Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011)

Benefits and Feasibility of the Flexible Airspace Management Concept: A Human-in-the-loop Evaluation of Roles, Procedures, and Tools

Paul U. Lee, Connie Brasil, Jeffrey Homola,
Angela Kessell, Hwasoo Lee, Matt Mainini
San Jose State University
Moffett Field, CA USA
Paul.U.Lee@nasa.gov

Thomas Prevot
NASA Ames Research Center
Moffett Field, CA USA
Thomas.Prevot@nasa.gov

Abstract*— A human-in-the-loop simulation was conducted to assess potential user and system benefits of the Flexible Airspace Management (FAM) concept, as well as designing role definitions, procedures, and tools to support the FAM operations in the mid-term en route environment. The study evaluated the benefits and feasibility of flexible airspace reconfiguration in response to traffic overload caused by weather deviations versus a baseline condition with no airspace reconfiguration. The test airspace consisted of either four sectors in one Area of Specialization or seven sectors across two Areas. The test airspace was assumed to be at or above FL340 and required all aircraft to be fully equipped with data communications, automated transfer-of-communication, and advanced conflict detection and resolution capabilities on the controller stations. Overall, results showed that FAM operations with multiple Traffic Management Coordinators, Area Supervisors, and radar controllers worked remarkably well. The results showed both user and system benefits, including decreased flight distance, fewer reroutes, and increased airspace utilization. Also, the roles, procedures, airspace designs, and tools were well received by the participants. Airspace configuration options that resulted from a combination of algorithm-generated airspace configurations with manual modifications were well accepted during the airspace reconfiguration process. The results suggest a positive impact of the FAM operations in an en route environment with low traffic complexities and when aircraft are fully equipped with data communications. Further investigation needs to evaluate whether the benefits and feasibility of FAM extend to other environments such as those with mixed equipage and/or higher traffic complexities.

Keywords-Dynamic Airspace Configuration; Flexible Airspace Management; NextGen; airspace reconfiguration; dynamic resectorization; human-in-the-loop simulation

I. INTRODUCTION

A fundamental aspect of air traffic management is to balance traffic demand with existing airspace capacity. If demand is predicted to exceed capacity (e.g., due to weather-related congestion, controller workload, etc.), then traffic flows are restricted using several methods such as miles-in-trail, ground delays, and playbook routes. All of these methods result in delays and extra costs to the users.

A complementary approach to demand-capacity imbalance, called Flexible Airspace Management (FAM), has been proposed for the Next Generation Air Transportation System (NextGen). In response to changes in traffic demand or weather related airspace congestion, FAM allows for flexible airspace changes such that capacity can be reallocated dynamically to balance the traffic across multiple sectors, resulting in fewer restrictions of traffic flows relative to current management methods. By better utilizing air traffic resources, the adapted boundaries enable higher airspace throughput and therefore reduce the amount that aircraft need to be delayed or rerouted. The FAM concept is a part of the Federal Aviation Administration’s (FAA) NextGen implementation plan. The concept was initially proposed as a component of the High Altitude Airspace (HAA) [1] but has been expanded to other airspace types (e.g., Terminal airspace).

II. BACKGROUND

A. *Flexible Airspace Management*

In many ways, flexible airspace management is nothing new. In current day air traffic management (ATM) operations, sectors are combined, split, and reconfigured in response to traffic demand and other situations. In the current system, airspace is reconfigured in response to events such as equipment outages, weather events, special use airspace, airport configuration changes, traffic volume changes, and oceanic track changes [3]. Airspace reconfiguration today is limited (i.e., non-dynamic) due to the need to work within the constraints of the current Host Computing System.

There has been a long interest in expanding and adapting existing FAM capabilities for future applications [2-4]. Expansion of the current airspace practices to include more dynamic reconfiguration could result in a greater ability to accommodate more user-preferred routings if a modest set of new procedures and tools were developed for traffic/airspace assessments and coordination of the airspace configuration changes [5]. In Europe, adaptive airspace management has been researched as a means to deal with Special Activity Airspace in which certain airspace is flexibly designated as “civil” or “military” depending on the traffic situation and the

---

The research was sponsored by the Flexible Airspace Management project under the FAA Concept Development & Validation Group and the Dynamic Airspace Configuration research focus area of NASA’s NextGen Concepts and Technology Development Project.

real-time usage of the airspace within a specific time period in order to maximize the joint use of the airspace and potentially increase the capacity of the air traffic system [6].

B. Prior Human-in-the-Loop Studies

The FAA conducted a human-in-the-loop (HITL) simulation to examine potential human factors issues in airspace reconfiguration and found that reallocation of predefined airspace to different sectors in response to weather movement or traffic loads could allow the controllers to manage the sectors with less coordination and more balanced workload [7]. The FAA recommended that more research be conducted to better understand the impact of dynamic airspace reconfiguration on controllers as well as the effects of the timing and frequency of airspace changes.

In 2009, a HITL simulation was conducted by the National Aeronautics and Space Administration (NASA) to understand the types of airspace reconfiguration that would be feasible and acceptable to controllers [8,9]. The results suggested that most of the airspace configuration options, except those with the largest airspace changes, were feasible and acceptable to the controller participants. Following are some insights and guidelines for a number of human factors issues related to airspace reconfiguration:

- ***Frequency.*** In the study, the airspace configuration was changed every five to thirty minutes, Results showed that such frequent configuration changes did not pose problems for the majority of the changes. However, significant coordination costs were associated with these modifications. Considering those costs, the frequency of airspace reconfiguration that involves multiple sectors should nominally be no more often than once an hour, although it can be done more often if the traffic situation demands it.

- ***Magnitude of Change.*** A number of airspace-related factors were analyzed to examine their impact on controllers [8,9]. As expected, large shifts in airspace volume that require a large number of aircraft to change sector ownership were infeasible, but more moderate airspace changes did not pose significant problems. The study also identified a number of sector design-related factors that were relevant to the magnitude of the change. For example, moving a major traffic stream from one sector to another, or changing upstream/downstream relationships between adjacent sectors, were workable but adversely impacted controllers' traffic awareness during the airspace configuration change.

- ***Lead Time for Change.*** In the study, Area Supervisors communicated the upcoming changes to the controllers as soon as they knew about it. At three minutes prior to the re-configuration, the newly proposed airspace configuration was overlaid directly on top of the existing airspace configuration on the controller screen. Based on study observations, a three minute lead time was not enough in certain situations. The results suggested approximately five minutes of lead time to preview the new airspace on the controller display would be better.

- ***Timing of Change***. The configuration needs to be changed early enough prior to the upcoming traffic congestion to allow sufficient coordination time, late enough to ensure that the traffic prediction is relatively accurate, and at an opportune time when the traffic volume is low so that controller workload is manageable during the transition.

