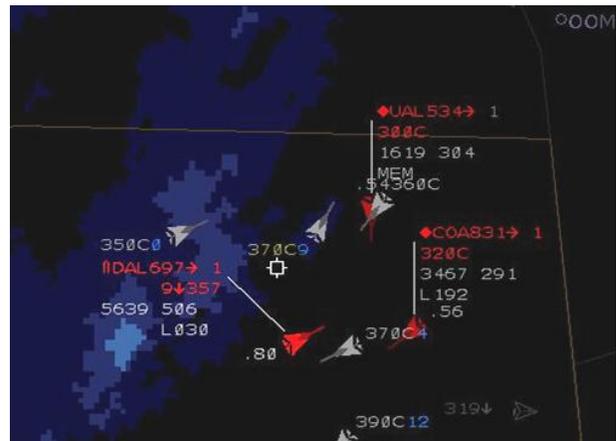


Figure 13. short-term conflict caused by an unexpected early descent of one aircraft and vectoring solution

automatically sent the heading change(s) at two minutes to predicted LOS. The vectoring resolution function issued a left turn to a heading of 030 to DAL6974 and a

left turn to a heading of 192 to COA831.

While the heading changes usually solve the immediate conflict, they leave the aircraft in 'free track' with no trajectory to the destination, requiring the controller to use the trial planning tools to create and send a new trajectory to the aircraft. This turned out to be one of the areas for improvement discussed later.

### H. Weather Avoidance

The prototype used in 2010 included a weather penetration probe that alerted the controllers to potential weather penetrations and displayed the time to penetration in the data tag. Controllers then used manual trial planning integrated with weather and conflict probing to find a clear trajectory around the weather that would also avoid traffic conflicts. Fig. 14 illustrates the process. The automation displays that the aircraft on the lower left will

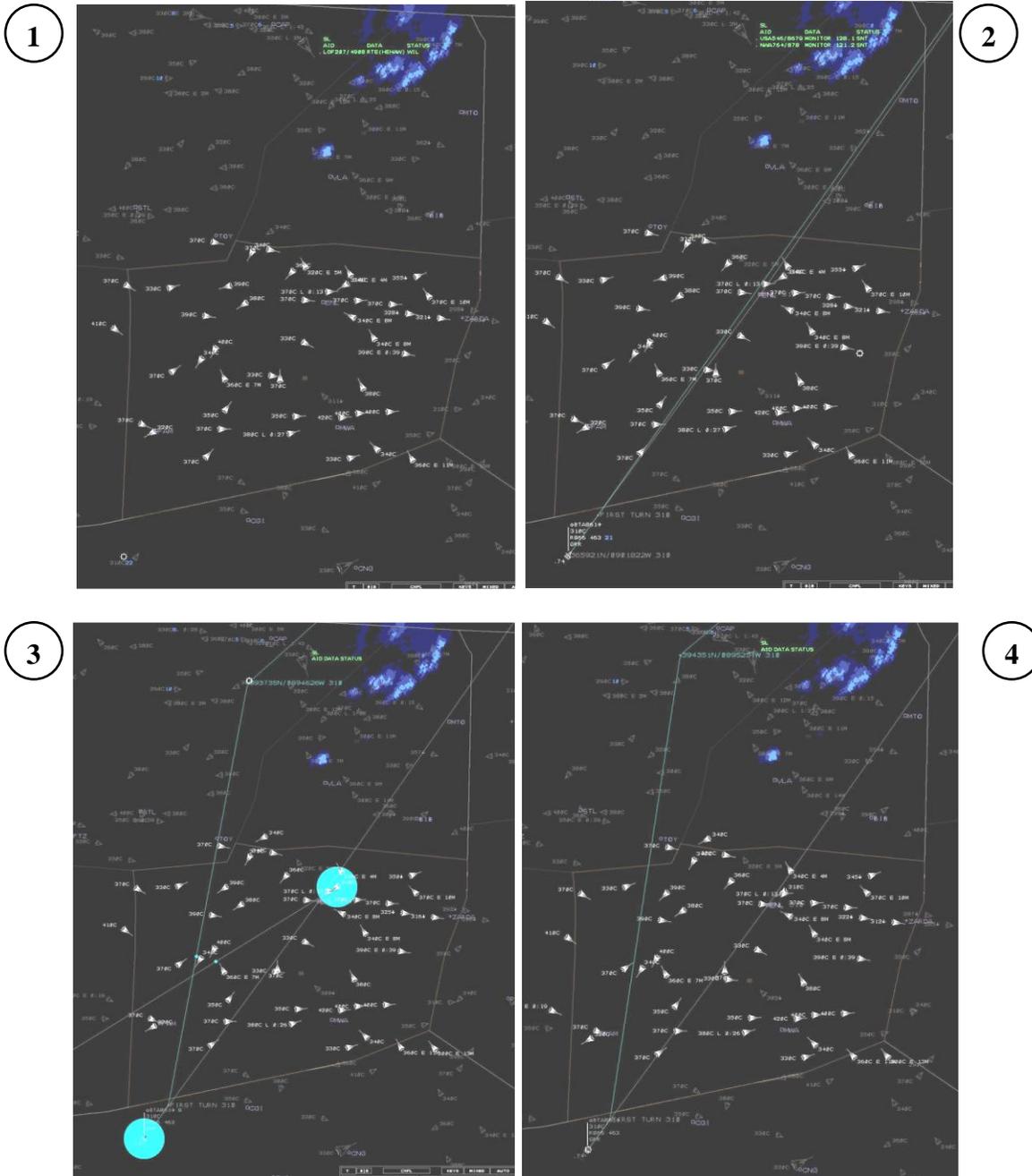


Figure 14. Weather avoidance process. Top left → top right → bottom left → bottom right

penetrate the weather in 21 minutes (1). The controller then starts a manual trajectory plan that shows that the predicted penetration would occur east of the current weather system (2). The controller then trial plans a route west of (behind) the weather. On this flight path, however, the aircraft would encounter traffic conflicts (3). So the controller moves the trial plan further west until clear of traffic and weather (4). Work is ongoing on more automated weather avoidance functions and will be discussed in the improvements sections of the paper.

### I. Scheduling and Time-Based Metering

Scheduling and time-based metering were implemented into the prototype system. A scheduling capability was built into MACS that allows single-point scheduling at any waypoint in the system. This scheduler uses a first estimated/first scheduled logic based upon flight plan trajectories with nominal speed profiles. This scheduling capability was used to create arrival schedules for major airports in the area. These schedules were used as stand-ins for actual schedules coming from more comprehensive arrival management systems, such as the Traffic Management Advisor (TMA).

The scheduling functions produce scheduled times of arrival (STA). The goal of time-based metering is to meet those scheduled times of arrival. The prototype system feeds back the status of time-based metering by providing timelines for scheduling points on the controllers' displays. As shown in Fig. 15, for each scheduled aircraft the left side of the time line indicates the estimated time of arrival (ETA) and the right side indicates the STA. The difference between the STA and the ETA is also shown in the data tag of any scheduled aircraft (see Fig. 6).

