An Evaluation of Controller and Pilot Performance, Workload and Acceptability Under A NextGen Concept for Dynamic Weather Adapted Arrival Routing

**Walter W. Johnson, *Joel Lachter, *Summer Brandt, *Robert Koteskey, *Arik-Quang Dao,
*Josh Kraut, *Sarah Ligda, and *Vernol Battiste
*San Jose State University; **NASA Ames Research Center

Abstract

In today's terminal operations, controller workload increases and throughput decreases when fixed standard terminal arrival routes (STARs) are impacted by storms. To circumvent this operational constraint, Krozel, Penny, Prete, and Mitchell (2004) proposed to use automation to dynamically adapt arrival and departure routing based on weather predictions. The present study examined this proposal in the context of a NextGen trajectory-based operation concept, focusing on the acceptability of this proposal to both pilots and controllers, as well as its effect on the controllers' ability to manage traffic flows.

Six controllers and twelve transport pilots participated in a human-in-the-loop simulation of arrival operations into Louisville International Airport with interval management requirements. Three types of routing structures were used: Static STARs (similar to current routing, which require the trajectories of individual aircraft to be modified to avoid the weather), Dynamic routing (automated adaptive routing around weather), and Dynamic Adjusted routing (automated adaptive routing around weather with aircraft entry time adjusted to account for differences in route length). Spacing Responsibility, whether responsibility for interval management resided with the controllers (as today), or resided with the pilot (who used a flight deck based automated spacing algorithm), was also manipulated. We collected subjective workload and acceptability ratings at the end of each trial. Participants also provided additional ratings and comments in a debrief questionnaire administered at the end of the simulation. Task decisions and behaviors as well as verbal communications were also recorded.

Dynamic routing as a whole was rated superior to static routing, especially by pilots, both in terms of workload reduction and flight path safety. Controllers also expressed a clear preference for dynamic routing. However, a downside of using dynamic routing was that the paths flown in the dynamic conditions tended to be somewhat longer than the paths flown in the static condition.

Introduction

Today, fixed routing structures such as standard terminal arrival routes (STARS) can become blocked by storms cutting across them. This leads to significant flow reductions as pilots request vectors around these blockages and controllers work to keep up with these requests. This, in turn, causes back-ups into the en route airspace, with accompanying fuel costs and delays. The Next Generation Air Transportation System (NextGen), seeks to transform the management of the National Airspace System (NAS), with one specific goal being to reduce these weather related delays (see JPDO, 2010). One proposal to accomplish this is to use automation, in combination with weather predictions, to adapt the arrival routing at regular intervals so that it bypasses weather systems (Krozel, Penny, Prete, & Mitchell, 2004). This could offload the problem of finding and implementing a clear path from the pilot and controller, thus reducing required communications and workload. However, the controller will then need to manage traffic on unfamiliar routes, which may be as difficult as simply managing spacing and separations without dynamic routing. A primary question for this study is whether dynamic routing is more acceptable to controllers and pilots than static routing. We have not looked at the quality of the weather avoidance algorithm itself, as we assume that this will improve over the years needed to implement such a system. Therefore, in this initial test, we provided perfect weather prediction and did not use weather patterns through which the algorithm could not find a clear path.

Method

Participants

Twelve commercial airline pilots with glass cockpit experience and six retired controllers were recruited for this simulation. Pilots were divided into two person crews with the more experienced pilot chosen as the captain. Confederate pseudo-pilots were used to fly additional background aircraft.

Equipment

Pilot stations. Low fidelity desktop systems were used to simulate two dual-pilot flight decks while a mid-fidelity fixed based simulator was used to simulate a third flight deck. All simulations used the Multi Aircraft Simulation system (MACS; Prevot et al., 2006) to emulate Boeing transport aircraft. All participant aircraft were equipped as high-end present day flight decks including, in particular, FANS and airborne weather radar simulations.

Controller stations. Air traffic control (ATC) station simulators emulating an advanced prototype traffic display based on the standard ATC Display System Replacement (DSR) were also implemented using MACS, and displayed on a 30" high resolution monitor. The DSR was equipped with advanced conflict detection and resolution tools coupled with a graphical route planning tool and also displayed dynamic NexRad weather. Controllers were also provided with a schedule window that allowed them to see the time each plane was predicted to cross the TRACON meter fix. See Prevot et al. (2006) for a complete description of the DSR capabilities, and Battiste, Lawton, Lachter, Brandt, & Johnson, (2012) for further description of the controller procedures used in this study.