C. Objectives of the Current Study

Since the prior studies found FAM operations feasible and promising, the following objectives were defined to further investigate benefits, procedures, and tools:

1. Assess the possible benefits of FAM operations.
2. Identify the appropriate air traffic personnel to plan and implement FAM operations, and develop the roles, procedures and Decision Support Tools (DSTs) to support operations.
3. Evaluate the prototype tools developed to support the FAM operations.

To address the above objectives, a follow-on simulation was conducted in 2010. The details of the study and its results are reported in the following sections.

III. METHOD

For the study, operational procedures and DSTs were designed for use in the environment where FAM would be implemented. The operational environment was assumed to be mid-term en route airspace above FL340 with, among other things: full data communications (Data Comm) equipage of all aircraft occupying the airspace; automated conflict detection and resolution (CD&R) capabilities on the ground; ground-ground Data Comm with real-time interactive exchanges of trajectory and airspace management plans; airspace configurations generated by algorithms; and DSTs that enabled air traffic operators to view the predicted traffic situation and modify either the airspace or aircraft trajectories when needed. The simulation consisted of four or seven test sectors across multiple Areas of Specialization (AOS) and the Traffic Management Unit (TMU). The following sections describe the experimental setup and design of the study.

A. Participants

Four participants who had experience as Traffic Management Coordinator (TMC) and/or Front Line Manager (FLM) (also called the Area Supervisor) were recruited as test participants. Four was the minimum number of participants required to test FAM operations, particularly with respect to intra- and inter-area coordination. One participant was a recently retired (2008) Supervisor TMC (STMC) from Oakland Center (ZOA) and another was an active FLM from Washington Center with recent TMC experience. Two other participants were active FLMs from Houston Center and Atlanta Center, respectively. All participants had prior exposure to the basic tools used in the simulation, but not the airspace management functions.

In addition to the four test participants, eight recently retired controllers from ZOA participated as the radar controllers (R-sides) for the test airspace sectors. The eight sector controllers were recently retired ranging from 3 months to 5 years (M = 1.96, SD = 1.61) with over 25 years of controller experience on average (M = 25.31, SD = 1.58). Other retired controllers performed the duties of “ghost” controllers and “ghost” TMCs (i.e., non-test participants at support positions) responsible for all adjacent airspace outside of the test airspace. The simulated aircraft were flown by simulation-pilots, who were active commercial pilots or students from the Aviation Department at San Jose State University.

B. Airspace

The test sectors consisted of either four (Sectors 28, 29, 30, and 92) or seven sectors (Sectors 3, 28, 29, 30, 47, 92, and 94) in Kansas City Center (ZKC), depending on the scope of the traffic problem. These were the number of sectors determined to be adequate for composing one and two AOSs, which allowed for a comparison of FAM operations in both a single AOS (4-sector) and two AOS (7-sector) environment. The altitude floor of the simulated test sectors was set at FL340 to conform to the original HAA mid-term assumptions.

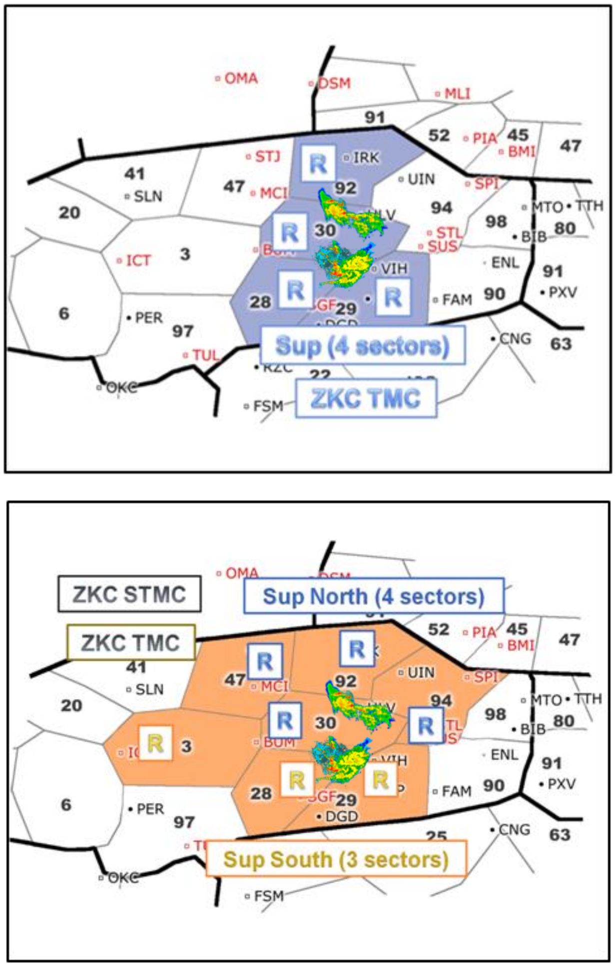

Figure 1. Test sectors for the ‘4-sector’ (top) and ‘7-sector’ (bottom) traffic problems.

During the 4-sector traffic problems, the Area was staffed with four retired controllers as the radar controllers and two test participants as Area Supervisor (labeled as “Sup” in Fig. 1) and TMC. During the 7-sector traffic problems, the seven test sectors were divided into two Areas, North and South, each with retired controllers staffing the sector positions and a test participant staffing the Area Supervisor position. Two test participants with TMU experience alternated by run between the TMC and STMC position in the simulated TMU that managed traffic for the entire ZKC airspace. No clear distinction of roles between the TMC and the STMC was provided to the participants, other than the suggestion that the STMC would be the central coordinator when communicating with the Area Supervisors and the TMUs from the other facilities (staffed by a “ghost” TMC). The STMC, TMC, and Area Supervisors are sometimes referred to as “planners” or a “planning team” in this paper.

C. Traffic Scenarios

Four traffic scenarios were developed for the study, two for the 4-sector problems and two for the 7-sector problems. The scenarios were designed to create overload situations that would lead to an unmanageable traffic problem for certain sectors if no corrective traffic or airspace management action were taken. Although data were only collected over 1 hour for 4-sector runs and 1.5 hours for 7-sector run, the traffic scenarios were designed to maintain traffic at an elevated level well past the end of the simulation runs. This was done to create a substantial task load of assessing the future traffic situations for TMU participants throughout the duration of the run. The flows in the traffic scenarios consisted mostly of aircraft in level flight with a small mix of arrivals and departures to and from the local area airports (~10%). In general, half of all flights flew West-to-East and the remaining flows were evenly distributed. For each traffic scenario, convective weather cells were developed graphically using in-house weather editing software. The aircraft were rerouted around the weather cells inside the test airspace, which in turn created load peaks and imbalances. Additional weather cells outside the test airspace were added to act as barriers to make it difficult to simply reroute aircraft outside of the test airspace to solve the overload problem.