In order to meet the schedule the ETA should match the STA, so that if the aircraft arrives at its estimated time it will have an arrival slot available. To perform this task the controller can use the automation to quickly and easily generate trajectory changes that a) meet the STA b) have no traffic conflicts and c) do not penetrate the weather. The automation may change the lateral path, the altitude and the cruise/descent speed profile at the same time in order to accommodate all three objectives. The controller invokes the function by using a keyboard command ("TS: Trajectory to meet STA"), using the PLAN button on the timeline, or a trackball ENTER on the delay number in the data tag. The system will then try to determine a trajectory that meets all constraints. This is done by utilizing the conflict and weather avoidance capabilities of the Autoresolver in conjunction with a speed adjustment function. The Autoresolver creates options for various lateral and vertical paths and the speed adjustment function creates a speed profile for each of them to meet the time constraints. The resulting trajectories are then probed for traffic and weather conflicts and accepted or rejected. When accepted they arm the manual trial planner and the controller can further adjust them. When the controller makes lateral changes, the speed adjustment function keeps computing respective speed profiles to meet the time constraints.

Once the controller finds a trajectory acceptable s/he can send it to the aircraft via data link as explained before. The process may sound somewhat cumbersome, but by using the timeline, meet time trajectories can be generated and uplinked within seconds. First the controller types "TS" then s/he selects the aircraft in the timeline. As soon as the trajectory appears on the screen and the ETA lines up with the STA, a keyboard entry "UC" with another click on the aircraft in the timeline completes the process.

The automation support described above represents a subset of the tools available to the controllers to interact with the separation assurance/trajectory automation. These tools and interaction mechanism have been developed over a decade until they received very high usability and usefulness ratings by all controllers. Therefore, the tools were deemed appropriate for the investigation described next. It should also be noted that even though the simulated environment assumes full data link equipment, most of the tools have also been used in simulations at lower levels of automation for non data link equipped aircraft in mixed equipment environments [15].

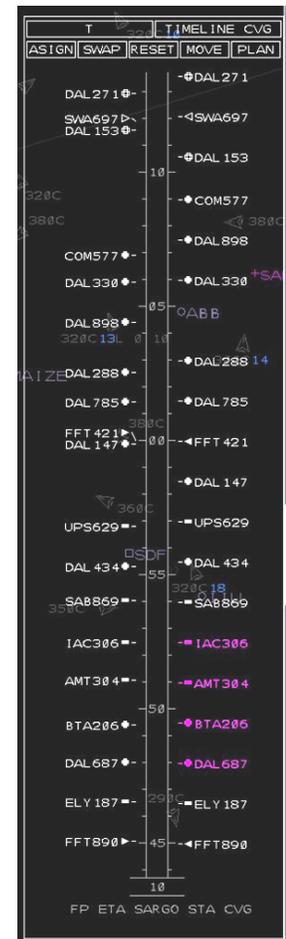


Figure 15. Timeline

#### IV. Simulation in 2010

A high fidelity human-in-the-loop simulation of air traffic control operations with ground-based automated separation assurance was run in 2010. Fig. 16 shows one of the air traffic control rooms used for the study [12, 16]. During the simulation, traffic at much higher densities than today transited the airspace and had to be sequenced into various nearby airports. The operations were sustained for multiple hours and were impacted by convective weather cells that grew, decayed and moved. This long run duration with realistic weather scenarios was chosen to observe operational aspects that are not represented in typical shorter simulations, such as shift changes, stress, boredom, and fatigue.



Figure 16. Air traffic control room in the AOL

##### A. Experiment Design

The experiment was designed as an exploratory study rather than a formal evaluation. Controllers operated in a comprehensive work environment that required them to perform a wide range of air traffic control tasks. Three parameters were varied: (1) traffic demand on the airspace, (2) traffic demand on the metering fixes, and (3) convective weather situation. The operator stations, tools, and function allocation stayed constant throughout all runs.

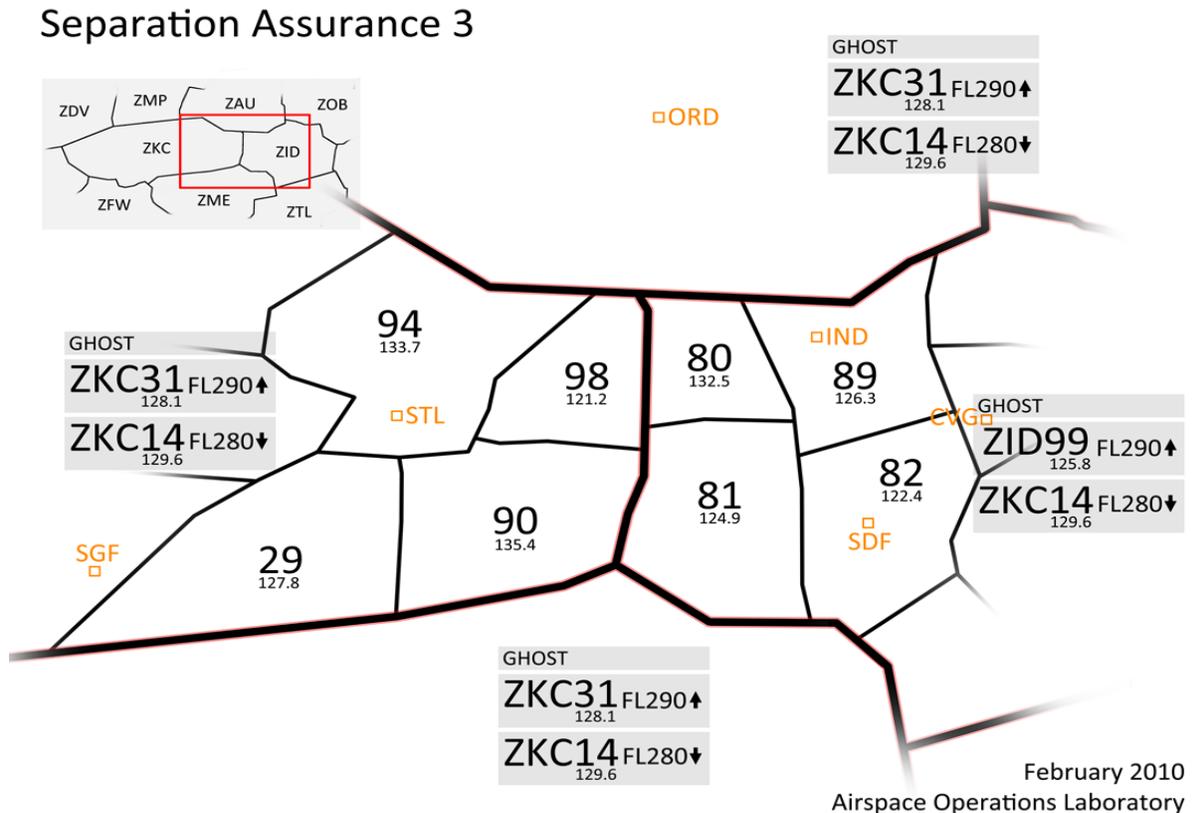
Traffic demand on airspace and metering fixes was varied within and between runs, with two basic traffic scenarios: (1) a Light Metering scenario with 2216 aircraft, moderate arrival flows with little meter delay and (2) a Heavy Metering scenario with 3060 aircraft and dense arrival flows often requiring more than five minutes of meter delays to be absorbed. Two different weather scenarios were used, in which the convective weather was growing or decaying within half of each scenario and absent during the other half. This resulted in four different challenging traffic, weather and metering problems designed to stimulate a wide range of controller activities related to air traffic control and coordination. Each scenario lasted for three hours and for analysis purposes can be divided into three consecutive one-hour long phases. Each phase was a combination of a light or heavy metering situation and the presence or absence of growing or decaying weather. Table 3 shows the design and run schedule.