Collection of Real Time Workload. In addition to the equipment described above, each participant also had a separate touch-screen computer used to collect real time workload ratings.

Scenarios

The dual-pilot and confederate flight decks were part of an arrival stream headed for Louisville International Airport (SDF), reaching top of descent shortly after entering the final high altitude en route sector. These arrivals flew west to east through the sector and negotiated a storm front near the center of the sector. In addition there was IFR departure traffic that used FANS datacom to request deviations around weather, and crossing en route VFR traffic that was pre-deviated to fly appropriately with respect to the weather. Each scenario lasted approximately 50 minutes, and focused exclusively on the en route arrival up to the meter fix. Each plane took about 20 minutes to fly from a point prior to the top of descent to the meter fix. Controllers worked the entire scenario which was followed by a brief post trial questionnaire about the scenario and a break before the next scenario. Within each scenario the participant pilots flew two aircraft. They successively flew the 3rd and 15th aircraft in the stream of arrivals, filling out a brief post trial questionnaire after each flight.

Procedures

For both of these options we presume the use of trajectory based operations (TBO), a fundamental part of NextGen, in which complete flight plan modifications are exchanged between aircraft and air traffic control. All dual-pilot flight decks (those not piloted by confederates) were arrival aircraft headed for Louisville International Airport (SDF), reaching top of descent shortly after entering the sector. Flight decks flew west to east through the sector and negotiated a storm front near the center of the sector.

Each arrival entered the scenario 130 ± 10 seconds behind the previous aircraft (constrained so that every three planes had an average delay of 130 seconds); and was assigned an initial flight level (FL 330, FL 350, FL 370, FL 390). All arrivals started the scenario with the en route arrival (CBSKT) loaded in their flight management system. For arrival in the dynamic routing trials the arrival routing was pre-deviated for weather. Thus, if the crew was comfortable with the route relative to the weather, no further deviation were needed. In the static routing trials the route was not pre-deviated, see Figure 1, crews in this condition were required to use their onboard tools to create and datalink a weather free route to ATC for approval. Departure traffic leaving SDF used FANS datacom to request deviations around weather and VFR en route traffic was created and pre-deviated to fly appropriately with respect to each weather patterns.

Experimental Design

Two independent fixed factors were manipulated: Tree Type and Spacing Responsibility. In addition there were three random factors, Aircraft Crew, Controller and Scenario. There were three levels of Tree Type: Static, Dynamic and Dynamic Adjusted. The static tree is a control condition where, much like today, the controller is required to respond to pilot deviation requests. The left side of Figure 1 shows the static tree. It is a symmetrical tree with four potential entry points, each equidistant from two downstream merge points and from the meter fix. Aircraft enter the tree at any of these points temporally spaced so they would reach the meter fix appropriately spaced if they followed the static tree. The Dynamic and Dynamic Adjusted conditions both used Metron's simple tree planner algorithm with fixed quadrant size, fixed RNP, and a single TRACON entry meter fix (Prete, Krozel, Mitchell, Kim & Zou, 2008). As can be seen in Figure 1, the tree planner warps the routing, with the goal of a route that will allow aircraft to avoid the weather while in the tree. The tree adapts to the predicted weather every 15 minutes so the controller will have as many as three different simultaneous tree structures. The difference between the Dynamic and Dynamic Adjusted conditions arises from the way aircraft are initially spaced as they enter the scenario. This factor was introduced because creating dynamic trees has interesting consequences for arrival spacing. Due to the warping of routes in a dynamic tree, and the fact a preceding aircraft may enter on any of the four entry points, an entering plane might have a very different distance to fly to the meter fix than the plane preceding it, making the spacing problem at merge points and the meter fix more difficult. In principle, under TBO such path stretches need not cause problems. Aircraft could know of weather deviations for the plane entering the tree just ahead of them and adjust their speed to arrive at the entry points appropriately spaced. As a result, we implemented the dynamic trees in two ways: "Dynamic" and "Dynamic Adjusted." In the Dynamic condition, aircraft arrive at the outer leaves of the tree at intervals that are unaffected by the path length to the meter fix. In the Dynamic Adjusted condition, aircraft on shorter paths are delayed relative to those on longer paths. Because the difference between Dynamic and Dynamic Adjusted was subtle, participants were only informed as to whether the condition was Dynamic to avoid biasing them.