D. Airspace Reconfiguration Options

During the airspace reconfiguration process, participants assessed eight different pre-defined airspace configuration options and implemented their preferred solution. The airspace configuration options had been chosen from two sets of airspace designs: four algorithm-generated solutions and four algorithm+manual solutions, as explained below.

Algorithm-generated solutions were chosen from a set of algorithms that were developed for NASA’s Dynamic Airspace Configuration (DAC) project [10-13]. The traffic scenarios used in the study were processed by these algorithms prior to the study to generate the “best” airspace configurations; that is, those configurations that mitigated the traffic congestions while maintaining acceptable sector designs as determined by subject matter experts in prior studies [8]. Examples of these algorithm-generated sector designs are shown in Fig. 2.

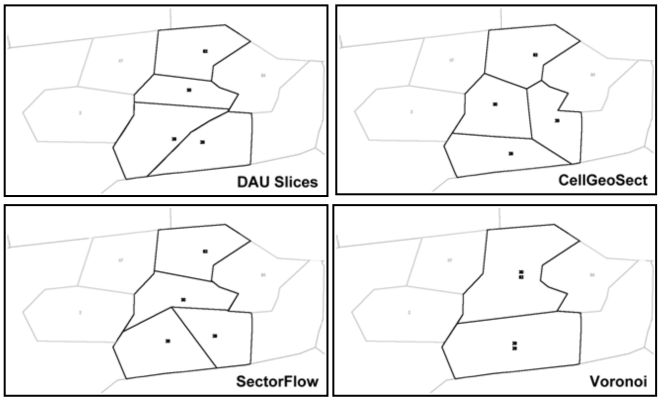

Figure 2. Algorithm-generated airspace designs for a 4-sector traffic problem (Note: Voronoi design has vertically-stacked sectors.).

Algorithm+manual solutions were generated by the participants prior to the start of this study by selecting one of the four algorithm-generated airspace solutions and modifying it manually. Fig. 3 shows an example of the algorithm+manual solutions developed by the four participants for the same traffic scenario that was used to generate the algorithm-generated solutions depicted in Fig. 2.

Figure 3. Algorithm+manual designs by the four participants (Note: Bottom two designs have vertically-stacked sectors.).

A comparison of Figures 2 and 3 suggests the algorithm+manual airspace designs were similar (or identical in some cases) to the algorithm-generated solutions, indicating that the original algorithm-generated solutions were acceptable and required only minor adjustments by the participants.

E. Experiment Design

The study consisted of a 2x2 within-subjects design with two factors: the *boundary change* condition **(***BC* or *No BC***)** and the *number of sectors* involved in the reconfiguration (*four* or *seven* sectors). The two BC conditions are described below:

- ***No Boundary Change (No BC):*** The traffic overload situation was entirely resolved with aircraft reroutes and no boundary changes. This condition provided *a baseline measure of how many aircraft needed to be rerouted to resolve the overload issue.*

- ***Boundary Change (BC):*** Both TMCs and Area Supervisors assessed eight different pre-defined airspace configuration options and implemented the best option through consensus. After the configuration change, overloaded sectors were managed further by rerouting aircraft, similar to the No BC condition.

The same suite of traffic load assessment, management, and control tools/automation were used in both conditions. By keeping a consistent toolset, improvements in capacity, throughput, workload, traffic distribution, and required reroutes could be directly attributed to FAM operations rather than differences in toolsets or automation support.

The experimental conditions were presented in a block design in which two 4-sector problems were conducted in the mornings and two 7-sector problems in the afternoons. The conditions were blocked in this manner to accommodate the longer laboratory setup time required when changing the number of sectors. For the 4-sector problems, the laboratory was configured to run two simulation worlds in parallel. This arrangement maximized the number of data collection runs given the schedule and the available participants. Therefore, there were a total of 8 data collection runs for the 4-sector problems and 4 data collection runs for the 7-sector problems, for a total of 12 data collection runs.

F. Apparatus

The simulation was conducted using the Multi Aircraft Control System (MACS) and its advanced air traffic management and control prototype functions [14]. TMU and Area Supervisors had access to planner stations that included airspace and trajectory management functions. Controllers used a prototype of a mid-term controller workstation designed to support trajectory-based operations (TBO) and FAM.

1) Planner Station

Fig. 4 illustrates the airspace planner station that was prototyped for the trajectory management and airspace reconfiguration functions used in this study. The planner station provided the ability to adjust airspace boundaries manually or to pick pre-configured airspace boundaries from a menu of options *(Note: Only pre-configured airspace boundaries were used in this study)*.

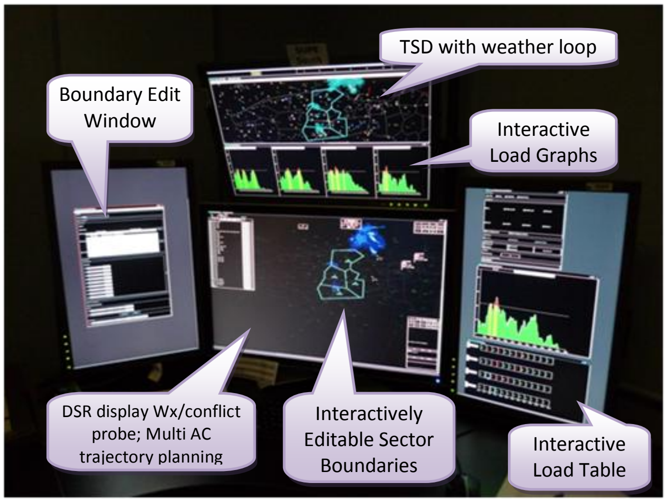

Figure 4. Prototype Airspace Planner station.

The station provided real-time filtering and analysis tools for traffic flow, sector load, and complexity assessment, including an interactive traffic Load Table, interactive Load Graphs, and plan view displays that were based upon the interactive Display System Replacement (DSR) and Traffic Situation Display (TSD). The Load Table and Load Graphs provided predictive traffic load related information on current and proposed airspace configurations and what-if feedback on re-routes. The Load Table was a numerical representation of future traffic loads in selected sectors in 15-minute increments, and Load Graphs were a graphical representation of the same traffic load information with a 1-minute resolution.