Table 3. Experiment Design

	Day1		Day2		Day3		Day4	
	traffic	Wea- ther	traffic	Wea- ther	traffic	Wea- ther	traffic	Wea- ther
Phase 1 1:00 PM	Light  Mete-  ring	Growing weather	Heavy  Mete-  ring	Decaying weather	Light  Mete-  ring	Decaying weather	Heavy  Mete-  ring	Growing weather
Phase 2 2:00 PM								
Phase 3 3:00 PM								

## B. Airspace

The simulation was situated in the central United States and covered eight high altitude sectors: four on the eastern side of Kansas City Center (ZKC) and four on the western side of Indianapolis Center (ZID), as shown in Fig. 17. To create challenging metering problems, arrivals into various airports were scheduled over certain meter fixes such that they could conduct optimum profile descents from the en route airspace. Airports with meter fix time-constraints included BNA, CVG, MSP, ORD, SDF, and STL. See Fig. 17 for the locations of CVG, ORD, SDF and STL. BNA and MSP are outside the depicted airspace.



**Figure 17. Test Airspace.**

Fig. 18 shows a scene as it was displayed on an overhead projector in the ZID control room during the simulation. Each colored symbol on the traffic situation display on top represents one active aircraft within the scenario. The grey area in the middle represents weather impacting the center of the test airspace. The displayed weather looped from 30 minutes past the current time to 30 minutes into the future, indicating the predicted weather. Underneath the traffic situation display are load graphs for the four ZID sectors 81, 80 and 89 and 82. Indicated in red are predicted sector loads of more than 45 aircraft for a given sector. These sectors have current day Monitor Alert Parameters of maximum 18 aircraft. During the study controllers could look up to this display, which was driven by the area supervisor and gage their current and future load as well as the overall traffic situation.



**Figure 18. Scene from simulation as displayed on overhead projector**

### C. Apparatus

The simulation was conducted in the Airspace Operations Laboratory (AOL) at the NASA Ames Research Center [12]. The AOL's Multi Aircraft Control System (MACS) software was used for all simulation and rapid prototyping activities [11]. MACS provides high-fidelity display emulations for air traffic controllers and managers as well as user interfaces and displays for confederate pilots and flight crew participants, experiment managers, analysts, and observers. Scenario and target generation capabilities are also built into MACS, which were used to generate and run the traffic and weather problems. MACS' integrated data collection system was used to collect the quantitative measures of interest at each operator station as well as overall traffic progression, including aircraft states, conflicts, and sector counts.

In order to provide the required automation support to the controller, the NextGen ATC workstation prototype was developed based on an emulation of the operational en route controller system as described in the previous section. For this study, the AOL was configured with two participant control rooms, each hosting the four air traffic control sector positions and one supervisor position in ZID and ZKC, respectively. Fig. 15 shows one of the air traffic control rooms with four radar positions and the supervisor workstation. Each workstation displayed one sector that was worked by a single radar (R-Side) controller.

### D. Participants

Six active FAA front line managers that were certified as current on the radar positions were complemented by six recently retired air traffic controllers and one supervisor from Oakland Center. Together, they staffed the eight air traffic control and two area supervisor positions in the two air traffic control rooms. Three additional confederate controllers worked the traffic flows into and out of the test sectors, and ten general aviation pilots served as pseudo pilots, who operated the simulated traffic.

### E. Experimental Procedure

After three days of training, data were collected during the afternoons on four consecutive days, when a three-hour long scenario with either 2,216 or 3,060 aircraft was run. In each run, four teams of three controllers rotated through two neighboring sectors, so that each controller worked each sector for one hour. The rotation was scheduled such that a controller had a 30 minute break after each shift and was therefore never on position for longer than one hour. Shift changes were scheduled and posted in the control room and the break room. During each shift change, the outgoing controller briefed the incoming controller, who then signed into the workstation.

System data as well as user inputs were recorded with the MACS data collection system. At three-minute intervals throughout each run, participants were prompted visually and audibly to rate their perceived workload. The position-relief briefings were recorded with the voice communication system. The sign-in/sign-out process at the shift change recorded the exact time at which a new operator took over a position. At the end of shifts in the first

two phases of each afternoon the outgoing participants responded to a short questionnaire in the break room. After Phase 3, all participants completed a more comprehensive post-run questionnaire that included items on function allocation. All questionnaires (post-shift, post-run, and post-simulation) were posted electronically.

## V. Results

In this section, we present results on airspace capacity and throughput, controller workload, safety, efficiency, acceptability, and function allocation.

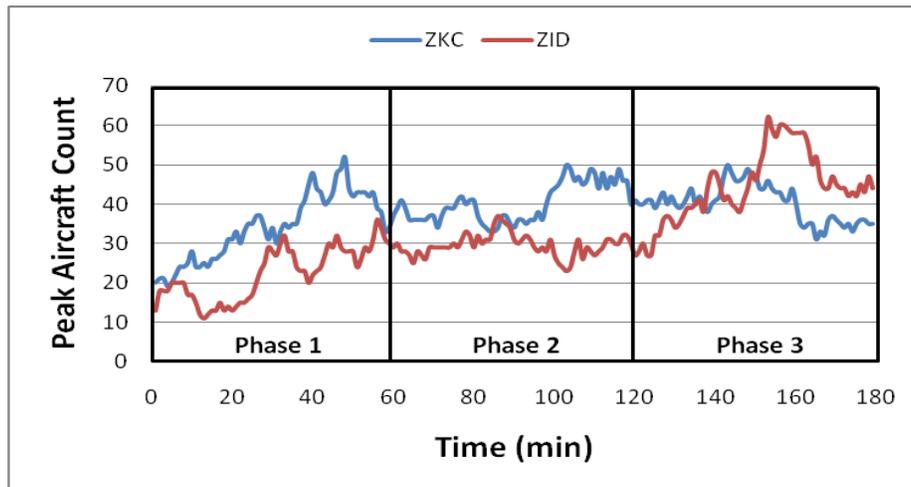
### A. Airspace Capacity and Throughput

Table 4 presents the mean aircraft count per sector within the eight-sector test airspace for the three phases of each run accompanied by the standard deviations. The results show that the mean number of aircraft in each sector was much higher than is experienced today, particularly for the counts in Phases 2 and 3. Table 2 also shows that the weather had little impact on the aircraft count, indicating that high throughput was maintained in the presence of weather. The peak aircraft count in the peak sector within the test area provides a more striking depiction of the elevated traffic levels that were experienced and managed by the participants.

**Table 4. Mean Aircraft Count per Test Sector for the Light and Heavy Metering Conditions.**

	Phase 1			Phase 2			Phase 3		
	AC Count	SD	Peak	AC Count	SD	Peak	AC Count	SD	Peak
Light Meter.-Decaying Wx	<b>19.0</b>	2.7	32	<b>27.5</b>	5.9	48	<b>25.9</b>	5.0	42
Light Meter.-Growing Wx	<b>19.4</b>	3.8	36	<b>27.1</b>	5.7	51	<b>21.2</b>	6.5	44
Heavy Meter.-Decaying Wx	<b>20.1</b>	7.4	52	<b>25.3</b>	8.7	50	<b>29.1</b>	7.4	60
Heavy Meter.-Growing Wx	<b>19.6</b>	8.0	48	<b>24.1</b>	8.1	47	<b>28.1</b>	8.6	62

Fig. 19 presents time-series plots of the peak aircraft counts in the peak sectors within the ZKC and ZID test areas throughout the three-hour runtime in the Heavy Metering condition that show the detailed characteristics of the traffic load. It shows that in the ZKC area, there were sectors that experienced aircraft counts between 40 and 50 for sustained periods of time, and one sector in particular in ZID experienced counts above 60 aircraft. As a reference point, today the peak aircraft count for these sectors is not supposed to exceed the Monitor Alert Parameter (MAP) of 18 aircraft.



