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Airborne spacing and merging in the terminal area

Joey Mercer
San Jose State University

AIRBORNE SPACING AND MERGING IN THE TERMINAL AREA

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Joey Mercer

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APPROVED FOR THE DEPARTMENT OF INDUSTRIAL

SYSTEMS ENGINEERING

Kevin Jordan, Ph.D.

Kevin Corker, Ph.D.

Everett Palmer, Ph.D.
NASA Ames Research Center

APPROVED FOR THE UNIVERSITY

Rhea I. Williamson 1/29/08

ABSTRACT

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Due to the natural compression of aircraft decelerating in preparation for landing, current-day air traffic control operations in terminal areas are characterized by several clearances, including speed instructions and heading vectors. These operations often create excess spacing between consecutive aircraft, which adds an extra buffer to the safety margin, but reduces the number of aircraft that can land at an airport over a period of time. Having aircraft equipped with advanced cockpit tools that can utilize Airborne Separation Assistance System (ASAS) clearances like "merge behind then follow" could increase system performance by minimizing in-trail spacing buffers. Providing air traffic controllers with Decision Support Tools (DSTs) that accommodate such a strategy could further improve system performance. In August 2004, NASA Ames Research Center conducted a simulation of ASAS operations. Analyses of the simulation data suggest that airborne spacing and merging operations are acceptable to controllers and reduce excess spacing between aircraft.

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INTRODUCTION

The air transportation system of the United States, part of the country's National Airspace System (NAS), manages complex traffic at high capacities. The American public per capita uses more air travel than any other country on Earth (National Aeronautics and Space Administration, 2002). In 2004, the NAS saw 49,545 flights each day pass through its 17,017,092 square miles of airspace, serving 688.5 million passengers, or nearly two million per day (Statistics and Forecast Branch, 2005). There seem to be no signs of slowing either. Current predictions suggest that traffic levels will continue to increase, with demand at least doubling by 2025, and by the year 2015, it is estimated that more than one billion passengers will be transported annually (Statistics and Forecast Branch, 2005). However, the system is already reaching capacity limits, bringing increased delays and other costs to its users. Many of the nation's major airports are already operating at or near their maximum capacities.

The congestion and limitations of the current air traffic infrastructure resulted in aviation delays costing $9 billion in 2000. Without any improvements, those numbers are predicted to be $30 billion in 2015 (Commission on the Future of the United States Aerospace Industry, 2002). Today's air transportation system is based on dated technology and operations, and if left as-is, will be unable to support the future demands for air travel. In particular, air traffic controllers will not be able to manage the projected amount of traffic if changes are not made.

Background

It is widely recognized that the NAS is in need of modernization. Advancements in technologies available today provide the ability to improve automation systems and support the projected growth in air traffic by utilizing better communications, navigation, and surveillance (CNS) capabilities. A report by the National Research Council identifies the need for "ubiquitous and transparent CNS capabilities, enabling cost-effective and reliable air traffic management" (Committee on Aeronautics Research and Technology for Vision 2050, 2003). NASA has also incorporated this into their plans, acknowledging the challenge to increase situational awareness to be able to meet system growth. They suggested the projected increase in traffic could be made possible by improving the safety of today's system, perhaps by moving towards a more distributed system that gives the cockpit a larger role (National Aeronautics and Space Administration, 2002). Advanced CNS would provide flight crews with the situation awareness necessary to make such operations feasible.

The FAA has already begun some real-world testing, and in some cases implementation of, advanced CNS capabilities. Applications of these existing technologies include the Safe Flight 21's Capstone and Ohio River Valley activities, focused on Automatic Dependent Surveillance-Broadcast (ADS-B) technology (Office of System Architecture and Investment Analysis, 2002).

ADS-B is seen as a critical technology for future air traffic operations. To meet their goal of greater capacity, the FAA identifies several initiatives, including the operational implementation of ADS-B, as well as the increased use of time-based metering with the Traffic Management Advisor (TMA) and the continued development and implementation of Area Navigation (RNAV) routes (Federal Aviation Administration, 2005). ADS-B is a type of electronic communication, or broadcast of information, between computers via a digital datalink connection (Office of System Architecture and Investment Analysis, 2002). For example, an aircraft equipped with ADS-B can broadcast its position, altitude, speed, and routing to receivers on the ground used by Air Traffic Service Providers (air-to-ground), and to the cockpits of neighboring aircraft also equipped with ADS-B avionics (air-to-air). This information can then be processed and displayed to the controller or flight crew to provide an accurate picture of the area's traffic. Data from ADS-B technology will be more accurate than today's radar system since it is planned to have a one second update rate, compared to the 12 second update rate for en route radar, or 4.7 second update rate for TRACON radar (Office of System Architecture and Investment Analysis, 2002). The benefits of improved surveillance accuracy and update rate with ADS-B are so significant that it has been suggested the technology could "contribute to the reduction of separation standards without compromising safety," (Committee on Aeronautics Research and Technology for Vision 2050, 2003).

Combining ADS-B with other technologies could enable further enhancements to air traffic operations. In concordance with their *Flight Plan* document, the FAA's *Operational Evolution Plan* describes the need to address terminal area congestion by, in addition to using time-based metering, combining the benefits of ADS-B and RNAV routes (Federal Aviation Administration, 2006). An improvement over the vectoring performed in today's TRACON operations, RNAV routes provide a structured and precise path for aircraft to follow. Aircraft equipped for RNAV routes would have advanced guidance systems capable of following a path at tolerances much tighter than today's standards. Using RNAV routing in conjunction with the highly accurate position data from ADS-B, controllers can more closely monitor aircraft in dense areas (e.g. on final approach), giving them the ability to issue more parallel approaches (Federal Aviation Administration, 2006). The benefits are very significant when an airport no longer needs to decrease throughput during difficult weather conditions.

Time-based metering is another currently available means for improving air traffic operations. Maximizing the full potential of an airport's resources will be critical for handling the expected increase in air traffic over the next several years. Under-utilization of an airport's runways is often referred to as "missed slots" or "gaps." To avoid these inefficiencies, the Traffic Management Advisor (TMA) tool provides an arrival/departure management plan and all the necessary information to achieve a balanced use of airport resources (Federal Aviation Administration, 2006). By knowing the current and predicting the future state of arriving/departing traffic, airports can optimize aircraft flows to more efficiently use the full capacity of their runways. The FAA has implemented TMA in several facilities already, and is planning to expand its deployment to other busy airports.

Terminal Radar Approach Control Operations

The stated goal of air traffic control is to accomplish the safe, efficient flow of traffic from origin to destination (Nolan, 1999). Air traffic control services are organized among different facilities, one of which is known as the terminal radar approach control, or TRACON. Controllers in these facilities use computer-based radar displays to manage departing and arriving aircraft through the busy airspace surrounding airport facilities. They establish and maintain the sequence and separation of aircraft that are taking off, landing, or operating within the terminal airspace. This typically involves handling departing aircraft from takeoff until their transition into the en route phase of flight. Arriving aircraft are typically handled from the transition out of the cruise phase of flight until their final approach, in preparation for landing at their destination airport. The area of responsibility for TRACON facilities is commonly the airspace within 40 miles of an airport and below 12,000 feet in altitude (Nolan, 1999).

Due to the natural compression of arrival aircraft as they descend and decelerate in preparation for landing, current-day operations in the TRACON area are characterized by several successive clearances, such as speed instructions, temporary altitude assignments, and radar vectors (i.e. heading commands). Additionally, arriving aircraft typically approach a single runway from several different routes, all of which must eventually merge into just one route. This requires the controller to identify the final sequence and issue more clearances to ensure the safe spacing between aircraft as the routes merge together. All of these operations often leave excess spacing between aircraft. The excess space adds a buffer to the safety margins, but consequently also reduces the number of aircraft that can land at a given airport over a period of time.

Having aircraft equipped with advanced tools in the cockpit that can utilize Airborne Separation Assistance System (ASAS) clearances like "merge behind then follow" could increase system performance by minimizing in-trail spacing buffers and yielding higher throughput (Application Definition Sub-group, 2004a). ASAS operations would allow equipped aircraft to maintain spacing relative to another aircraft through advanced on-board speed guidance. This enables the aircraft to more accurately achieve the desired spacing interval than would be possible with speed clearances issued from the controller. The ASAS clearances could be designed to use temporal, rather than distance-based intervals, which could effectively compensate for the compression of descending and decelerating aircraft. Providing air traffic controllers with Decision Support Tools (DSTs) that accommodate a complementary time-based strategy could further improve system performance. This approach has the potential to reduce controller workload when managing aircraft merging from multiple arrival streams.

Current Study

In December of 2004, the Joint Planning and Development Office (JPDO) produced the "Integrated National Plan for the Next Generation Air Transportation System." The plan emphasizes the need for a technology-enabled approach to future air transportation in the U.S. One of the strategies of the JPDO is to "Establish an Agile Air Traffic System", addressing critical system attributes such as performance, human factors, capacity, and safety (Joint Planning and Development Office, 2004). One possible approach to meeting these objectives is a re-allocation of spacing tasks between the controller and the flight crew. This concept of limited delegation has many applications, one of which is airborne spacing, specifically the ASAS category 2 application of Enhanced Sequencing and Merging, or ASPA-S&M (Application Definition Sub-group, 2004b).

It is thought that air traffic management can be enhanced by better involving flight crews and avionics systems with air traffic controllers in a cooperative manner. This is already done in today's operations, but only with visual separation clearances. In clear weather situations, it is not uncommon for controllers to ask a flight crew during their final approach to provide separation from another visually identified aircraft. If accepted by the flight crew, a visual separation clearance transfers the full responsibility of separation to the flight crew, who determine the appropriate separation distance themselves. Beyond the safety of flight, the flight crew is not subject to any separation requirements, and can potentially achieve a closer spacing than a controller's rules would allow. However, in degraded weather situations, or Instrument Meteorological Conditions (IMC), visual separation cannot be used (Federal Aviation Administration, 2006).

Comparable in certain respects to the visual separation clearance, the complete ASAS concept is defined as "an aircraft system that enables the flight crew to maintain separation of their aircraft from one or more aircraft, and provides flight information concerning surrounding traffic" (Action Plan 1, 2001)." The two are similar in that they are optional, and are initiated by the controller, but the two differ in which responsibilities and authorities are transferred. Hoffman, Zeghal, Cloerec, Grimaud, and Nicolaon (1999) describe all separation assurance tasks in three components: identification of a problem, identification of a solution, and implementation of a solution. Hoffman et al. define limited delegation as ASAS operations transferring only the implementation of a solution to the flight crew, keeping the separation responsibility with the controller, who stays engaged in the evolving traffic situation. Here the motivation for ASAS is to increase the controller's availability through this re-allocation of tasks that expand the capabilities of the flight crew under instrument conditions to those similar in a visual environment. The motivation for ASAS is not to transfer problems, or give more freedom to the flight crew, but rather to identify a more effective distribution of tasks that is beneficial to all parties (Grimaud, Hoffman, Rognin, & Zeghal, 2003). Possible benefits from the use of ASAS include more precise spacing between aircraft, as well as improved traffic situational awareness and understanding of ATC instructions for flight crews, and reduced workload for controllers that could lead to increases in traffic throughput and capacity.

A cooperative research and development committee between the FAA and Eurocontrol recognizes the potential for numerous uses of ASAS, and identifies four main application categories, each with different levels of tasks and responsibilities delegated from the controller to the flight crews. Airborne Spacing, the second category, encompasses applications that keep the separation responsibility with the controller, while requiring flight crews to achieve and maintain an assigned spacing interval from a designated aircraft (Action Plan 1, 2001). It is assumed that controllers typically use several speed and altitude clearances to maintain an orderly flow of aircraft in approach. Time-based ASAS clearances enable the flight crew to use speed adjustments to maintain a proper spacing relative to a lead aircraft, effectively relieving the controller of maintaining that sequence. ASAS is thus treated as a new DST for the controller, who can issue ASAS clearances to equipped aircraft if and when they deem appropriate. It is still part of the controller's task to determine the lead aircraft and the necessary spacing interval for the flight crew to follow. ASAS operations which transfer full separation responsibility to the flight crew were not addressed in the current study and are outside its scope, but such implications are discussed by Schubert (2002). Applications in the Airborne Spacing category then, rely on one aircraft using enhanced surveillance information and spacing guidance to space relative to another aircraft as instructed by the controller (Action Plan 1, 2001). Advanced CNS tools, specifically ADS-B, are the enabling technologies for the implementation of ASAS operations.

Example maneuvers of the ASPA-S&M application include "remain behind," where the instructed aircraft remains behind the lead aircraft at the controller-assigned spacing interval, and "merge behind," where two aircraft are merging together at a downstream waypoint. The "merge behind" situation calls for the instructed aircraft to adjust its speed to be behind the other aircraft at the desired spacing value at the merge point. Other variations of these maneuvers can be formed by adding an open-ended radar vector at the start of the maneuver, as in "radar vector then remain behind" (Application Definition Sub-group, 2004a).

Early research looked at the behavior of flight-deck airborne spacing algorithms, studying the dynamics of in-trail following, and identified potential risks from oscillatory effects, and potential situation awareness benefits from the flight crew perspective (Chappell & Palmer, 1981; Williams, 1983). Human-in-the-loop ASAS experiments with controllers and pilots were conducted several years later, after advancements in technology presented new concept possibilities. A series of experiments by Eurocontrol researchers has indicated that in Extended Terminal Maneuvering Areas (equivalent to en route transition airspace), ASAS operations have great potential. The ASAS clearances were used often by the controller participants, and contributed to improved traffic flow patterns, increased controller availability by enabling the earlier building of sequences, and a decrease in overall controller instructions (Grimaud, Hoffman, Rognin, & Zeghal, 2001; Grimaud, Hoffman, Rognin, & Zeghal, 2002; Rognin, Grimaud, Hoffman, & Zeghal, 2001). Experiments studying ASAS operations in the TRACON showed similarly positive results (Grimaud, Hoffman, Rognin, & Zeghal, 2003; Grimaud, Hoffman, Rognin, & Zeghal, 2004). A later experiment by Boursier et al. (2005) demonstrated the potential for using ASAS operations in conjunction with a runway scheduler. Reservations about the ASAS concept can be seen in a 2001 press release from the International Federation of Air Traffic Controllers' Associations (IFATCA), stating their concern for possible situation awareness and skill degradation with the controller, but concluding that the concept "warrants further examination and discussion."

The automation associated with ASAS brings other research issues, which need to be understood. General theories of the human's interaction with automation are well documented. Dekker and Woods (1999), propose the concept of a "double bind," where early intervention by the human to take manual control over an automated system is an inefficient use of the system's automation investment. On the other hand, later intervention by the human can lead to degraded situations from which recovery is not possible. Others suggest that the way in which humans use automation is the result of a comparison between the trust in the automation and the trust in oneself, defining this as the automation's "utility" (Dzindolet, Pierce, Beck, & Dawe, 1999).

Past research on controller display automation for advanced TRACON operations investigated "ghosting displays" for converging runway situations. As two flows of aircraft come together, the targets of aircraft in one stream are projected onto the other, providing the controller with better feedback on the spacing accuracy of converging flows. The visual feedback enables better awareness of the relative spacing between aircraft in different flows, essentially simplifying a merging task into the equivalent of an in-trail spacing task (Mundra, 1989: NAV CANADA, 2003). Taking a slightly different approach, research from NASA looked at the task of sequencing aircraft nearing final approach, investigating the use of graphical advisories integrated with the controller's display. The Final Approach Spacing Tool (FAST) and Final-Approach Spacing Aids (FASA) were designed to enhance the tactical nature of working arrival aircraft in the TRACON. The two dynamically analyze the traffic situation and present symbology on the controller's display to indicate where a speed clearance or heading vector should be issued for optimal runway utilization (Credeur et al., 1993; Davis, Erzberger, & Green, 1990). Human-in-the-loop experiments from MITRE report on other variations of advisories for the sequencing task. Two types of visual aids were examined for providing feedback relative to delay absorption. The Mileage Distance Marker (MDM) and Mileage in the Data Block (MDB) tools were presented on the controller's display to provide metering information to the controller. The MDM displays a marker relative to the target symbol of an aircraft, representing a spatial indication of the delay magnitude to be absorbed by an aircraft. The MDB is a numerical representation of the same information, but presents a positive or negative number, indicating the mileage adjustment needed to absorb the delay (DeSenti, 2000).