By selecting a certain cell or a time slice in the Load Table/Graphs, operators could highlight the associated aicraft on the DSR display. Highlighting aircraft from a specific overloaded sector can help the planner to determine which aircraft contribute the overloaded time period and develop a plan accordingly. The Table and Graphs can represent various factors such as aircraft count, number of aircraft predicted to be in conflict or penetrate weather cells, or the number of climbing/descending aircraft. These two tools can also show a "complexity" value that takes into account all individual factors described above. Also on the planner stations, multi-aircraft trial planning functions provide options for previewing the impact of several trajectory changes on the overall traffic situation (Fig. 5).

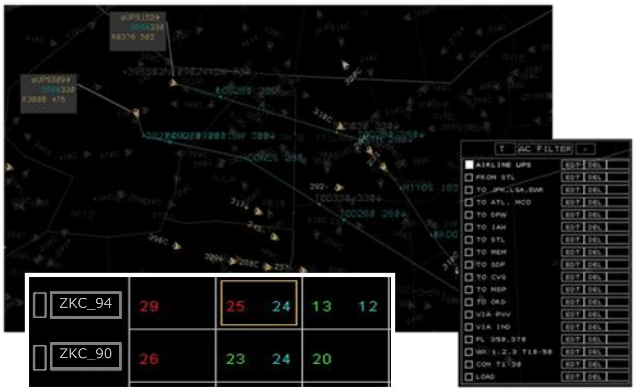

Figure 5. Multiple Aircraft Trajectory Modification Tools: Shows two aircraft being probed for combined altitude/lateral route modification.

2) Controller Station

The DSR based controller stations provided advanced functions for FAM and TBO. As a new feature, new sector boundaries were superimposed on the current boundaries starting five minutes before a change (Fig. 6) and a countdown to the boundary change time was displayed.

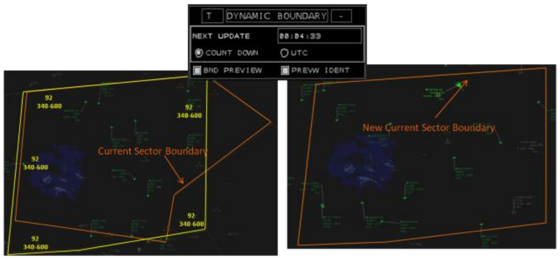

Figure 6. Radar Controller Boundary Change Preview Tool.

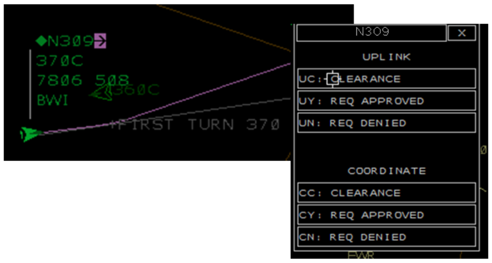

Figure 7. Trajectory change request as shown on the controller station (left); pop-up menu to uplink the trajectory clearance to the flight deck (right).

The controller stations also included a powerful set of integrated tools for TBO, including the ability to receive trajectory changes digitally from other positions, such as the planner stations. Fig. 7 depicts means to review and uplink the new trajectories to the aircraft as a clearance, or to reject them.

G. Operational Procedure

The objective of the simulated operations in both the BC and No BC conditions was to maintain traffic levels at or below a defined threshold of 22 aircraft per sector. In the BC condition, the TMCs and Area Supervisors first tried to reduce any traffic overload with airspace configuration changes. The TMCs generally focused on the traffic beyond 30 minutes but within their Center. The Area Supervisors focused on the traffic within 30 minutes and within their respective Areas.

Using the interactive traffic Load Table/Graphs as a reference, participants examined the impact of each of the eight airspace configuration options on the given traffic situation and assessed which option would be most suitable. During the airspace configuration selection process, either an Area Supervisor or a TMC proposed a new airspace configuration and coordinated it with other impacted Area Supervisors (7-sector problems only) and TMCs. Proposed configurations were shared using ground-ground Data Comm and discussed over the voice communication system. Once a final configuration was selected, the involved parties agreed upon a time to implement the change.

The impacted Area Supervisors then coordinated the changes with the controllers. A preview of the new sectors was displayed on the wall by an overhead projector. Five minutes prior to the boundary change, the new sector boundaries were also displayed on the controllers' screens. The controllers then transitioned the aircraft to the appropriate new sectors. Unlike current operations, the controllers only briefed the other controllers of the traffic when aircraft were in conflict near the sector boundaries or were not on their trajectories. In this study, handoffs and transfer-of-communication triggered automatically when the aircraft were near the sector boundary. However, controllers often handed off the aircraft manually during the airspace configuration change as added insurance. Pilot check-in was also omitted to reduce the overall workload during the configuration change.

Sectors that remained overloaded after the configuration change were managed further by rerouting aircraft using the trajectory modification tools. TMCs coordinated the trajectories with the Area Supervisors (by voice and ground-ground Data Comm). Once the TMCs and the Area Supervisors agreed on a set of trajectory changes, they sent the trajectory change proposals to the controllers via ground-ground Data Comm. Controllers reviewed these proposals and either accepted and uplinked them to the aircraft as a clearance, or rejected them if they adversely impacted the sectors.

In the No BC condition, the participants could not reconfigure the airspace and therefore could only reroute aircraft out of the overloaded sectors. Except for the initial airspace reconfiguration process, they used the same tools and procedures as in the BC condition to reroute aircraft.

H. *Experiment Procedure*

Participants were initially briefed on the general roles of the TMCs, Area Supervisors, and controllers, followed by a briefing of the operational procedures for the airspace reconfiguration. They then had a day of training to refresh on the DSTs, their anticipated roles and responsibilities, communication and coordination procedures, and workload scales. Practice runs were conducted both with and without airspace reconfigurations for 4-sector and 7-sector problems.

During the data collection, four simulation runs were conducted each day. Two 4-sector problems were run in the mornings followed by two 7-sector problems in the afternoons. The BC and No BC conditions were alternated for each of the four runs without any repeats during a given day's runs. In the BC condition, there was one airspace BC planned in the 4-sector and two BCs in the 7-sector problems. The second BC was added in the 7-sector problems so that the planners could continue to assess the future traffic for potential airspace changes and not "overwork" the current traffic once they were done resolving the first traffic peak. The data from the second BC were not analyzed.

At the end of each simulation run, the participants were given one or more questionnaires related to the acceptability of their roles, traffic situations, and coordination mechanisms. The retired controllers who managed the test sectors were also given questionnaires to rate their workload and the acceptability of the resulting airspace change. At the end of the study, they were asked to give extensive feedback on the tools that were built to support the FAM concept, as well as additional questions related to the coordination and communication procedures. Finally, everyone participated in a comprehensive debrief discussion with the researchers to give feedback on the overall concept, procedures, and tools.

