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Human-In-the-Loop Evaluation of NextGen Concepts in the Airspace Operations Laboratory

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The Airspace Operations Laboratory (AOL) at the NASA Ames Research Center hosts a powerful simulation environment for human-in-the-loop studies of air traffic operations. The primary real-time simulation capabilities are developed by the AOL development team as part of the Multi Aircraft Control System (MACS) and cover a wide range of operational environments from current day operations to future operational concepts like those envisioned for the Next Generation Air Transportation System (NextGen). The research focus in the AOL is on examining air traffic control and traffic management operations across multiple air traffic control sectors and Centers in rich air/ground environments that can include oceanic, enroute and terminal airspace. The basic simulation capabilities and earlier research was presented at the AIAA Modeling and Simulation Technologies conference in 2006. Since then, the AOL capabilities have been continuously improved and expanded. Over the past four years the AOL has been extensively utilized to investigate a variety of NextGen concepts for NASA's NextGen Airspace Program and the FAA's Air Traffic Organization for Planning, Research and Technology. The primary focus areas under investigation in the AOL are Separation Assurance and the associated Functional Allocation for NextGen, Controller Managed Spacing for near- to mid-term Terminal area operations, flow-based trajectory management and multi-sector planning and dynamic airspace configuration and flexible airspace management. This paper first gives an overview over the most significant capabilities that were added since 2006 and then reviews at a high level the main activities and findings in the different research focus areas.

Nomenclature

AAC = Advanced Airspace Concept
ADS-A/B = Automatic Dependent Surveillance-Addressed/Broadcast
ADRS = Aeronautical Data link and Radar Simulator
ANSP = Air Navigation Service Provider
AOL = Airspace Operations Laboratory at NASA Ames
ATM = Air Traffic Management
ATOL = Air Traffic Operations Laboratory at NASA Langley
BC = Boundary Change
CD&R = Conflict Detection and Resolution
CDTI = Cockpit Display of Traffic Information
CPDLC = Controller Pilot Data Link Communication
DAC = Dynamic Airspace Configuration

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DSR = Display System Replacement (Center Controller Workstation in the NAS)
DST = Decision Support Tool
FAA = Federal Aviation Administration
FAM = Flexible Airspace Management
FMS = Flight Management System
JPDO = Joint Planning and Development Office
MACS = Multi Aircraft Control System
MSP = Multi Sector Planning
NAS = National Airspace System
NASA = National Aeronautics and Space Administration
OPD = Optimized Profile Descent
NextGen = Next Generation Air Transportation System
TBO = Trajectory-Based Operations
TMA = Traffic Management Advisor
TMU = Traffic Management Unit
TMC = Traffic Management Coordinator
TRACON = Terminal RADAR Approach Control
TRAC = Tcsim Route Analyzer/Constructor
RFA = Research Focus Area
SA = Separation Assurance
STARS = Standard Terminal Automation Replacement System (TRACON Controller Workstation in the NAS)
VSCS = Voice Switching and Communication System

I. Introduction

At the AIAA Modeling and Simulation Technologies conference in 2006 we presented a comprehensive paper entitled “The Airspace Operations Laboratory (AOL) at NASA Ames Research Center”[1]. This current paper can be considered the sequel to the 2006 paper. The research conducted in the AOL over the past four years followed the path outlined in 2006 addressing some of the most challenging research areas included in the NextGen vision. As the context of the work is unchanged we will introduce this paper with the following paragraphs that are almost identical to the first few paragraphs of the 2006 paper:

A. Simulating NextGen – An Ongoing Challenge

Simulating air traffic operations is challenging. Complex interactions between air traffic controllers, flight crews, traffic managers, airline operators and their respective automation systems result in the organized or chaotic movement of thousands of aircraft through the airspace. Covering all the potential interactions in simulation is impossible. Therefore, each simulation has to be designed to cover those aspects that are relevant to answer particular research questions. Realizing the vision for the Next Generation Air Transportation System (NextGen) outlined by the Joint Planning and Development Office (JPDO)[2] requires simulations to address numerous research questions.

The NextGen vision calls for a system-wide transformation leading to a new set of capabilities that will allow the system to respond to future needs of the Nation’s air transportation. The list includes communication and physical infrastructure, the acceleration of automation and procedural changes based on 4-dimensional (4D) trajectory analyses to substantially increase capacity and efficiency of the National Airspace System (NAS) without impacting safety, and dynamic reconfiguration of airspace to be scalable to geographic and temporal demand. A key element of the NextGen vision is the complete transformation to the concept of Trajectory-Based Operations in a Performance-Based environment.

The primary focus of NASA’s NextGen Airspace project is to explore and develop integrated solutions providing research data to define and assess the allocation of ground and air automation concepts and technologies including the human roles necessary for the NextGen.[3]

Simulations are a primary research tool. In order to address the NextGen Airspace research needs ambitious operational concepts with highly advanced automation support have to be rapidly prototyped and evaluated in simulation. These simulations need to be visionary and realistic at the same time. Realizing NextGen operational concepts cannot be limited to today’s technologies, and distribution of roles and responsibilities. At the same time disregarding the many aspects that make today’s system safe and relatively efficient would also be a mistake.

Furthermore, it can be expected that today's state of the art aircraft will still represent the majority of aircraft in the NextGen environment and that the operators, controllers and pilots trained in the next decade will represent a majority of operators for the NextGen. Therefore, finding the appropriate transition path will also be crucial in implementing the NextGen vision and simulations need to be able to address both, the far-term vision and the transitional stages.

The Airspace Operations Laboratory (AOL) at the NASA Ames Research Center has been designed for studying air traffic operations in the current environment, possible NextGen environments as well as the transitional stages between now and then.

B. New Capabilities to Create a Better NextGen Experience

New capabilities in the AOL have made it possible to conduct human-in-the-loop simulations at very high levels of fidelity, complexity, vigilance and operational validity. Participants, visitors and researchers are able to experience specific flavors of NextGen in new ways. Earlier simulations had already been conducted at fairly high levels of fidelity, but the following enhancements have enabled the laboratory to create a near full mission control room experience for the participants:

- Physical changes to the air traffic control and management lab facilities
- Staffing of area supervisor and traffic management positions in addition to controller positions
- Integration of a new voice system that adds realistic ground/ground communication
- Expansion of simulation technologies to include advanced traffic management functions
- Simulation of thousands of aircraft across multiple Centers
- Simulation of realistic convective weather situations
- Integration of unique, highly advanced automation function prototypes envisioned for NextGen

Figure 1. Air traffic control room (1) in the Airspace Operations Laboratory with research staff

Following this introduction, Section II of this paper gives an overview over the physical changes and new participant positions provided in the AOL. Section III describes the new real-time software capabilities implemented in the AOL since 2006 that are available at the associated operator stations. Section IV summarizes off-line capabilities with respect to scenario and weather generation as well as data analysis functions that are crucial to the successful simulation conduct. Section V summarizes simulations and findings of the primary research areas since

2006. A few short remarks conclude this paper. This paper is intended to complement the 2006 paper and does not replicate the complete capability description given in the earlier paper.

II. Physical Layout and New Participant Positions

The AOL, its hardware, and its Multi Aircraft Control System (MACS)[4] software are designed to be easily configured for any study needs. In 2008 and 2009 particular emphasis was placed on adding traffic management unit (TMU) and area supervisor functions and workstations and fitting them into the physical layout of the laboratory.

A. Physical Layout

Currently the AOL space has been configured to enable the simulation across two air traffic control areas and include a traffic management unit. Figure 2 below shows the current configuration with some sample pictures. Within the air traffic control rooms wall projectors have been added to display the traffic situation, load graphs or any other information the area supervisor selects to display to the controllers. Controller stations can be configured as either Radar (R-) or Data (D-) Side. Neighboring R- and D-Sides can be linked to synchronize data tag movements and certain other display elements, which enables team operations on a given sector. The traffic management functions available at the traffic management positions were developed for the FAA co-sponsored research on multi sector planning and flexible airspace management and represent advanced flow based trajectory management airspace functions as envisioned for NextGen.

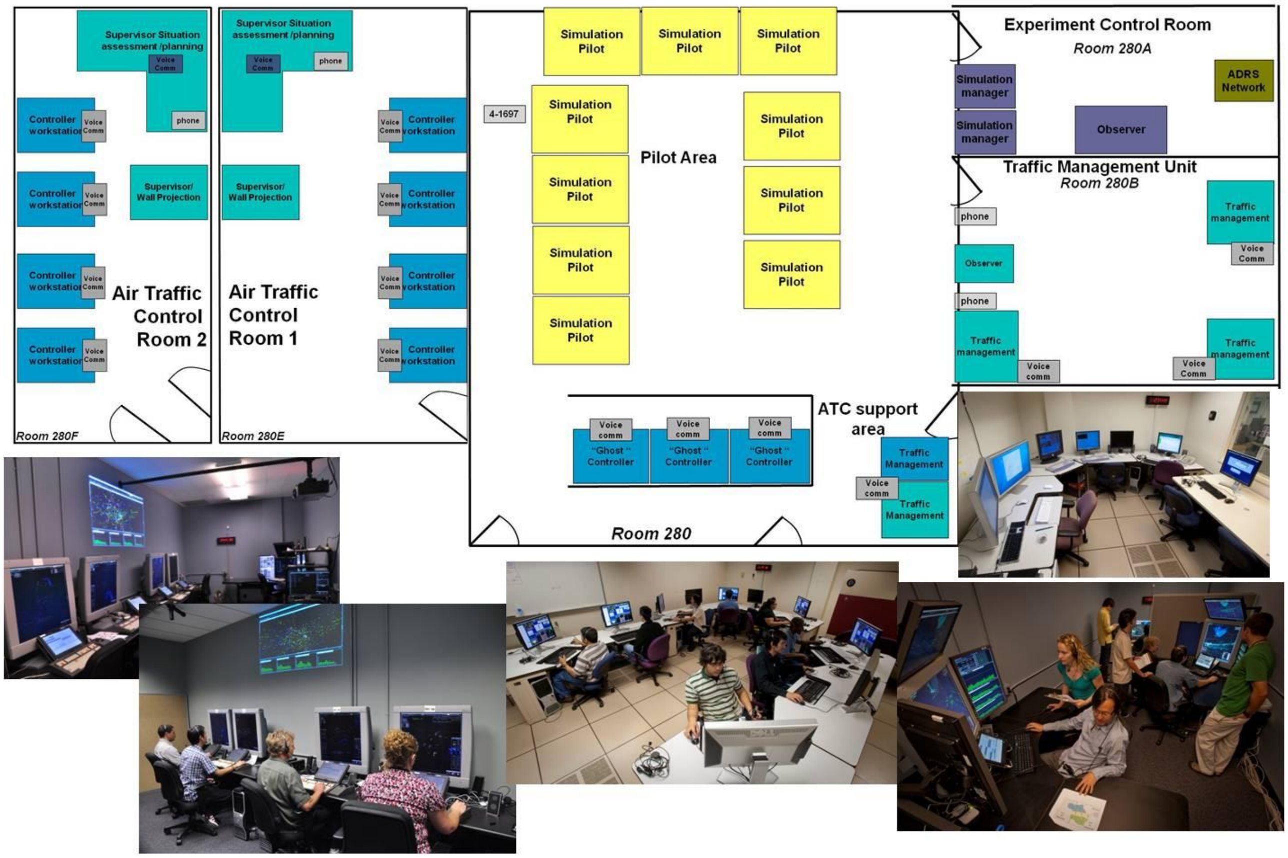


Figure 2. Current Layout of Original Airspace Operations Laboratory Space (280 lab), some configuration options are shown in the pictures.

The AOL is expanding its laboratory space and adding a new simulation environment that will initially be used as a TRACON laboratory. Figure 3 illustrates the expansion area with the initially planned configuration. This area is currently under construction and expected to be fully usable by the end of 2010.

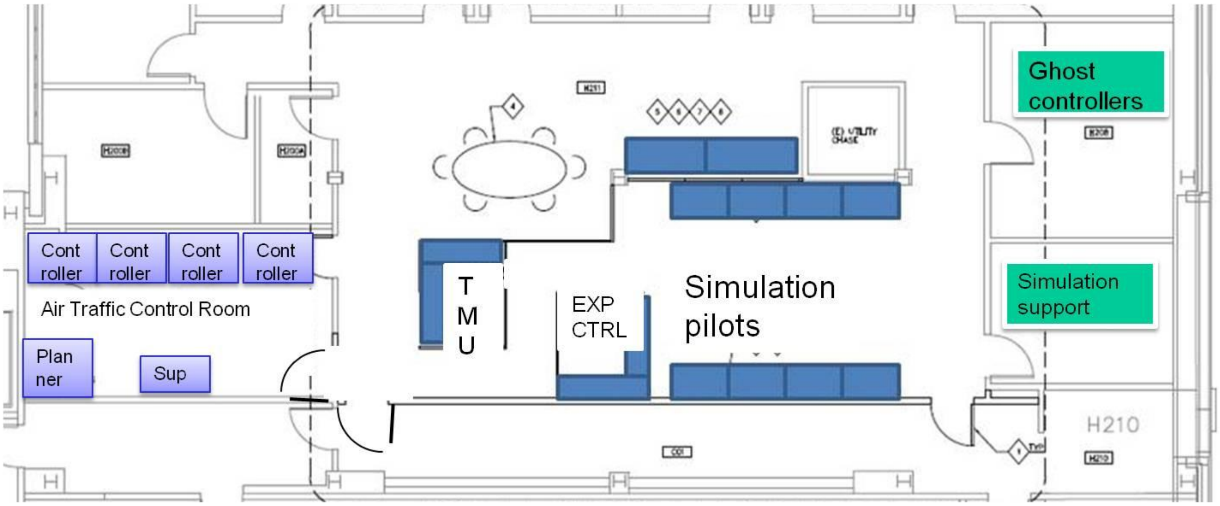


Figure 3. New AOL expansion area (H200 lab).

The new area will provide additional room for one air traffic control room with additional air traffic control positions, 8 simulation pilots, a TMU area, experiment control and space for ghost controllers. This lab space can be used to run simulations independently of the original area or both spaces can be combined into one simulation. When completed, the AOL will be able to run various simulation configurations. Some examples are:

- Three simulation worlds

Three independent simulations (worlds) can be run simultaneously, each consisting of one air traffic control area with four controllers and one area supervisor, a TMU, ghost controller and 5 simulation pilots. This configuration can be used to conduct a study with three different teams in parallel, which saves time and support requirements compared to running three teams sequentially

- Combined Center/TRACON simulation

The lab space can also be configured such that the 280 lab provides Center operations across two control rooms with TMU and pilots and the H200 lab simulates the TRACON operations with its TMU and separate simulation manager.

The overall capacity of the new AOL will provide for simulations with up to 15 high fidelity sector controller positions, 3 area supervisor positions, 6 traffic management workstations, 6 ghost controller stations and 18 simulation pilots. This combined capacity will be used when the research questions require a comprehensive multi-area or multi-facility simulation. Frequently the capacity will be used to conduct simulations within different research focus areas in parallel.

B. Staffing of Additional Participant Positions

The layout described above was created to integrate area supervisors and traffic managers into the simulation. As the research was expanding from the tactical air traffic control domain into the area of multi sector planning and dynamic airspace management, additional communication paths had to be simulated. Air traffic control areas have front line managers to supervise the operations in the control room and coordinate with other supervisors and traffic managers. The actions of the supervisors and the TMU have a major impact on the air traffic control operations. When the first simulation in the AOL included an area supervisor and traffic management coordinators, it became obvious that these positions added significant value to the fidelity of the operations. Not only was the staffing necessary, because these positions were data collection positions, but also the air traffic controllers received additional support. Each air traffic control room can now be treated as area in a facility that has a supervisor and can coordinate with other areas and TMUs as necessary. Figure 4 shows example pictures from simulations conducted in 2009 in the AOL's 280 lab.