**Figure 19. Peak aircraft counts for the ZKC and ZID test areas**

## B. Controller Workload

### 1. Real-time Ratings

The real-time workload ratings were on an interval scale from one to six, with six representing the highest level of workload possible. Fig. 20 presents the overall mean workload reported by the R-side test participants in each of the Metering-Weather conditions across the three phases of each run.

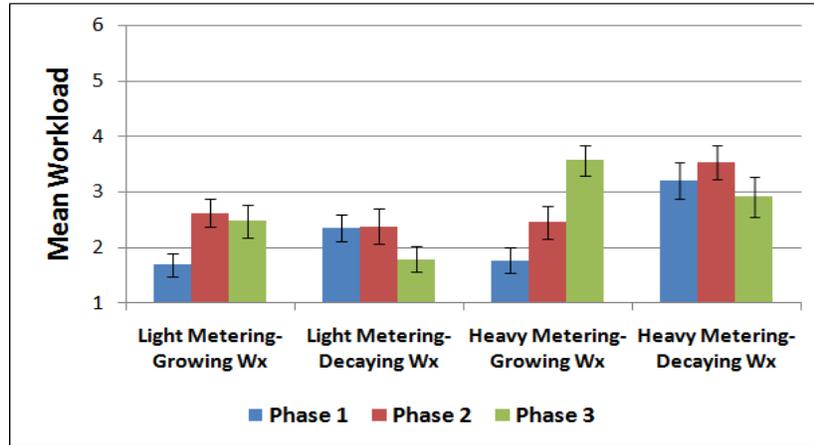


Figure 20. Mean reported workload for each Metering-Weather condition and run phase.

From these results and the post-run ratings discussed in the next section (see Fig. 22), it appears that the workload increased with more severe weather and metering conditions. This is not surprising given that there were controller's tasks associated with the aircraft that required metering and weather reroutes. In contrast, the raw aircraft count does not appear to correlate with workload. This is indicated in Fig. 20 where a phase without convective weather received consistently the lowest mean workload rating in each run independent of aircraft count. Additional evidence is given in Fig. 21, which presents the mean workload reported by the ZKC R-sides overlaid on the mean AC counts for the Heavy Metering runs. Phase 1 of the Growing Weather run (upper portion) did not involve any weather cells, and the mean workload was relatively low despite high levels of traffic. In contrast, the workload reported for Phase 1 in the Decaying Weather run (lower portion) was much higher despite nearly

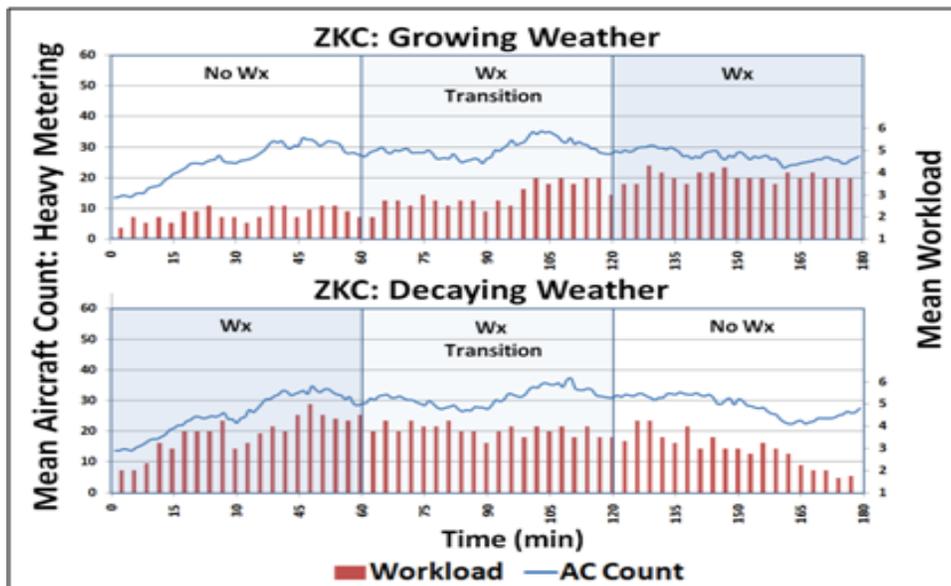


Figure 21. Mean workload overlaid with mean AC count in the Heavy-Growing and Decaying run for the ZKC test area.

identical AC counts. The only difference was that Phase 1 of the Decaying Weather run started with weather cells affecting the test airspace whereas weather affected later phases in the Growing Weather run.

## 2. Post-Run Workload Ratings: NASA TLX

In addition to runtime workload ratings, participants provided assessments of their workload following each phase and at the conclusion of each run. Participants completed two of six workload ratings – mental load and time pressure – that form the NASA-TLX workload scale [17] after Phases 1 and 2 in each run. They completed the full TLX scale after the third phase. In each case, the scale ran from 1 (very low) to 7 (very high).

Comparing mental workload and time pressure by the metering and weather conditions showed that on average the Heavy Metering condition (whichever phase it occurred in) was always rated as producing a higher workload than the Light Metering condition. When there was weather, workload was rated as higher than when there was none. A Friedman test showed significant differences between participants' responses on both post-run scales for mental workload ( $\chi^2(3)=12.87$ ,  $p=.005$ ) and time pressure ( $\chi^2(3)=13.79$ ,  $p=.003$ ).

Fig. 22 illustrates the mental workload mean rating for the four conditions (the graph for the time pressure variable is similar). When the weather and metering variables were tested separately using a Wilcoxon Signed Ranks Test, both the presence of weather and the heavy metering significantly increased participants' mental workload ratings (weather:  $M_{\text{no-weather}} = 3.67$ ,  $M_{\text{weather}} = 4.75$ ,  $Z=3.27$ ,  $p=.001$ ), (metering:  $M_{\text{heavy-metering}} = 4.62$ ,  $M_{\text{light-metering}} = 3.41$ ,  $Z=3.38$ ,  $p=.001$ ), supporting the real-time workload findings.

However, although the level of metering was related to a significant difference in participants' time pressure responses ( $p=.000$ ;  $M_{\text{heavy-metering}} = 3.67$ ,  $M_{\text{light-metering}} = 2.12$ ), the presence of weather was not.

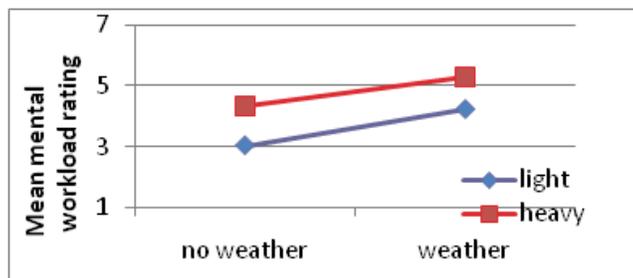


Figure 22. Mean mental workload across the four study conditions

Participants' general comments on the questionnaires indicated that workload varied considerably depending upon the

weather and metering conditions. After phases with Light Metering and no weather, participants said the run was “dull and boring” and they “never had to step in” to assist the automation; after phases with weather and Heavy Metering, participants said “the workload was pretty intense” and that runs were “very busy due to weather reroutes”.