IV. RESULTS

TMCs and Area Supervisors, worked together to manage the traffic by assessing different airspace configuration options and collectively selecting the best airspace configuration option (BC condition) before rerouting traffic. The BC condition was compared to a baseline condition in which no sector boundaries were modified (No BC condition). The benefits and safety of FAM operations are discussed in the following sections.

A. *Benefits*

The benefits of FAM operations were assessed by examining the number of rerouted aircraft, flight distance, and airspace utilization. Overall, the results suggested that FAM operations provided significant system-wide benefits as well as benefits to individual flights.

1) *Number of Rerouted Aircraft.*

One of the key hypotheses of FAM is that with better airspace management, more aircraft could be left on their original, user-preferred trajectories [15]. The same underlying traffic scenarios containing streams of traffic around local weather cells were used in both conditions and the TMCs and Area Supervisors were asked to reroute aircraft and/or move sector boundaries (BC condition) to relieve the overloaded sectors. We hypothesized that in general the BC condition would result in fewer rerouted aircraft than in the No BC condition.

Fig. 8 shows the average number of unique aircraft that were rerouted in each boundary change condition. A paired samples t-test showed that the BC condition resulted in significantly fewer rerouted aircraft (M = 65.2, SD = 47.6) than the No BC condition (M = 93.3, SD = 41.6) (paired $t(5) = 5.0$, $p < .005$). The results suggest that more aircraft remained on their original trajectories in the BC condition.

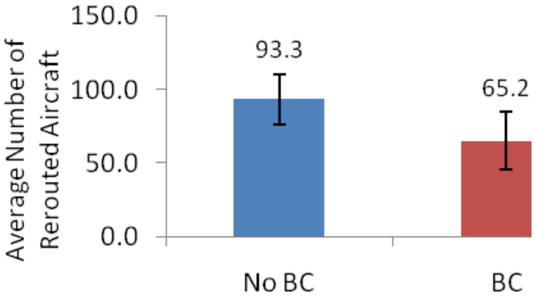

Figure 8. Average number of rerouted aircraft per run in the two experimental conditions for 4- and 7-sector problems.

2) *Flight Distance*

Per simulation run, approximately 30 more aircraft were able to maintain their original trajectories in the BC compared to the No BC condition (Fig. 8). Another, potentially greater benefit to the airlines would be realized if FAM operations resulted in overall flight efficiency in terms of fewer delays or shorter flight distance for the rerouted aircraft. Flight efficiency was examined by measuring the path length changes for the rerouted aircraft.

In order to assess system-wide benefits, as opposed to the benefits to individual flights, the average change in the path length per aircraft was calculated across all aircraft, including those that were not rerouted. A paired samples t-test showed that the BC condition resulted in a small increase in average path length to resolve the traffic problem (M = 0.26 nmi, SD = 0.56 nmi per aircraft), but it was significantly less than that of the No BC condition (M = 2.05 nmi, SD = 1.99 nmi per aircraft) (paired $t(5) = 2.73$, $p < .05$). By applying this average difference to the approximately 575 aircraft per simulation run, the BC condition resulted in a 1,029 nmi path length savings compared to the No BC condition.

Further analysis examined only the aircraft whose path lengths were impacted (i.e., those aircraft that were rerouted). Final path length was subtracted from simulation-initial path length to categorize aircraft into groups with shorter path lengths (defined as a path length difference of less than -1 nmi), unchanged (between +/- 1 nmi), and longer (greater than 1 nmi). As expected, even when the paths were extended, the BC condition resulted in shorter paths compared to the No BC condition (Fig. 9): path lengths increased by 9.84 nmi (SD = 2.43 nmi) in the BC condition compared to 18.63 nmi (SD = 7.59 nmi) in the No BC condition. A paired samples t-test showed that this difference was significant (paired $t(5) = 2.64$, $p < .05$). Similarly, when paths were shortened, they were shorter in the BC condition (M = -14.28 nmi, SD = 5.77 nmi) than in the No BC condition (M = -12.96 nmi, SD = 3.92 nmi) although this difference was not significant (paired $t(5) = 1.27$, $p > .2$).

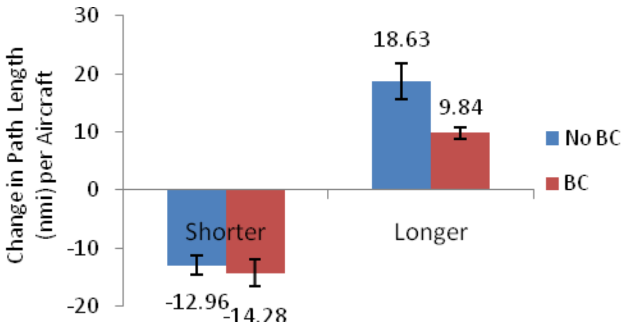

Figure 9. Average change in the path length per aircraft for the aircraft that had longer or shorter final path lengths compared to their original trajectories.

3) *Airspace Utilization*

Another potential benefit of the FAM concept is to increase airspace utilization compared to operations without FAM by managing traffic congestion with airspace changes instead of aircraft reroutes. The airspace utilization metric was calculated by taking the instantaneous aircraft counts at each time slice across all test sectors and averaging them across the simulation time. The first 30 minutes of the runs were excluded because the traffic was low during this build-up period. A paired samples t-test showed a significantly higher mean number of aircraft transited the airspace in the BC condition (M = 81.88, SD = 26.33) than in the No BC condition (M = 75.70, SD = 24.15) (paired $t(5) = 3.90$, $p < .02$). The results showed an average of 8% increase in the aircraft count over the traffic period in the BC condition, relative to the No BC condition.

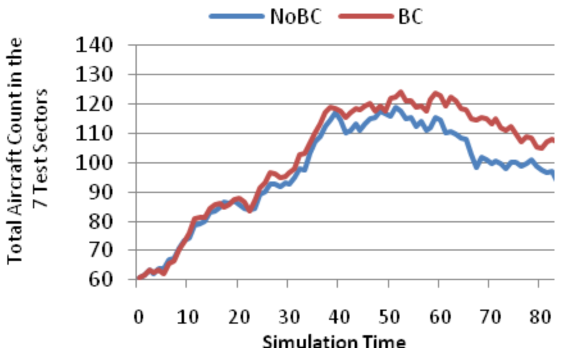

Figure 10. Average aircraft count in the seven test sectors for the two experimental conditions, averaged across the simulation runs.