Figure 4. Example participant position in the AOL during Multi Sector Planner simulation in 2009. Clockwise from top left: Traffic Management Coordinator, Area supervisor position (front right), air traffic control area, Center controller workstation with new voice communication system located below the radar display and behind the DSR keyboard.

C. Voice Communication System

Another area that needed to be addressed to facilitate coordination between the various positions was the voice communication system. Therefore, in 2008 and 2009 NASA entered into contract with Quintron Systems, a Santa Maria-based company to build a new voice communication system for the AOL. AOL researchers developed specifications and requirements that would allow Quintron to use their DICES VoIP[7] (an internet protocol based voice communication system) product as the basis for an emulation of the FAA's Voice Switching and Communication System (VSCS)[8]. The most important functions and interactive features for air/ground and ground/ground voice communication were specified in great detail and engineered into a PC-based environment. The voice application at the air navigation service provider (ANSP) stations was integrated into separate tablet PCs' with touch screens and USB based headsets, foot switches and speakers. The voice application for simulation pilots or confederate controllers usually runs on the same PC as their primary workstation.

The new voice communication system enables participants in the AOL to conduct ground/ground coordination via direct calls and conference calls and therefore adds an important element to the laboratory environment. This coordination element has been poorly modeled in the past. When the first simulations were conducted using the new voice communication system, it not only raised the fidelity of the simulation environment substantially, but it also required researchers and study participants to address important coordination aspects. New insights have been gained in various research focus areas about coordination requirements and associated workload as well automated aids to facilitate better coordination in NextGen operations. Figure 4 (bottom left) shows a controller station in the AOL equipped with the new voice communication system. Figure 5 shows a typical layout for a small scale simulation with an air/ground communication page on the left and a ground/ground communication page on the right. The system was built to emulate many of the functionalities of the VSCS installed throughout air traffic control facilities in the US, so that controllers are already familiar with its behavior.

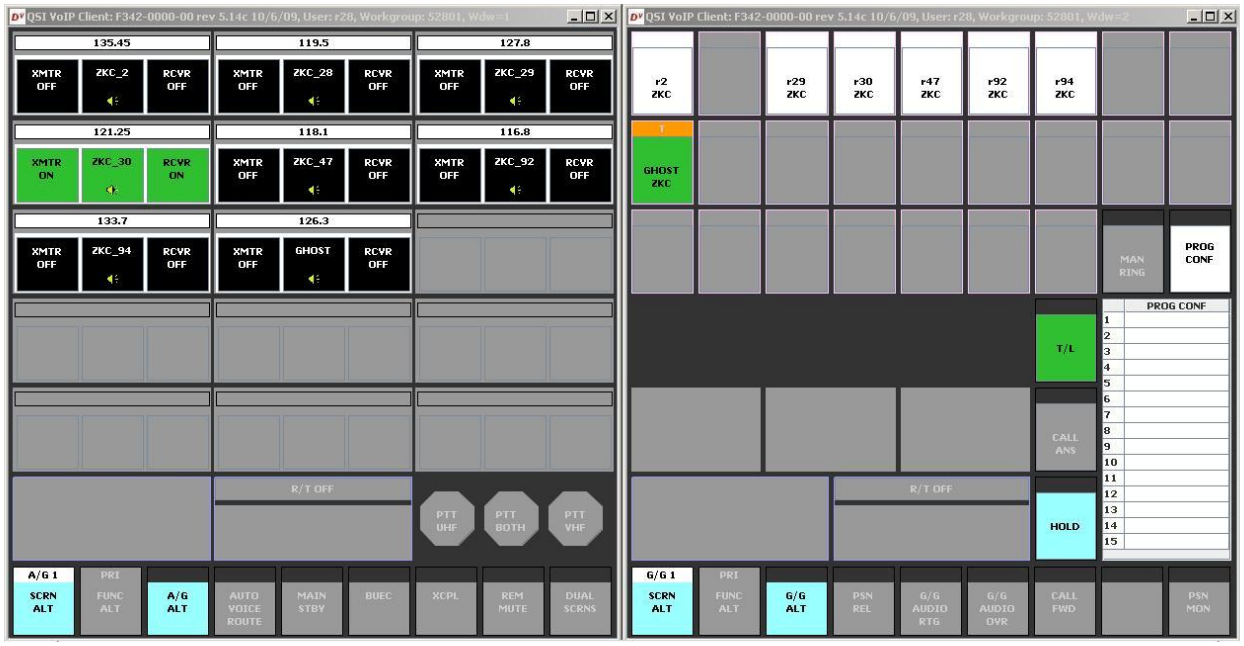


Figure 5. Voice communication system in the AOL configured for small scale simulation.

The physical changes, addition of new participant positions and the new voice communication system greatly enhanced the range of simulations that can be conducted in the AOL. However, since the research focus is on NextGen capabilities, which do not exist yet, many new functions had to be added to the AOL's real-time software in order to equip the operator workstations with the capabilities needed to simulate operations the way they could be ten or twenty years from now. These new functions will be described in the next section.

III. Simulation Software

The AOL uses the Multi Aircraft Control System (MACS) with its networking supplement, the Aeronautical Data link and Radar Simulator (ADRS) as its basic simulation software. Both processes have been developed by the AOL engineers and are constantly advanced. The basic capabilities are described in earlier publications.[1, 4, 5, 6]

A. Multi Aircraft Control System (MACS)

As each simulation lends itself to improve the effectiveness, usefulness and usability of the system, the functions implemented in MACS have undergone many levels of refinements. The current capabilities cover a wide range of air traffic environments: current day functionality, near-term improvements to phase in NextGen functions, mid-term transitional stages that deal with equipage mixes in the air and on the ground, traffic management modernization, airspace reconfiguration and far-term highly automated stages that enable handling many more aircraft than today.

Research in the AOL pursues primarily ground-based approaches to NAS modernization with modest improvements to airborne equipage. This level of airborne equipage is reflected in the flight deck functions integrated into MACS that enable aircraft to conduct trajectory based operations with flight management systems, integrated with data communication. Furthermore MACS flight decks can display weather and other aircraft. To

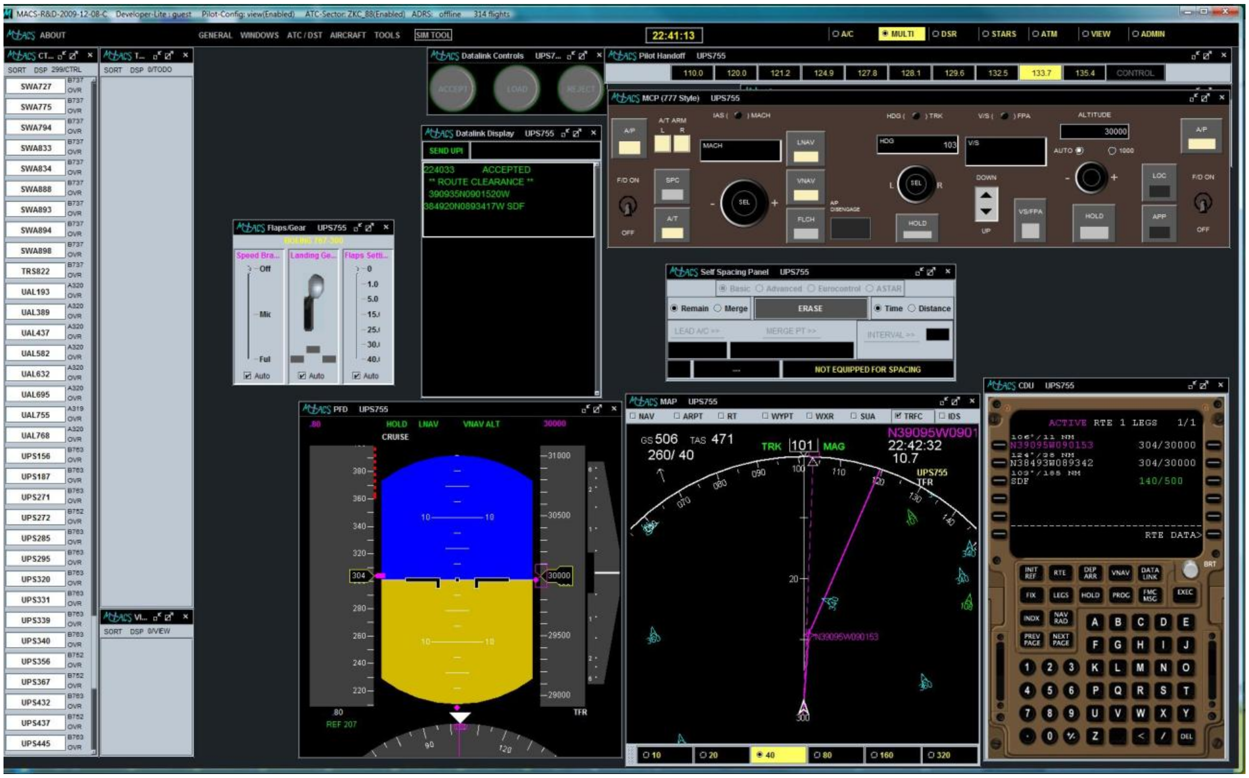


Figure 6. MACS multi aircraft pilot station configured for mid-term environment with integrated data link and airborne spacing functions

simulate airborne spacing MACS contains an emulation of the COSPACE airborne spacing algorithm developed by Eurocontrol[9] and provides access to the ASTAR[10] algorithm developed by NASA Langley. Most flight deck capabilities can either be operated by pilots or by automated agents that can load, execute and respond to data link transmitted instructions according to selectable performance parameters. Figure 6 shows a typical MACS pilot station configured with aircraft lists, primary flight displays, data link, airborne spacing panel, mode control panel and flight management system control and display unit.

B. Advanced Air Traffic Control Functions

In order to provide the required automation support to the controller, NextGen ATC workstation prototypes were developed as part of the MACS emulation of the operational en route controller system. These workstations provide access to key functions that support the operator in managing high traffic densities effectively.

1. Controller Workstation Design for Far-Term Operations with Automated Separation Assurance

Figure 7 shows the most advanced controller display as implemented in MACS that is used for the research on ground-based automated separation assurance for the year 2025 and beyond. The general idea of ground-based automated separation assurance is to let the ground-side automation monitor and/or manage nominal trajectory-based operations of equipped aircraft (low-lighted on the display in Figure 7), while the operator handles off-nominal operations, provides additional services and makes decisions on situations that are presented to him/her (high-lighted on the display). The separation responsibility resides with the service provider, which means the air traffic controller and ground-based automation. The primary difference to today’s system is that the ground-based automation is responsible for conflict detection and that separation assurance automation generates conflict resolution trajectories integrated with data link. These modified trajectories are sent to the aircraft either by the controller or, whenever certain predefined criteria are met, directly by the ground-based automation. The flight crews’ responsibilities related to separation assurance do not change from the current day.[11, 12]

All functions for conflict detection and resolution, trajectory planning and routine operations are directly accessible from the tactical controller display. Transfer of control and communication between controllers is conducted by the automation close to the sector boundaries. Nominally, aircraft are displayed as chevrons with altitudes, a design originally developed for cockpit displays of traffic information[13]. Traffic conflict information, hazard penetration and metering information is presented where applicable. Full data tags are only displayed in short-term conflict situations, or when the controller selects them manually. Time-based metering is supported via timelines and meter lists. The timelines show aircraft's estimated and scheduled arrival times at specific fixes, which are often meter fixes into congested airports.

The controller can request trajectories to avoid traffic conflicts, weather hazards and solve metering conflicts via various easy-to use mechanisms, using keyboard entries, data tag items, the conflict list or the timeline. The automated trajectory-based conflict resolutions are generated by an autoresolver module originally developed as part of the Advanced Airspace Concept[14]. When initiated by the controller, the automatically generated trajectory becomes a trial trajectory (indicated in cyan in Figure 7). The controller can then modify and/or uplink the trajectory constraints to the aircraft. During the trial-planning process, all trajectory changes are immediately probed for conflicts and provide real-time feedback on their status, before they are sent. Therefore, the tools are designed to be interactively used.

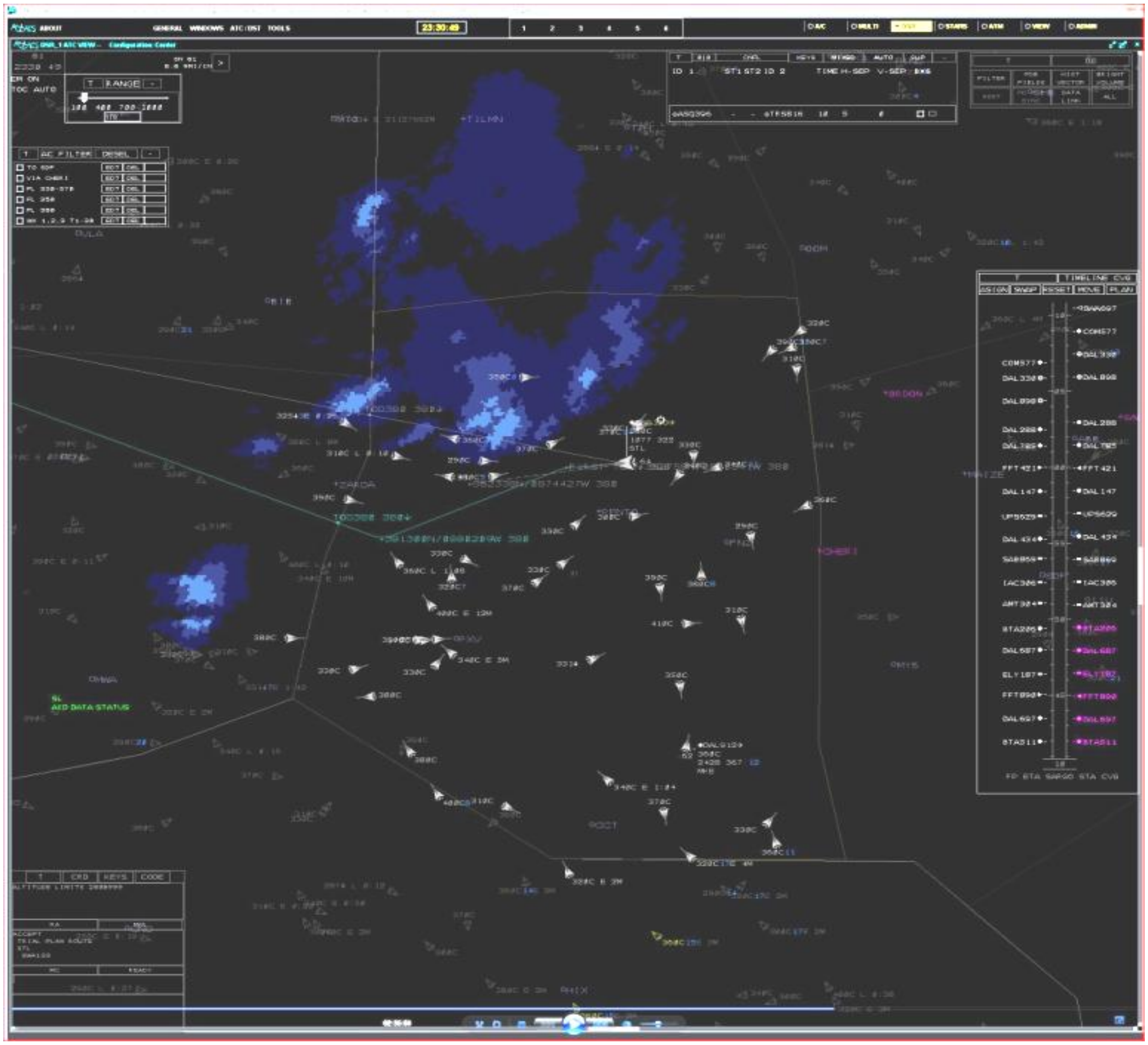


Figure 7. Controller display designed for far-term (e.g.2025) NextGen operations at more than three times today's traffic levels with weather and metering

2. Underlying Ground Side Automation

The ground side automation system prototype implemented in MACS represents a synergy between Erzberger's work on ground-based automated separation assurance[15] and the AOL's prior human-in-the-loop research on interactive NextGen air traffic control technologies.[16, 17] Erzberger's Advanced Airspace Concept is theoretically designed to provide fully automated separation assurance and air traffic control operations. The technologies developed in the AOL with the help of many controller-in-the-loop simulations were designed as highly responsive semi-automated decision support tools. The resulting superset of these tools enables simulating a wide range of concepts for functional allocation between the controller and the automation.