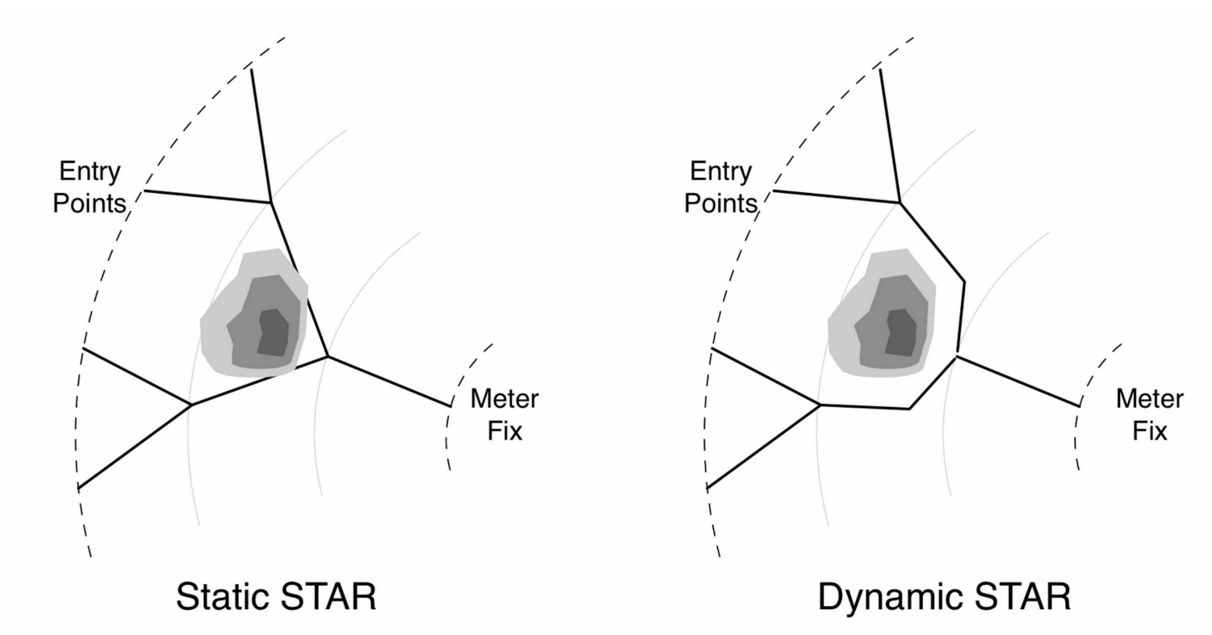

Figure 1: Examples of Static and Dynamic tree structures, with weather. Notice how the STAR is adjusted in the Dynamic tree to avoid the weather.

Because dynamic routing also affects the spacing solution, we wanted to examine these routing options in the context of how interval management is handled. There were two Spacing Responsibility conditions: Controllers Responsible and Pilots Responsible. In the Controllers Responsible condition, controllers managed spacing between aircraft much as they do today. In the Pilot Responsible condition, automation generated speed guidance to achieve the desired spacing goal of 130 seconds at CBSKT. Unless the pilots chose to intervene, the spacing algorithm commanded speed was coupled with the autopilot and did not require manual Mode Control Panel speed inputs (see Battiste et al, 2012).

Results

Real-time subjective workload probe ratings were collected during each trial, while retrospective subjective workload and acceptability ratings were collected at the end of each trial. In addition, at the end of the simulation, study questionnaires were administered to all of the participants and additional ratings and comments gathered. Pilot and controller performance data were also collected. Here we discuss the distance flown. For results pertaining to interval management, frequency of communication, and other additional measures of performance, see Battiste et al. (2012).

Workload Ratings

Pilots and controllers rated their workload on a 1 Low - 5 Typical - 9 High scale at three-minute intervals throughout each trial. In the controller ratings there was no main effect of Tree Type on controller workload ratings collected during the trials (p = .26). Controllers rated real-time workload close to typical for the Static (M = 5.10), Dynamic (M = 4.87) and Dynamic Adjusted (M = 4.92) routing. There was, however, a main effect of Spacing Responsibility on controller workload ratings, $F(1,5) = 11.66$, $p < .05$. Controllers reported higher workload throughout the trial during Controller Managed Spacing (M = 5.20) compared to Pilot Managed Spacing (M = 4.73) trials. No interaction was found (p = .93).