Fig. 10 illustrates the average number of aircraft that passed through the test sectors in the 7-sector problem, plotted over time. The traffic scenarios were designed to have the traffic overload start around 45 minutes into the scenario. Accordingly, the graph shows little difference in the aircraft count during the first 45 minutes. From 45 minutes to the end of the simulation run, the number of aircraft through the test sectors is higher in the BC than in the No BC condition, suggesting greater airspace utilization due to airspace reconfiguration.

B. *Safety*

Safety of the FAM concept was assessed by examining the number of convective weather penetrations and separation violations. Overall, the results indicated that FAM operations were at least as safe as the baseline condition with no boundary changes.

1) *Weather Penetrations*

Because aircraft in the simulation were already rerouted around convective weather as part of the scenario design, the boundary changes were not expected to affect the number of weather penetrations. Few weather penetrations were expected in general, unless the traffic overload in either condition forced the controllers, Area Supervisors, or TMCs to reroute aircraft back into the weather cells.

The number of weather penetrations in the Medium and High intensity areas (e.g., the central and more severe areas of the storm) did not differ by condition – there was only one penetration in the Medium intensity weather and none in the High intensity weather in each condition. Overall, there were more weather penetrations in the No BC (M = 3.0 penetrations, SD = 1.9) than in the BC condition (M = 2.17 penetrations, SD = 1.9). However, this difference was not statistically significant (paired $t(5) = -1.27$, $p > .2$).

2) *Separation Violations*

Analysis of separation violations showed a total of ten cases of separation violation events within the test airspace. Each violation was carefully reviewed by analyzing the data logs and reviewing video recordings of controller screens. The separation violation events were categorized into Proximity Events (PE), in which an aircraft pair had a closest point of approach (CPA) of less than 800 ft vertically and between 4.5 nmi and 5.0 nmi laterally, and Operational Errors (OE), in which the CPA was less than 800 ft vertically and less than 4.5 nmi laterally. In the No BC condition, there were four PEs and one OE while in the BC condition there were only two PEs and no OEs, suggesting that the BC condition was at least as safe as the No BC condition. Half of the PEs were caused by the controller misjudging the rate of climb/descent of an aircraft underneath or above another aircraft at level flight. The other half was caused by the controller overestimating the distance to the CPA and not acting upon it until it was too late.

C. *Roles, Procedures, and Overall Feasiblity*

One of the main objectives of this study was to define roles and responsibilities and to design operational procedures for the airspace reconfiguration process for both the planning team and the controllers. In post-run and post-simulation questionnaires and in a debrief session, the participants were asked about the appropriateness of their roles, the acceptability of the coordination and procedures, the difficulty of reconfiguring airspace, and the workload associated with the resultant traffic. Overall, the results suggest that the distribution of tasks and roles, as well as the coordination mechanisms between the TMU and Areas worked well as designed. Airspace reconfiguration was fairly easy for both the planning team and the controllers. These results are described in more detail below.

1) Roles and Task Distribution for the Planning Team

In the study, the traffic/airspace assessment and the coordination tasks associated with airspace reconfiguration were divided among the Area Supervisors and TMCs. The Area Supervisors were asked to focus on the traffic situations that impacted their Areas while the TMCs were asked to assess the impact of the predicted traffic situation within their facility, but across multiple Areas. In addition to the TMC roles, the STMC was asked to play a central coordinator role between Area Supervisors, TMCs, and the TMU of the surrounding facilities.

Overall, this distribution of tasks worked well. Participants felt that the task distribution allowed each to perform a specific role and simplified the coordination process. They agreed afterwards that it was an efficient task distribution. They commented that there was a "little bit of overlap" in their work, but that it was not a problem if there was a high level of communication and understanding within the team. The participants overwhelmingly stressed the importance of defining clear roles and adhering to a defined timeline and airspace for the given position.

The TMCs and Areas Supervisors were asked to work out the best procedures for initiating and deciding on an airspace configuration. TMCs often took the lead on determining which airspace configuration would be implemented and when because their position provided them a view of the bigger, system-wide picture. They took the lead more in the 7-sector than the 4-sector problems because the 7-sector problems required a clearer understanding of the situation at a system-wide level. However, the Area Supervisors' local knowledge of the airspace was highly regarded by the TMCs. A team effort developed over the course of the study and decisions were made with mutual agreements. In the event that a consensus could not be reached, TMCs had final authority.

2) Selection, Coordination, and Implementation of Airspace Configuration Change

Feedback from the TMCs and Area Supervisors indicated that it was easy to select, coordinate, and implement airspace configurations. A comparison of the results between TMCs and Area Supervisors showed that the airspace assessment/selection was more difficult for the TMCs while the implementation of the changes were more difficult for the Area Supervisors.

Table I summarizes the participants' ratings. The planners rated the airspace configuration selection to be somewhat easy. TMCs rated the airspace selection to be marginally more difficult than did the Area Supervisors ($F(1,11) = 3.34$, $p < .10$), which is consistent with the greater role that the TMCs played in initiating and deciding on an airspace configuration. The planners also commented that the best timeframe for implementation of airspace configuration change was when there was more than 30 minutes available to solve the problem. With less than 30 minutes, the TMCs did not feel that they had enough time to generate and implement the most effective strategies. Finally, the planners thought that eight airspace configuration options was too many and suggested that three would have been ideal.

TABLE I. POST-SIMULATION RATINGS (AND STANDARD DEVIATIONS) ON THE DIFFICULTIES OF SELECTING, COORDINATING, AND IMPLEMENTING AIRSPACE CHANGES

	TMU (TMC and STMC)	**Area Supervisor**
Selecting the airspace configuration (1 = Very Easy; 6 = Very Difficult)	**2.71** **(1.11)**	**1.83** **(0.41)**
Coordinating with other TMU (1 = Very Easy; 6 = Very Difficult)	**1.50** **(1.00)**	--
Coordinating with Area Supervisors (1 = Very Easy; 6 = Very Difficult)	**1.75** **(0.96)**	--
Coordinating with own controllers (1 = Very Easy; 6 = Very Difficult)	--	**1.25** **(0.50)**
Coordinating with own TMU (1 = Very Easy; 6 = Very Difficult)	--	**1.75** **(0.96)**
Implementing airspace reconfiguration (1 = Very Easy; 6 = Very Difficult)	**1.63** **(0.52)**	**2.38** **(0.74)**

Overall, the participants thought that communication and coordination worked well. The communication was described as natural, often involving many "back-and-forth" conversations similar to communication in the field. The overall difficulty of coordination between the planners was rated fairly low for both TMCs and Area Supervisors (Table I). When the TMC coordinated the airspace designs through the ground-ground Data Comm system and by voice communication, there were many discussions on which design should be implemented. Although there were different opinions, a decision was made by majority vote or, if necessary, TMU's final authority. Both methods seemed to work well and did not pose any problems to the participants.