In order to provide the automated separation assurance functionality the ground automation creates flight plan based trajectory predictions for all aircraft from their present position to the destination airport. A conformance monitoring function compares each aircraft's actual position and velocity vector to its flight plan trajectory. When vertical non-conformance is detected, the trajectory generation process uses estimates of the current vertical rate as well as the aircraft supplied target altitude, if available, to generate the prediction. When an aircraft is in lateral non-conformance, or in other words "off-track," the automation uses the aircrafts heading target to generated flight state based trajectory prediction for the next 5 minutes. Since off-track aircraft create an undesirable state, as the system has no medium term trajectory prediction, these aircraft are indicated prominently to the controllers, highlighting a need for implementing a new trajectory for the aircraft. Ideally, all aircraft are in lateral and vertical conformance, and their active trajectories are therefore highly predictable.

All currently active trajectory predictions are tested within each conflict detection cycle as to whether a loss of separation is likely to occur within a predefined look-ahead time, typically 8-10 minutes. If a conflict is first detected with more than three or four minutes to initial loss of separation, the system automatically invokes the autoresolver[15] to determine the best overall conflict resolution according to its built in heuristics. The conflict resolution tries to avoid traffic and weather hazards and meet any potential time constraints. If a resolution does not violate preset parameters, such as change altitude more than 2200 feet, change heading more than 60 degrees, or violate a meet-time constraint, or if unconstrained, cause an overall flight delay of more than 90 seconds, the automation automatically creates and sends a data link message to the aircraft that includes all parameters that need to be loaded into the aircraft FMS to compute a trajectory that sufficiently matches the ground-based trajectory. The ground-based database of flight plans and trajectories is immediately updated so that the next conflict probe cycle will no longer flag this conflict and future conflict resolutions can take the new trajectory into account.

If a conflict resolution falls outside these parameters, it is flagged to the controller for review. The controller can then use semi-automated functions (including the autoresolver) to evaluate different options or approve solutions that are outside the tolerances for automated issuance. If a conflict is predicted to occur within less than three minutes, the TSAFE[18] module is activated and computes tactical heading changes for one or both of the aircraft involved in the conflict. In the current setup, the automation sends the heading change(s) at two minutes to predicted LOS automatically.

While detection and resolution of traffic conflicts can be basically automated, other tasks are conducted by the controllers using automated aids. To enable arrival management in high density operations MACS has a prototype capability to make sure aircraft adhere to scheduling constraints. Controllers can invoke a meet time function that combines the autoresolver logic with a speed advisory function and computes a combination of route, altitude, and speed change to achieve the desired STA on a conflict free path. To deal with convective weather situations, the automation displays the time to predicted weather penetration for all impacted aircraft, and the controllers can create trajectories avoid the weather and other traffic with a responsive trajectory planning tool or an autoresolver function. All automated conflict resolutions in these cases also avoid the convective weather areas and ensure compliance with metering constraints whenever possible.

All functions are implemented in MACS. The autoresolver and TSAFE source code modules developed by Erzberger and Heere are integrated into the MACS java code and use the MACS built-in trajectory generation and conflict probing functions.

The highly advanced ATC automation described above and shown in Figure 7 uses the same underlying trajectory-based technologies that are used for near-term and mid-term ATC workstation prototypes in other studies. Therefore, transitional stages can be addressed and researched and the far-term vision becomes an achievable goal rather than a pie-in-the-sky idea.

3. Controller Workstation Design for Mid-Term Operations with Automation Support

Figure 8 shows an ATC workstations configured for mid-term operations. In this case the automation is used in a supporting role, providing the controller with decision support tools that integrate into the current human/automation paradigm, but pave the way for future concepts. The trajectory-based automation and data link infrastructure that is core to these mid-term functions is used as for the far-term concepts described above, but with a different functional allocation. The difference becomes obvious when comparing the two displays. Since the far-term workstation is designed for the automation to be responsible for separation assurance, it depicts limited data tags for all aircraft that do not require the controller's attention. In contrast, the mid-term prototype is designed for the controller to be responsible for separation assurance with automation support and therefore shows full data tags for all aircraft within the controllers airspace. The following is a description of the mid-term operating mode.[17]

The controllers use primarily trial-planning functions that allow them to construct provisional trajectories and send them via data comm. or voice to the aircraft. Using the trackball (keyboard commands are 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 controllers can then uplink the trial-plan to equipped aircraft as a packaged route that can be directly loaded into its FMS. At the same time that the trajectory data comm. 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 computations. For unequipped aircraft the system can be set up to survey the airspace for named waypoints and snap the trial plan to those. Avoiding the use of latitude/longitude points in this mode allows the controller to more easily issue a verbal route amendment to an unequipped aircraft.

Figure 8. Controller display configured for mid-term (e. g. 2018) NextGen operations at 33% higher traffic density than today'

The trial-planning function can also be used for altitude changes, either as a separate trial-plan or combined with a lateral modification. Trajectory-based and particularly data comm.-enabled trial-plans have the benefit of reducing the controller 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 comm. clearances electronically as well, which further reduces frequency congestion by replacing the clearance read-backs.

Conflict detection automation is integrated directly into the primary controller workstation similar to the far-term prototype, complementing the controller's scan and minimizing disruptions to their workflow. The conflict detection probe within MACS uses a deterministic search for conflicts along the trajectories of the ground system's stored flight plans. In case aircraft are out of conformance with their trajectory, ADS-B state information from the aircraft is used to create a five-minute "dead reckoning" trajectory. Detected conflicts are presented to the controller both in the top right of the Flight Data Block (FDB) as a number (minutes until predicted loss of separation), and in a conflict list view.

The conflict detection probe also checks trial-planning trajectories. If the system detects a conflict between two aircraft, the controller can start a trial-plan and drag or move a point on the route of one of the conflict aircraft, and in real-time the conflict detection probe continuously checks the provisional trial-plan for conflicts with other aircraft. Potential conflicts are clearly indicated on the screen, and it becomes a visual search task for the controller to move the trial-plan until it appears conflict-free. This functionality was implemented in a manner that provides highly responsive feedback to the controller, making it very easy to use and still very useful in high workload and/or time-critical situations.

The autoresolver is also included, which provides efficient trajectory changes to resolve medium-term conflicts. If the ground system detects a conflict between two aircraft, the controller can request a conflict resolution from the automation by clicking on the conflict indications in the flight data block or the conflict list view. Within a few milliseconds, a conflict-free resolution is presented to the controller as a trial-plan that attempts to avoid the other traffic, convective weather areas and adheres to time constraints. Presenting the resolution in this way allows the controller to “tweak” the resolution if necessary, and then send it to the aircraft in the same way manual trial-plans are uplinked.

Additionally, a deterministic weather probe is incorporated, alerting the controllers to predicted weather penetrations. The weather probe information is presented to the controllers in the form a blue number (minutes until predicted weather penetration) in the bottom right of the FDB. While trial-planning to avoid the weather, the controllers can move the trial-plan until the weather probe’s number would disappear. Work is currently underway to integrate advanced autoresolver features that will further improve the automation-assisted generation of weather avoidance trajectories. Since the same automation is used for the mid-term and the far-term prototype, enhancements like these will benefit a wide range of functions.

C. Advanced Air Traffic Management

New technologies were implemented into MACS to combine options for managing demand and capacity into advanced trajectory-based operator stations to enhance the traffic flow and airspace management aspects of the operations. The new functions can be configured to effectively simulate traffic management coordinator (TMC) stations, area supervisor stations, multi sector planning (MSP) stations and airspace manager stations. New tools for situation assessment, planning and plan coordination were distributed throughout the system to create a common understanding of the current situation in order to see the available options and communicate and execute plans.

All operator stations access an information management system for retrieving and providing information. Operators can use voice and data comm. to communicate between each other. Traffic flow planners use functions provided at their workstations to create provisional trajectories that can be coordinated with other traffic management coordinators, supervisors, or controllers. Provisional trajectories for single or multiple aircraft can be sent via the automation for review at other planning stations. Once the trajectories are ready to be issued they can be sent to the sector controllers for execution. Sector controllers evaluate if they pose a separation problem and send the trajectory changes to the aircraft as necessary. Under certain situations, planners can send downstream trajectory changes directly to the aircraft. Operationally the exact rules will have to be determined, but in initial simulations a simplified rule allowed traffic flow planners to send trajectory changes to the aircraft if the first change point was at least 30 minutes away.

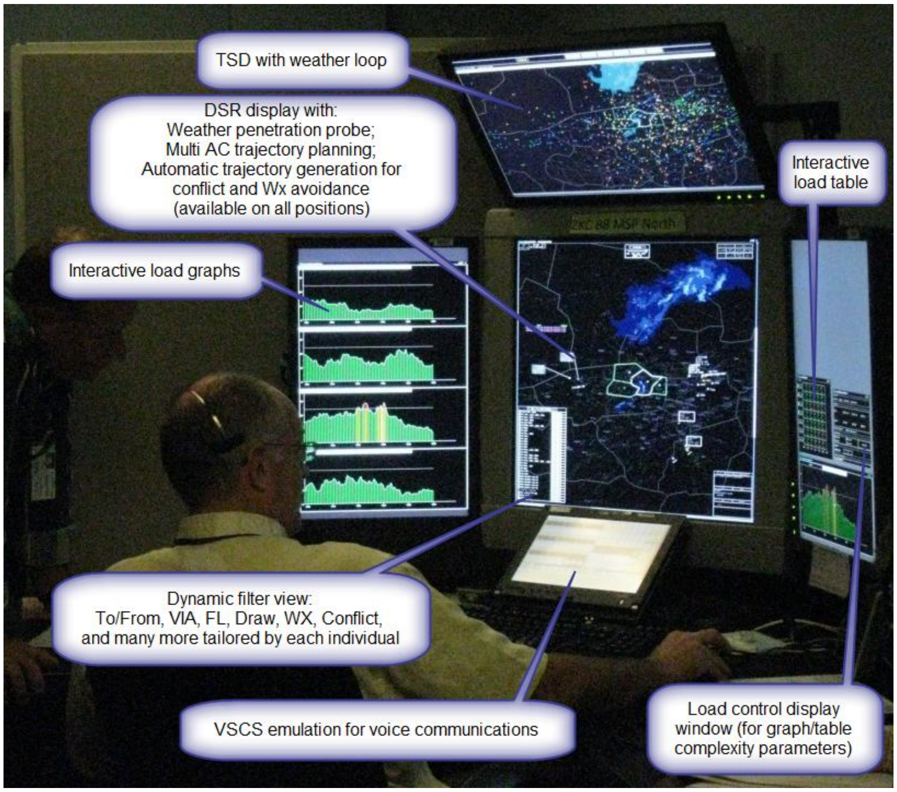


Figure 9. Workstation prototype for trajectory management and multi sector planning

Similar to the controller stations, the planning stations rely on accurate trajectory predictions to enable their functions. Figure 9 shows a planning station and indicates some of the new capabilities. Real-time filtering and analysis tools provide for traffic flow, sector/load and complexity assessment. Multi-aircraft trial planning functions provide options for previewing the impact for several trajectory changes on the overall situation. Any plans can be sent to other operators for their review. A short summary of the central new trajectory management functions follows.

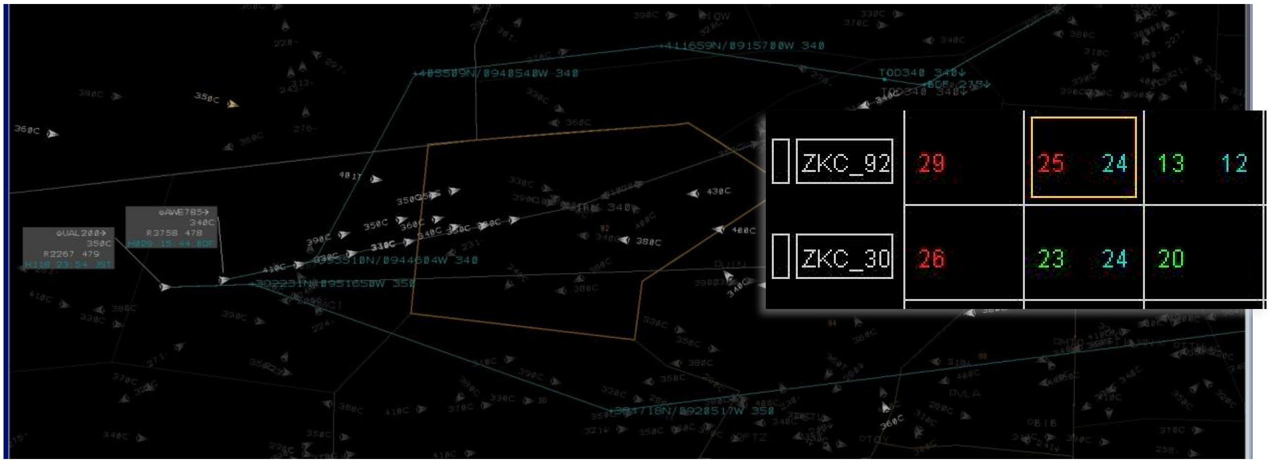
1. *Traffic Flow Assessment*

In order to assess the traffic flow within a large congested airspace, new dynamic filter capabilities have been prototyped that allow operators to highlight only specific aircraft. All traffic can be filtered such that only aircraft that fly to or from specific airports, or via designated routes, waypoints, or altitudes are highlighted. Aircraft can be highlighted that pass through specific sectors, dynamically drawn objects or forecasted convective weather areas. Filters can be combined, dynamically added, deleted or edited and color coded. Aircraft that do not pass the filter test are pushed into the displays background; aircraft that meet the selected criteria are brought into the foreground. Figure 9 shows an example of how operators can use these filters. When the picture was taken, the operator was examining reroute options around a convective weather cell. Therefore, he selected a filter on the DSR display that highlighted only aircraft that were predicted to penetrate the convective weather area within the next 30-90 minutes.

2. *Load/Complexity Assessment*

Similar to traffic management tools today, traffic loads for sectors are computed as the number of aircraft predicted to be in the sector for a given time frame. The results are presented in tables and graphs. When the operator selects a specific time slice these aircraft are also highlighted on the display. In order to account for complexity factors that go beyond a single number of aircraft, the graphs and tables can be switched to show only subsets of the aircraft, such as the unequipped and transitioning aircraft, aircraft predicted to be in conflict, or aircraft predicted to penetrate weather hazards. In addition to these values a real time estimate of the sector complexity is also computed. The complexity calculation includes the factors described above as well as the sector shape and size. Therefore, operators can use the complexity values instead of the total number of aircraft to have a more accurate estimate of the workload within any given sector. Results presented in other papers and in the section on multi sector planning later in this paper indicate that planning controllers ranked this complexity computation among the highest rated overall tools.