In the pilot ratings, there was a significant main effect of Tree Type on pilot real-time workload ratings, $F(1.24,13.65) = 6.22$, $p < .05$. Pilots reported greater workload with Static (M = 3.23) routing compared to Dynamic Adjusted (M = 2.84, p = .058) routing. Dynamic (M = 2.89) routing was not significantly different from other routing. However, there was no main effect of Spacing Responsibility on pilot workload ratings, p = .23. Pilots reported similar workload levels during the Controller Managed Spacing (M = 2.96) and Pilot Managed Spacing (M = 3.03, p = .23) trials. No interaction was found (p = .20).

Pilots and controllers were also asked to rate their workload at the end of each trial. These ratings generally followed the real time ratings with controllers rating the controller spacing condition higher and little difference between tree types and pilots rating the static tree higher with little difference between spacing conditions. Pilots and controllers were also given more detailed questionnaires after completing all runs. These too followed the pattern of controllers being affected primarily by the spacing condition while pilots were affected primarily by the tree type. However, there were two exceptions to this which may give some insight into the participants thinking. First, even though controllers rated their workload and the outcomes (e.g., trajectories of aircraft in their sectors) similarly across the tree types, when asked which tree type they preferred they overwhelming choose the dynamic trees (because participants were not informed about the two types of dynamic trees, they couldn't rate them separately). Specifically, controllers were asked about their preference with managing aircraft. Overall, controllers preferred to manage aircraft using Dynamic (M = 4.83) routing compared to Static (M = 2.5) routing, $F(1,4) = 22.27$, $p < .01$. Controllers also somewhat agreed (M = 4.17) that managing arrivals with Dynamic routing gave them more time and that with more practice or training, they could safely manage a higher traffic density (M = 4.33).

Distance and Time Flown

This analysis was based on the participant aircraft only. The length of the path flown was taken to be the sum of the path flown at the end of the trial and the remaining distance to the runway at that point.

The distributions of distance flown in each condition is shown in Figure 2. The median distance flown was noticeably shorter for Static routing than in either of the dynamic routings (183.6 vs 186.7 and 186.8 nm in the Static, Dynamic, and Dynamic Adjusted, respectively). Three ANOVAs were conducted with distance flown as the dependent measure. The effect of Tree Type was significant when analyzed by Controller ($F(2,10) = 10.42$, $p < .01$) and Scenario ($F(2,34) = 4.82$, $p < .05$) but only marginally significant when analyzed by Aircraft Crew ($F(2,10) = 3.98$, $p = .054$).

The reason Static routing produced shorter paths is apparent if you look at the paths actually flown by the aircraft. These paths are shown in Figure 3 broken down by Tree Type. Note that many aircraft on Static routing did not deviate. In fact, 25 of the 72 experimental aircraft in that condition made no lateral deviations from the original STAR, while all aircraft in the Dynamic conditions made significant deviations due to the warping of the Static Star routes. This is because the concept underlying this simulation required that the path flown by aircraft in the Dynamic conditions be weather free for approximately 35 minutes (the path must be able to accept aircraft for 15 minutes and must remain clear of weather while aircraft are in the tree, about 20 minutes) while aircraft on Static routing only deviated when weather impacted the path at the moment the aircraft passed. Note that no attempt was made to synchronize the weather with individual aircraft during scenario development.