However, there were a few occasions where issues did arise. For example, participants noted that sometimes one Area needed a boundary change when the other Area did not. In this case, they agreed that if a TMC decided a boundary change was necessary, Area Supervisors would comply unless there was a specific reason why they could not (e.g., high controller workload during the proposed boundary change). On a related note, one Area Supervisor was concerned about the radar-to-radar controller coordination when the boundary change occurred because the controllers were unfamiliar with the neighboring sectors as well as their own airspace. He believed that the coordination would be difficult between different AOS because they would not be fully familiar with the airspace and cannot easily view each other's sectors.

Finally, participants rated the difficulty of implementing airspace configuration change. Both TMCs and Area Supervisors found changing the airspace configuration to be easy (Table I), with TMCs finding it somewhat easier than the Area Supervisors, $F(1,14) = 5.48$, $p < .04$.

3) Feasibility/Acceptability of FAM Operations

Feedback from the TMCs and Area Supervisors indicated that the FAM operations were feasible (Table I). Operational acceptability was high for both Area Supervisors and TMCs, with Area Supervisors finding the operations somewhat more acceptable ($M_{AreaSup}$ = 5.00, SD = 0.82) than the TMCs (M_{TMC} = 4.69, SD = 0.95; $F(1,14) = 4.75$, $p < .05$).

Controllers also gave positive ratings on the safety, situation awareness, airspace designs, and boundary change procedures (Fig. 11). Overall, they also gave high acceptability ratings to the FAM operations (M = 5.38, SD = 0.38).

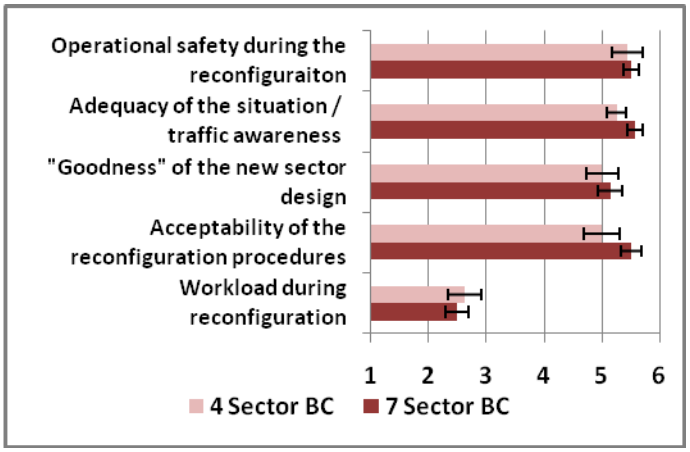

Figure 11. Results of R-side's post-run questionnaire.

D. *Traffic and Airspace Management Tools*

Another key component of the study was to prototype and evaluate the functions and tools that supported the planners in the reconfiguration process. DSTs were prototyped to manipulate the airspace designs, assess the impact of different airspace options, select and share those options with other team members, schedule a new configuration into the system, preview the new configuration on the controller stations, and implement the new configuration.

The airspace-related tools used in this study were initial prototypes and therefore were not as refined as other tools that were developed and used in prior studies. Nevertheless, the airspace-related tools were generally rated highly in their usefulness and usability. Traffic and complexity Load Table and Graphs were integrated with the airspace configuration options such that they quickly reflected the changes in the traffic in response to each airspace configuration option. These traffic monitoring and assessment tools were considered highly useful and usable (Fig. 12). During the debrief discussion, participants commented on additional functions that they would like for FAM operations. One of the Supervisors mentioned that he wanted to see proposed departure time information for aircraft that have yet to depart incorporated with the Load Table and Graphs. He believed that issuing reroutes for aircraft on the ground might be enough to balance workload and that it was a critical element missing from the simulation. Another suggestion was to integrate top-of-descent and top-of-climb points into the calculations of aircraft reroutes and airspace configurations to facilitate the planning and execution of the airspace change.

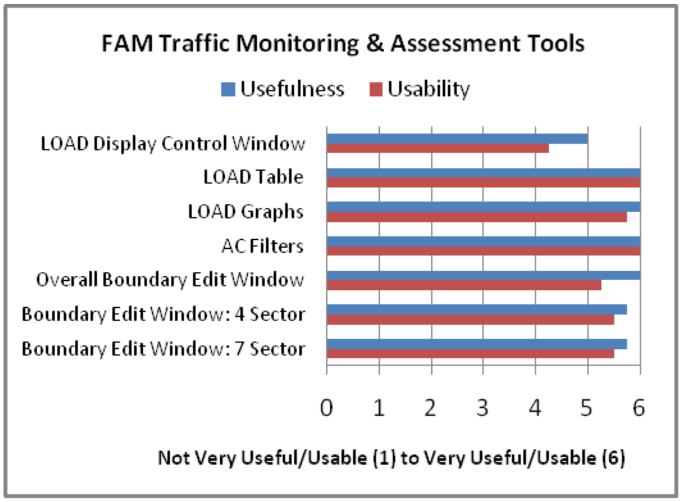

Figure 12. Usefulness and usability ratings given in post-simulation questionnaire on traffic monitoring and assessment tools.

The tools related to selecting airspace configuration options, sharing them with other planner stations, and adding them to an active queue for implementation were built specifically for this simulation. Overall, these prototyped tools were well received by the participants (Fig. 13). However, some participants did comment that some of the functions required an excessive number of button clicks.

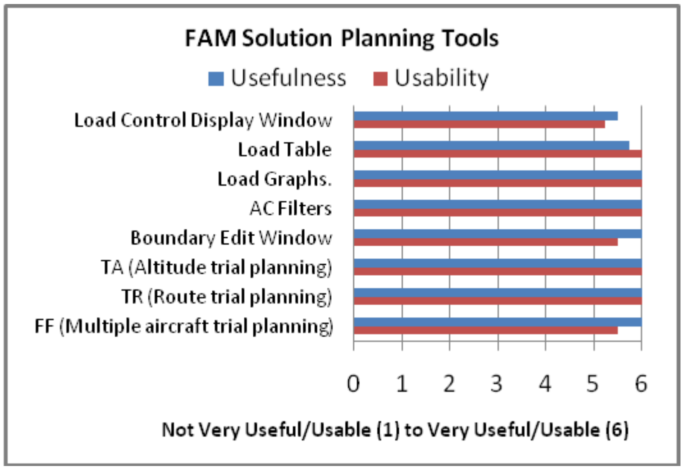

Figure 13. Usefulness and usability ratings given in post-simulation questionnaire on solution planning tools.