All load graph and table values reflect active trajectories. Predictions for provisional trajectories are given whenever new trajectory plans are viewed. These plans could have been initiated at the station or received from other stations. Figure 10 shows an example for how the peak sector load impact can be previewed when planning two trajectory changes.



☐	ZKC_92	29	25 24	13 12
☐	ZKC_30	26	23 24	20

Figure 10. Two trajectory changes being performed via lateral trial planning. The load tables indicate the new peak aircraft counts in the impacted sectors

3. *Multi Aircraft Trajectory Planning*

All the automation-assisted trajectory planning functions that exist at the tactical controller positions are also available at the planner positions. In order to assess the impact of moving an entire flow over a different routing, changing altitudes on multiple aircraft or other flow based trajectory management tasks, the planner can create a selection of several aircraft and manipulate their trajectories at the same time. This multi aircraft trajectory planning can be done graphically and/or via keyboard entries. All trajectories can be probed for conflicts and hazard penetrations as desired. Figure 10 shows a trial plan that moves two aircraft around a busy sector. The load table indicates how the peak number of aircraft will change when these new trajectories are implemented.

4. Plan Coordination

Plans can be coordinated between traffic planner/manager stations for review. A single command can send a selection of trajectories to a different station. The receiving operators can review the plan using their own complexity assessment tools and approve or disapprove trajectory changes. Once a plan has been agreed upon, it can be sent to the sector controller or directly to the aircraft, under certain conditions. Coordination with area supervisors should precede trajectory changes impacting operations in the area. Each individual trajectory can be reviewed by the sector controller. When acceptable he or she sends the trajectory change to the aircraft. An approval message is automatically returned to the originator of the trajectory change and a new trajectory amendment is made in the information management system.

D. Airspace configuration functions

In support of research on flexible airspace management, the capability was added to MACS to dynamically create and invoke airspace sector boundary changes. There are two types of new functions associated with this: functions to modify the airspace configuration and functions to preview and invoke the dynamic boundaries throughout the system, including the sector controller display

1. Airspace Configuration Editing

In support of a flexible airspace management study in August 2010 MACS has been enhanced with the capability to review, edit, share and activate dynamic sector boundaries. Using a boundary edit control panel (not shown), the operator can select from a set of predefined configurations, and modify the boundaries graphically. During the editing process the load graphs and tables indicate how the predicted traffic load and complexity change if the boundaries are implemented. While editing sectors, the system makes sure that airspace constraints do not get violated. For example, boundaries that neighbor airspace that cannot be configured cannot be moved, intersections of multiple sectors are moved together and sectors always need to have a closed set of boundaries around them. In addition to the graphical editing, sectors can also be merged and split vertically and horizontally through the edit panel.

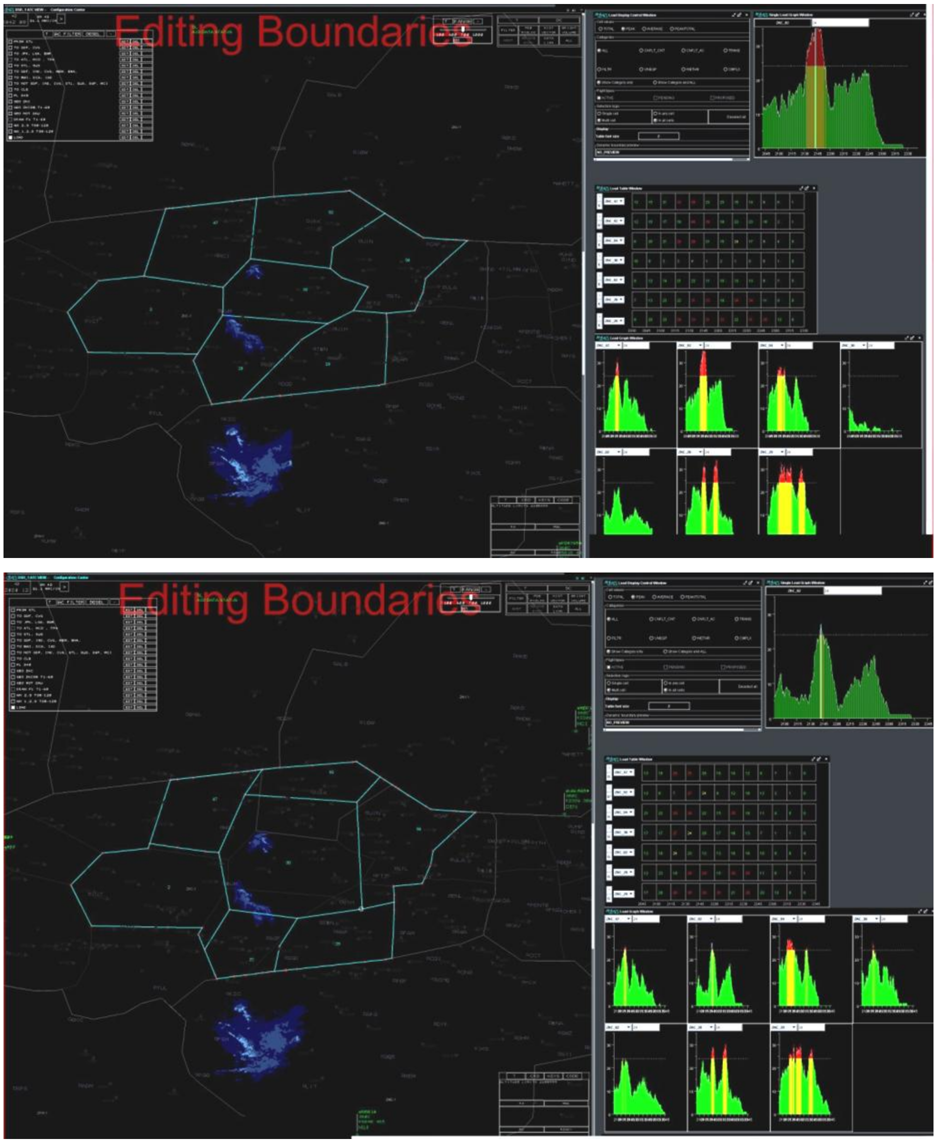


Figure 11. Sector boundary editing in MACS.

Figure 11 shows an

example. The sector boundaries that are being edited are shown in cyan on the plan view display. The traffic load predictions for these sectors are updated in real-time and shown on the right in the load tables and graphs. In this case the two sector configurations on the top and bottom would create very different traffic loads for some sectors.

Once the airspace designer has created a suitable sector configuration, he or she can then share it with other operators, such as the impacted area supervisors for review. During that process the sector configuration can be modified further until everybody approves. Once approved a time for activation can be entered and the air traffic controllers can prepare changing to the new sector configuration.

2. Airspace Reconfiguration

During a simulation the AOL has the capability to activate the new sector boundaries and transition all controller stations from the old to the new sector configuration. The area supervisor can display the new sector configuration on the wall projection and staff the R and D-Side positions as necessary for the transition and the new configuration. Initial controller orientation can be done using the wall projection. At a predefined time before the boundary change (usually 3 to 5 minutes) the new boundaries are overlaid on the air traffic controllers' displays. Figure 12[43] shows a controller display during the transition from one sector configuration to the next.

The controllers can familiarize themselves with the new configuration. The workstation contains a countdown displayed indicating when the actual transition will occur. At the appropriate time the controllers start transferring aircraft to other air traffic control positions as required and brief each other on any noteworthy situations.

At the predefined time the boundary change occurs and all system functions, such as automated handoffs, conflict predictions, etc. use the new sector boundaries, as do the controllers.

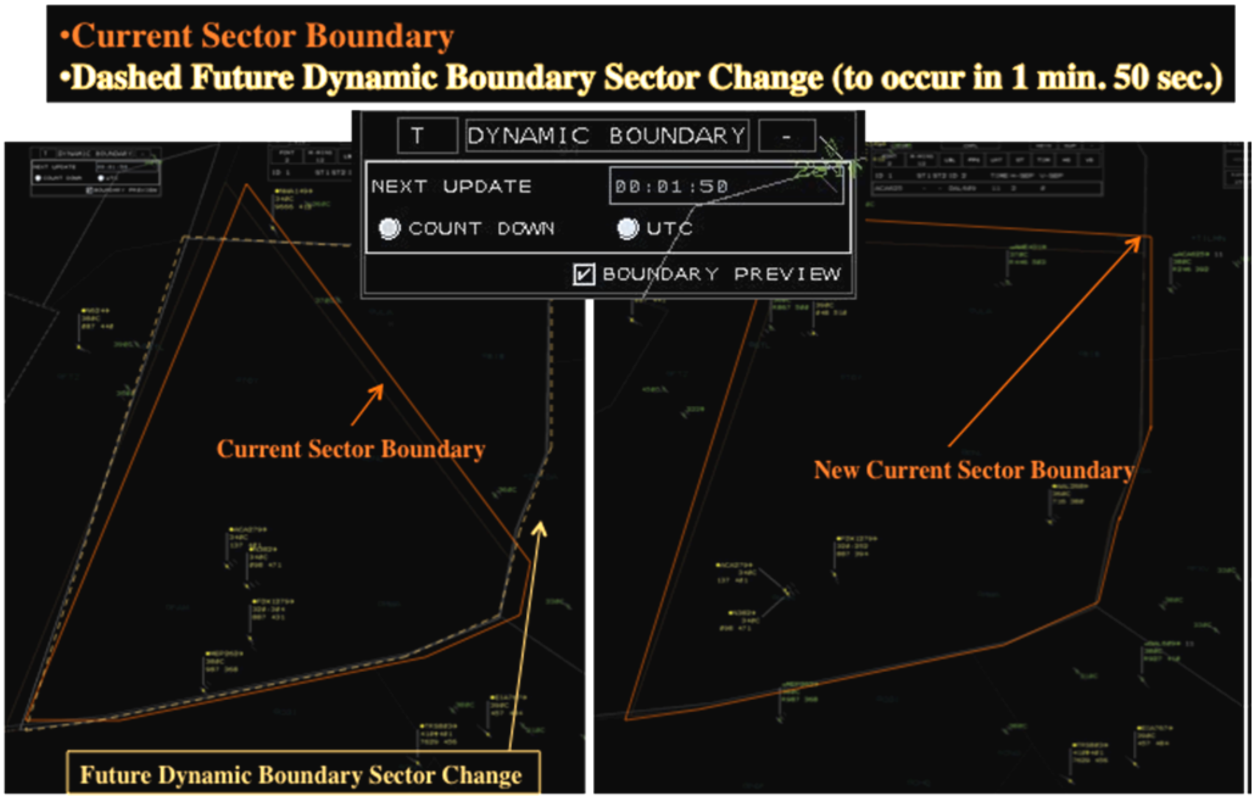


Figure 12. Controller display during transition period from one airspace configuration to the next.

Before, during and after the airspace configuration all other traffic management tools for flow based trajectory management remain intact. Therefore, both airspace changes and traffic flow changes can be used together in a complementary way by the operators to manage traffic load and complexity. As with all MACS features in the AOL, all functions are part of the same MACS software version. Only the configuration files have to change to adapt the version to the respective research objectives.

Simulation Support Software

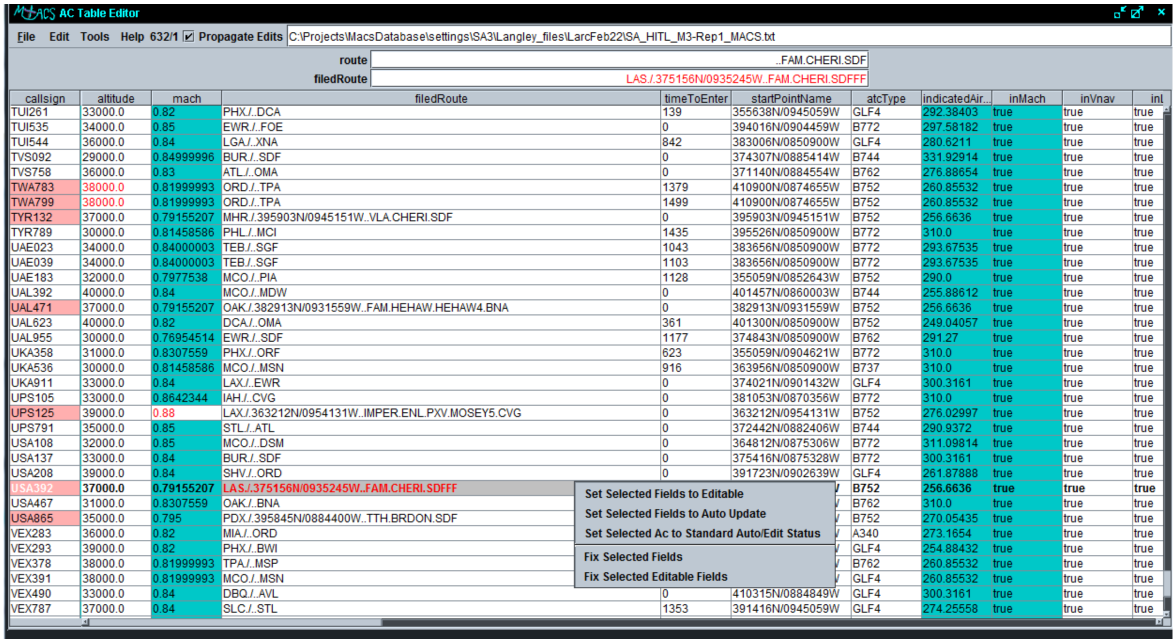
The simulation support software for off-line processing is integrated into two different software systems. MACS hosts many semi-automated tools for simultaneous generation of traffic and weather scenarios. MACS also supports certain types of data analysis. An additional tool frequently used in AOL research is the TCSim Route Analyzer/Constructor (TRAC), a Java-based, graphical airspace design, fast-time simulation, and data analysis tool.[20] Both, the new scenario generation capabilities in MACS and TRAC are described in the following sections.

A. Scenario Generation in MACS

Generating large scale traffic scenarios for human-in-the-loop simulations is very challenging. The scenarios unfold in a high fidelity simulation with controllers and pilots, who are very familiar with aircraft characteristics and traffic flows. Each aircraft in a scenario is relevant; otherwise it would not need to be there. Therefore, each aircraft needs to behave correctly. Small simulations may only require a few aircraft, such as part-task simulations of final approach control that may only need 20 or 30 aircraft. In these cases a manual process of scenario generation may be feasible. However it becomes less feasible, if for example specific characteristics for the spacing between aircraft are required. Larger scale simulations of NextGen en route traffic exercising traffic management and operational control room aspects require enough traffic to create flow problems across a large enough airspace for multiple hours at higher densities than today. Therefore, scenarios for thousands of aircraft need to be generated and often synchronized with specific weather situations. A manual process for this exercise is basically impossible. Live traffic is often considered a starting point, but NextGen is expected to eliminate many current day constraints, which make live traffic less usable. In order to address this problem the MACS built in scenario generator has been substantially improved and now provides many automated and semi-automated features available through the synchronized graphical editor and the spreadsheet style editor.