NASA's Ames Research Center conducted an air-ground simulation to investigate the effectiveness of DSTs used in TRACON airspace for airborne spacing and merging operations. The simulation included merging arrival flows with two certified professional controller participants working adjacent sectors. The current study analyzes a subset of the data from the NASA Ames simulation in order to discuss system performance and controller strategies under ASAS operations with and without the presence of corresponding ground-side DSTs. Recommendations for ground-side tools to support ASAS operations are also discussed.

Hypotheses

Upgrades or modifications to NAS ground infrastructure can be extremely costly and slow to happen. Even though are some enabling technologies are already available, such as digital datalink communication and Automatic Dependent Surveillance-Broadcast (ADS-B), incorporating them into the system infrastructure is extremely slow due to certification processes, prudent caution, and labor environments. Similarly, individual airlines and general aviation operators facing weak financial situations find it in their best interest to delay or minimize equipage (Commission on the Future of the United States Aerospace Industry, 2002). As a result, the airlines will not all equip their fleets at the same time or to the same degree, producing a mixture of different aircraft capabilities. A far-term concept for Air Traffic Management (ATM) would likely envision sophisticated ground-side capabilities with total aircraft equipage, but an intermediate or more near-term implementation of the concept should also be considered. The current study investigates the operational acceptability of the ASAS concept in the TRACON area, hypothesizing that airborne spacing and merging operations under a mixed-equipage environment provide system performance benefits and are acceptable to air traffic controllers without any modifications to the ground system.

METHOD

Source of Archival Data

A simulation was conducted at NASA's Ames Research Center during August of 2004. The simulation was a large-scale human-in-the-loop (HITL) study of airborne spacing and merging in the TRACON (Advanced Air Transportation Technologies Project Office, 2004; Callantine, 2006). This research was conducted as part of the Advanced Air Transportation Technologies (AATT) project's Distributed Air-Ground Traffic Management (DAG-TM) element, with funding from the NASA Airspace Systems program (Advanced Air Transportation Technologies Project Office, 2002). The simulation was conducted with approval from NASA Ames' Human Research Institutional Review Board (HRIRB). All participants were informed that any data collected from them would be kept anonymous and confidential. The data from the simulation does not contain any identifying information, and participants will not be identified in any way. This thesis plans to sample a subset of the data collected from the NASA Ames simulation.

Participants

The simulation conducted at NASA Ames Research Center included four certified professional TRACON controllers, all with at least 15 years of experience. Nine air transport and/or commercial rated pilots were also part of the simulation, all with 1000 flight hours or more. Supporting simulation participants included two retired controllers and eight general aviation and/or student pilots.

Apparatus and Stimuli

Controllers used the Multi Aircraft Control System (MACS) emulation of a Standard Terminal Automation Replacement System (STARS) display. As shown in Figure 1, the mid-fidelity STARS emulation was shown on 28” Liquid-Crystal Display (LCD) monitors at a resolution of 2048 x 2048 pixels, similar to those used in some current Air Traffic Control (ATC) facilities.

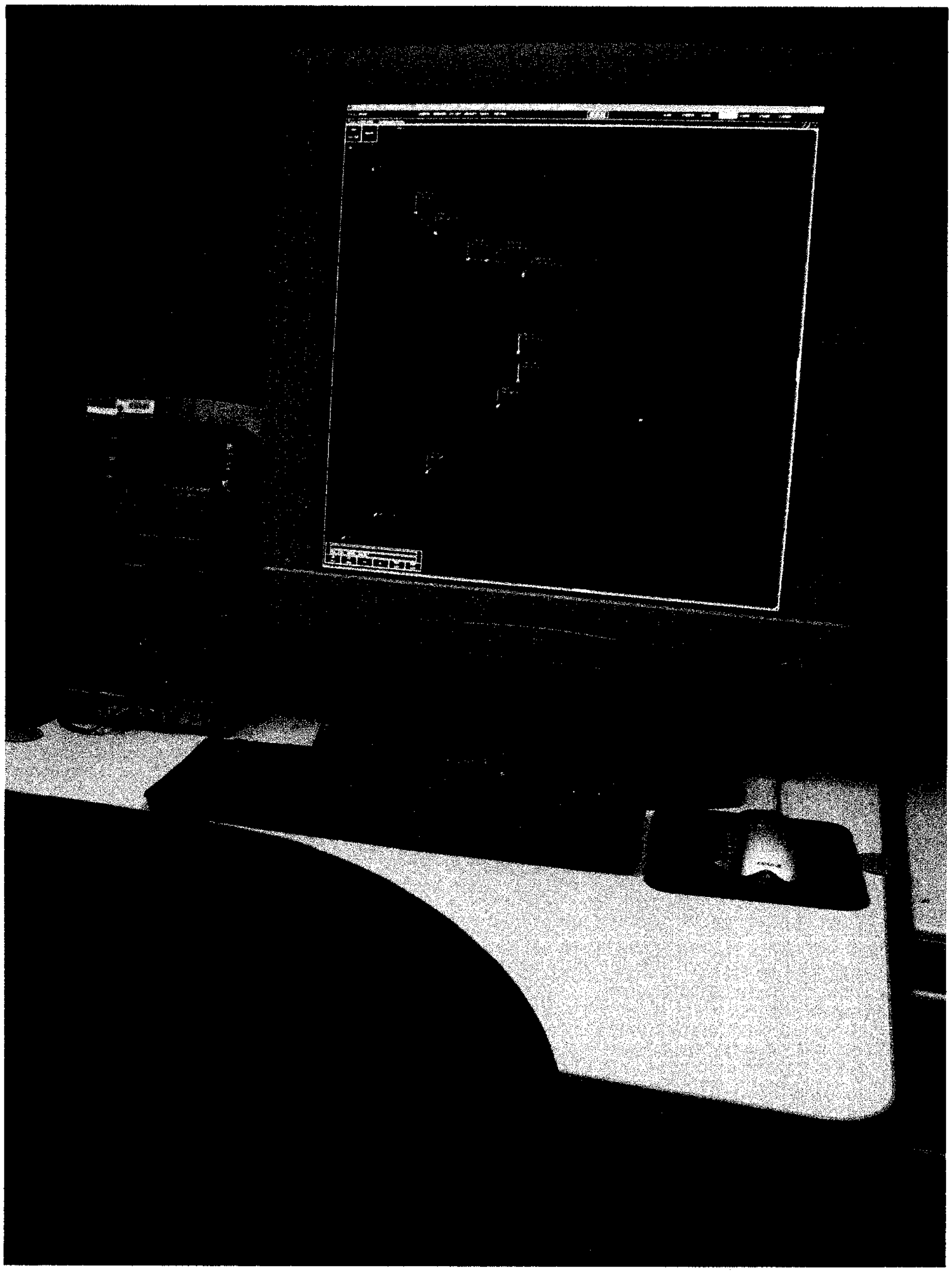

Figure 1. ATC Workstation. The workstation used for the controller positions included a mid-fidelity STARS emulation shown on a 28" LCD monitor.

The simulation conducted at NASA Ames Research Center involved a simulation of air traffic in the Dallas-Fort Worth (DFW) Air Route Traffic Control Center (ARTCC), focused in the TRACON airspace. Figure 2 depicts the simulation airspace, encompassing the western portion of DFW TRACON. One controller staffed the "Feeder" position, a combination of the "NW Feeder" and "SW Feeder" sectors. The Feeder controller received traffic arriving on charted FMS procedures over the northwest (i.e., BAMBE) and southwest (i.e., FEVER) meter fixes delivered from an en route confederate controller ("Center Ghost"). A second controller staffed the "Final" position, a combination of the "13R Final" and "18R Final" sectors. The Final controller was responsible for aircraft on approach to runways 18 Right (18R) and 13 Right (13R), and also handed aircraft off to a confederate tower controller ("TRACON Ghost").
The traffic scenarios were designed for aircraft landing in a south-flow configuration to runways 18R and 13R. Runway 18R was used as the primary landing runway.

The traffic scenarios represented traffic patterns consistent with DFW traffic, having a mixture of mostly large and Boeing-757 (B757) class aircraft. All aircraft in the simulation arrived at the meter fix in descent on a charted arrival procedure. The aircraft routings were RNAV routes designed to be flown in conjunction with the aircraft's Flight Management System (FMS). All traffic scenarios included twenty-one arrival aircraft assigned to runway 18R, divided between two streams across the northwestern BAMBE and southwestern FEVER meter fixes. The FMS procedures were also designed to conform to current-day traffic patterns. Different altitude restrictions were selected to ensure that northwest and southwest arrivals were vertically separated at their merge point. Figures 3 and 4 show the FMS procedures used in the study. The arrival aircraft assigned to runway 13R were also part of the BAMBE stream, but were synchronized such that when they diverged onto the approach routing for their runway, the resulting gaps were left available for 18R aircraft merging from the southwestern stream. Consequently, runway 18R saw high levels of traffic, while runway 13R's traffic was very light.

To help determine the runway schedule, a spacing matrix defines the necessary spacing between aircraft as a function of their weight class. A large category aircraft following another large category aircraft needed to be 80 seconds behind, and 100 seconds were needed when following a Boeing 757 (B757) aircraft. When translated into distance, these values satisfy current-day wake vortex separation minima, corresponding to three and four nautical miles spacing between aircraft, respectively, as measured at the final approach fix (Federal Aviation Administration, 2006). These values also allowed for a margin of error of five seconds.

As part of the simulation, a scheduling mechanism used a reference point at the runway threshold and the aforementioned spacing matrix of temporal separation intervals to predict the trajectory of an aircraft flying the charted FMS

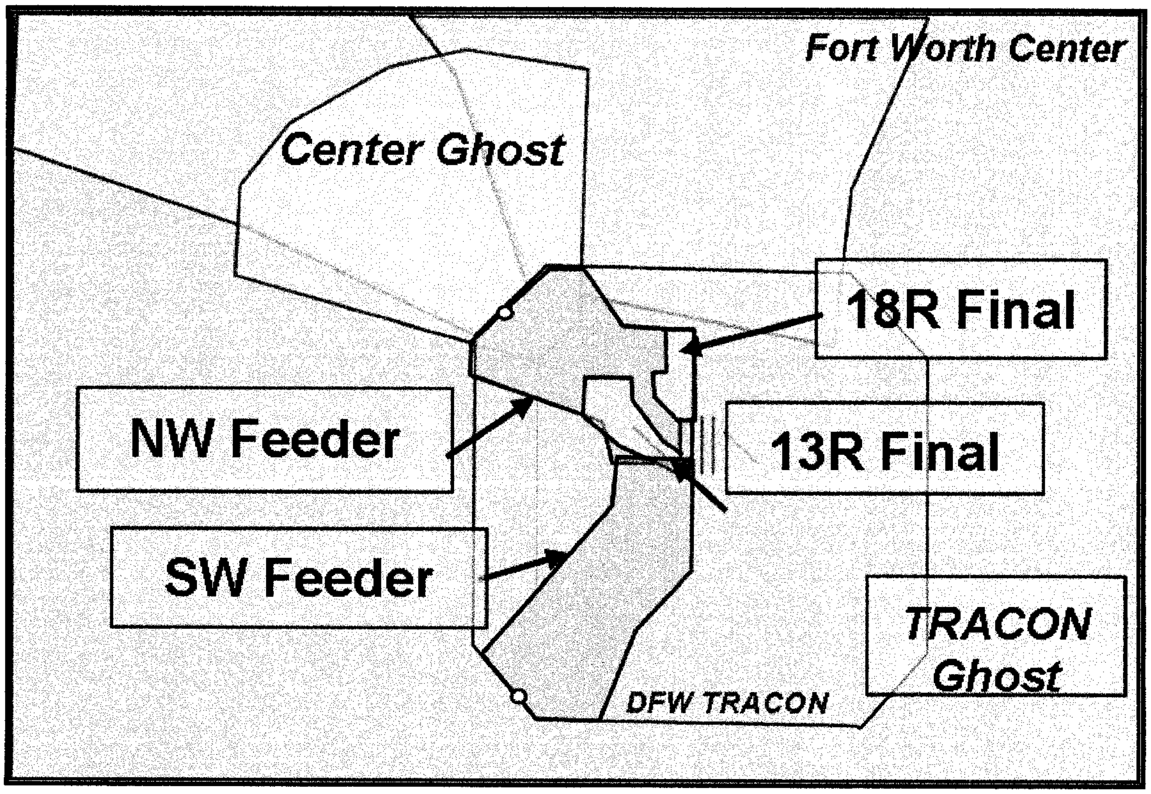

Figure 2. Airspace Map. A map of the airspace used in the simulation conducted at NASA Ames Research Center. The simulation focused on the western half of the DFW TRACON airspace, configured for south-flow operations to runways 13R and 18R.

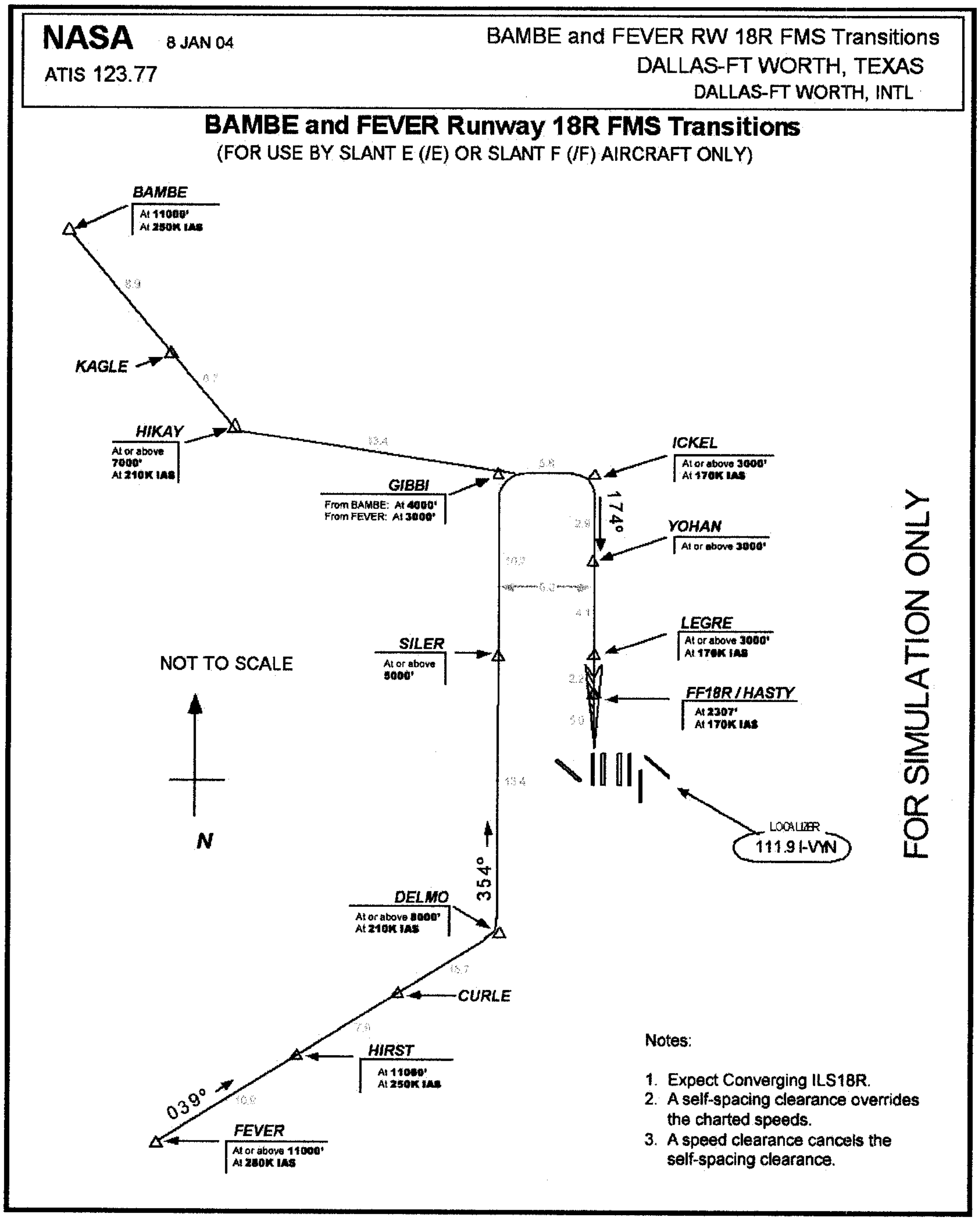

Figure 3. Runway 18R Charted Approach Procedure. An image of the charted approach procedure for runway 18R, including the transitions from both the BAMBE and FEVER meter fixes.