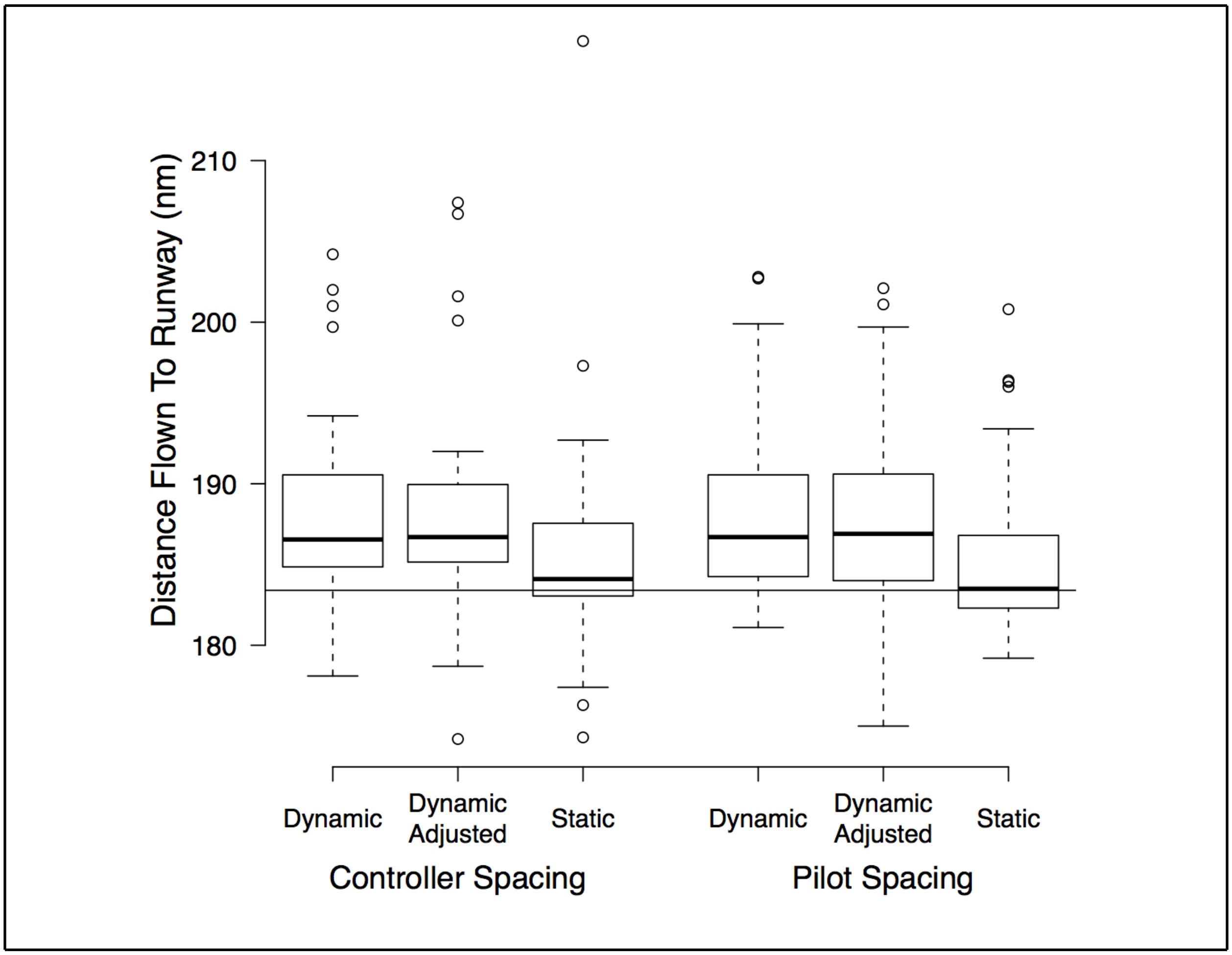

Figure 2: "Tukey" boxplot (Tukey, 1973) of the distance flown to the runway by the experimental planes in each condition. For each condition the solid line indicates the median; the box indicates the inter-quartile range (IQR); the whiskers indicate the range excluding "outliers"; and the circles indicate outliers, points more than 1.5 IQR from the box. The horizontal line indicates the distance flown (183 nm) on the static tree.

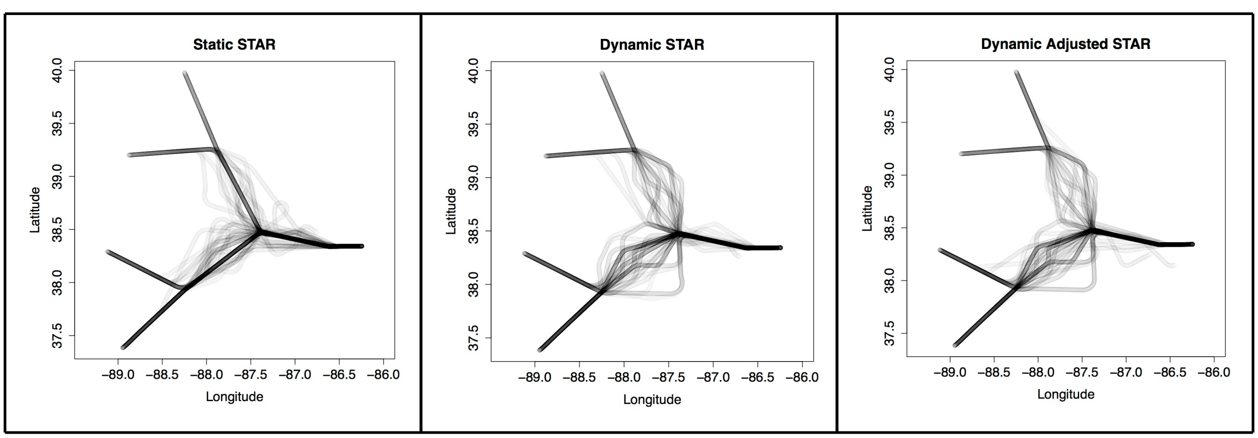

Figure 3. Paths of all experimental aircraft in each condition. Paths are transparent so that multiple aircraft taking the same path results in the path being darker.