1. Spreadsheet –Style Scenario Editing

Figure 13 shows an example of the spreadsheet-style "AC Table Editor" in MACS. The data for each aircraft are represented in one row. The columns contain the many parameters that allow the experimenter to specify the aircrafts behavior in the scenario precisely. The scenario editor contains an error checking function that can be customized to specific rule-sets. Typically the scenario values are checked against the performance parameters for given aircraft types, the routes are checked for consistency and certain rules about airlines and respective aircraft are implemented to some degree. In the example in Figure 13 the aircraft highlighted in red have errors in the fields indicated with red text. Three errors in this example are wrongful altitude for direction of flight, one aircraft has an



632/1 ☑ Propagate Edits C:\Projects\MacsDatabase\settings\SA3\Langley_files\LarcFeb22\SA_HITL_M3-Rep1_MACS.txt

route ..FAM.CHERI.SDF

filedRoute LAS./.375156N/0935245W..FAM.CHERI.SDFFF

callsign	altitude	mach	filedRoute	timeToEnter	startPointName	atcType	indicatedAir...	inMach	inVnav	inl
TUI261	33000.0	0.82	PHX./..DCA	139	355638N/0945059W	GLF4	292.38403	true	true	true
TUI535	34000.0	0.85	EWR./..FOE	0	394016N/0904459W	B772	297.58182	true	true	true
TUI544	36000.0	0.84	LGA./..XNA	842	383006N/0850900W	GLF4	280.6211	true	true	true
TVS092	29000.0	0.84999996	BUR./..SDF	0	374307N/0885414W	B744	331.92914	true	true	true
TVS758	36000.0	0.83	ATL./..OMA	0	371140N/0884554W	B762	276.88654	true	true	true
TWA783	38000.0	0.81999993	ORD./..TPA	1379	410900N/0874655W	B752	260.85532	true	true	true
TWA799	38000.0	0.81999993	ORD./..TPA	1499	410900N/0874655W	B752	260.85532	true	true	true
TYR132	37000.0	0.79155207	MHR./.395903N/0945151W..VLA.CHERI.SDF	0	395903N/0945151W	B752	256.6636	true	true	true
TYR789	30000.0	0.81458586	PHL./..MCI	1435	395526N/0850900W	B772	310.0	true	true	true
UAE023	34000.0	0.84000003	TEB./..SGF	1043	383656N/0850900W	B772	293.67535	true	true	true
UAE039	34000.0	0.84000003	TEB./..SGF	1103	383656N/0850900W	B772	293.67535	true	true	true
UAE183	32000.0	0.7977538	MCO./..PIA	1128	355059N/0852643W	B752	290.0	true	true	true
UAL392	40000.0	0.84	MCO./..MDW	0	401457N/0860003W	B744	255.88612	true	true	true
UAL471	37000.0	0.79155207	OAK./.382913N/0931559W..FAM.HEHAW.HEHAW4.BNA	0	382913N/0931559W	B752	256.6636	true	true	true
UAL623	40000.0	0.82	DCA./..OMA	361	401300N/0850900W	B752	249.04057	true	true	true
UAL955	30000.0	0.76954514	EWR./..SDF	1177	374843N/0850900W	B762	291.27	true	true	true
UKA358	31000.0	0.8307559	PHX./..ORF	623	355059N/0904621W	B772	310.0	true	true	true
UKA536	30000.0	0.81458586	MCO./..MSN	916	363956N/0850900W	B737	310.0	true	true	true
UKA911	33000.0	0.84	LAX./..EWR	0	374021N/0901432W	GLF4	300.3161	true	true	true
UPS105	33000.0	0.8642344	IAH./..CVG	0	381053N/0870356W	B772	310.0	true	true	true
UPS125	39000.0	0.88	LAX./.363212N/0954131W..IMPER.ENL.PXV.MOSEY5.CVG	0	363212N/0954131W	B752	276.02997	true	true	true
UPS791	35000.0	0.85	STL./..ATL	0	372442N/0882406W	B744	290.9372	true	true	true
USA108	32000.0	0.85	MCO./..DSM	0	364812N/0875306W	B772	311.09814	true	true	true
USA137	33000.0	0.84	BUR./..SDF	0	375416N/0875328W	B772	300.3161	true	true	true
USA208	39000.0	0.84	SHV./..ORD	0	391723N/0902639W	GLF4	261.87888	true	true	true
USA392	**37000.0**	**0.79155207**	**LAS./.375156N/0935245W..FAM.CHERI.SDFFF**			**B752**	**256.6636**	**true**	**true**	**true**
USA467	31000.0	0.8307559	OAK./..BNA			B762	310.0	true	true	true
USA865	35000.0	0.795	PDX./.395845N/0884400W..TTH.BRDON.SDF			B752	270.05435	true	true	true
VEX283	36000.0	0.82	MIA./..ORD			A340	273.1654	true	true	true
VEX293	39000.0	0.82	PHX./..BWI			GLF4	254.88432	true	true	true
VEX378	38000.0	0.81999993	TPA./..MSP			B762	260.85532	true	true	true
VEX391	38000.0	0.81999993	MCO./..MSN			GLF4	260.85532	true	true	true
VEX490	33000.0	0.84	DBQ./..AVL	0	410315N/0884849W	GLF4	300.3161	true	true	true
VEX787	37000.0	0.84	SLC./..STL	1353	391416N/0945059W	GLF4	274.25558	true	true	true

Figure 13. Spreadsheet-style "AC Table Editor" in MACS

excessive Mach number for its aircraft type, and another error is an ill-defined route. The scenario editor can correct many errors automatically and the operator can use menus to invoke these functions.

The blue/green fields indicated in Figure 13 are set to “automatic”, which means that the values in these fields are propagated from other fields. This can be used in many different ways. For example Mach number and indicated airspeed can be linked to each other; sector assignments can be propagated from the start position. Or an entire set of flight management speed profile parameters can be automatically computed from weight, cost index and cruise altitude of an aircraft and inserted into all respective speed values in the spread sheet.

Other editing functions integrated into the tabular scenario editor allow the operator to duplicate, delete or crop aircraft, and select aircraft by certain rules, such as aircraft that are predicted to penetrate weather or are predicted to be in conflict with each other (see Figure 14).

In order to generate scenarios that create specific traffic load characteristics in the air traffic control sectors of interest, the operator can use the scenario editor to compute the load graphs for the sectors of interest and manipulate the scenario until the desired characteristics are achieved (Figure 15). Scenario variations can be achieved by using several “jiggle” functions to change altitudes and initial positions of aircraft within pre-defined tolerances.

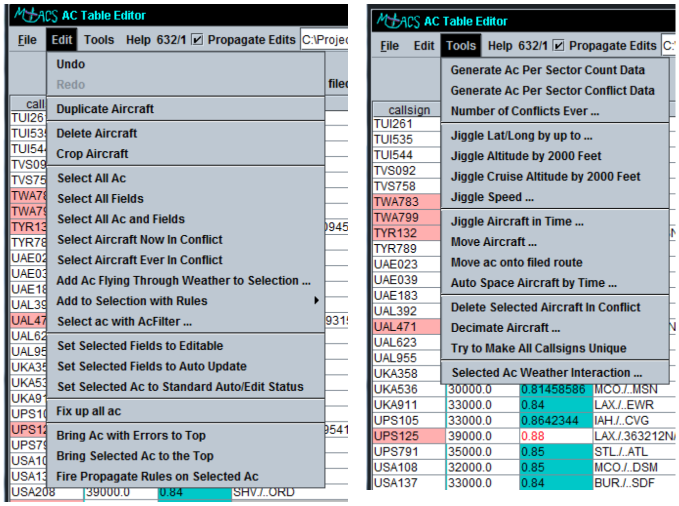
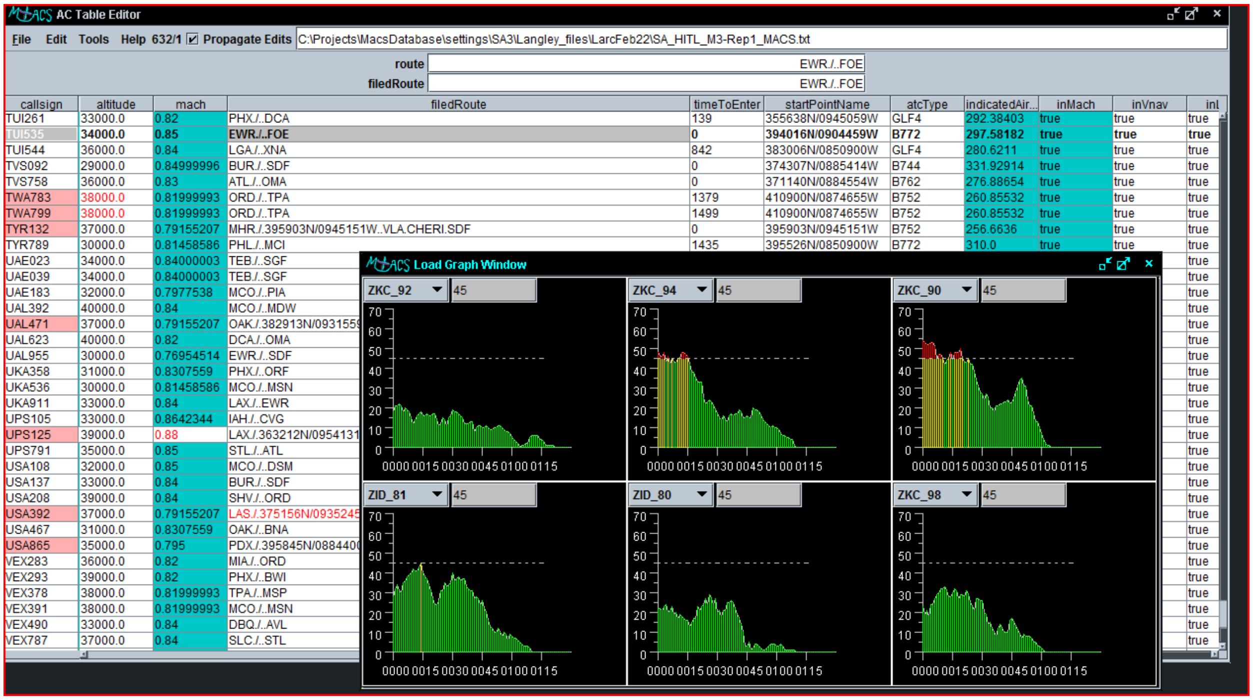


Figure 14 Edit and Tools menus available in the table-based MACS scenario editor



C:\Projects\MacsDatabase\settings\SA3\Langley_files\LarcFeb22\SA_HITL_M3-Rep1_MACS.txt

route: EWR./..FOE

filedRoute: EWR./..FOE

callsign	altitude	mach	filedRoute	timeToEnter	startPointName	atcType	indicatedAir...	inMach	inVnav	inl
TUI261	33000.0	0.82	PHX./..DCA	139	355638N/0945059W	GLF4	292.38403	true	true	true
TUI535	**34000.0**	**0.85**	**EWR./..FOE**	**0**	**394016N/0904459W**	**B772**	**297.58182**	**true**	**true**	**true**
TUI544	36000.0	0.84	LGA./..XNA	842	383006N/0850900W	GLF4	280.6211	true	true	true
TVS092	29000.0	0.84999996	BUR./..SDF	0	374307N/0885414W	B744	331.92914	true	true	true
TVS758	36000.0	0.83	ATL./..OMA	0	371140N/0884554W	B762	276.88654	true	true	true
TWA783	38000.0	0.81999993	ORD./..TPA	1379	410900N/0874655W	B752	260.85532	true	true	true
TWA799	38000.0	0.81999993	ORD./..TPA	1499	410900N/0874655W	B752	260.85532	true	true	true
TYR132	37000.0	0.79155207	MHR./.395903N/0945151W..VLA.CHERI.SDF	0	395903N/0945151W	B752	256.6636	true	true	true
TYR789	30000.0	0.81458586	PHL./..MCI	1435	395526N/0850900W	B772	310.0	true	true	true
UAE023	34000.0	0.84000003	TEB./..SGF							true
UAE039	34000.0	0.84000003	TEB./..SGF							true
UAE183	32000.0	0.7977538	MCO./..PIA							true
UAL392	40000.0	0.84	MCO./..MDW							true
UAL471	37000.0	0.79155207	OAK./.382913N/093155							true
UAL623	40000.0	0.82	DCA./..OMA							true
UAL955	30000.0	0.76954514	EWR./..SDF							true
UKA358	31000.0	0.8307559	PHX./..ORF							true
UKA536	30000.0	0.81458586	MCO./..MSN							true
UKA911	33000.0	0.84	LAX./..EWR							true
UPS105	33000.0	0.8642344	IAH./..CVG							true
UPS125	39000.0	0.88	LAX./.363212N/0954131							true
UPS791	35000.0	0.85	STL./..ATL							true
USA108	32000.0	0.85	MCO./..DSM							true
USA137	33000.0	0.84	BUR./..SDF							true
USA208	39000.0	0.84	SHV./..ORD							true
USA392	37000.0	0.79155207	LAS./.375156N/0935245							true
USA467	31000.0	0.8307559	OAK./..BNA							true
USA865	35000.0	0.795	PDX./.395845N/088440							true
VEX283	36000.0	0.82	MIA./..ORD							true
VEX293	39000.0	0.82	PHX./..BWI							true
VEX378	38000.0	0.81999993	TPA./..MSP							true
VEX391	38000.0	0.81999993	MCO./..MSN							true
VEX490	33000.0	0.84	DBQ./..AVL							true
VEX787	37000.0	0.84	SLC./..STL							true

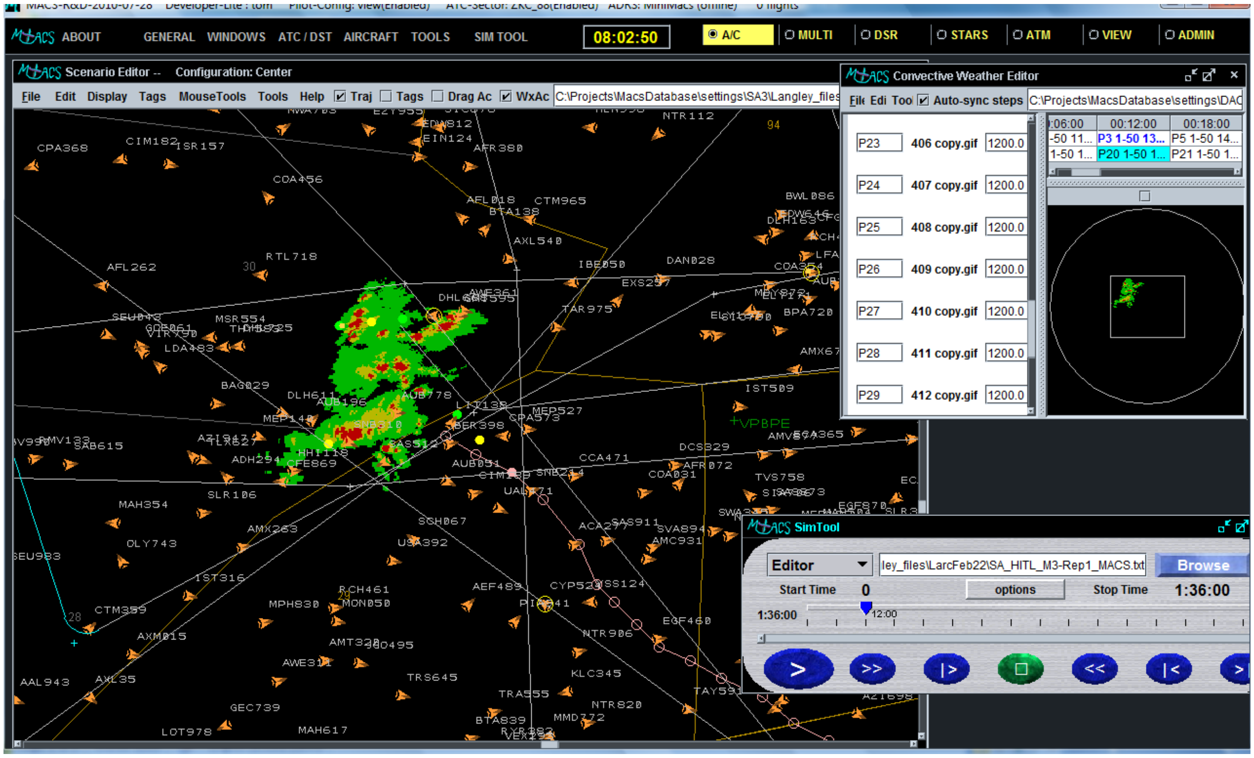
Figure 15. Load graphs showing the predicted number of aircraft in the selected sectors for this scenario

2. *Graphical Editing of Weather and Traffic*

A very important new capability within MACS is the graphical generation of weather and traffic scenarios. A sophisticated weather editor was built into MACS that enables importing actual weather images, converting them into MACS-usable images, and creating complex weather paths with cells that realistically grow, decay and change shape and position. These weather simulations can then be displayed as weather loops for traffic managers, displayed in real-time on the controller and pilot displays, and in various ways to drive weather penetration probes. The scenario editor enables the experimenter to preview and edit weather and traffic at the same time. The manual weather editing functions, unlike snapshots of real weather, enable researchers to place the weather path at the exact location that will be most valuable for the research question. Often weather is intended to close certain routes or impact specific sector operations. These manipulations can easily be done with the graphical weather editing functions built into MACS.