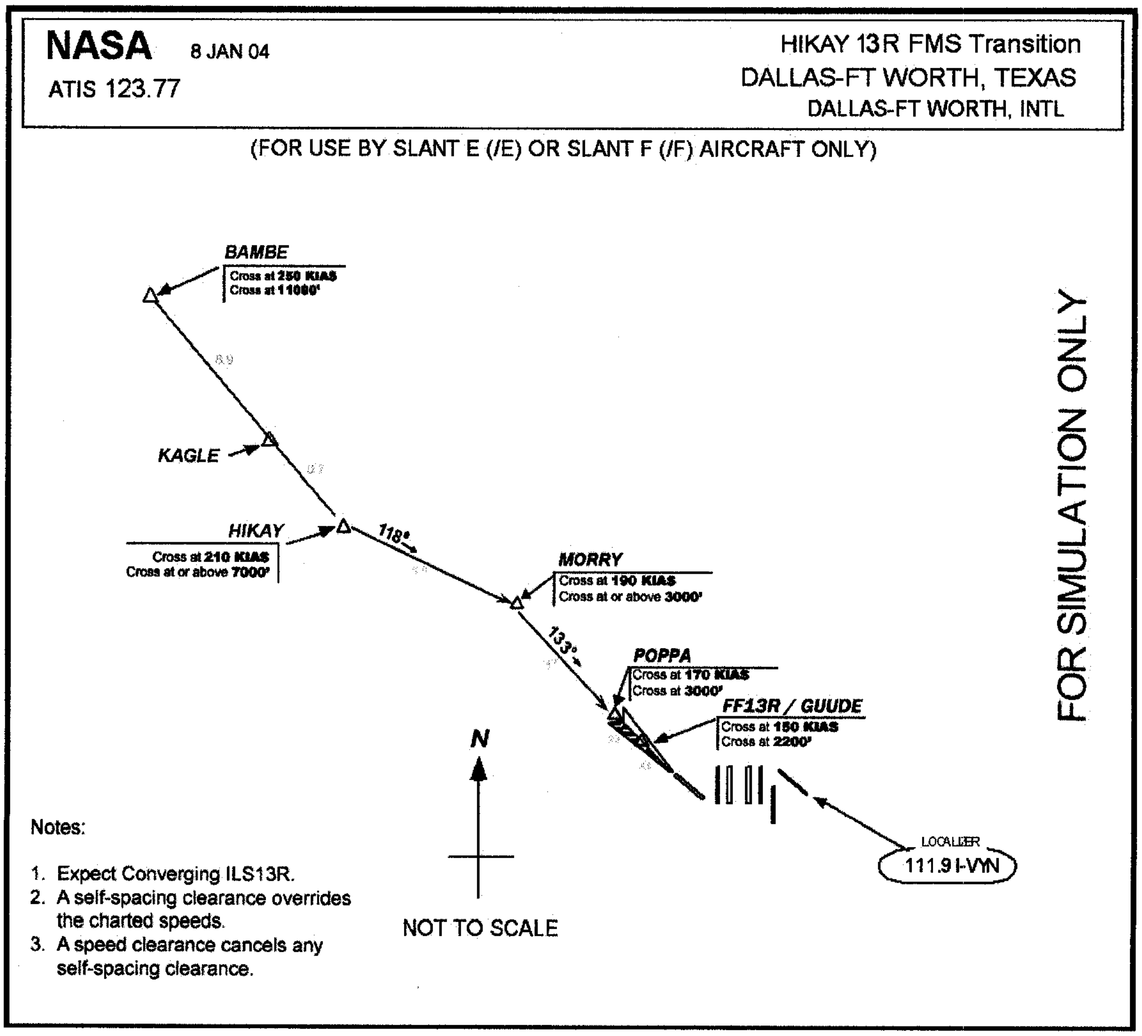

Figure 4. Runway 13R Charted Approach Procedure. An image of the charted approach procedure for runway 13R, showing the transition from the BAMBE meter fix.

procedures through a three-dimensional (3D) wind field. This information was used to compute an estimated time of arrival (ETA) for each aircraft at the runway threshold. The scheduling mechanism then generated a landing sequence and scheduled arrival times (STAs) for all aircraft.

The traffic scenarios were divided into coordinated and uncoordinated flows. The coordinated flow consisted of the first twelve 18R aircraft arriving at their respective meter fix within 15 seconds of their meter fix STA, as if they had been delivered to the TRACON under time-based traffic flow management operations in the en route airspace. The coordinated flow was designed to enter the TRACON according to the overall landing sequence generated by the scheduling mechanism, somewhat synchronizing the northwestern and southwestern streams of aircraft. The uncoordinated flow consisted of the last nine 18R aircraft arriving at the meter fix without the benefit of time-based metering in en route airspace, yielding no synchronization between the northern and southern streams, delivering a flow of aircraft less consistent with the scheduling mechanism's overall landing sequence.

Because of the nature of the scenario design and the functionality of the scheduling mechanism, throughout the simulation the controllers were only allowed to issue descent clearances to the first aircraft (i.e., no speed or route changes). This served to maintain the original intentions of the traffic scenarios. Throughout the entire study, all clearances from the controllers were issued via voice.

All aircraft in the study were piloted by either confederate (multi-aircraft), or participant (single-aircraft), pseudo-pilots. All of the pseudo-pilots' workstations used the Multi Aircraft Control System (MACS) platform for their desktop flight simulators. MACS provides full flight guidance and flight management capabilities to all aircraft. Within the MACS software the flight management and guidance functions are implemented as generic functions that provide the same capabilities as today's systems, but use a very different implementation (Prevôt, 2006). MACS pilot stations also provide advanced functions such as precision Required Time of Arrival (RTA) capabilities, conflict detection, and airborne spacing guidance, the latter being the focus of the NASA Ames simulation. For the simulation conducted at NASA Ames Research Center, the avionics environment was assumed to be somewhat advanced, incorporating as the baseline a Flight Management System (FMS) and Automatic Dependent Surveillance-Broadcast (ADS-B) equipage for all aircraft.

The simulation conducted at NASA Ames Research Center used full pilot involvement- there was no "background" traffic. The pseudo-pilot workstations handled several aircraft simultaneously, with a multi-aircraft pseudo-pilot "flying" anywhere from 1 – 30 aircraft. Because these pseudo-pilots are responsible for the command entries of several aircraft, their cockpit displays are configured as generic input devices designed to enable quick entry of ATC commands. Figure 5 depicts an example of a MACS pseudo-pilot station. Displays included a Control (CTRL) list showing the aircraft being controlled by this workstation, and

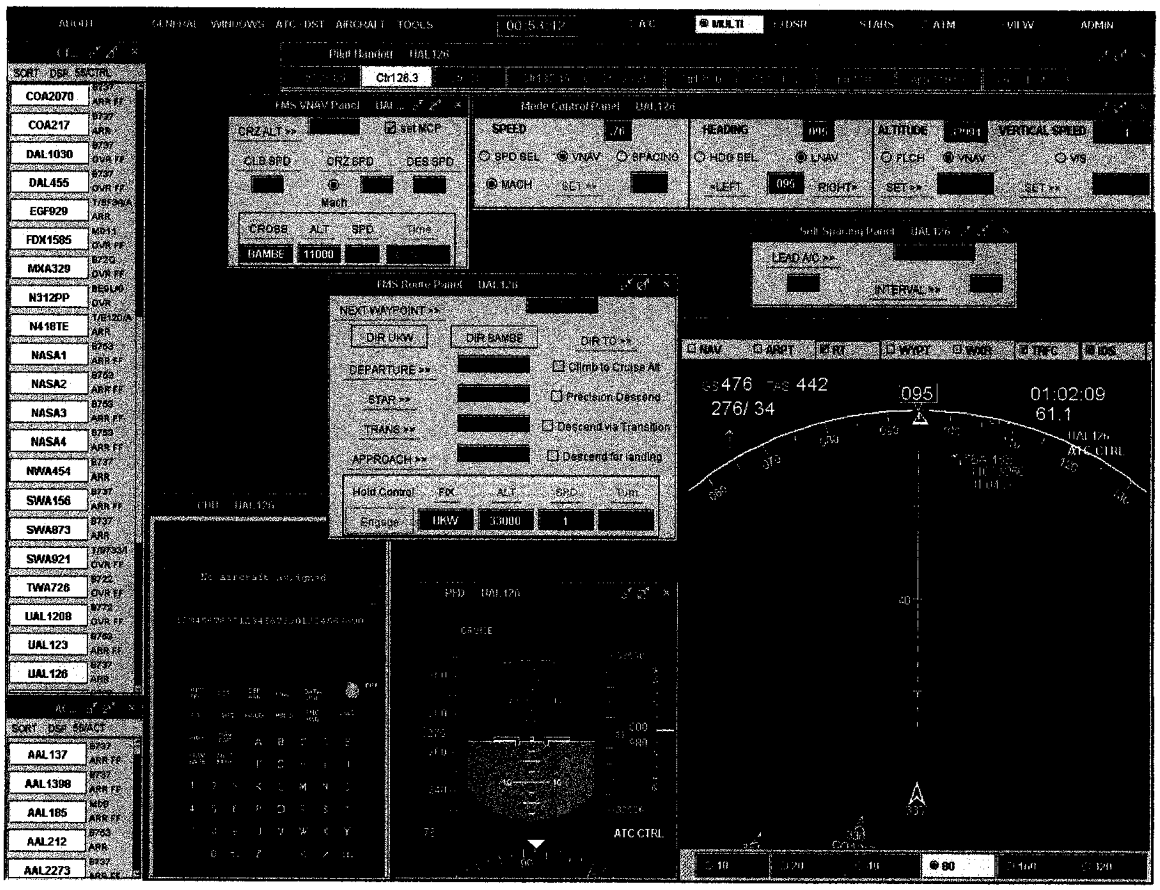

Figure 5. MACS multi-aircraft pseudo-pilot workstation. The cockpit displays used by the multi-aircraft pseudo-pilots were configured for generic, quick entry inputs in response to ATC clearances.

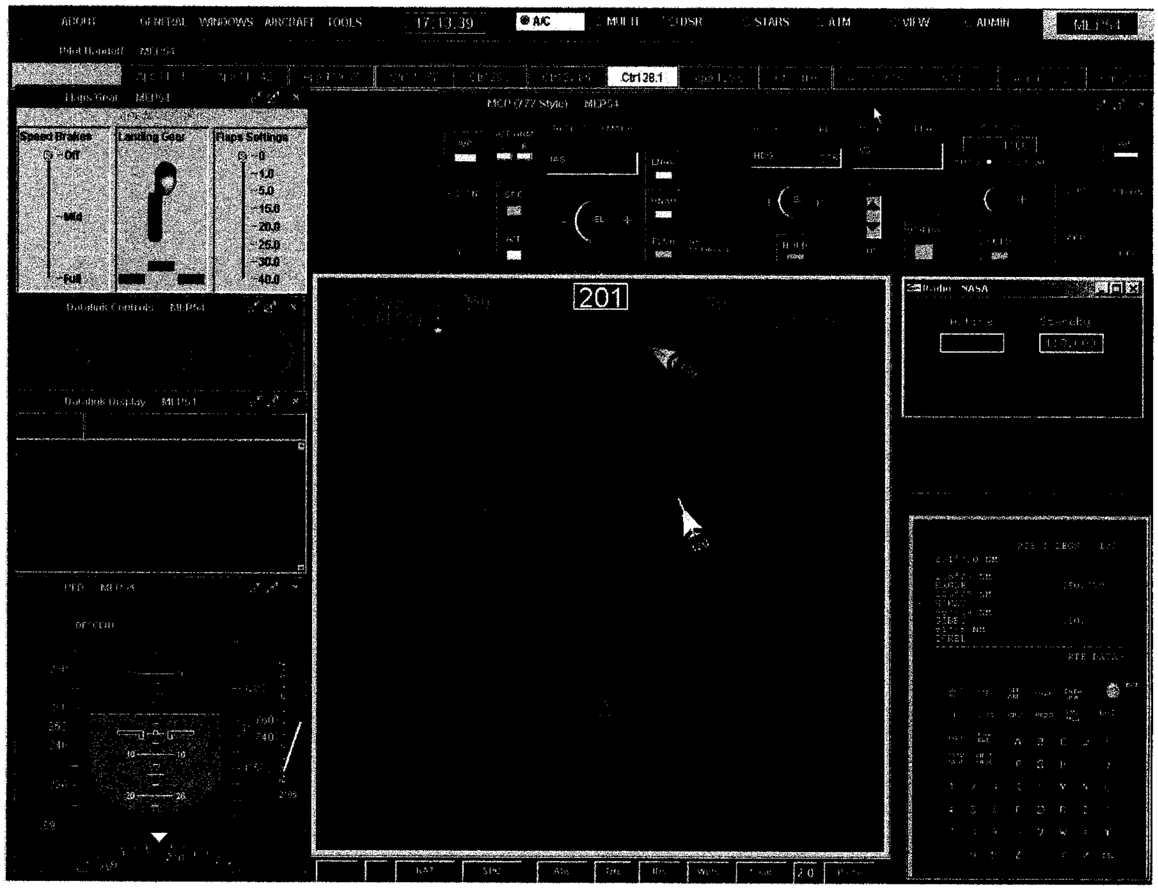

Figure 6. MACS single-aircraft pseudo-pilot workstation. The cockpit displays used by the single-aircraft pseudo-pilots were styled after the controls of a Boeing 777 cockpit.

an Active (ACT) list providing access to all aircraft currently in the simulation. The pseudo-pilot can select any aircraft displayed in any of the aircraft list windows, or can click on the aircraft symbol of another aircraft shown in the Map display. Connected to ATC via digital radio, the pseudo-pilot waits for ATC clearances, or requests them. If ATC issues a clearance to an aircraft, the pseudo-pilot only needs to select that aircraft from their Control list to step into the "cockpit" of that aircraft. With an aircraft selected, the pseudo-pilot can enter basic autopilot commands on the Mode Control Panel and can enter LNAV and VNAV commands on the "FMS Route Panel" and "FMS VNAV Panel." The "Pilot Handoff" panel allows the pseudo-pilot to handoff the aircraft to the MACS pseudo-pilot controlling aircraft on a different frequency.

For the single-aircraft participant pilots, MACS was configured to use cockpit displays reflecting the look of a modern aircraft, emphasizing the correctness of the controls. During the simulation these single-aircraft pilot stations were combined with a Cockpit Situation Display (CSD) providing a Cockpit Display of Traffic Information (CDTI) with advanced trajectory management functions (see Figure 6).