## C. Safety

### 1. Losses of Separation

A LOS was recorded anytime two aircraft were simultaneously closer than 5 nmi laterally and less than 800 feet apart vertically. To be included in the following analysis a LOS had to occur within the tests sectors after the first 5 minutes of a run and last for at least 12 consecutive seconds. These LOS events were further categorized into Operational Errors (OE) and Proximity Events (PE) based upon the lateral separation at the closest point of approach (CPA) measured between the aircraft. If that distance was between 4.5 nmi and 5.0 nmi, the LOS was counted as a PE; whereas if that distance was less than 4.5 nmi the LOS was counted as an OE.

Across the 12 hours of simulation, a total of 1450 LOS events were scripted to occur inside the test airspace, 325 in each Light Metering Scenario and 400 in each Heavy Metering Scenario. 42 LOS events actually occurred. Of these, 8 were PE and 34 were OE. Fig. 23 shows the number and kind of LOS per weather/metering condition. Initial examinations including video-based analyses were undertaken to broadly characterize LOS in terms of sector counts, weather, phase, shift changes, altitude geometries, locations, cause and severity.

Neither the aircraft count nor the amount of weather present within a sector at the time of a LOS appeared to affect the probability of a LOS occurrence. The sector aircraft counts for the 10 minutes prior to a LOS were averaged for each LOS, and this distribution of pre-LOS sector aircraft counts (Min=9.3, Max=43.2, M=26.9, SD=8.7) was seen to be generally representative of the full set of sector aircraft counts seen across all runs (Min=4, Max=62, M=23.9, SD=9.1). Weather was present in the sector of the LOS 11 times, but only five of these occurrences involved a situation where 10% or more of the sector was covered by weather in the minutes leading up to and during the LOS.

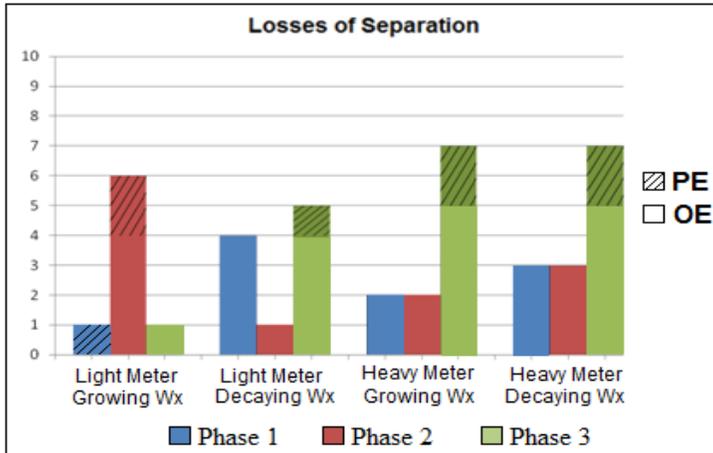


Figure 23. LOS for each phase and weather/metering condition.

Interestingly, it initially appears that time factors might have contributed to LOS events. Regardless of the specific run condition, the majority occurred in Phase 3 (20 LOS events) compared to Phase 2 (12) and Phase 1 (10). Additionally, with respect to the controller rotation, 31% took place within either the first 10 minutes or last 3 minutes of a controller's shift.

Locations and altitude geometries revealed a significant impact of arrival/departure flows of aircraft on the occurrence of LOS events in the simulation. A clear majority (62%) of LOS events were located within

portions of ZKC98 and ZID81 with traffic going to/from the STL and SDF airports respectively. Both aircraft were level at cruise altitude in only nine LOS events; all others involved at least one aircraft that was descending (25) or climbing (8). This supports the common understanding that transitioning aircraft pose the biggest challenge to current conflict detection/resolution algorithms. Video recordings of the radar scopes (as well as radio communications) for each LOS were reviewed to assess potential causes. Allowing for a LOS event to have more than one cause, causes were initially attributed as follows: pseudo pilot mistakes (5%), controller judgment/error (12%), conflicting resolution overlap between controller and automation (12%), insufficiencies in trajectory-based conflict resolutions/trial-planning (19%), secondary conflict interactions during off-trajectory operations resulting from prior tactical conflict resolutions (i.e. TSAFE) (24%), and last-minute or no conflict detection (64%).

Fig. 24 illustrates the relationship between cause and closest point of approach (CPA) of the LOS events. The results indicate that the majority of less severe LOS events (CPA > 3 nmi) are caused by conflict detection problems that can likely be avoided by expanding the buffers around the separation minimum of 5 nmi when probing for conflicts. Conflict detection problems, off-trajectory operations following tactical TSAFE resolutions, and controller judgment errors contributed to the most severe LOS events. This result indicates that additional research emphasis needs to be placed on the controller/automation function allocation in short-term conflict situations.

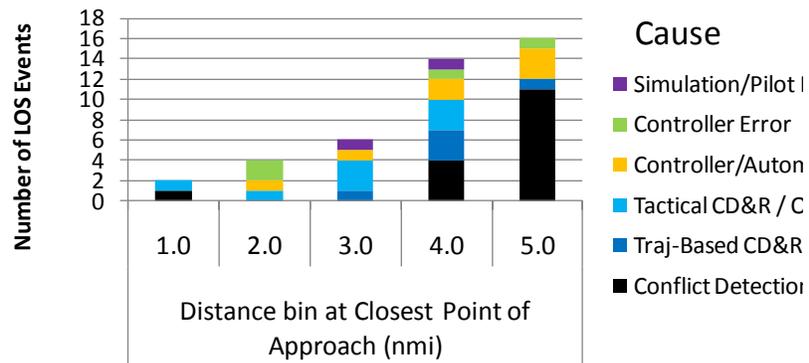


Figure 24. Number of LOS events per distance bin of CPA and cause for LOS (e.g. a LOS with a CPA of 2.3 nmi appears in the 3.0 distance bin).

## 2. Weather Penetration

Instances of aircraft penetrating convective weather provide another safety measure. As mentioned, there were two types of weather patterns used in both the Light and Heavy Metering conditions: Decaying and Growing. The decaying weather pattern was present both in and near the test airspace at start time and gradually dissipated over the course of the first 90 minutes. The growing weather pattern appeared as a smaller collection of cells at the 90th minute and amassed over the final 90 minutes of a run. These patterns were composed of three intensity levels (low, medium, and high), differentiated on the controller displays by color. Throughout each of the runs, the participants were asked to use lateral reroutes to avoid the weather. The controllers used a 'time to weather penetration' indication in the aircrafts data tags to assess when an aircraft needed to be rerouted, and interactive trajectory