Additionally the aircraft locations and trajectories can be modified within the same scenario editor to adhere to the generated weather situation. A frequent use of this function is indicated in Figure 16 and explained in the following example:

In many cases a scenario has to be designed so that it appears that aircraft have already been rerouted around the weather. Specifically at the beginning of the simulation, aircraft should not get initialized inside a convective weather cell or head straight into a thunderstorm. The operator editing the scenario can make use of a “time slider” to preview the traffic and weather situation at any future time in the scenario. Those aircraft that penetrate the weather can then be highlighted. Next, the operator can select all aircraft that penetrate the weather during a specific time-interval. Using the scenario editor the operator can graphically drag the aircraft’s route around the weather. With the automated functions built into MACS, these route changes get propagated to the routes and the filed routes fields displayed in the tabular scenario editor and the aircraft will avoid the weather during the simulation.



P23 406 copy.gif 1200.0
P24 407 copy.gif 1200.0
P25 408 copy.gif 1200.0
P26 409 copy.gif 1200.0
P27 410 copy.gif 1200.0
P28 411 copy.gif 1200.0
P29 412 copy.gif 1200.0

Start Time 0
Stop Time 1:36:00

Figure 16. Scenario editor and convective weather editor. A time slider enables previewing the weather and traffic locations for any time in the scenario

In order to launch these scenarios in a coordinated way to all station within a simulation, MACS distributes scenario control information upon scenario initialization. This information contains the traffic scenario to use, the weather file, any specific sector boundaries, and the data collection directory.

B. TRAC

TRAC (TCSim Route Analyzer/Constructor) is a Java-based, graphical airspace design, fast-time simulation, and data analysis tool. [20] TRAC provides a useful complement to MACS in the AOL by enabling researchers to design routes and airspace sectors, conduct analyses in fast time, then export the routes/sectors for use in MACS simulations. It also automates MACS data analysis and enables researchers to visualize data and produce a wide variety of important metrics almost immediately after a simulation trial is complete. TRAC also supports visualization and analysis of aircraft track data from a number of other sources important in NASA NextGen research, as well as conversion of track data to traffic scenarios.[21]

TRAC also provides tools for rapidly constructing fast-time simulations that include scheduling functionality and various mechanisms for applying and analyzing control interventions. TRAC simulations run at up to approximately one hundred times real time using BADA performance models (depending on the complexity of scheduling functionality and simulated controller agents) and output key metrics automatically. All aircraft trajectories, including trial-planned trajectory modifications, are available for inspection (Figure 17). Mechanisms for modeling forecast wind errors and applying different fidelities of trajectory predictions are built in to support controllability and uncertainty analyses. [22] The TRAC codebase is readily extensible to support evolving research needs, and the TRAC executable is available to interested researchers.

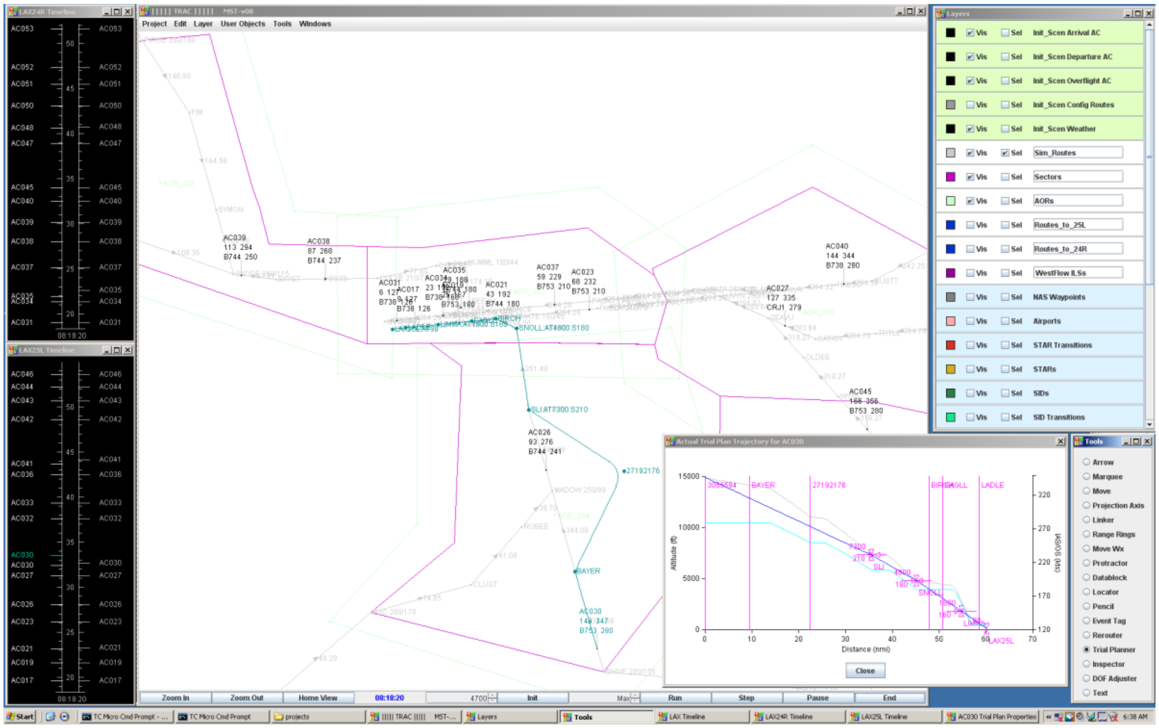


Figure 17. TRAC simulation display, showing schedule timelines and graphical display of a trial-planned trajectory profile

IV. Research Focus Areas

The AOL has conducted many simulation activities since 2006 that were funded by different research focus areas (RFA) within NASA's NextGen Airspace Systems Program and by the FAA's ATO Planning, Research and Technology. The RFA's are

- Airspace Super Density Operations
- Separation Assurance/Functional Allocation
- Dynamic Airspace Configuration
- Multi Sector Planning

The following presents high level descriptions of research carried out under these RFAs.

A. Super Density Operations: Controller Managed Spacing Studies (2008-2010)

In the terminal area the research focus in the AOL has been on enabling fuel efficient Optimized Profile Descents (OPD) with high throughput. In a series of controller managed spacing studies, situated at Atlanta and Los Angeles airports, controllers were given various tools to manage the spacing for aircraft arriving along RNAV/RNP arrival trajectories.

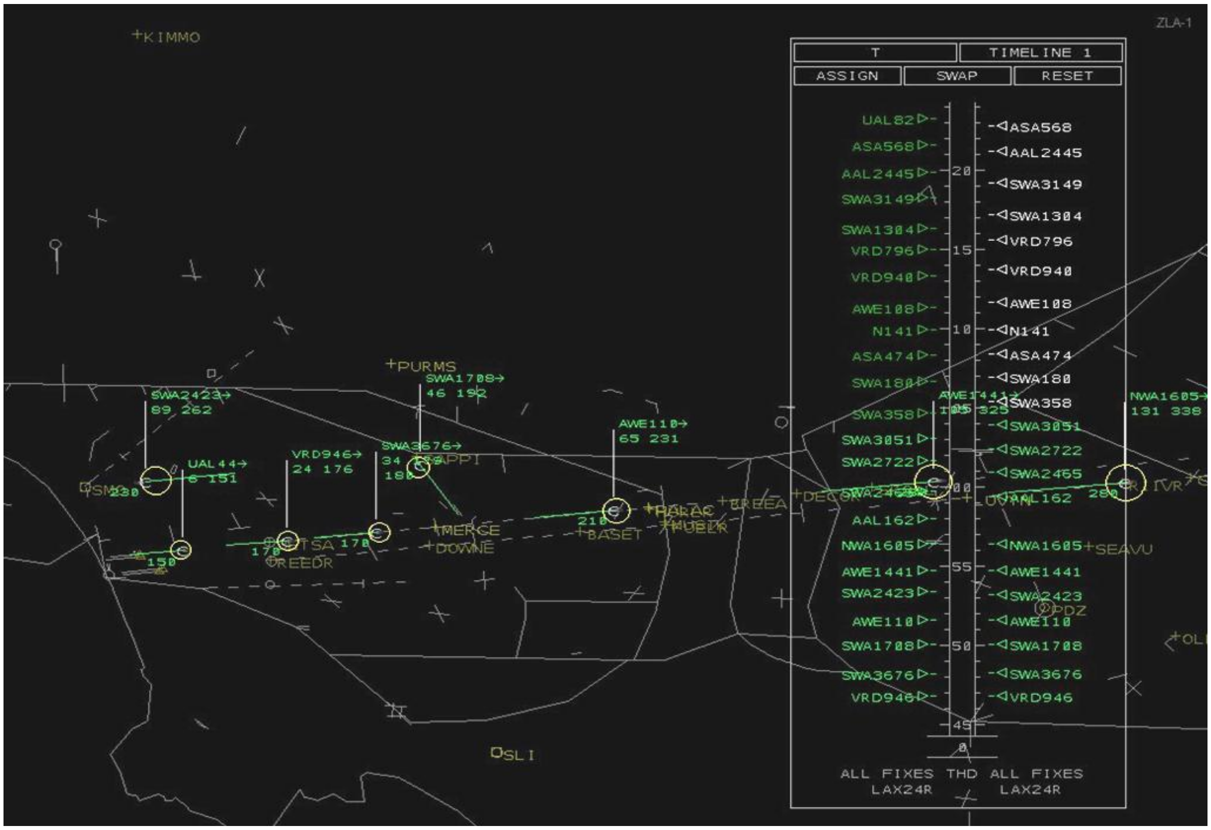


Figure 18. Prototype approach controller tools: Timeline, slot markers and speed advisories

A series of human-in-the-loop simulations investigated decision support tools and display enhancements to aid terminal-area air traffic controllers managing high-density arrival traffic flying optimized profile descents along Area Navigation (RNAV) routes. The simulations used MACS emulations of the Standard Terminal Automation Replacement System (STARS) Graphical User Interface to provide a rich operational environment. The STARS interface was enhanced with timelines that display runway and other key schedules, 'slot-marker' circles, speed clearance advisories, and airspeed displays (assumed available via ADS-B). Figure 18 shows an example MACS STARS display. The enhancements were designed to help controllers in conditioning terminal-area traffic flows for merging, and achieve proper inter-arrival spacing without resorting to tactical heading vectors, instead using speed clearances that enable aircraft to remain on their assigned RNAV routes.

Figure 19 shows an example of a slot-marker circle and speed advisory. Dwelling on an aircraft highlights an aircraft's slot marker, which is driven by the runway schedule and nominal speed profile for the aircraft's assigned RNAV route so that it appears where the aircraft should be if it were flying the nominal profile on schedule. The radius of the slot marker represents ten seconds of flying time, so that the circles become smaller as aircraft ground speed decreases throughout the descent. Speed advisories are also presented to the controller when aircraft are predicted to arrive with more than ten seconds of schedule error. The advisory is formulated to specify a speed to fly before crossing a specified waypoint at the charted speed. For example, Figure 19 shows an advisory to 'Maintain 265 knots; cross BAYST at 240 knots (as charted) and maintain charted speeds thereafter.' The current airspeed of both the aircraft (260 kts) and the slot marker (280 kts) is also displayed.

Figure 19. Slot marker circle and speed advisory displayed in the third line of the data block

Results from a recent controller-managed spacing simulation[23, 24] indicated that controllers could use the tools to control arrivals using speed advisory clearances, enabling aircraft to stay on their RNAV routes (Figure 20). While the decision support tools did not significantly increase throughput or improve wake vortex spacing errors over those observed in simulation trials without tools, the tools also did not result in increased workload, and subject controllers found them both useful and easy to use. Feeder controllers responsible for conditioning arrival flows for merging on final approach found the schedule timelines helpful for identifying available slots and coordinating with each other.

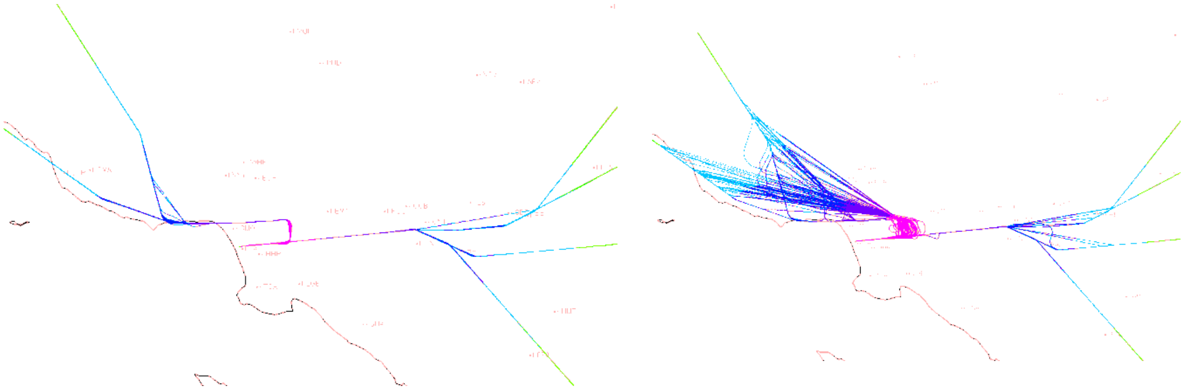


Figure 20 Ground tracks for aircraft in trials with prototype decision support tools (left) versus tracks in trials without tools (right).

B. Separation Assurance/Functional Allocation (2007-2010)

Within NASA's separation assurance research focus area, a series of controller-in-the-loop experiments has been conducted on high density air traffic operations with automated ground-based separation assurance. This human-in-the-loop (HITL) research in the AOL is coordinated with algorithm development, fast-time simulations and laboratory analyses conducted in the Aviation Systems Division at NASA Ames.[15, 18, 25, 26] and research on airborne separation assurance at NASA Langley[27]. The AOL uses the advanced ground-side automation capabilities described earlier in this paper for simulating the separation assurance operations. Levels of automation as well as off-nominal operations were investigated with controllers and pilots in the loop. Results of these studies have demonstrated the initial operational feasibility of this approach to provide two to three times current day capacity in en route airspace with all aircraft equipped with FANS 1/A-type data link capabilities.[11, 12]

One specific research focus in the AOL is on the functional allocation between the automation and controller for NextGen separation assurance (SA). To date there have been three studies devoted specifically to this area, each one building upon the last and informing the next. One common thread linking these studies is that each one involved components of what is envisioned as a part of the NextGen environment with trajectory based operations, data comm. equipage, and ground-based automation to assist with the safe separation of aircraft.