Sequencing and Merging Conditions

The simulation conducted at NASA Ames Research Center investigated the feasibility and operational benefits of ASAS operations in the TRACON under varying conditions. This generated four test conditions:

1. **No Tools (N).** The controllers had no additional DSTs related to ASAS operations. None of the aircraft in this condition were equipped for ASAS clearances. This condition served as a baseline.
2. **Ground Tools (G).** The controllers had advanced DSTs supporting ASAS operations, providing information regarding relative aircraft spacing. None of the aircraft in this condition were equipped for ASAS clearances.
3. **Air Tools (A).** The controllers had no additional DSTs related to ASAS operations. Seventy-five percent of the aircraft scheduled for runway 18R were equipped for ASAS clearances, enabling them to accept ASAS clearances from the controllers.
4. **Air and Ground Tools (AG).** The controllers had advanced DSTs supporting ASAS operations, providing information regarding relative aircraft spacing. Seventy-five percent of the aircraft scheduled for runway 18R were equipped for ASAS clearances, enabling them to accept ASAS clearances from the controllers.

For all test conditions, the STARS emulation enabled the controllers to display an aircraft's FMS route. Indicated air speed was also displayed just beneath an aircraft's target symbol. These enhancements were an assumed part of the simulated future environment with all aircraft fully FMS- and ADS-B-equipped. A shortcut panel containing command entries for common tasks, such as handoffs and distance measurement, was also available during all test conditions. These features were the extent of what was available to the controllers during trials in the No Tools condition. An example of a controllers' display during the No Tools condition is shown in Figure 7.

In addition to the features of the No Tools condition, trials for the Ground Tools condition added other advanced DSTs supporting ASAS operations. A timeline, serving as a graphical representation of the landing sequence generated by the runway scheduling mechanism, displayed ETAs on the left side, and STAs on the right side. Discrepancies between an aircraft's ETA and STA were intended to give the controller an idea of how well the aircraft fit into the overall flow of aircraft. The timeline also enabled controllers to perform manual STA assignments and swaps. Additionally, dwelling on an aircraft displayed a "spacing history circle." Serving as a conformance monitoring tool, the center of the spacing history circle indicated where the lead aircraft was *X* seconds ago, where *X* is the advised spacing interval. The spacing history circles also had a radius of 10 seconds. An aircraft directly following its lead at the correct spacing interval appeared in the center of the spacing history circle. In Figure 8, aircraft COA538 appears slightly behind the spacing history circle that shows were aircraft UAL629 was 100 seconds ago.

For the Air Tools condition, 75% of the scenario's aircraft were equipped to receive ASAS clearances, but the controllers only had the DSTs available from the No Tools condition. Even though no spacing advisories were suggested by the automation, the controllers could still issue spacing clearances via voice. As

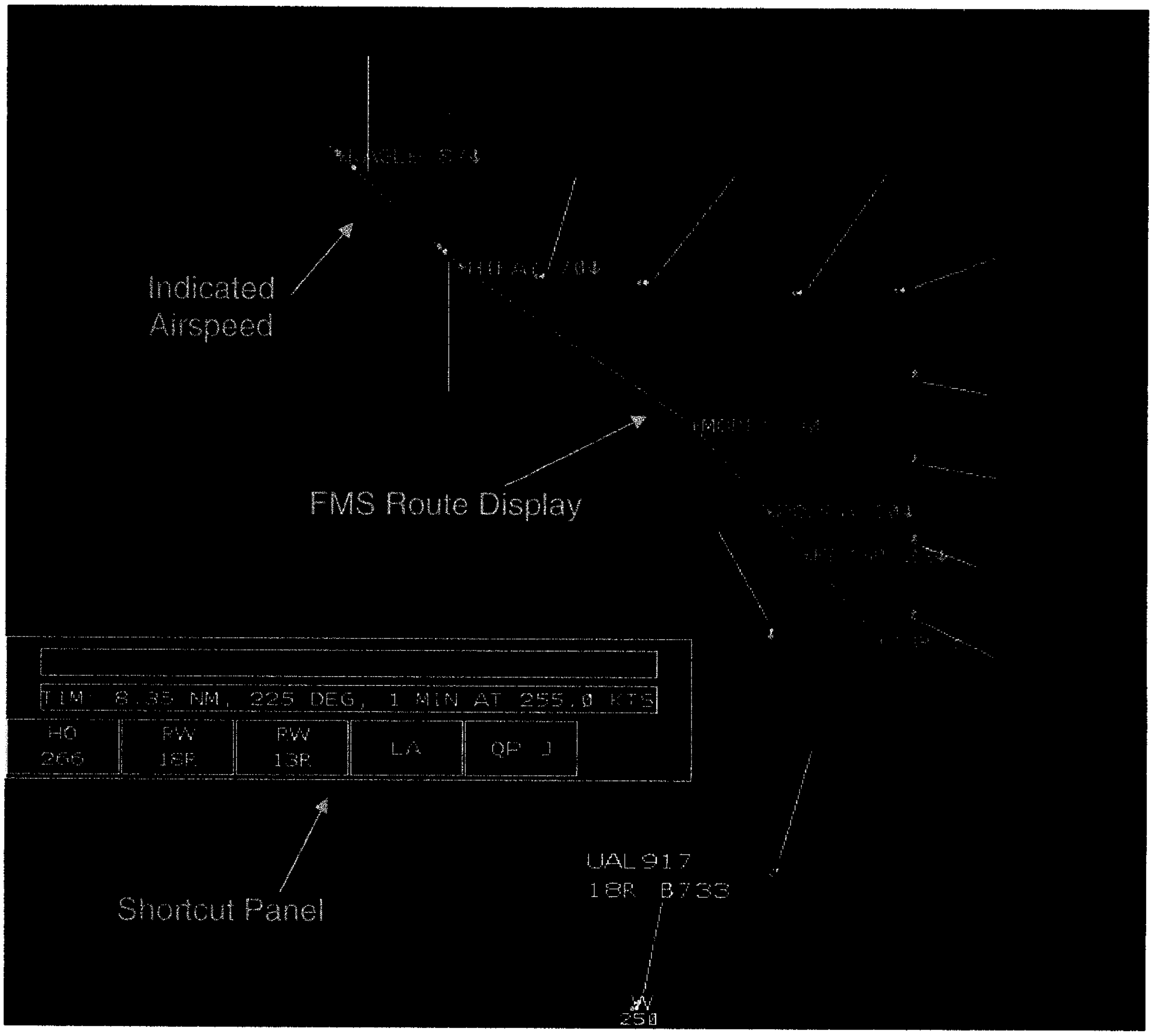

Figure 7. Baseline MACS STARS display. A controller's display from the No Tools condition, showing only basic functionality.

a memory aid, controllers had a spacing equipage indicator for the ASAS-equipped aircraft, enabling them to highlight which aircraft had received spacing clearances. The spacing equipage indicator was included in the datablock, to the right of an ASAS-equipped aircraft's callsign. The presence of a green "/S" indicated to the controller that the aircraft was equipped to receive ASAS clearances, distinguishing equipped and non-equipped aircraft. After assigning a spacing clearance to an aircraft, the controller could make an entry into their workstation, turning the spacing equipage indicator white, as a reminder that the spacing clearance had been assigned, and that the aircraft should be following airborne spacing and merging procedures (see Figure 8). This was the only additional tool given to the controllers that had not been included in the No Tools condition.

During the AG condition, 75% percent of the scenario's aircraft were equipped to receive ASAS clearances. This enabled more DSTs for the controllers, in addition to those available during the other conditions. A spacing advisory tool was presented to the controllers, which used the aircrafts' routing and the separation intervals specified in the spacing matrix to generate an advised lead aircraft and spacing interval. The routing information was used to ensure the selection of a lead aircraft going to the same runway, and the spacing matrix was used to assign a spacing interval based on the lead aircraft's wake vortex category. When an aircraft's current temporal spacing was within 30 seconds of the advised spacing interval, its datablock expanded to display the

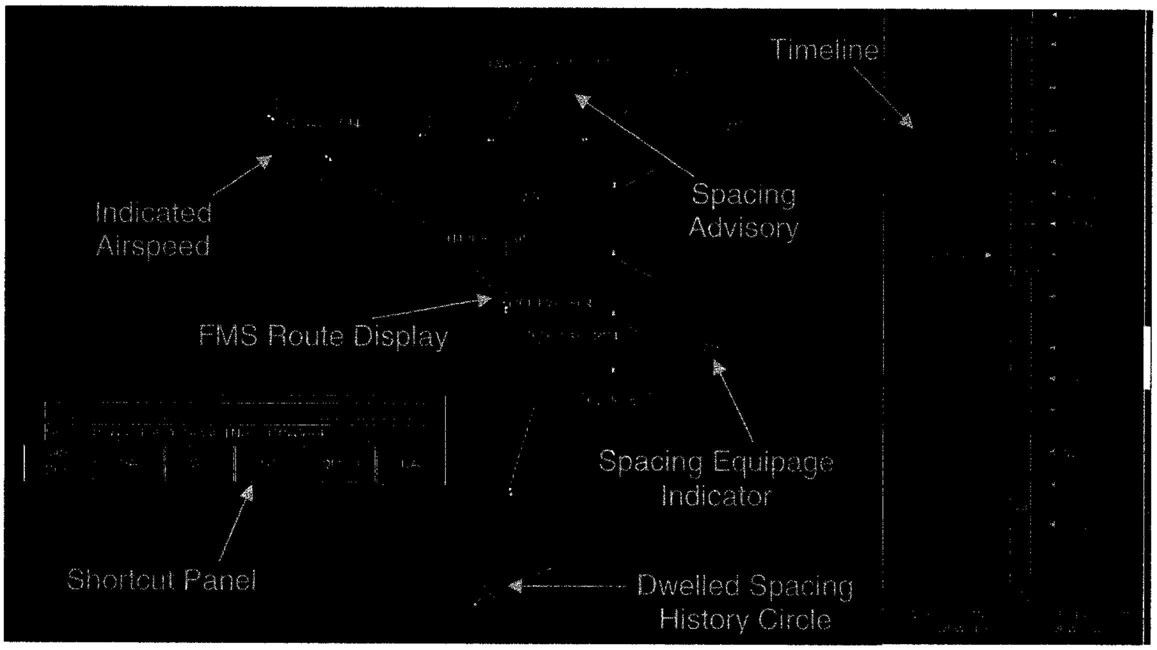

Figure 8. Advanced MACS STARS display. A controller's display from the AG Tools condition, showing advanced ASAS functionality.

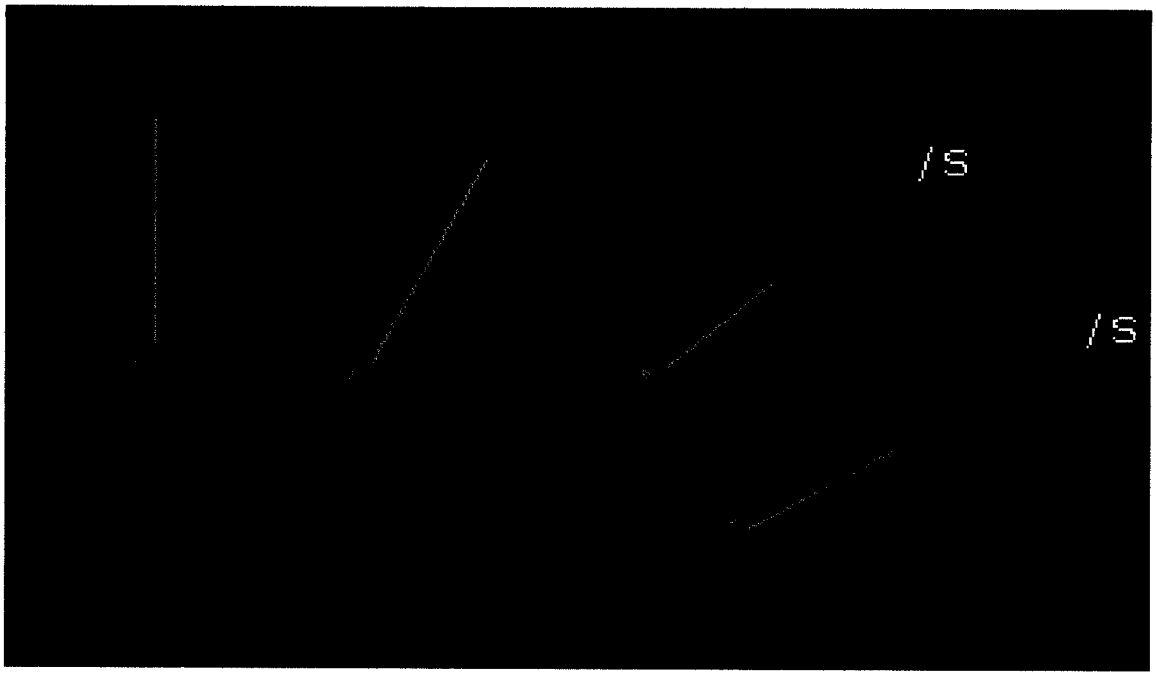

Figure 9. Spacing advisory close-up. Controller displays during the AG Tools condition presented spacing advisories, showing the advised lead, the advised spacing interval, and the current estimated spacing interval.

spacing advisory in a third line. The presented spacing advisory included the advised lead aircraft, the advised spacing interval, and the current estimated spacing interval. In Figure 8 for example, aircraft DAL614 is showing a speed advisory, identifying aircraft NWA882 as the advised lead aircraft with an advised spacing interval of 80 seconds. It is also displaying that currently, the actual spacing behind NWA882 is estimated to be 102 seconds. Figure 9 shows a close-up of the spacing advisory. When dwelling on an aircraft's datablock, the controller saw that the information in the spacing advisory corresponded to the spacing history circle, as observed with aircraft COA538 in Figure 8. The controllers had the option to manually edit spacing advisories using keyboard entries or buttons in the shortcut panel. Controllers could manually create spacing advisories as well.

Design and Procedure

In this 2 x 2 within-subjects repeated-measures design, the two independent variables manipulated among the different conditions were the availability of ground-side ASAS DSTs, and the proportion (either 0% or 75%) of aircraft equipped for ASAS clearances.

One of the tasks of the feeder controller was to issue the descent clearance for the FMS transitions (e.g., "NASA123, continue your descent on the HIKAY 18R FMS transition") upon accepting aircraft from the center ghost controller. The feeder controller would then issue instructions and clearances to separate the aircraft and provide a good flow to the final controller. During test conditions with airborne spacing operations, in addition to standard radar vectors, the feeder controller could issue “follow” or “remain behind” spacing clearances to equipped aircraft (e.g., “Continental 321, follow Southwest 654, 80 seconds in trail,” or “NASA123, merge behind then follow United 456, 80 seconds in-trail”). They were not allowed to issue merge clearances to aircraft arriving from different feeder sectors that would be merging inside the final controller’s airspace. This restriction only applied to the test conditions with airborne spacing tools. When handing aircraft to the final controller, the feeder controller was encouraged to, when possible, deliver the aircraft on their trajectory. This helped give the final controller a more predictable flow. The typical “delivery points” were GIBBI, for the BAMBE flow aircraft, and SILER, for the FEVER flow aircraft.

The final controller’s responsibilities included sequencing and merging the two traffic flows by issuing any radar vectors or spacing clearances necessary. If the feeder controller was able to deliver a well spaced feed, the final controller’s job would be one of “fine tuning,” requiring only minimal sequencing and/or merging control actions. The final controller also issued the approach clearance (e.g., “NASA31, cleared ILS runway 18R”) and was responsible for handing off properly spaced aircraft to the tower’s TRACON ghost controller.

The controllers were informed that the ASAS clearances and ground-side DSTs could be used at their discretion. The controllers were also able to cancel a spacing clearance at any time; if a spacing clearance was not working out as planned, controllers could cancel it explicitly (e.g., “NASA31, cancel self-spacing") or cancel it by issuing a radar vector (e.g., "NASA31, maintain 190 knots"). Throughout the simulation, the controllers issued all clearances via voice and maintained responsibility for separation at all times.