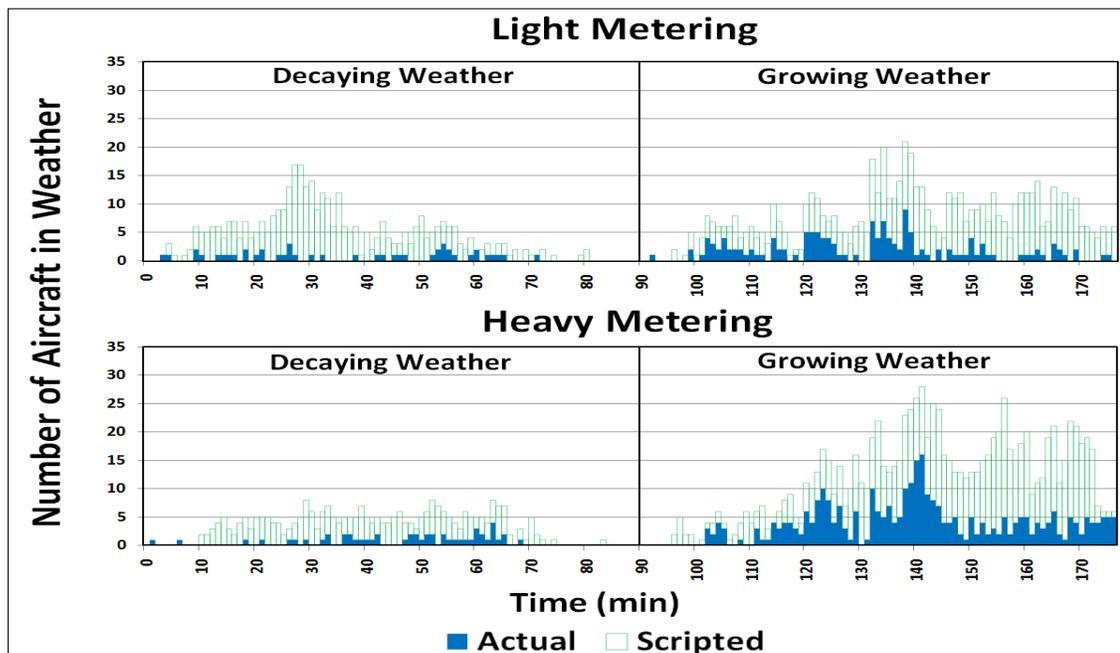
automation to plan the weather reroute. Both based their weather prediction upon an imperfect weather forecast model that predicted that the current weather moved linearly without changing its shape, while the actual weather changed its shape and direction every six minutes. Therefore reroutes that initially appeared clear of weather, could lead to a weather penetration a few minutes later, because the weather behaved differently than predicted by the linear forecast model.

The number of minutes that an aircraft was in weather at any intensity level was used as the measure of comparison for the weather penetration analysis and is referred to as penetration minutes. Table 5 and Fig. 25 describe how many penetration minutes were scripted (green) into each scenario and how many penetration minutes actually occurred (blue) with controllers working the traffic.

**Table 5. Aircraft Minutes In Weather by Condition**

Weather	Decaying		Growing	
	Scripted	Actual	Scripted	Actual
Light Metering	329	45	502	144
Heavy Metering	233	51	664	325

The totals in Table 5 and the time series plot in Fig. 25 indicate that the controllers were able to avoid weather penetrations almost entirely in the decaying weather problems. The growing weather patterns posed a greater challenge, since the underlying forecast model estimated the size of each weather cell to stay constant while it was actually growing. In the Light Metering condition controllers were still able to reroute all but 29% (144 of 502) of the aircraft successfully, but the complexity and workload in the Heavy Metering condition caused 49% (325 of 664) of the scripted weather penetrations to actually occur.



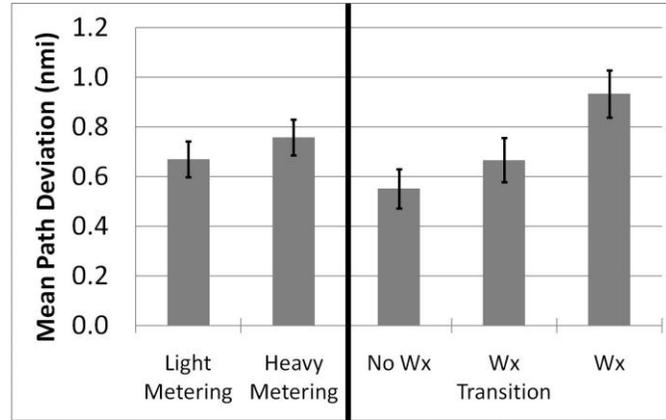
**Figure 25. Timeline of weather penetrations per condition**

#### D. Efficiency

##### 1. Lateral Path Deviation

An initial investigation into efficiency was conducted using the amount of lateral path deviation (away from their original flight plan) recorded for each flight. Trajectory changes issued for strategic medium-term conflicts, tactical short-term conflicts, weather avoidance, and for schedule conformance, issued either by the controller or the automation, can all impact lateral path deviation.

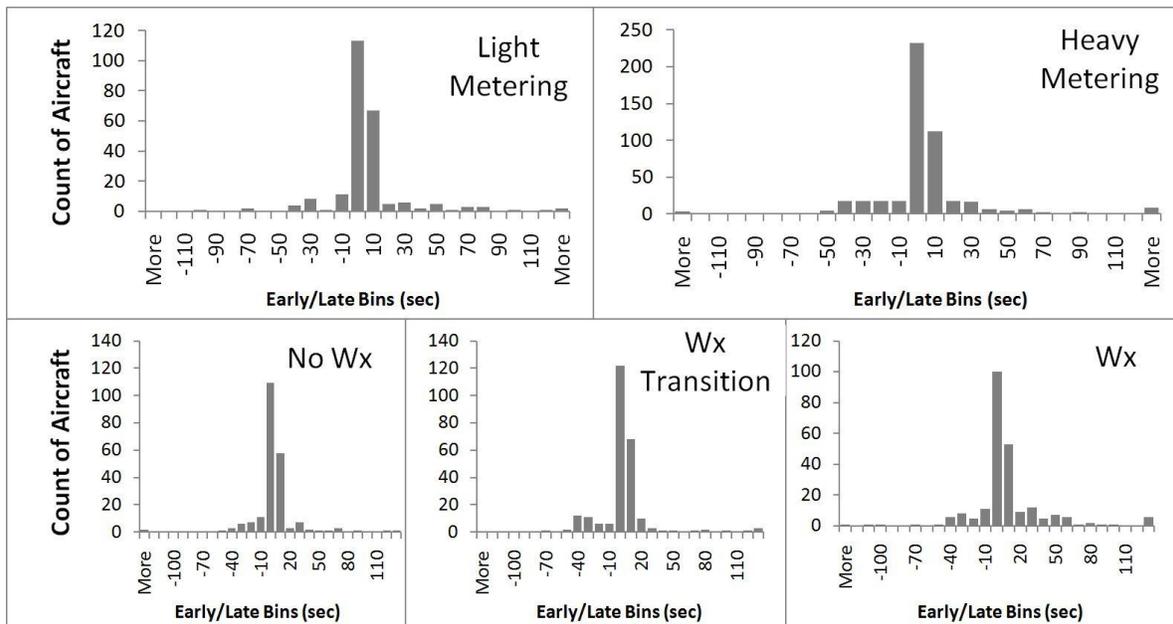
When comparing the mean path deviation between the Light and Heavy Metering conditions, the data are similar, with mean values of 0.67 nmi and 0.76 nmi of extra path length, respectively (Fig. 26, left). This suggests that even in the high levels of dense traffic experienced in the Heavy Metering conditions, there was still sufficient maneuverability in the airspace. This finding also indicates that, under this concept of operations, large increases in traffic levels in the NAS can possibly be accommodated without loss of efficiency. The right side of Fig. 26 shows the mean lateral path deviation as a function of weather. Not surprisingly, as more weather is present, path deviations increase, albeit slightly.