The first in this series of human-in-the-loop studies, referred to as SA1, was conducted in 2007 and evaluated the differences in performance between participants resolving conflicts in a manual and interactive mode as well as a fully automated mode. This was done at current day (1x), twice (2x), and three times (3x) that level of traffic. At the heart of the interactive and fully automated modes lay the autoresolver algorithm outlined earlier. Workload impact and acceptability of the algorithm's resolutions were also investigated. Results suggested that the automation provided significant benefits in terms of safety and efficiency particularly at higher levels of traffic.[28] Figure 21 highlights this finding as the number of separation violations increase by traffic density and manual functional allocation modes between the controller and the automation become insufficient. There was also a significant reduction in workload with higher levels of automation. The resolutions provided by the automation were also rated as being generally acceptable.

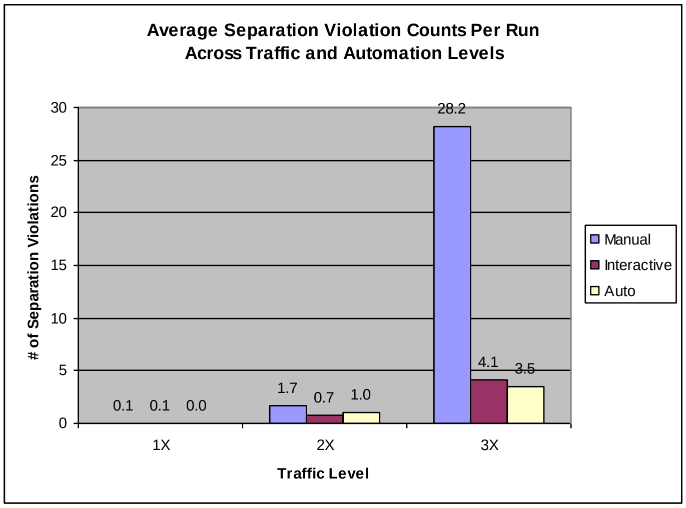


Figure 21. Separation violations per run by operating mode and traffic density captured in SA1

The second study, SA2, was conducted in 2008 and tested air/ground operations in an environment where ground-based automation was responsible for safely managing aircraft trajectories. Controller participants were responsible for handling pilot requests that were deferred by the automation and also handled scripted off-nominal events and tactical conflict situations both with and without Tactical Separation Assurance Flight Environment (TSAFE) support. Operations were conducted at 2x and 3x levels of traffic. Results showed that the strategic conflict resolution automation was able to resolve 98% of conflicts, 95% of uplinked trajectories were rated as acceptable to the flight crew participants, and workload was generally low. Of the tactical conflicts, 75% were resolved, which served as a springboard for discussion of the issues related to such automation and how they could be addressed in future research.[12]

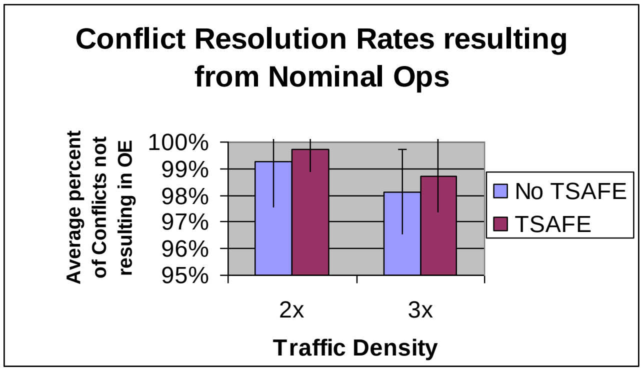


Figure 22. Conflict resolution rates captured in SA2

The most recent of the SA studies (SA3) was conducted in 2010 and was a joint effort between NASA Ames and Langley Research Centers. The joint aspects of study examined the functional allocation of separation assurance between the flight deck and the ground. The AOL's focus was on ground-based automated separation assurance operations in a near full mission NextGen control room environment. Advanced ground-side operations were simulated where controllers managed by exception through the handling of conflict situations deferred by automation and managing aircraft following a conflict avoidance event. This was done under various arrival metering situations in short, medium, and long runs of varied and fluctuating levels of traffic. Weather avoidance was also a key element in the long, three hour runs. Thus far, results show that workload was generally low despite high levels of traffic; Operational Errors occurred but appeared to be localized based on complexity, and feedback from the controller participants on the overall concept was positive. [29]

An initial comparison of results from the ground-based study to the companion study at NASA Langley on the airborne approach to separation assurance is underway. Initial results will be presented at the AIAA ATIO conference in 2010.[30]

The studies within the area of SA have provided a wealth of knowledge on many of its relevant issues and those important to the ability to meet the demands of the future. Each of the studies has laid the groundwork for the next and, based on that, a great deal of continued work, both collaborative and independent, is planned for the future. The results of this work will not, however, be confined to SA research, but will be, as it already has been, applied and integrated into other concepts being explored.

C. Dynamic Airspace Configuration: Mixed Operations and Flexible Airspace

In a related study conducted under the Dynamic Airspace Configurations (DAC) research focus area, separation assurance for equipped aircraft was entirely automated and controllers managed only unequipped aircraft. It was shown that a certain number of unequipped aircraft could be handled within the same airspace as equipped aircraft that are managed by another entity. [31]

Research on flexible airspace concepts has evaluated the impact of small, modest and extreme dynamic sector boundary changes on air traffic controllers. Software was implemented to run scripted sector boundary changes during real-time simulations. Tools were designed to allow supervisors and controllers to preview new boundaries and take the required actions before the boundary change occurs. Results indicate that changing sector boundaries is feasible. Main contributors to controller workload during the boundary change were initially identified.[32]

Both areas, mixed operations in the same airspace and flexible airspace management are described below.

1. Mixed Equipage Operations of Automation-separated and Controller-managed Aircraft (2008)

As the concept for automated separation assurance evolves, the airspace requirements needed to support it must be established. One key design question is whether this future airspace should be segregated or integrated. Segregated (or ‘exclusionary’) airspace would only permit access to those aircraft that are supported by either ground-based or airborne separation management automation. Integrated (or ‘non-exclusionary’) airspace would also permit access to unequipped aircraft that require controller involvement in the separation assurance process. The main advantage of segregated airspace is that it provides a more homogeneous operating environment (less variation in aircraft equipage, roles and responsibilities for human operators, potential differences in separation requirements, etc.). However, segregated airspace could come at a significant cost in underutilized airspace capacity and in reduced user flexibility because such partitioning by definition limits access to all users. This could be especially problematic during weather or other flow restricting events. Therefore, research into the feasibility of integrated airspace is warranted to determine whether aircraft with different levels of equipage can co-exist in the same airspace and under what conditions this may be possible[31]. Prior literature on mixed equipage or mixed operations airspace has shown initial feasibility in some studies[33, 34] and uncovered feasibility issues in others[35,36]. A study was conducted in 2008 to examine the implications of mixed equipage on airspace configuration requirements for advanced separation assurance operations, particularly under higher traffic densities.

The main objective of this study was to explore the feasibility and impact of mixed operations between equipped aircraft managed by automation and unequipped aircraft managed by air traffic controllers. The experiment consisted of four conditions, incorporating a within-subjects design. The number of equipped aircraft was varied across the conditions. In the Baseline condition (0x), there were no equipped aircraft. In the Conditions 1x, 2x, and 3x, the number of equipped aircraft was held relatively constant at 15, 30, and 45 aircraft, respectively, across the 45-minute scenario. These were approximately 1, 2, and 3 times the maximum traffic count that a single controller could manage in the test sectors under current day operations. In contrast, the number of unequipped aircraft was varied *within* each scenario, increasing linearly from around 5 to 20 aircraft during the simulation runs.

Figure 23 (left-side) illustrates the traffic load for 3x condition in sector 90. In this condition, relatively constant equipped aircraft (approx. 40 – 45) fly through the sector while the unequipped aircraft increases from two to around twenty aircraft during a simulation run. Figure 23 (right-side) shows the corresponding workload for the 3x traffic condition, as well as the 0x, 1x, and 2x traffic conditions. The workload ratings correspond mostly to the number of unequipped aircraft. The data suggest that the number of equipped aircraft also impact the workload but at a much lesser scale, as evidenced by the overall increase in workload with increase in the number of equipped aircraft (i.e. workload increase from 0x to 3x traffic).

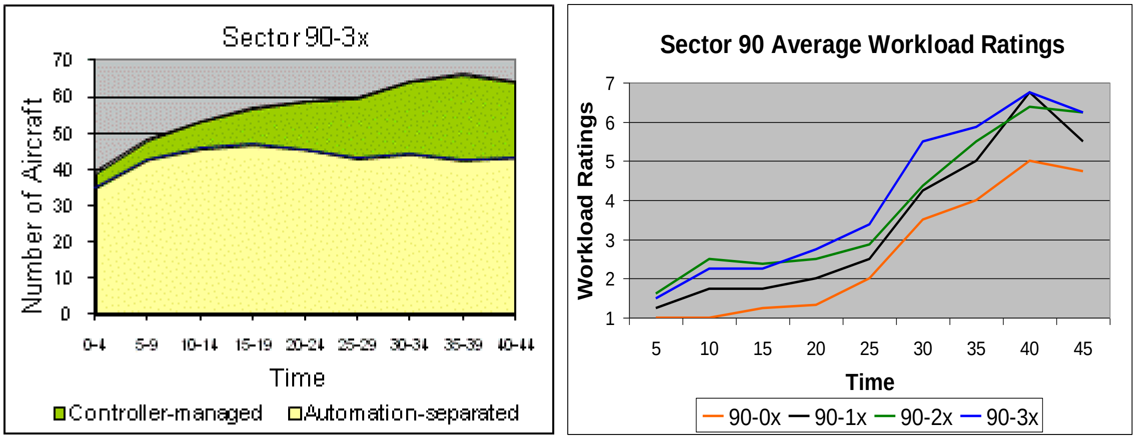


Figure 23. Average aircraft count in sector 90 – number of unequipped (green) and equipped (beige) aircraft observed during 3x traffic conditions (left); Average workload ratings for sector 90 for 0x, 1x, 2x, and 3x traffic conditions.

A confederate 'supervisor' assigned to each participant was asked to monitor controller workload and restrict unequipped aircraft entry into the sector as needed. This procedure was used during the simulation to establish a maximum unequipped aircraft count and 'turn away' count for each run. As the number of equipped aircraft increased, more aircraft were turned away, suggesting that equipped aircraft contribute to the airspace complexity for the controllers managing the unequipped aircraft (see Figure 24).

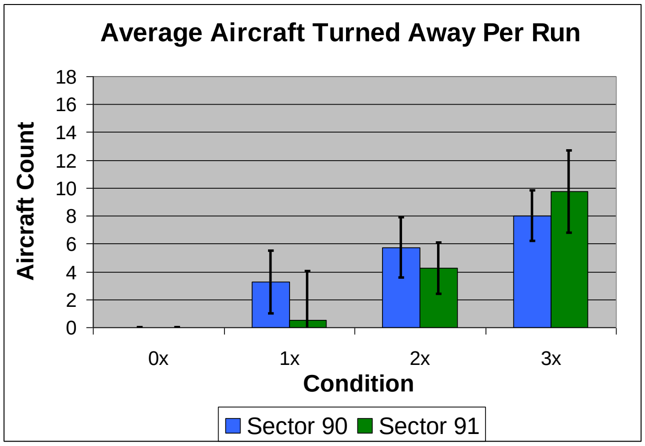


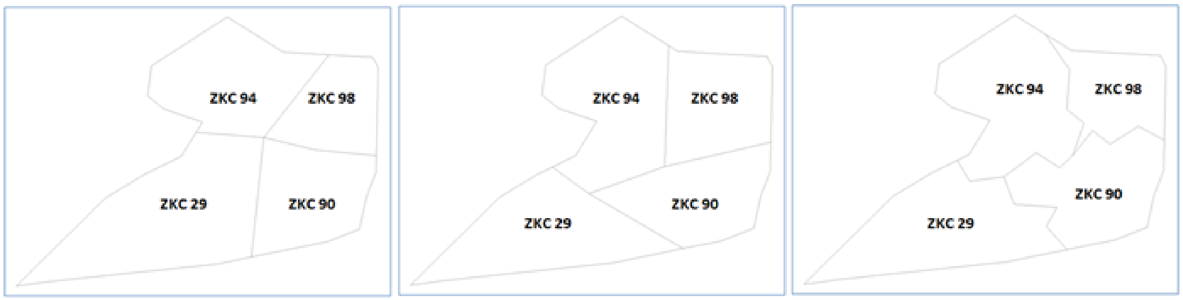
Figure 24. number of aircraft turned away in sector 90 (blue) and sector 91 (green)

The above results and participant feedback suggest that the mixed equipage operations are feasible, to a limit, within the same airspace. Airspace can be integrated and unequipped aircraft can get access as long as an examination of the primary complexity factors does not exceed certain thresholds. Primary factors include the number of unequipped aircraft already in the airspace, the overall traffic density and the number of current and expected off-trajectory operations. Overall, this study indicates that static and strict airspace segregation is not needed and could unnecessarily limit capacity.[31]

2. *Dynamic Airspace Configuration (2009)*

In the National Airspace System, a key aspect of air traffic management is to adapt to changing traffic demand, traffic flow, and airspace/system constraints while maintaining safe and efficient operations. In NextGen, the traffic is predicted to increase substantially, creating an environment in which effective balancing of demand and capacity becomes a high priority. In Dynamic Airspace Configuration, it is expected that the demand-capacity balance can be achieved by selectively managing the airspace capacity in conjunction with managing the traffic demand. Instead of reducing the traffic demand to address the demand-capacity imbalance, sector boundaries can be flexibly reconfigured to redistribute the traffic volume and demand across sectors[37, 38]. In such operations, the demand and capacity can be calculated for one to two hours into the future to identify sectors that could exceed the traffic threshold as well as sectors that are under-utilized. Using various airspace optimization algorithms, airspace can be reconfigured to manage the existing traffic demand without moving aircraft away from existing routes. A number of airspace optimization algorithms are currently being explored to find the best ways to reconfigure the airspace.[39, 40, 41, 42]

For a wider implementation of Dynamic Airspace Configuration, general questions related to where, how often, and how fast the sector boundary changes can occur need to be examined, because there may be an adverse impact of flexible sector boundary changes on the ANSPs. Better understanding of the ANSPs' abilities to handle the transition is needed. A human-in-the-loop simulation was conducted in 2009 to address some of the questions posed above. Traffic scenarios with varying types and severity of boundary changes (BCs) were used to test their impact on the controllers. The experiment consisted of four test conditions. A *Baseline* condition with no boundary changes was used to establish the baseline workload and other performance metrics. Three additional conditions consisted of *Low*, *Medium*, and *High* severity of BCs (see Figure 25). Three airspace resectorization algorithms were selected based upon their approach and aggressiveness related to the magnitude of the sector boundary change and they were labeled as Low, Medium, and High according to the severity of the BCs. The algorithms that were leveraged for this study are a part of an ongoing research effort at NASA to explore different ways to create dynamic sectorizations.



Low Magnitude **Medium Magnitude** **High Magnitude**

Figure 25. Low, Medium, and High Magnitudes of BC severity

Predictably, the greater severity of the BCs resulted in higher workload and lower acceptability ratings. The greater BC severity also increased the controller task loads, such as the number of handoffs and pointouts (see Figure 26).