Summary and Discussion

A large simulation like this creates a very large data set with many nuanced findings. Statistically, a few differences will be found to be significant when no real difference exists and some will not be found significant even when real differences do exist. It is important, therefore, to look at which differences show up repeatedly, across a variety of measures, and which show up rarely or not at all. In doing so, a few generalizations become clear:

- Dynamic routing is rated superior to static, especially by pilots.
- The two dynamic tree conditions (Dynamic and Dynamic Adjusted) are rated similarly

We will briefly discuss each of these.

Dynamic Routing vs Static Trees

Pilots rated their workload lower in the dynamic routing conditions than they did in the static condition on every workload question except for the workload due to spacing (where it was roughly equivalent to the Dynamic). Workload for the Static Star condition was higher relative to the Dynamic condition for both overall and peak workload associated with avoiding weather, and relative to the Dynamic Adjusted condition for real-time workload (marginal), overall and peak flight (marginal). Pilots also felt safer in the Dynamic conditions than they did in the Static conditions. They rated the flight path flown least safe on the Static trials on the post trial questionnaire and they rated operations less safe in the Static conditions in the post simulation questionnaire. This is perhaps unsurprising since they came closer to the weather on the Static trials. Finally, on the post simulation questionnaire, pilots rated their ability to manage weather deviations higher in the Dynamic conditions than in the Static.

Interestingly, controllers did not rate the Static and Dynamic conditions differently on any of the workload or safety questions. Yet, controllers agreed with the statement that it was easier to manage traffic in the Dynamic condition than the Static condition and they expressed a clear preference for Dynamic when asked if they prefer to manage traffic using the Static or Dynamic trees in the post simulation questionnaire.

Dynamic vs Dynamic Adjusted

It is interesting to note that few differences were found between the Dynamic and Dynamic Adjusted conditions in respect to subjective responses. While there are measures on which Dynamic Adjusted seems to have some advantage over Dynamic (e.g., pilot ratings of their workload associated with spacing) there are several on which Dynamic trends better than Dynamic Adjusted (e.g., controller real-time ratings, controller ratings of workload associated with maintaining spacing and controller ratings of workload associated with spacing). Clearly there was a spacing problem to be solved in all conditions as the controllers found their workload increase noticeably when they were responsible for managing it. In the Dynamic condition, planes entered the scenario with much more variable spacing than in the Dynamic Adjusted scenario (about double the RMS error). However, it is possible that even in the Dynamic Adjusted condition, controllers only have to make slight adjustments to the spacing of most planes or that larger adjustments are not more difficult than smaller ones.

References

Battiste, V., Lawton, G., Lachter, J., Brandt, S. & Johnson, W. W. (2012). Comparison of controller and flight deck algorithm performance during interval management with dynamic arrival trees (STARS). This volume.

Joint Planning and Development Office. (2010). Next Generation Transportation System: Concept of Operation V 3.0, Washington D.C, Government Printing Office.

Krozel, J., Penny, S., Prete, J., & Mitchell, J. S. B. (2004). Comparison of algorithms for synthesizing weather avoidance routes in transition airspace. *AIAA Guidance, Navigation and Control Conf*.

Prete, J., Krozel, J., Mitchell, J. S. B., Kim, J., & Zou, J. (2008). Flexible, performance-based route planning for super-dense operations. AIAA Guidance, Navigation, and Control Conference.

Prevot, T., Smith, N., Palmer, E., Mercer, J., Lee, P., Homola, J., & Callantine, T. (2006). The Airspace Operations Laboratory (AOL) at NASA Ames Research Center. Proceedings of the AIAA Modeling and Simulation Technologies Conference.

Tukey, J. W. (1977). Exploratory Data Analysis, Reading, MA: Addison Wesley.

Acknowledgements

This study is a follow on to concept development work and fast-time explorations conducted under an Airspace Systems NRA led by Jimmy Krozel and Joe Prete of Metron Aviation, with significant help from Phil Smith of The Ohio State University. Authors Contact Info: Walter W. Johnson, NASA Ames Research Center, MS 262-2, Moffett Field, CA 94035; PH 650-604-3667; walter.johnson@nasa.gov