The simulation at NASA Ames Research Center was conducted during a two-week period that included two travel days for participants. Two days of training were the first stage of the simulation, familiarizing the participants with the different DSTs and discussing roles and responsibilities for each of the different test conditions. Data was collected for 16 repetitions of each condition. To accomplish all this within the two-week period, two identical simulations were conducted in parallel. The four controllers rotated among the resulting positions, forming two-person "teams." Controllers paired together remained a team for an entire day. Each day, the four conditions were tested in random order, with two trials per condition. Each of the conditions' two trials was run back to back, allowing both members of a controller team to work in both the feeder and final positions for every condition. Each trial lasted 35 minutes, regardless of whether all the aircraft had been handed off to the TRACON ghost controller. A short ten-minute break occurred between the back to back trials, and between conditions there was a 15-minute break. A one-hour lunch break occurred after the second condition of each day. A sample of one day's schedule is shown in Table 1.

Data was logged at all participants' computer stations and other dedicated data collection stations through internal software processes. The objective measures consisted of system performance data (i.e., aircraft position information, aircraft crossing times at the final approach fix, etc.) and task data (i.e., controller and pseudo-pilot interface inputs). Voice communication recordings and video captures of the airspace during all simulation trials were collected. Subjective data measures collected included perceived controller workload and questionnaire feedback. Workload Assessment Keypads (WAKs) probed the controllers' workload at five-minute intervals during simulation trials using Air Traffic Workload Input Technique (ATWIT) ratings (Stein, 1985). Workload questionnaires followed each trial, and participants provided feasibility, acceptability, and usability feedback in questionnaires and debrief discussions at the conclusion of the study. Audio recordings of the debrief discussions were also collected.

The primary dependent measures for this thesis include frequency and type of clearances issued by controllers, spacing between subsequent aircraft as they crossed the final approach fix, and also controller feedback. These measures will be used to test the hypothesis that ASAS operations in a mixed-equipage environment improve system performance and are acceptable to air traffic controllers without any modifications to the ground system.

Table 1.

Data collection schedule. After the participants completed their training, this was the daily schedule used during the data collection runs.

PST	Friday, 08/06/2004
8:00	Session 1 : AIR TOOLS condition
8:15	Run 9
9:00	Run 10
9:35	break
9:50	Session 2 : NO TOOLS condition
10:00	Run 11
10:45	Run 12
11:20	lunch
12:30	Session 3 : AIR AND GROUND TOOLS condition
12:45	Run 13
13:30	Run 14
14:05	break
14:20	Session 4 : GROUND TOOLS condition
14:30	Run 15
15:15	Run 16
15:50	end
16:00	

RESULTS

The current study analyzes the data from a controller's and overall system's perspective, with minor references to pilot data where necessary. For a more detailed analysis of flight deck issues and the pilots' data and feedback regarding CDTI-based ASAS operations, refer to Battiste et al. (2005).

Operational Efficiency

Flight efficiency is an important component of concept acceptability. Perhaps more important than showing an efficiency benefit, a viable concept for new air traffic operations should not have a negative impact on flight efficiency. An analysis, using the total distance flown as a dependent variable, was done to examine any possible effects from ASAS operations on flight efficiency. The distance flown was defined as the total number of nautical miles (nmi) flown between two standard points: the meter fix and the final approach fix. To minimize confounds, the aircraft from the BAMBE meter fix were analyzed separately from those coming over the FEVER meter fix. Because there were relatively so few, the aircraft landing at runway 13R were excluded from this analysis. The results of a two-way, repeated-measures Analysis of Variance (ANOVA) show a significant main effect for the availability of ground tools for both the BAMBE, $F(1, 428) = 4.195$, $p < 0.05$, and FEVER flows, $F(1, 200) = 4.310$, $p < 0.05$ (Figures 9 and 10). The data suggests that in conditions with ground tools, aircraft flew slightly longer paths (an increase of less than 0.7 nmi) inside the TRACON. This also suggests that airborne spacing and merging

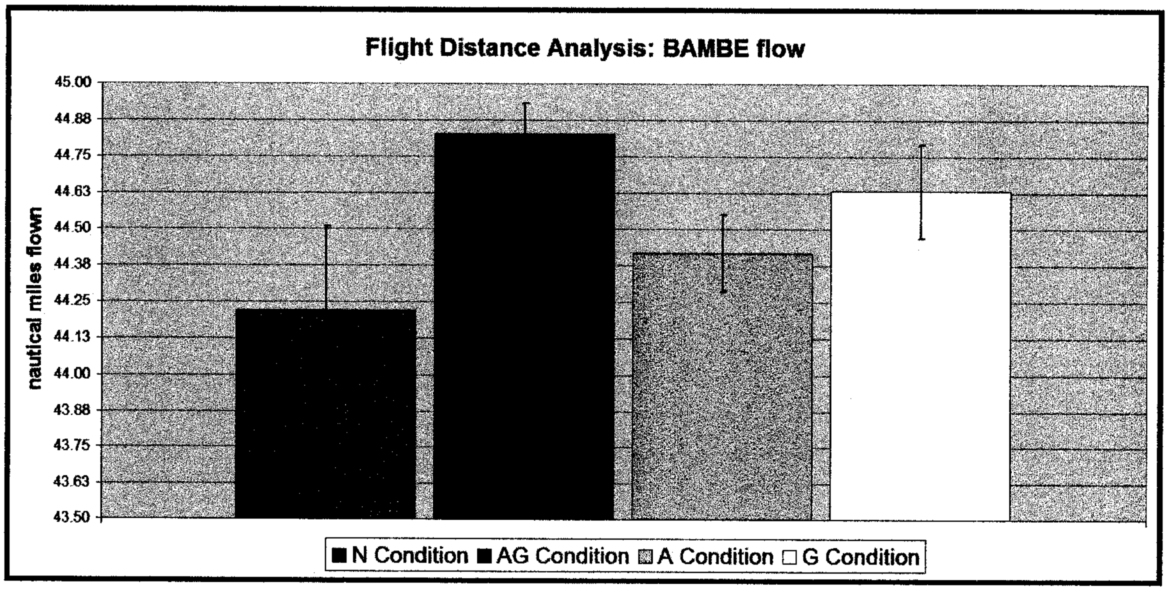

Figure 10. Cumulative flight distance for BAMBE aircraft. A significant main effect for the presence of ground tools was shown, indicating a small increase in total distance flown in conditions with ground tools.

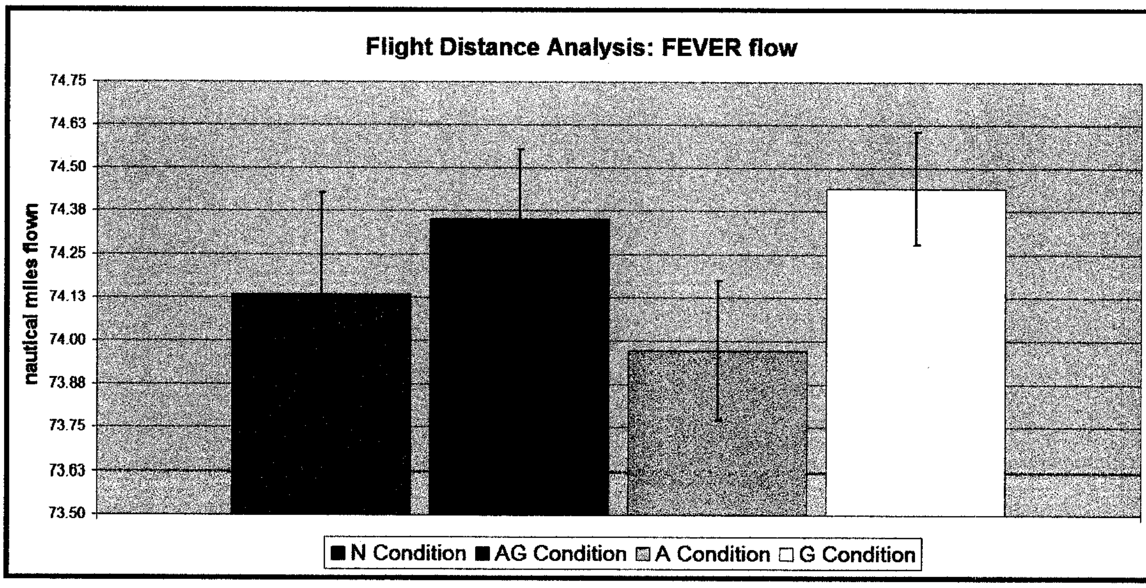

Figure 11. Cumulative flight distance for FEVER aircraft. A significant main effect for the presence of ground tools was shown, indicating a small increase in total distance flown in conditions with ground tools.

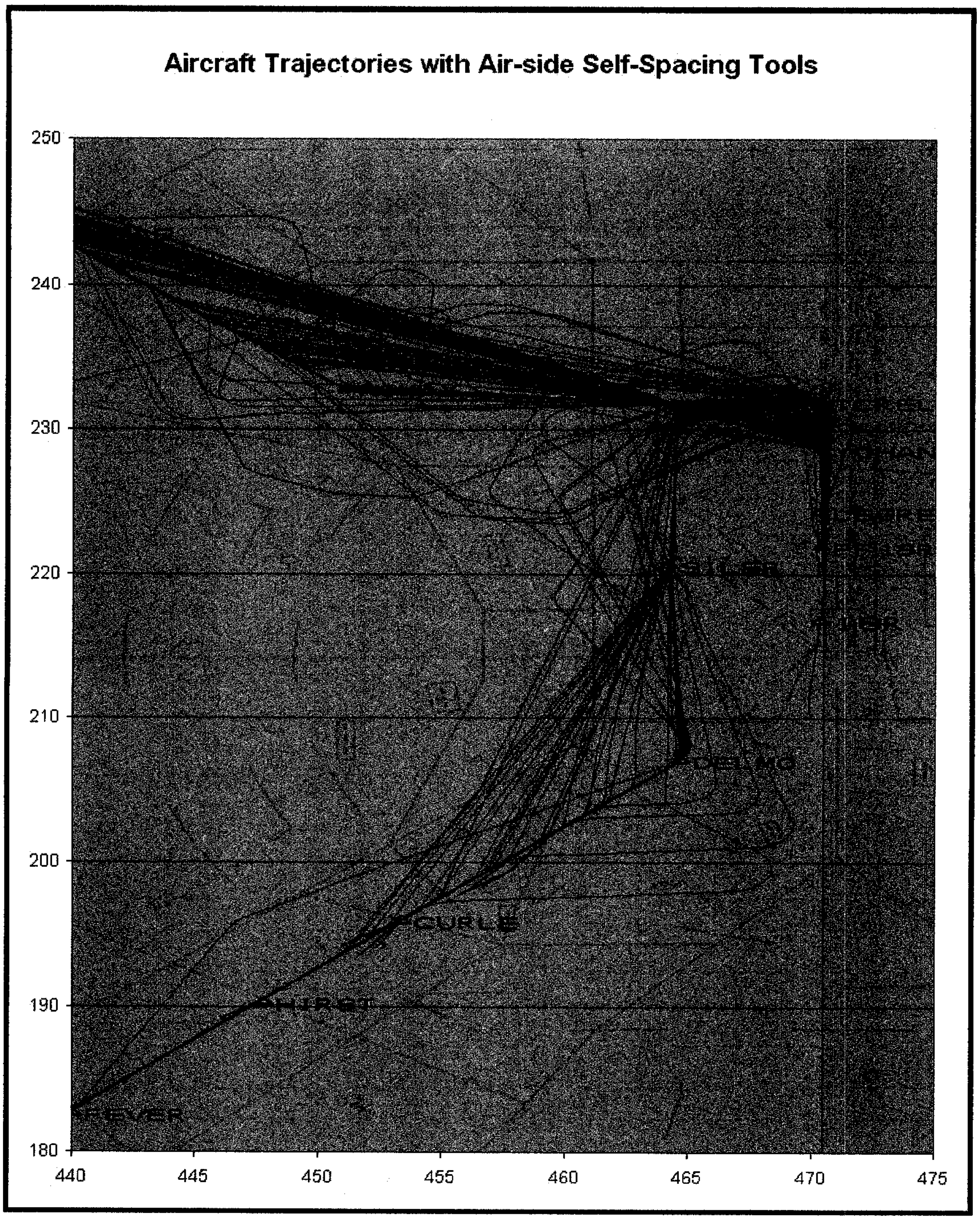

Figure 12. Recorded aircraft trajectories for the A condition. A visualization of the lateral paths flown by all the aircraft throughout the simulation, overlaid onto a portion of the TRACON airspace map.

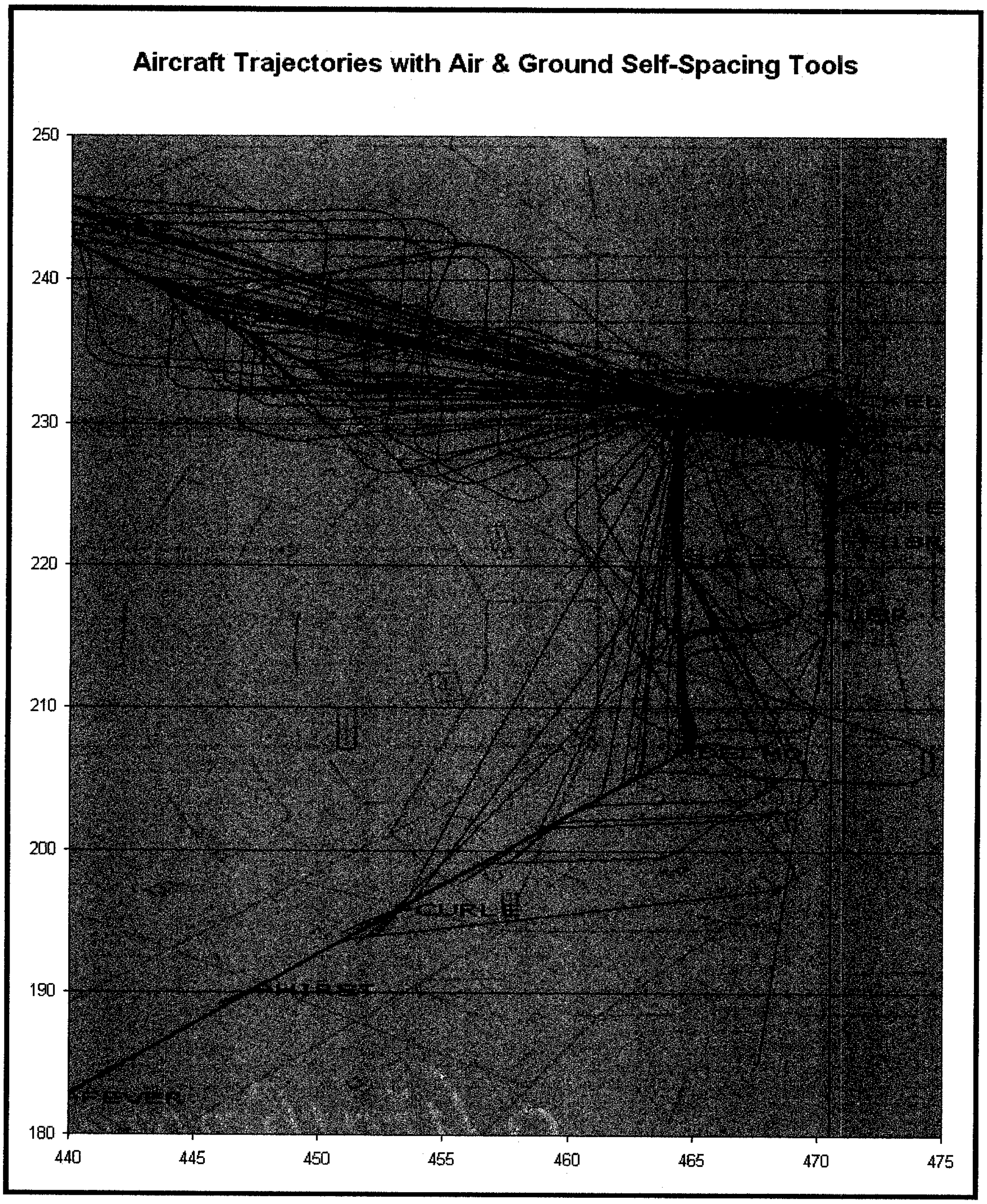

Figure 13. Recorded aircraft trajectories for the AG condition. A visualization of the lateral paths flown by all the aircraft throughout the simulation, overlaid onto a portion of the TRACON airspace map.

operations do not negatively affect the total distance flown. The effect of the ground tools can also be seen by visually comparing the data from the A and AG conditions, thereby controlling for the effect of airborne spacing and merging. Figures 11 and 12 provide geographic representations of the lateral trajectories from the A and AG conditions, in which the paths flown by aircraft in the AG condition seem to include slightly more vectoring. Comparisons between the N and G conditions similarly control for the effect of airborne spacing and merging while isolating the effect of the ground tools, and show comparable results.