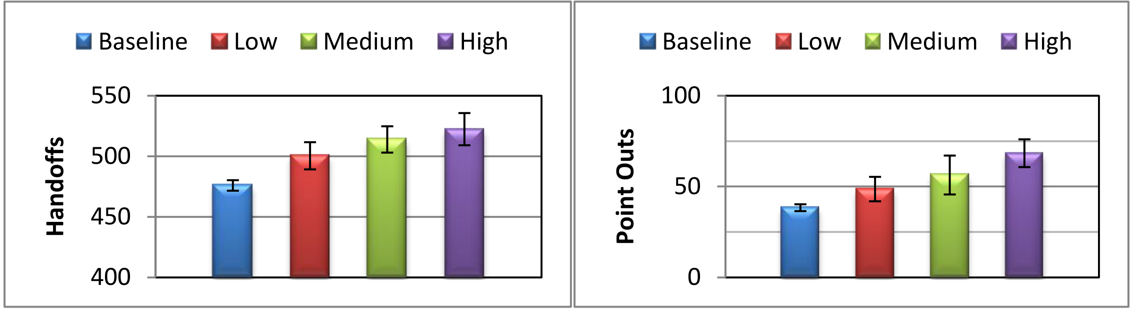


Figure 26. Mean number of handoffs and pointouts for Low, Medium, and High Magnitudes of BC severity

Per each boundary change, metrics such as airspace volume change, number of aircraft, and various task loads (e.g., handoffs, pointouts, etc.) were compared against subjective metrics such as workload and acceptability, as well as the safety implications in terms of separation losses and other operational errors. Hierarchical stepwise regression narrowed the explanatory variables for *overall workload during BCs* down to the following:

- airspace volume change
- aircraft count
- number of late handoff acceptances

Since prior research showed aircraft count to be the main predictor of workload, it is notable that airspace volume change was a better predictor than the aircraft count during BCs. Hierarchical stepwise regression of the *acceptability* ratings identified aircraft gained/lost as the single predictor of the ratings.

Subjective feedback on workload and acceptability identified a similar set of predictors as the regression and correlation analyses. Interestingly, high frequency of boundary changes (between 5 to 30 minutes) was not a factor for either workload or acceptability ratings. Observations also supported that as long as controllers had enough time to prepare for each BC (three minutes in this study), high BC frequency did not pose a major problem. In terms of the timing of the BC, finding and/or creating an appropriate time when fewer aircraft are present would help reduce the BC workload. Participants commented that they would be able to handle large volume changes if they had sufficient transition time to monitor the traffic and prepare for the BC. An important caveat to the concept feasibility is that participants needed a reliable conflict probe to manage the BCs. They reported that they did not have adequate situation awareness of the incoming traffic for separation management without the help of the decision support tools.

Overall, the results and feedback from the study showed that Flexible Airspace is a promising concept worth further development and refinement.[32, 43] A number of tradeoffs may be required in finding the most effective way to address the demand-capacity imbalance while keeping the human controller integrated and functioning meaningfully within the system. Based on the results from this study, further research can begin in addressing these issues.

D. Multi Sector Planning

As discussed before, when demand for an airspace sector exceeds capacity, the balance can be re-established by reducing the demand, increasing the capacity, or both. The Multi-Sector Planner (MSP) concept has been proposed to better manage traffic demand and it has been examined both in the U.S. and Europe [44, 45, 46, 47]. The MSP concept introduces an ANSP position/function that modifies in-flight trajectories for aircraft within specific flows, reducing traffic or airspace complexity to manageable levels across multiple sectors. The potential benefit for such a position or function could be a more responsive and dynamic management of traffic with greater efficiencies relative to current management methods, thereby providing a better distribution of workload/resources at the sector level and reducing impact to system users. The concept was originally developed as a set of functions that would be performed by a new facility position called the MSP. The multi-sector planning process includes problem identification, situation assessment, solution development, and plan coordination. Initial identification of the local area problem may occur in the TMU or control floor, while situation assessment and plan development may involve traffic management, one or more MSPs, and front line managers depending on the scope and complexity of the problem and its proposed solution. The person(s) who has developed the solution identifies the person(s) impacted by the plan and coordinates with them accordingly. The solution is then sent to the radar sector as a clearance request which the controller reviews and issues to the aircraft if it is acceptable.

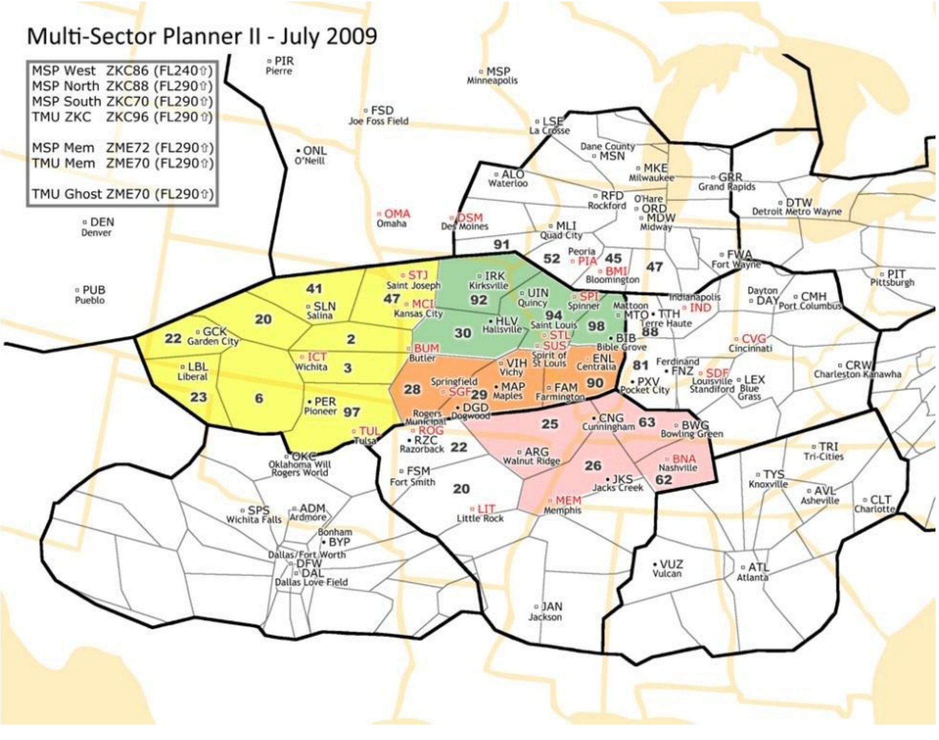


Figure 27. Airspace map for Multi Sector Planner simulation (2009)

Funded by the FAA's Air Traffic Organization for Planning, Research and Technology the AOL investigated the effectiveness of MSP functions and positions in a series of cognitive walkthroughs and human-in-the-loop studies. In 2009 a joint NASA/FAA simulation had 18 different air traffic control and management positions interact with each other and simulation pilots to investigate the MSP concept and the effectiveness of novel trajectory management tools and functions. In this simulation over 1200 aircraft and complex convective weather was simulated to create challenging problems to the traffic management and air traffic control positions.

The primary findings of the study will be published in fall 2010.[45, 48] A second goal of the study was to evaluate the air traffic management and air traffic control tools used during this simulation. The multi sector planning research was the initial reason for developing many of the advanced traffic management functions described earlier in this paper and depicted in Figure 9. Papers on the detailed findings of the effectiveness of the tools are forthcoming.[19] A few high level results are presented below.

Operationally current air traffic operator participants, who had experience as both, area supervisor and traffic management coordinator, served as MSPs during the study. After the simulation they rated the MSP toolset (68 functions) in a questionnaire. Overall, the ratings were high with an average of 4.47 on a scale of 1 (not at all useful/usable) to 6 (very useful/usable). Figure 28 depicts the thirteen highest rated tools and functions.

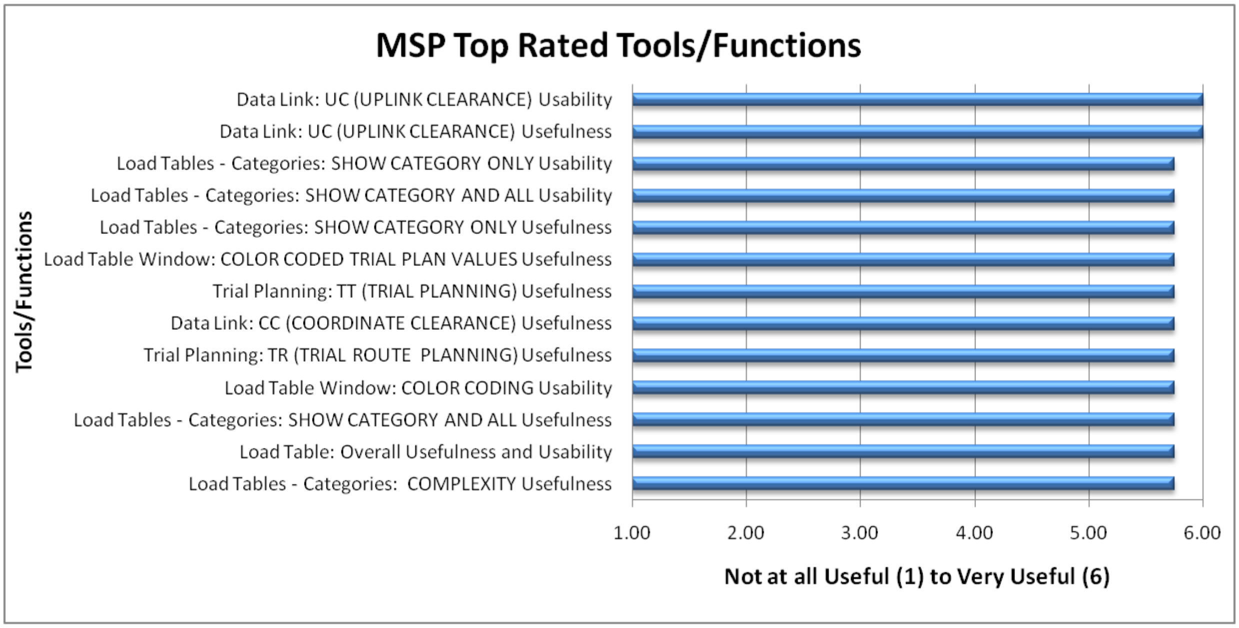


Figure 28. Top 13 MSP tools as rated by the MSPs

Air/Ground data link was rated as the most useful and usable tool. The 11 tools that followed were also rated very high at 5.75. Trial planning functions in general and route trial planning in particular were also part of the top ten. Load tables and Load graphs were among the remaining highest rated tools as was the real time complexity prediction available at the load tables and load graphs.

During the MSP study mid-term trajectory-based air traffic control operations were simulated that enabled controllers to handle up to 33 % more traffic than today without a drastic change in roles and responsibilities The air traffic controller tools at the sector positions were a continuation of radar controller tools that had been developed and tested in previous experiments on the R-side at NASA Ames. They had proven very effective in the past [49] and this simulation underscored this effectiveness.[17] The tools support trajectory-based sector operations similar to those envisioned in the NextGen high-altitude concepts. The philosophy is centered on implementing all flight path modifications via highly responsive semi-automated trajectory manipulation tools that are integrated with data link. With these tools the average Monitor Alert Parameter (MAP) for the test sectors could be raised from 18 to 24 without overloading the controllers. This is an increase in airspace capacity of 33% over today without changing the primary roles and responsibilities of controllers.

In a post simulation questionnaire tactical controllers were asked to rate the usefulness of some of the new tools that they used at the sector positions on a scale of 1 (Not at all useful) to 6 (Very useful). Figure 29 summarizes the results of the R-side controller ratings.

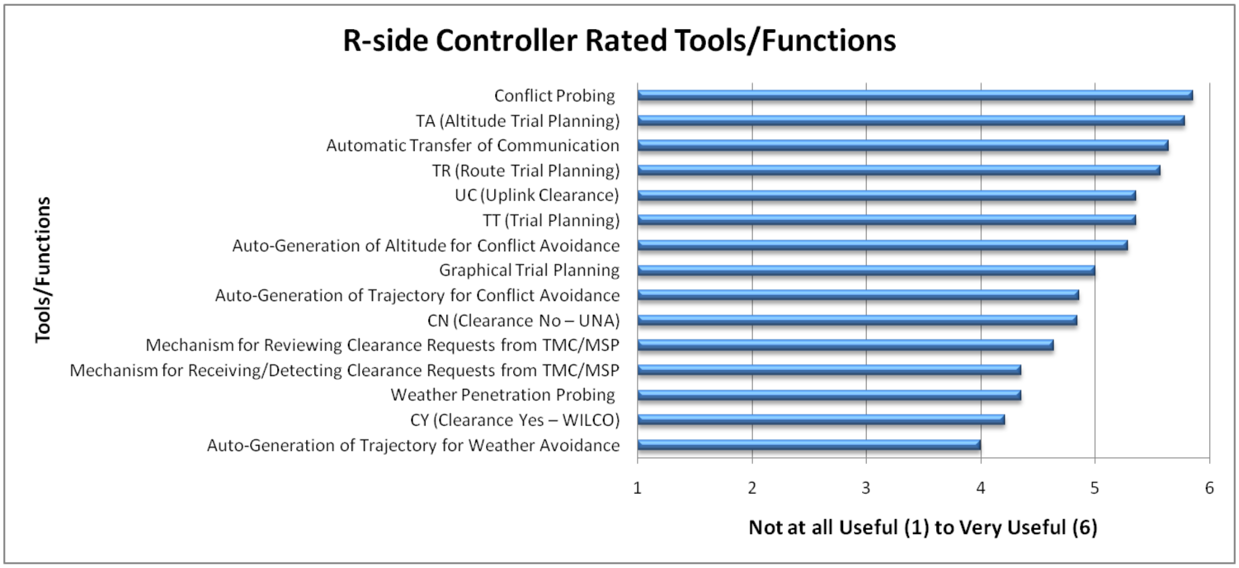


Figure 29. Usefulness ratings of sector controller toolset rated by eight air traffic controllers

The highest rated functions were related to conflict resolutions such as Conflict Probing (5.9), Altitude Trial Planning (5.8), and Route Trial Planning (5.6). Automated functions for conflict resolution were rated as useful, but could benefit from minor improvements. Data link functions such as Automatic Transfer of Communication (5.6) and Uplink Clearance (5.4) were also rated as very useful.

Some controllers commented that generated altitudes did not account for direction of flight rules but found the altitude trial planning as generally useful. The mechanisms for detecting and handling clearance requests from other positions were rated as useful as well. The weather tools received mixed ratings from the sector controllers with a standard deviation of 1.5 (weather probing) and 1.6 (weather resolution). Some controllers disliked that the vague predictability of convective weather often made their trajectory changes not as good as expected, but others gave the functions high marks and liked the capability.

Overall the provided toolset received high marks and can be considered adequate for the simulation of mid-term trajectory-based operations and to investigate NextGen concepts. Moreover, the capabilities available in the AOL can be considered a realistic prototype of many functions envisioned for NextGen.

V. Concluding Remarks

The Airspace Operations Laboratory at the NASA Ames Research Center hosts a powerful air traffic simulation environment. Many capabilities that are already integrated and the expandable rapid prototyping environment make it an excellent test bed for visionary NextGen concepts as well as transitional near- and mid-term operations. The continuous refinement of air traffic control and management capabilities has created powerful prototypes of systems that could become the backbone of NextGen. In order to get there, research needs to continue to address critical questions in the appropriate simulation environment. The AOL is well equipped to investigate the effectiveness of NextGen operational concepts in a meaningful air traffic control and management context.

Acknowledgments

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