**Figure 26. Mean Path Deviation for the two traffic demand levels (left), and the three weather phases (right).**

## 2. Schedule Conformance

As the aircraft that were scheduled over meter fixes feeding congested airports left the test airspace, their Estimated Time of Arrival (ETA) was compared to their Scheduled Time of Arrival (STA). This measure was used to determine how well the controllers were able to deliver aircraft according to the arrival schedule. Fig. 27 depicts the schedule conformance. Similar to the path deviation data, there was little difference between the Light and Heavy Metering conditions. On average, scheduled aircraft arrived at their meter fix 7.56 s and 5.97 s later than their STA, respectively. This finding indicates that the increase in traffic demand into congested airports and the increase in metering delay to be absorbed did not prevent the controllers from consistently delivering aircraft on schedule. The distribution of this schedule conformance data is presented in the upper histograms in Fig. 27



**Figure 27. Histograms showing the distribution of ETA-STA discrepancies for the two traffic demand levels (upper) and the three weather phases (lower).**

As to the effect of the presence of weather on schedule conformance, the data show that as more weather is present, the controllers tended to deliver aircraft later relative to the STA. Given that negative values represent an aircraft arriving early at its meter fix, and positive values represent an aircraft arriving late at its meter fix, mean schedule conformances observed were 1.98 s, 7.24 s, and 10.08 s for the No Wx, Wx Transition, and Wx phases, respectively. This is expected, given that multiple metered flows in the scenarios were at some point completely obstructed by the weather cells. The distribution of this data, seen in the lower portion of Fig. 27, is consistent with both the lateral path deviation data and the real-time workload ratings.

### E. Acceptability

Six of the post-run questions formed an acceptability scale which followed the Controller Acceptance Rating Scale (CARS) developed by [18] as closely as possible. Although the first question was mandatory, the other questions were conditional upon previous answers. Participant answers were compiled to form a scale from one to ten where “1” indicated that the SA operation was not safe through to “10” indicating the operation was acceptable. The CARS ratings were compared over the three phases of each run. On average participants found the SA operations slightly less acceptable as the run progressed, that is, the highest mean acceptability score was reported in Phase 1 (M=7.15, “Moderate compensation required to maintain adequate performance”) and the lowest mean CARS was in Phase 3 (M=6.56, “Considerable compensation required to maintain adequate performance”). These differences were statistically significant ( $\chi^2(2) = 6.73, p=.035$ ) when tested with a Friedman statistic. This is due to operations being rated as more acceptable in the first phase than in the third. Shown in Fig. 28, there were 12 “uncontrollable” responses in phase 3 (24.9%) versus only 5 in phases 1 and 2 (15.6%).

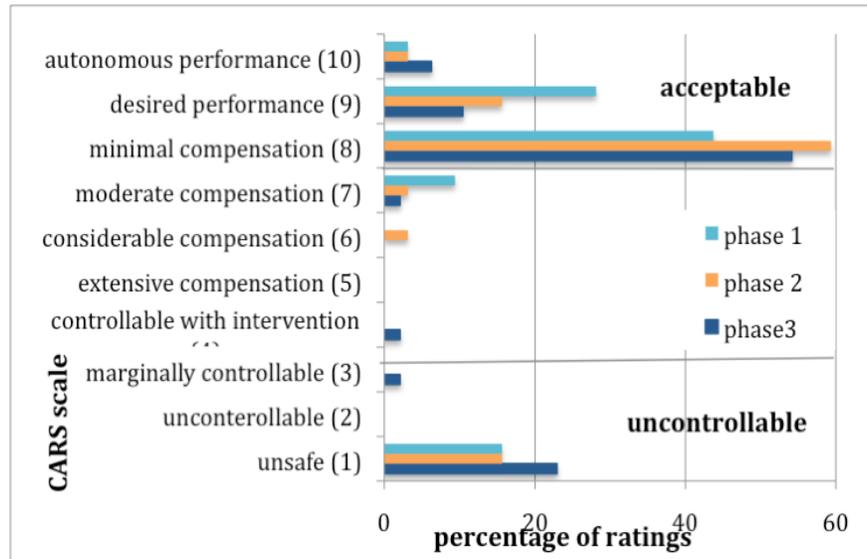
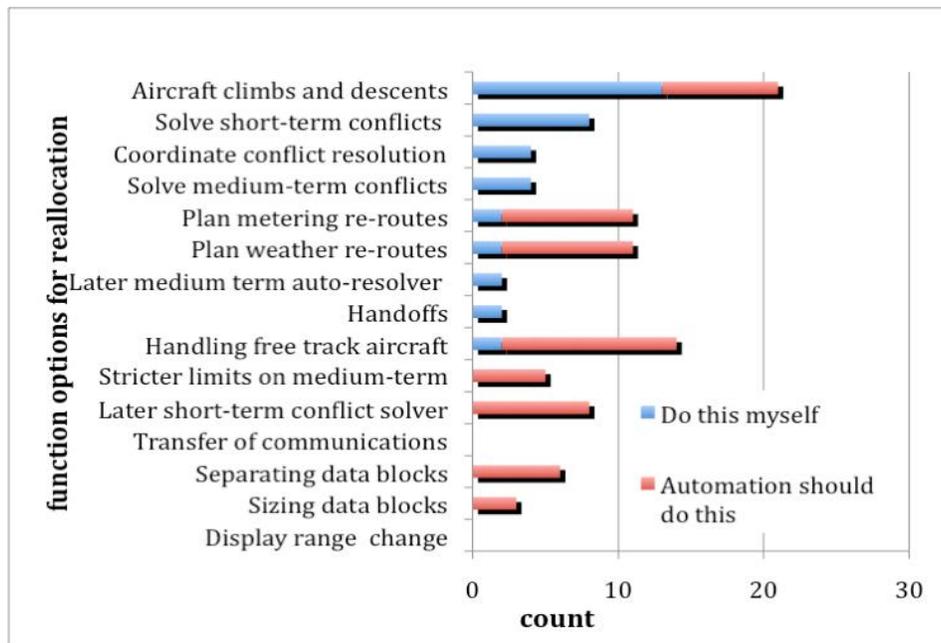


Figure 28. Percentage of CARS ratings in each scale bin for the three phases in each run.

### F. Functional Allocation between Controller and Automation

In the third phase questionnaire, a question asked participants whether there were tasks that they would have rather done themselves or whether there were tasks that they would have liked the automation to perform. The question about additional tasks that participants would rather perform themselves was asked 33 times. For 17 of these opportunities (51%) participants identified tasks that they would like to do themselves. This suggests that in the other cases (16), although a participant thought s/he had only ‘few’ or ‘some’ tasks, s/he did not feel that s/he needed to take control of any more functions. The question about allocating additional tasks to the automation was asked 13 times. In all 13 cases, participants identified functions that they would like to see automated, indicating that they felt they had too much to do. The bar chart in Fig. 29 shows how often a participant voted that a function should be reallocated between themselves and the automation.