Figure 13 depicts a histogram of the inter-arrival spacing between subsequent aircraft measured at the final approach fix for runway 18R. The analysis examined the wake vortex spacing error, as defined by the actual spacing between consecutive aircraft compared to the required spacing between consecutive aircraft. The results indicate that inter-arrival spacing accuracy improved in the two conditions with airborne spacing and merging, Browne-Forsythe $t(254) = 5.651$, $p < 0.001$. Further analyses revealed that, when comparing only the A and AG conditions, the addition of controller DSTs does not seem to improve spacing accuracy beyond that obtained in the condition with air tools alone.

Self-report Data

The subjective workload reported by the controllers remained in an acceptable range for all conditions, indicating that the concept of airborne spacing and merging is feasible from an air traffic controller's perspective, and

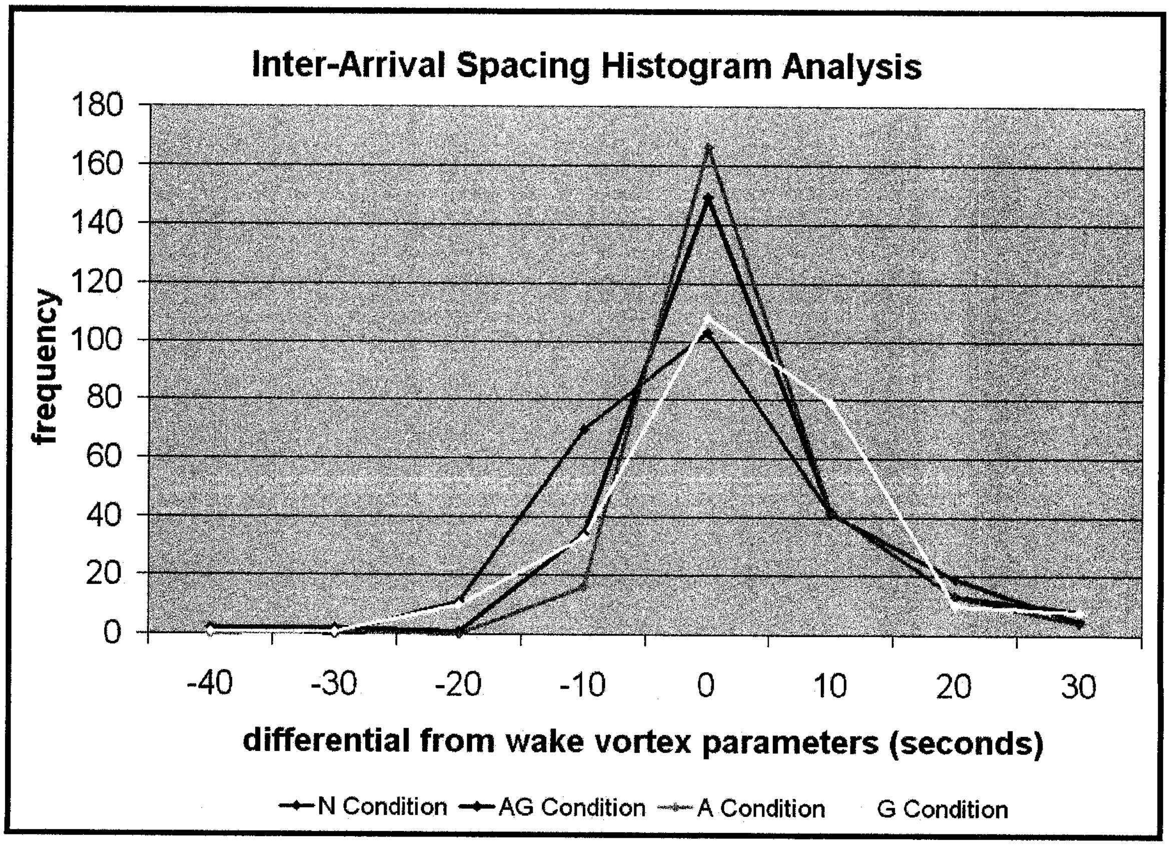

Figure 14. Inter-arrival spacing histogram. The amount of deviation from the wake vortex separation requirements plotted for all conditions. A significant main effect of the presence of airborne spacing and merging indicates that during ASAS operations there was less variance in the inter-arrival spacing.

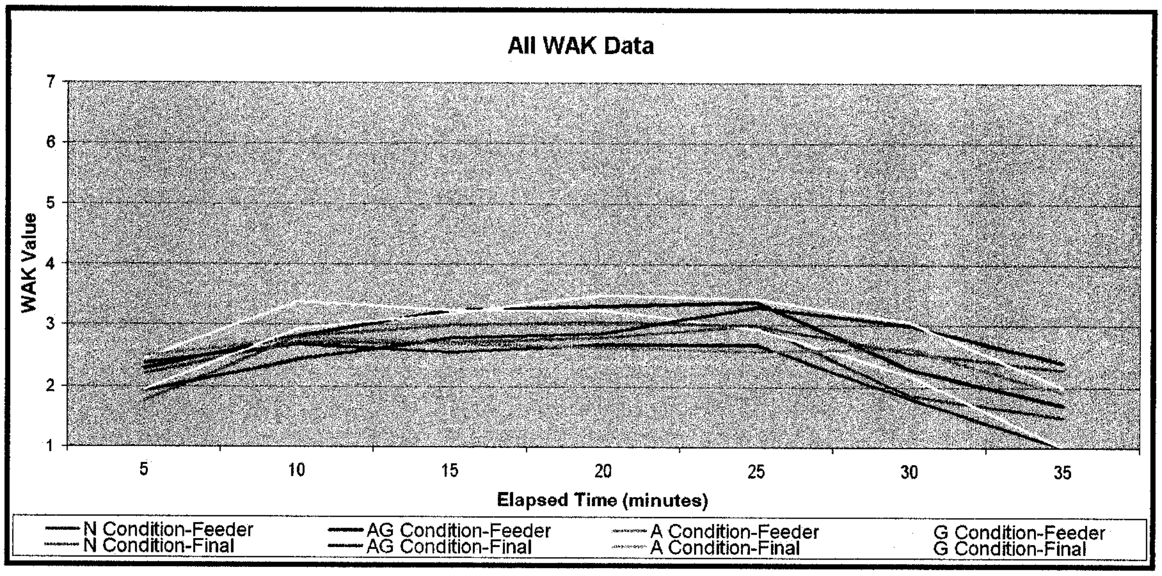

Figure 15. Controller self-reported workload ratings. Throughout the entire simulation, the ATWIT ratings across all conditions were in an acceptable range.

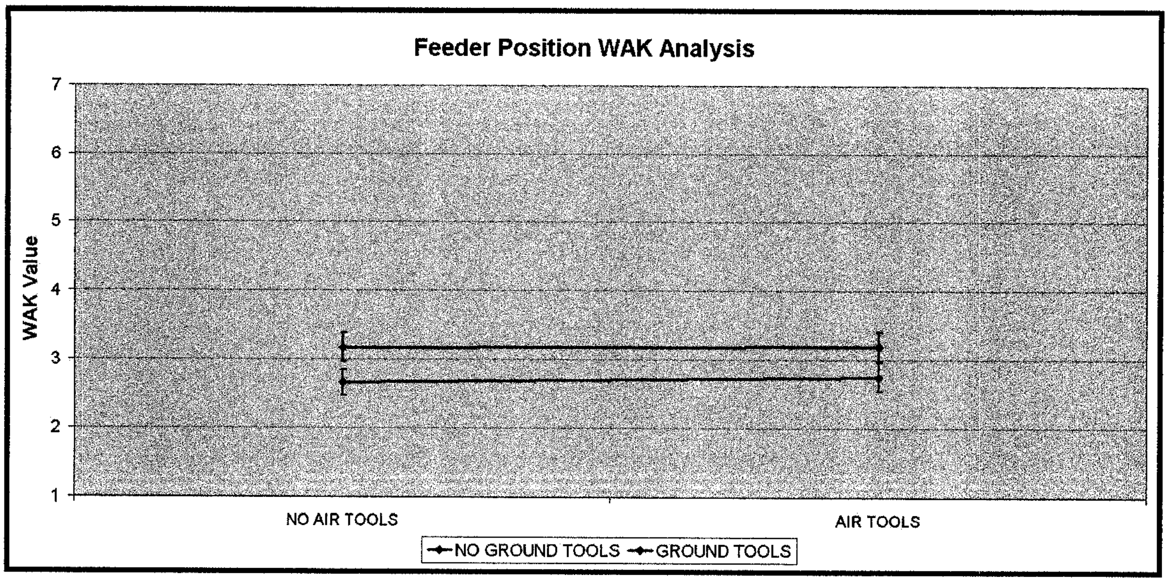

Figure 16. Feeder controller's perceived workload. The workload data for the feeder controller yielded a significant main effect of the presence of ground-side tools, indicating that ASAS operations did not negatively impact controller workload.

does not result in any unreasonable workload increases for the traffic loads used in this simulation (see Figure 14). From a 7-point scale, with seven representing high workload, the mean controller workload across all conditions was 2.92 (SD = 0.77). Overall, workload was on average lowest in the A condition (M = 2.69, SD = 0.78) and highest in the G condition (M = 3.19, SD = 0.74). As a subjective measure, defining an acceptable level of controller workload is difficult. However, previous research in the AOL indicates that WAK scores between 1 and 3 correlate with more relaxed controller body language. Additionally, scores of 4 and 5 are most common when controllers seem reasonably busy, and scores of 6 and 7 correlate with very intense workload situations. These views are based on over-the-shoulder observations from past human-in-the-loop research, and appear to generalize across most individual differences.

When distinguishing between the two controller positions, the feeder controller's data indicated a main effect for the availability of ground tools, $F(1, 60) = 5.570$, $p < 0.05$. The feeder's workload data showed a slight increase in perceived workload in conditions with ground-side tools (see Figure 15). Even with this increase, the workload ratings still remained within an acceptable range. This minor difference is perhaps an artifact of how the controllers internalize and interpret workload and taskload, highlighting the very subjective nature of this measure.

The controllers were also asked to rank each of the conditions in terms of workload. Overall, the G condition was ranked as the condition with the lowest perceived workload, followed by the AG and N conditions, leaving the A condition ranked as that with the highest relative workload. The opinions between controllers were not very consistent, as shown by the results of an ANOVA, which returned no significant differences for the workload rankings. The controllers expressed the feeling that without DSTs, monitoring the behavior and performance of aircraft actively engaged in airborne spacing and merging was very difficult. Interestingly, this data contradicts the WAK results, contrasting a controller's desire to have access to the information provided by the ground tools, while perhaps feeling a workload increase from the responsibility of providing separation after delegating spacing and merging tasks to the aircraft.

Concept acceptability in terms of safety was also analyzed. The controllers were asked to judge how safe the conditions were in comparison to current-day operations. The N condition, in this case, was included as part of current-day operations, thus the controllers only judged the A, G, and AG conditions. From a 5-point scale, (1 representing much less safe; 5 representing much safer than current day operations), controllers rated the operations as safe for all conditions ($M = 3.36$, $SD = 0.55$). However, when asked to rank the conditions by safety, controllers ranked safety highest for the G condition, followed by the N, AG, and lastly A conditions (note: one controller described all conditions as equally safe). An ANOVA for this data revealed no significant differences for the safety rankings. These results were consistent with the general patterns in the subjective workload rankings. Uncertainty regarding the behavior of the aircraft conducting airborne spacing under certain traffic situations may have contributed to the lower safety rankings of the conditions with airborne spacing and merging.

Additionally, the controllers ranked the conditions according to their preference for use. A majority of controllers preferred the condition with both air and ground tools. The condition with only air tools was unanimously found to be the least preferable. These results suggest that the controllers are partly in favor of the airborne spacing and merging concept, and improvements could be made to the tools to increase controller acceptance even further. Controller comments generally mirrored these preference rankings.

When asked to rate the general acceptability of the concept, the controllers rated the airborne spacing and merging operations rather highly. On a 5-point scale (with 1 representing "not at all acceptable"; 5 representing "completely acceptable"), controllers rated the acceptability of spacing and merging operations in a mixed equipage environment with a mean acceptability score of 4.5 (SD = 0.58). Addressing the particular aspect of limited delegation, the controllers were asked to rate the acceptability of permitting aircraft to control their own speed for spacing and merging operations. The controllers answered with a mean score of 4.3 (SD = 0.58). This data suggests that the controllers viewed the concept as promising, and had an overall positive feeling about airborne spacing and merging in the TRACON.

As part of a post-simulation questionnaire, the controllers were asked to rate the usefulness of the DSTs provided to them. From a 5-point scale, (1 representing very useless; 5 representing very useful), controllers rated most of the tools favorably, as shown in Figure 16, which represents their responses to the tools in the AG condition. The tools specific to airborne spacing and merging operations received high usefulness ratings (M = 4.5, SD = 0.73), indicating that the controllers liked the tools and found them effective for the task. During the A condition, the only tool the controllers had for airborne spacing and merging was the self-spacing equipage indicator, which was again rated as highly useful. The other tools available during the A condition received moderate or high usefulness ratings, suggesting that they saw the provided DSTs as beneficial for the task. The controllers' usefulness ratings for the A condition are shown in Figure 17.