Tools that worked well were those related to filtering (AC Filter), selecting, assessing, and trial planning (TA and TR) multiple aircraft according to user-defined criteria (FF), such as destination airport, fixes, etc. This allowed traffic flows to be managed from both TMC and Area Supervisor positions. Participants also liked the ability to preview the new airspace configurations both on the planner and the controller displays.

In general, the combination of airspace and traffic assessment tools worked well together for the planners. However, they felt that they could have made better decisions had they been given more time to work on the tasks of boundary selection and traffic flow management.

V. CONCLUSION

A HITL simulation was conducted in August 2010 to assess potential user and system benefits in the mid-term en route environment, and to design planner roles, procedures, and DSTs to support FAM operations. Overall, results indicated that FAM operations with multiple TMCs, Area Supervisors, and radar controllers worked well. Participants were able to implement airspace configuration changes using new operational procedures and tools prototyped in this study. The objective metrics showed both individual flight and system-wide benefits, including fewer reroutes, decreased flight distance, and increased airspace utilization with FAM. Also, the roles, procedures, airspace designs, and tools were all well received by the participants.

In this study, the operational environment was assumed to be mid-term high altitude en route airspace above FL340 with fully Data Comm equipped aircraft. An advantage of the high altitude airspace is that aircraft are mostly in level flight with relatively low traffic complexity. It also requires less local airspace knowledge, such as terrain and merging flows into local airports, requiring less training to manage unfamiliar airspace. Data Comm also provides significant support to FAM operations by relieving controllers from memorizing radio frequency information and being an enabling technology for TBO. TBO in turn allows the aircraft to conform closely to their intended flight trajectories, thereby assisting controllers with maintaining their situation awareness of the traffic. The reduced complexity and associated workload provided by these assumptions created an ideal situation which maximized the flexibility in the airspace configuration change without sacrificing the concept feasibility.

However, the conclusions from this study may not hold if airspace in the mid-term turns out to have mixed or no Data Comm equipage. Further research testing FAM operations in different types of airspace with different levels of equipage would be warranted to better understand the impact of FAM.

There is also a limit to what can be accomplished by airspace reconfiguration alone, ultimately requiring operator handling of the remaining excess traffic with reroutes or other forms of traffic flow management. This study took a first step toward integrating traffic flow and airspace management functions, but more research is needed to explore how to fully integrate these two functions.

ACKNOWLEDGMENT

The authors would like to thank Kristina Carr, Shannon Zelinski, and Anton Koros for their active engagement and support of the project. The authors would also like to thank the participants in this study for their support. Thanks must also go to the MACS development team and DAC researchers at NASA, UARC, CSSI, Metron, and Mosaic-ATM for providing the software and algorithms used in the study.

REFERENCES

[1] FAA ATO Planning, Research and Technology, An operational concept for mid-term High Altitude (High Performance-Based) Airspace, draft version 4.17, 2010.

[2] J. H. Goldberg and H. W. Eberlin, “Dynamic sectors: concept development and modeling,” Proceedings of the 42nd Annual Air Traffic Control Association Conference. Washington, DC: Air Traffic Control Association, 1997.

[3] N. J. Taber, F. Woodward, F., and D. Small, Limited Dynamic Resectorization Casebook, The MITRE Corporation, McLean, 2000.

[4] E. S. Stein, P. S. Della Rocco, and R. S. Sollenberger, Dynamic resectorization in air traffic control: human factors perspective, DOT/FAA/CT-TN05/19, Washington, DC: FAA Office of Air Traffic Organization Operations Planning, 2006.

[5] W. S. Pawlak, A. Bowles, V. Goel, and C. B. Brinton, Initial evaluation of the dynamic resectorization and route coordination (DIRECT) system concept, NASA Final Report #NAS2-97057. Boulder, CO: Wyndemere, Inc., 1997.

[6] Eurocontrol, Airspace Management Handbook for the Application of the Concept of the Flexible Use of Airspace. Eurocontrol-Guid-140, Brussels, Belgium, 2010.

[7] J. A. Hadley, and R. S. Sollenberger, “Dynamic resectorization of airspace boundaries between adjacent air route traffic control centers,” in Proceedings of the 11th International Symposium on Aviation Psychology. Columbus, OH: The Ohio State University, 2001.

[8] P. U. Lee, T. Prevot, J. Homola, H. Lee, A. Kessell, and N. Smith, “Sector design and boundary change considerations for Flexible Airspace Management”, 10thAIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, TX., 2010.

[9] J. Homola, P. U. Lee, T. Prevot, H. Lee, A. Kessell, C. Brasil, and N. Smith, “A human-in-the-loop exploration of the Dynamic Airspace Configuration Concept”, AIAA Guidance, Navigation, and Control (GNC) Conference and Exhibit, Toronto, Canada., 2010.

[10] A. Klein, M. Rogers, and H. Kaing, “Dynamic FPAs: a new method for Dynamic Airspace Configuration,” Integrated Communications Navigation and Surveillance (ICNS) Conference. Bethesda, MD., 2008.

[11] C. Brinton and S. Pledgie, “Airspace partitioning using flight clustering and computational geometry,” in Proceedings of the 27th Digital Avionics Systems Conference (DASC), St. Paul, MN., 2008.

[12] A. Yousefi, B. Khorrami, R. Hoffman, and B. Hackney, Enhanced Dynamic Airspace Configuration Algorithms and Concepts, Metron Aviation Inc., Technical Report No. 34N1207-001-R0., 2007.

[13] M. Xue, “Three-dimensional sector design with optimal number of sectors,” Proceedings of AIAA Guidance, Navigation, and Control Conference, August 2-5, 2010, Toronto, Canada., 2010.

[14] T. Prevot, P. Lee, T. Callantine, J. Mercer, J. Homola, N. Smith, et al., “Human-in-the-loop evaluation of NextGen concepts in the Airspace Operations Laboratory,” AIAA-2010-7609 AIAA Modeling and Simulation Technologies Conference, Toronto, Ontario, Aug. 2-5, 2010.

[15] P. Kopardekar, K. Bilimoria, and B. Sridhar, “Airspace Configuration Concepts for Next Generation Air Transporation”, Air Traffic Control Quarterly, Vol 16 [4], 2008.

AUTHOR BIOGRAPHY

Dr. Paul U. Lee earned his Bachelor's and Master’s degree in engineering from Caltech in 1989 and Stanford University in 1995, respectively. He also earned a Ph.D. in cognitive psychology from Stanford University in 2002.

He is a Senior Research Associate for San Jose State University, working in the Human-Systems Integration Division at NASA Ames Research Center, Moffett Field, CA. For the past several years, he has been engaged in research in the area of air traffic control management with a focus on human factors and operational issues related to NextGen-Airspace.