**Figure 29. Count of function re-allocation votes after phase 3 in each run.**

The most popular function that participants wanted to complete themselves was approval of aircraft climbs and descents (13 of 17= 76%), followed by manually solving short-term conflicts (8 of 17= 47%) and manually solving medium-term conflicts (4 of 17= 23%). No one preferred manual transfer of communications, stricter limits on medium-term conflict solutions, or later auto-solving of short-term conflicts to give them a larger role in these tasks. The most popular candidate for automating was putting free-track aircraft back on a 4D trajectory (12 of 13= 92%), followed by trial planning, and sending weather and metering reroutes (9 of 13= 69%). No participant wanted the range on their display to change automatically and few participants wanted data-blocks to automatically expand or collapse (3 of 13= 23%).

### G. Summary

The results show that with this concept, sustained high capacity is achievable, even in the presence of convective weather and with heavy metering constraints. They also confirm the results from earlier studies showing that, unlike today, aircraft count is no longer the primary limiting factor and many more aircraft than today can be controlled. However, safety remains an issue, highlighting the importance of robust and reliable automation. While some of the LOS data seem to suggest valid challenges for human operators (e.g., greater numbers in the last phase of any day and also near shift transitions), the majority of LOS events were associated with the problematic complexity that comes with dense departure and arrival flows and fundamentally automation, rather than human, issues. Recognizing this, the proper balance must also be struck between the roles of humans and automation in this concept to maintain a consistent and appropriate level of engagement for the controllers.

This study provided a glimpse of how an air traffic management system works over time, something not seen in most studies because they have runs that are (by necessity) too short in duration. The results show that some events take some time to recover from, and even when a problematic condition no longer exists, its effects can be seen in both controller workload reports and LOS counts. For example, the increase in reported workload matches the onset of weather but also persists after the weather is gone, implying that the controllers needed time to recover from its effects. The acceptability ratings also imply that using a tool for an extended period of time is not the same as using it for a few minutes. There were many more “uncontrollable” ratings in Phase 3 compared to Phase 1 and Phase 2. Testing a tool over time is important because it may highlight aspects of its functionality that need to be attuned for long-term use. Also, the study revealed many human-automation interaction issues, in particular with regard to short-term conflicts, and these require further development and research.

## VI. System and Procedure Improvements

The results from the 2010 simulation and prior research were encouraging. They also pointed to particular areas for improvements. Primarily, the number of LOS events and weather penetration events need to be further reduced. The approach to doing this is two-fold. (1) Improve the technologies based on its objective performance and (2) improve the procedures based on objective performance and subjective feedback from controllers.

The following functional improvements are currently being implemented:

- Altitude fly-out menu with real-time conflict feedback
- Free-track trajectory automation
- Semi-automated weather avoidance

### A. Altitude Fly-out Menu with Real-time Conflict Feedback

The analysis of the separation losses indicated that most losses were related to transitioning aircraft. Further analyses confirmed that most short-term conflict situations were related to transitioning aircraft [19]. Controller often found themselves in situations with a short-term conflict in which they had to first trial plan various altitudes before they could issue one, thus losing valuable time. Therefore, we implemented an updated version of an altitude fly-out menu with real-time conflict feedback that was used in a similar fashion within the Center TRACON Automation System (CTAS) [20].



Figure 30. Altitude fly out menu with real-time conflict feedback

In the new prototype, all flight levels displayed in the altitude menu are constantly probed for traffic conflicts and a status indicator shows whether the flight level is clear or when a first LOS would occur. In the example in Fig. 30 the aircraft is currently at FL330, which is clear. A descent to FL 320 would create a conflict in 6 minutes. Any climb to FL350 or above would create a conflict in 1 to 2 minutes. This feedback is updated as long as the menu is displayed. Initial tests with this function indicate that it is valued very highly by the controllers and can address some of the problems encountered in the short-term situations.

### B. Free-track Trajectory Automation

Controllers in the simulation commented that one of the most annoying and time-consuming tasks that they were asked to perform was placing free-track aircraft back on trajectories linked to their original trajectory. As discussed in the results section of this paper it was therefore also one of the most frequently requested tasks to be automated. An initial version of this is now implemented that will allow controllers to request a conflict-free trajectory for any off-track aircraft. The function first trial plans the most direct routing back to the original trajectory and if that creates a conflict, activates the Autoresolver to adjust the trajectory for that conflict. This function will be automatically activated after automatic vectoring solutions, when certain conditions are met.

### C. Weather Avoidance

Both the Autoresolver and the MACS prototype have been enhanced to provide improved automated weather avoidance routes. A new function now uses a multi-step process that first searches for weather avoidance routes based on polygons and then follows it up with a more sophisticated probing. Controllers can activate this function whenever a weather penetration is indicated.

Figure 31 shows a typical tactical weather avoidance route generated by this function.

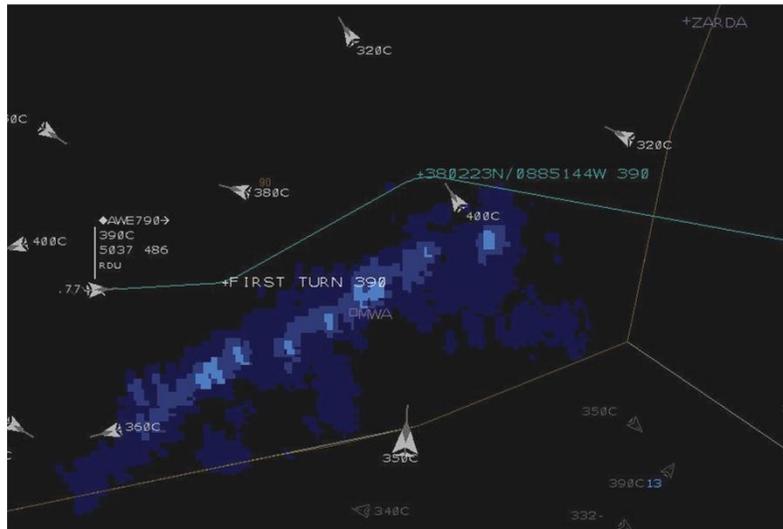


Figure 31. Weather avoidance route

#### **D. Human-Automation Interaction and Procedures**

Technical changes like those described above are being implemented. Once the automated system performs appropriately, more research is needed as to how much should be solved with automation and how much with procedures or both. Simulations are planned to evaluate the effectiveness of the system and procedure improvements. The new evaluation consists of two steps: (1) a closed loop evaluation of the prototype technologies in an automated environment and (2) controller-in-the-loop evaluation of technologies and procedures in a simulated operational environment. The preparations and initial shakedown simulations are underway and will continue into 2012.

### **VII. Concluding Remarks**

In 2010 we tested operations with automation for separation assurance, weather avoidance, and schedule conformance in human-in-the-loop simulations. The results from this study show that air traffic control operations with ground-based automated separation assurance can routinely provide currently unachievable levels of traffic throughput in the en route airspace. The ground-based automation system was stress tested in a highly dense and complex environment in the presence of heavy metering constraints and convective weather for sustained periods of time and performed very well overall. Controllers were able to work under this concept of operations in a realistic environment, and found it largely acceptable. We found high airspace throughput, excellent efficiency and schedule conformance, but saw issues with separation violations and weather penetrations. We hypothesize that technological and procedural modifications will eliminate most of the observed separation violations, improve weather avoidance while not negatively impacting throughput, efficiency and schedule conformance. If we achieve this goal, these operations can eliminate many airspace capacity constraints and significantly reduce inefficiencies, delays, as well as the environmental impact and cost of air travel.

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