Controller Activity and Strategy

Clearance data was analyzed to gain some insights into the impact of airborne spacing and merging clearances on controller activity and strategy. Figure 18 shows a comparison between the tactical altitude and speed clearances issued by controllers during the conditions with ASAS (A and AG) and without ASAS (N and G). When airborne spacing and merging was available, altitude and speed assignments were reduced, especially at the final controller position. For the feeder controller, altitude clearances were reduced by 10%, and speed clearances by 30%. At the final controller position, altitude clearances were reduced from 148 to 55 (a 63% reduction), and speed

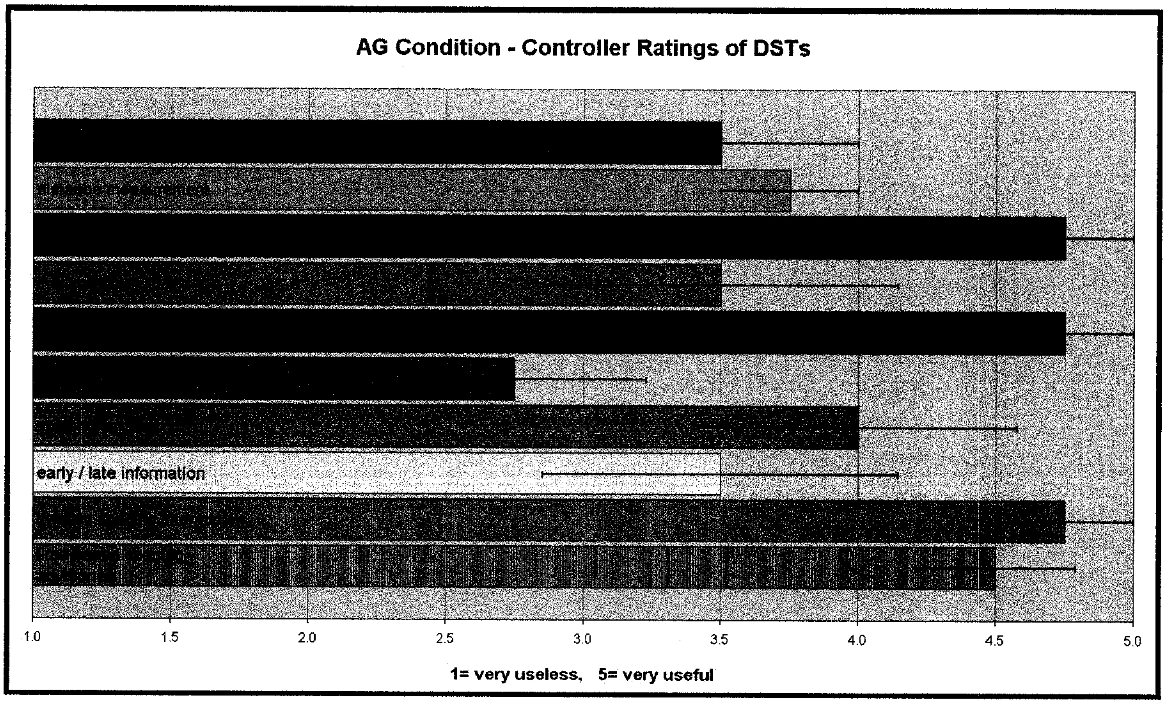

Figure 17. Tool usefulness ratings for the AG condition. In general, the controllers rated most of the DSTs in the AG condition as moderately or highly useful. The tools specific to ASAS operations (self-spacing equipage indicator, spacing circles, dwelled spacing information, and time-based spacing advisories) received high usefulness ratings.

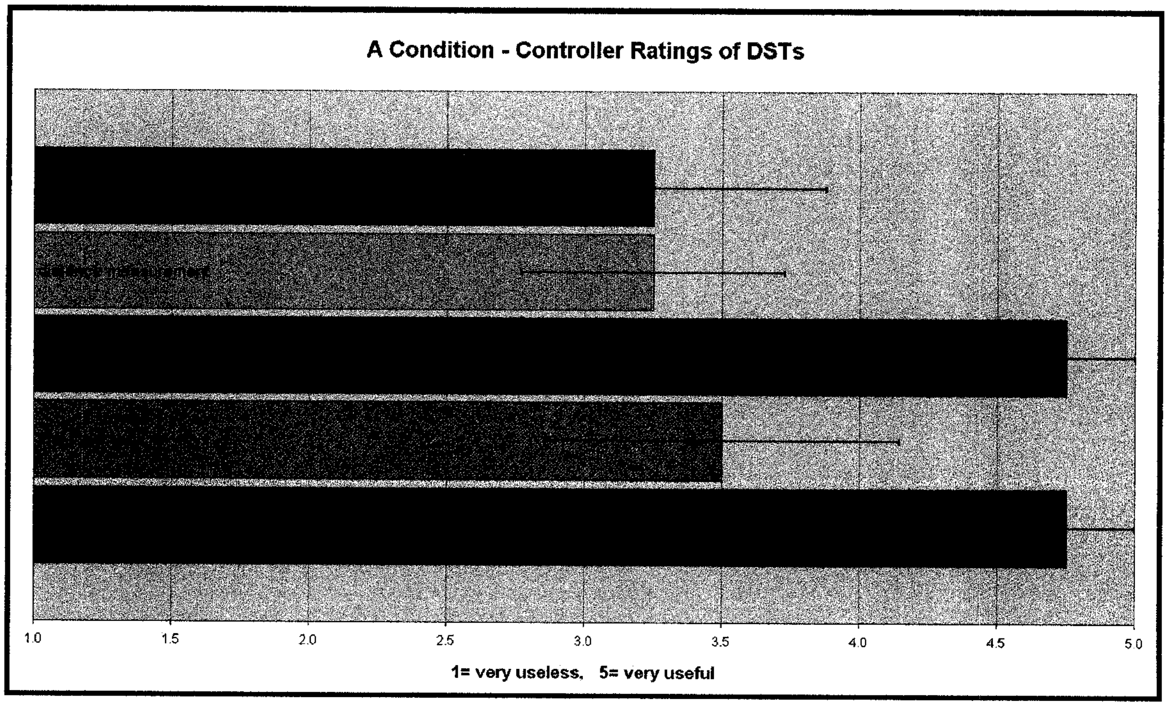

Figure 18. Tool usefulness ratings for the A condition. Controllers only had one tool related to ASAS operations, the self-spacing equipage indicator, which was seen as highly useful by the controllers. Their other tools received moderate and high usefulness ratings, suggesting that the controllers considered the tools as beneficial to the task.

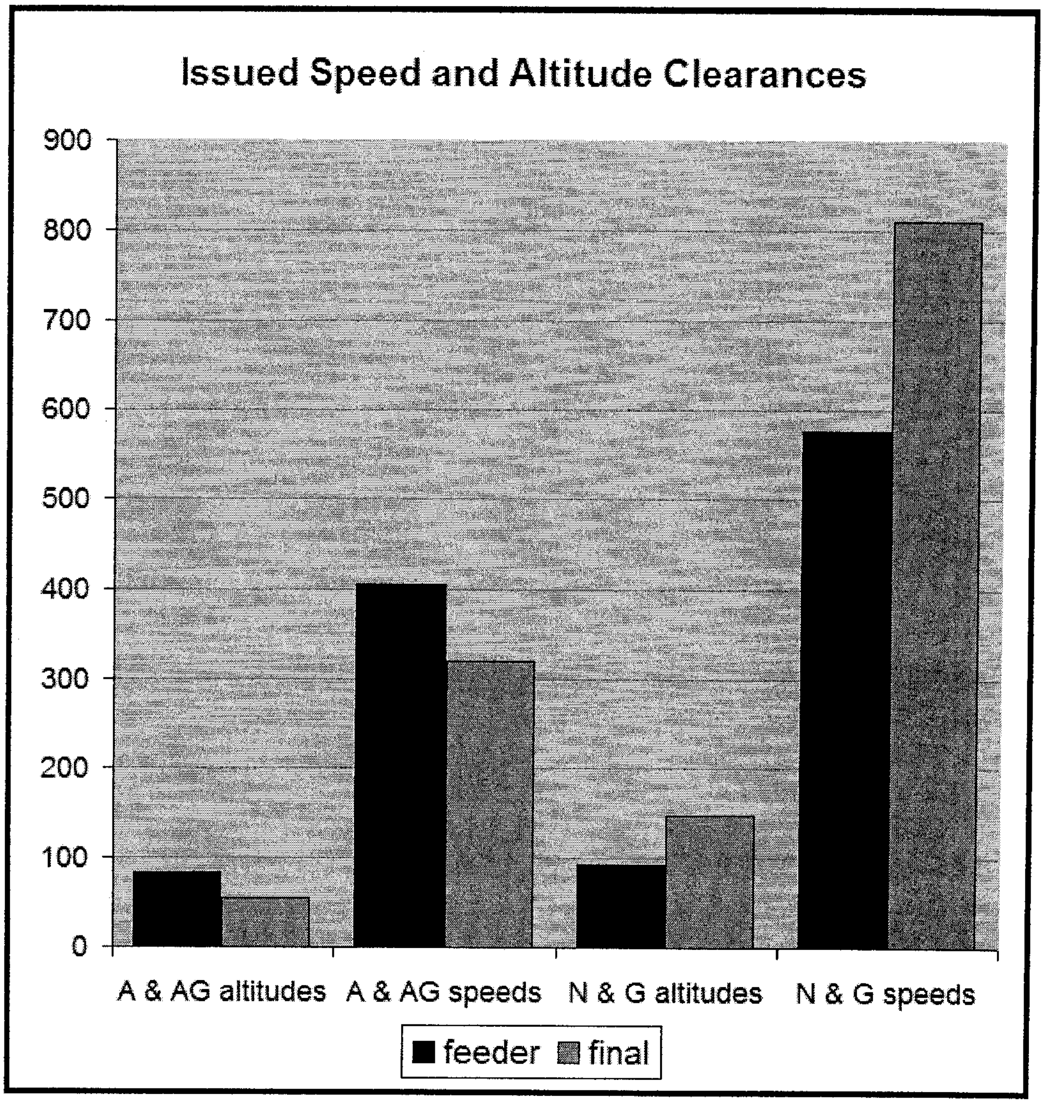

Figure 19. Total number of tactical speed and altitude clearances. Airborne spacing and merging operations reduced the number of altitude and speed clearances issued by the controllers. The effect is most notably seen with speed clearances issued by the final controller.

clearances were reduced from 811 to 320 (a 61% reduction). This suggests that the use of airborne spacing and merging clearances does help with the compression of descending and decelerating aircraft, resulting in fewer interruptions to an aircraft's descent profile. The decrease in issued speed clearances was significant for both the feeder and final controllers, $t(7) = -2.34$, $p < .05$, and $t(7) = -6.58$, $p < .001$, and is also consistent with the WAK data that reported lower workload in conditions with airborne spacing and merging.

Looking at Figure 19, we see a complementary trend. With airborne spacing and merging, on average the controllers issued less heading vectors to aircraft. The feeder controller saw a 13% reduction in heading vectors, while the reduction was higher and statistically significant for the final controller, $t(7) = -1.98$, $p < .05$, showing a decrease from 116 to 62 heading vectors (a 47% reduction) during conditions with ASAS. The data does correspond well with the inter-arrival spacing results and the WAK data, suggesting that airborne spacing and merging operations can help controllers deliver a more precise flow of aircraft with fewer clearances. These findings can also be seen from an overall look at the clearances issued in the different conditions, as illustrated in Figure 20.

Airborne spacing and merging operations not only impact the number of clearances issued, but also the location of clearances issued. Together, these two attributes of controller activity provide insight into the controller's strategy for managing the traffic. A look at the geographical distribution of clearances

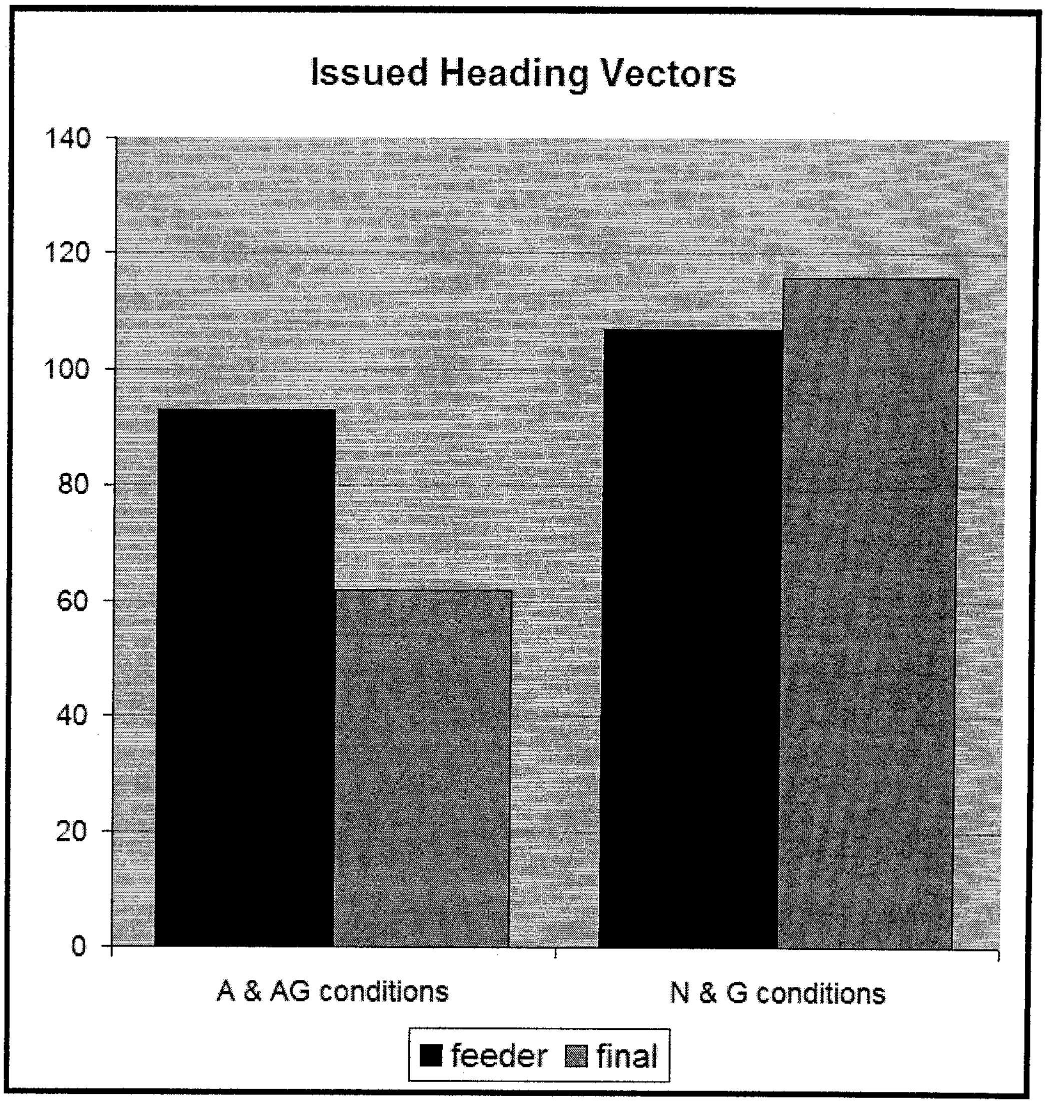

Figure 20. Total number of heading vectors issued by controllers. Fewer heading vectors were issued during conditions with airborne spacing and merging, indicating a more stable flow of aircraft.

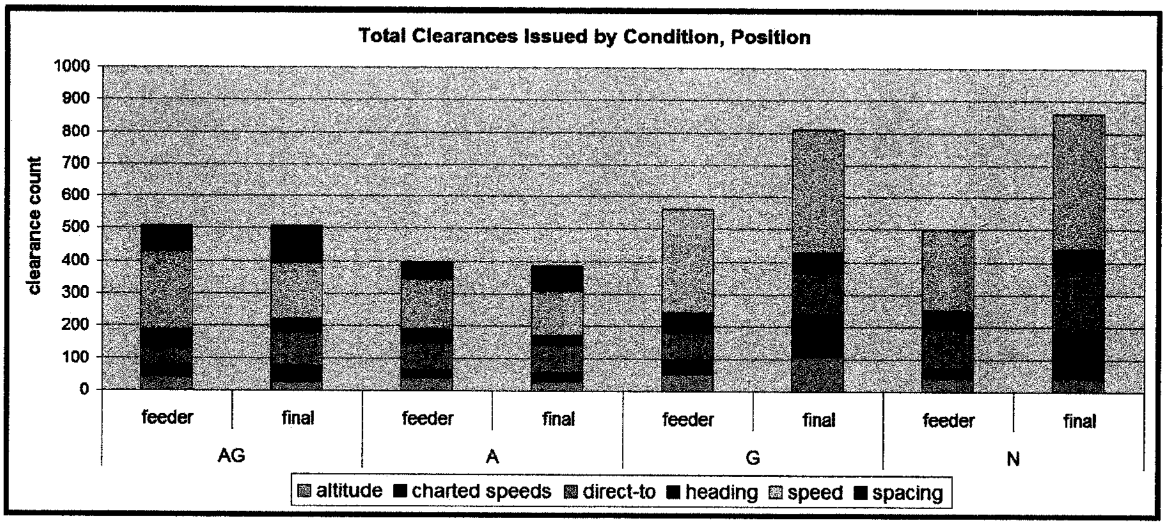

Figure 21. Counts of all clearances issued. The clearances issued throughout the study are broken down by type, and compared among the different conditions. With ASAS, overall clearance count is reduced, especially for the final controller, who is partly relieved of the "fine-tuning" task.

suggests a different pattern of control during the airborne spacing and merging conditions. The final controller appears to issue clearances earlier in their sector, possibly as a result of their increased availability from more stable flows of aircraft. In Figure 21, the locations of the heading vectors issued by both the feeder and final controllers are shown from the A and N conditions. Focusing on the final controller's clearances, there seems to be a slight shift to earlier in their sector for the clearance locations, indicating less late vectoring. Notice that the same effect does not seem to occur as much for the feeder controller, whose data shows this effect in the conditions with ground tools, suggesting that they benefit more from the tools than ASAS operations. Figure 22 shows the locations of the heading vectors issued in the G and N conditions, and when focusing on the feeder controller's clearances, reveals a similar shift to earlier in their sector for the clearance locations. An interesting discrepancy is that in this case, the same effect does not seem to occur for the final controller, suggesting that perhaps they benefitted more from ASAS operations than the ground tools. A comparison between the AG and N conditions reveals only minor comparisons to the trend observed for the feeder in the G condition, and does not show any emerging effect for the final controller.

Although it required a new clearance with new phraseology, controllers were able to use airborne spacing and merging operations without confusion. Throughout the study, the ASAS clearances were issued by voice, and used the spoken callsign of both the target and the lead aircraft (e.g., "United 456, merge

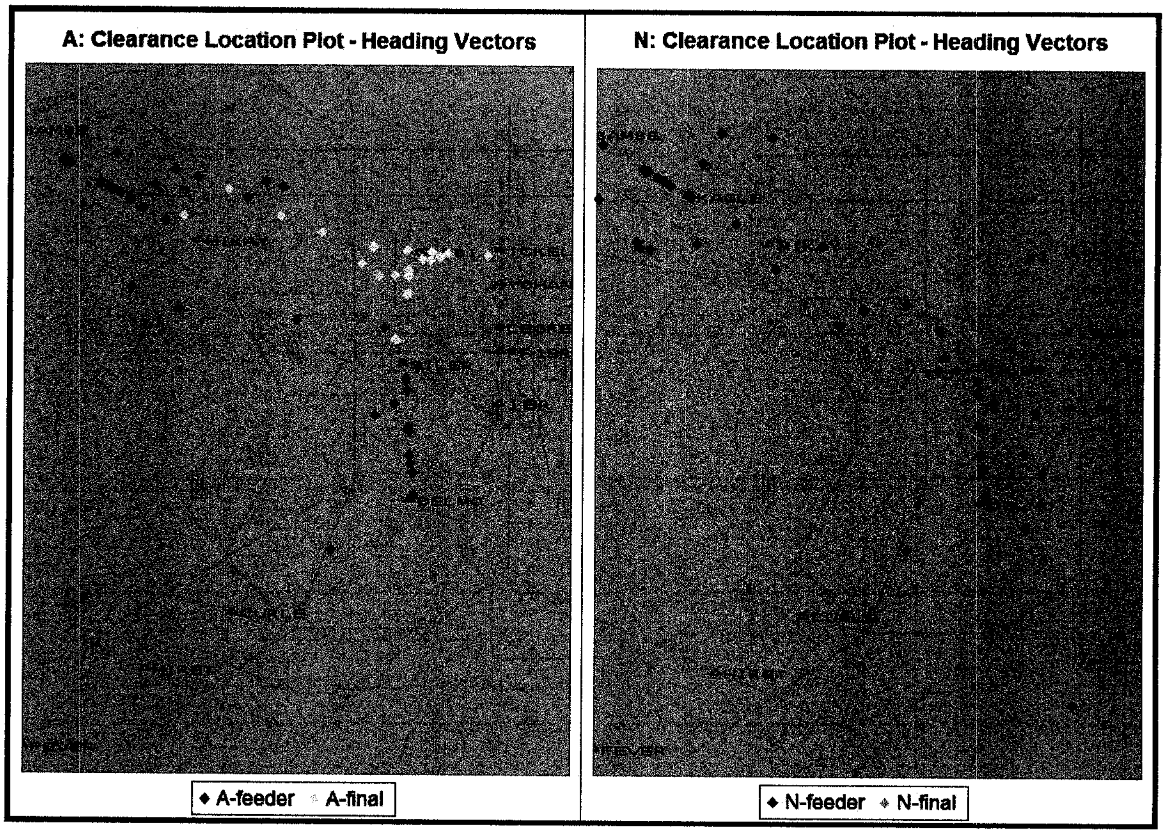

Figure 22. Locations of heading vectors in the A and N conditions. The airborne spacing and merging operations seem to affect the final controller more than feeder. Without ASAS (right side), the final controller issued more heading vectors late in their sector. The same effect does not seem to apply as much to the feeder controller.

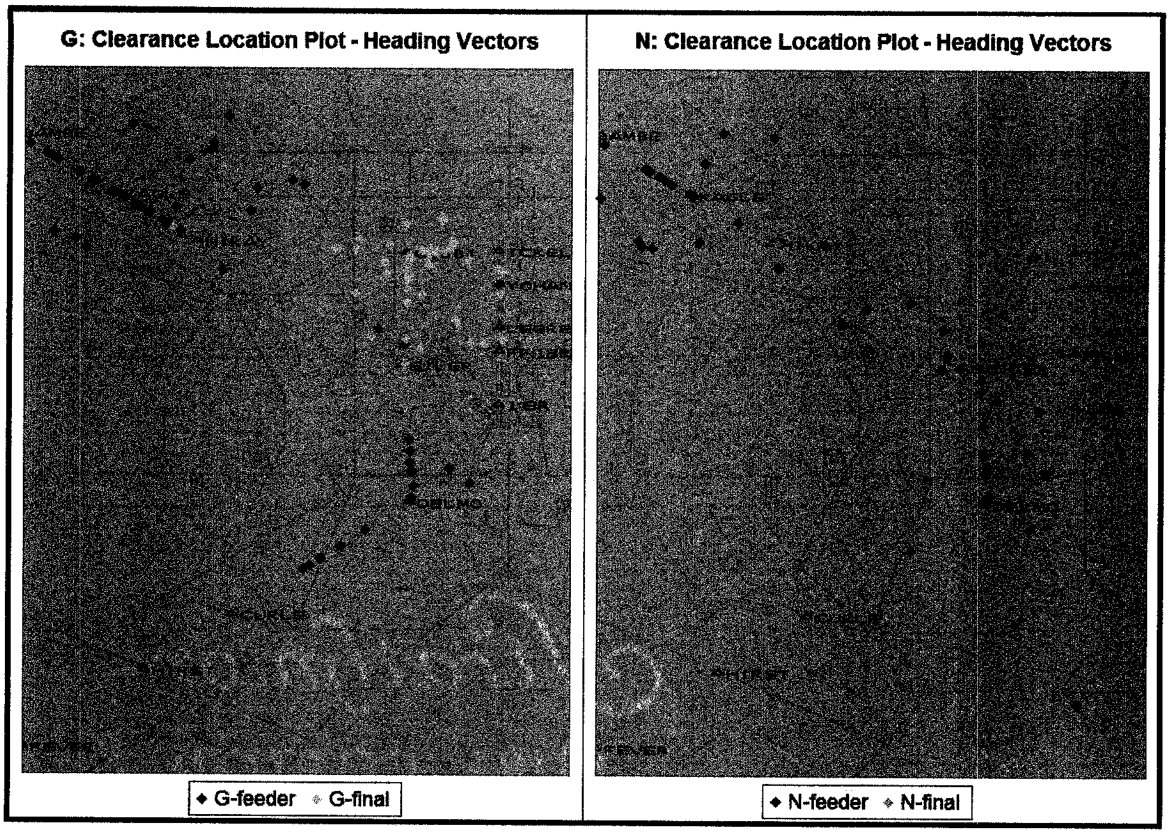

Figure 23. Locations of heading vectors in the G and N conditions. The ground tools seem to affect the feeder controller more than final. Without ground tools (right side), the feeder controller issued more heading vectors late in their sector. The same effect does not seem to apply to the final controller.

behind then follow Delta 789, 80 seconds in trail," or "Continental 321, follow Northwest 654, 80 seconds in trail"). Eurocontrol research has suggested the use of a separate "target identification" step as part of the phraseology (e.g., "TAP123, select target 4567") for ASAS clearances (Hoffman, Zeghal, Cloerec, Grimaud, & Nicolaon, 1999). An important result of this study was that, of the 323 airborne spacing or merging clearances issued, neither controllers nor pilots misidentified a target or lead aircraft.

DISCUSSION

The Ames DAG-TM CE-11 simulation study investigated airborne spacing and merging operations in the TRACON. The research was done in a rich operational environment with FMS operations and mixed spacing equipage. The controllers effectively managed the traffic while reporting very acceptable workload ratings throughout the entire study.

Airborne spacing and merging operations were shown to not only be feasible, but also beneficial. The flight distance analysis indicated that there was no negative impact from ASAS. The significant main effect from the availability of the ground tools could possibly be explained by a tendency of the controllers to over-control the traffic when they had advanced DSTs. Considering the A and AG conditions for example, perhaps the controllers were somewhat doubtful of the performance abilities of the system when ASAS ground tools were not available to them. The controllers may have not trusted that the aircraft would be able to absorb the necessary amount of delay with ASAS alone (i.e., the A condition), and that intervention from the controller would help. The clearance count analyses support this conclusion, since more clearances were issued in the AG condition, suggesting that the ground-side DSTs possibly encouraged these interventions via the finer level of feedback they provided.

The inter-arrival spacing analysis showed that airborne spacing and merging operations had a positive effect on system performance. The improvement observed during the conditions with ASAS was statistically significant, but there was very little difference between the A and AG conditions. This indicates that it is the delegation of spacing and merging tasks to the flight deck that is mostly responsible for the improved inter-arrival spacing, which lead to the increased runway utilization. This also suggests that such gains may be achievable without major investments in the ground system.

Another benefit from airborne spacing and merging operations was the productivity data in the form of clearance counts. Results showed a reduction in the number of clearances issued during conditions with ASAS, comparable with those reported by Eurocontrol researchers (Grimaud, Hoffman, Rognin, & Zeghal, 2004). When considered alongside the inter-arrival spacing results, this suggests that by delegating spacing and merging tasks to the flight crews, higher runway throughputs can be achieved with fewer control instructions. This also indicates that time-based airborne spacing and merging clearances are effective tools for managing the compression of descending and decelerating aircraft by reducing the need for heading vectors and temporary altitudes to build sequences, and speed clearances to maintain those sequences. Such a change in taskload can reasonably be interpreted as an increase in controller availability, fewer interruptions to aircraft descent profiles, and more predictable and stable flows to the runway.

The geographic distribution of clearances was also positively impacted by airborne spacing and merging operations. The final controller issued heading vectors earlier in their sector, a trend similar to the results presented in Grimaud, Hoffman, Rognin, and Zeghal (2001). This suggests that the final controller less frequently needed to use late vectors, again producing a more predictable and stable flow of aircraft to the runway. In this case, it was the final controller who received the benefits of ASAS, but through the efforts of the feeder controller. The role of the feeder controller was to deliver a good flow to the final controller, who would then make any necessary, ideally minor, adjustments. In conditions with airborne spacing and merging, the geographical analysis of heading vectors, and the reduction in clearances issued, suggest that the final controller received a smooth flow of aircraft from the feeder, and consequently in some cases did not need to issue any clearances, and was able to make the final adjustments earlier in their sector for the cases that did require minor tuning.

The locations of the heading vectors issued by the feeder controller were more affected by the presence of ground tools, an indication that the task they were performing was made easier with the help of the DSTs. This suggests that the feeder controller gains a better awareness and anticipation of the actions required for controlling traffic with the ground tools. Although this trend for the feeder controller is more pronounced in the G condition, it is also seen to a lesser extent in the conditions with airborne spacing and merging. Similar to the final controller's results, this indicates possible agreement with research by Grimaud, et al. that attributes the better anticipation of building sequences as a positive impact of ASAS.

Workload data collected from the controllers during the runs were within an acceptable range for all conditions, suggesting that ASAS operations do not negatively impact controller workload. Analyses found that the data favored the A condition slightly, which reported the lowest average WAK score, although no statistical differences were found. This trend is supported by the clearance count analysis, reiterating that ASAS operations reduced the number of clearances controllers needed to issue, which in turn may have led to their lower real-time workload ratings.

In contrast to this, the workload and safety rankings among the different conditions showed that the controllers were not in favor of the A condition. A possible explanation is that controllers felt uncomfortable when aircraft cleared to "merge behind" or "follow" a lead aircraft made speed changes inconsistent with the controller's expectations. Controllers felt that at times the algorithms were too aggressive in speeding up or slowing down the aircraft, a behavior that occurred in both straight path segments and ninety-degree turns, or when the controller would shorten the lead aircraft's route. To gain extra spacing between aircraft, the controllers would sometimes short cut the routes of aircraft by sending them direct to a downstream waypoint such that intermediate waypoints would be skipped. This allowed the controllers to get the spacing they needed without having to slow down or extend the path of the trailing aircraft, but would sometimes cause unpredictable speed changes for the actively spacing trailing aircraft.

Behaviors like excessive speed fluctuations and initial speed increases followed by slow downs, may have affected the controllers' opinion of both the concept and the operation's safety. This issue was perhaps more noticeable than in other studies because of the simulation's mixed equipage environment. Controllers mentioned the increased monitoring needed when a non-equipped aircraft was following an aircraft in spacing status. They explained that their goal was to assign a matching speed to the trailing aircraft, so as to avoid overtakes or wasted space. However the observed speed fluctuations of the aircraft in spacing status made it more difficult to pick the correct speed to issue to the trailing non-equipped aircraft. The result was that they would frequently check back on that pair of aircraft to see if the speeds were still compatible or not. These behaviors of the spacing guidance may have negatively impacted the controller's opinion of the concept, but a more refined spacing algorithm logic will likely increase controller acceptability of ASAS operations, particularly for mixed equipage environments.

From a systems performance perspective, of the four conditions tested, the A condition provided the best results, with the least variability in inter-arrival spacing, the fewest clearances issued, and nearly the shortest distances flown. However, although the A condition was quantitatively better in most cases, the controllers' qualitative impressions were lowest for the A condition. The behavior of the spacing algorithm combined with the responsibility to maintain separation at all times likely affected the controllers' experience and acceptability of the concept. The A condition was their least preferred condition, perhaps supporting the idea that, as implemented in the NASA Ames simulation, the algorithm's effect on the behavior of aircraft was difficult to comfortably manage for the controllers without the help of the ASAS ground tools. However, even with the concerns about the algorithm's behavior, they most preferred the AG condition, suggesting that they liked the concept and felt that there is a benefit to having ASAS-equipped aircraft, so long as they also have advanced DSTs to help them better monitor the traffic, and work it more efficiently. While this can be seen as an interaction between the behavior of the spacing algorithm and the controllers' desire for having advanced ground tools, it is more accurately a reflection of the stage of development the algorithm was in, and should not be interpreted as a limitation or shortcoming of the concept.

The ground-side tools provided to the controllers received positive ratings, but in the A and AG conditions, they may have been seen as overly important due to the observed unpredictability of aircraft behavior. Beyond what was available to the controllers in the N condition, the A condition only added a self-spacing equipage indicator in the datablock (which also doubled as a spacing status indicator). This minimal toolset and the limitations of the implemented spacing algorithm may explain how the A condition was the controllers' least favorite mode of operation, while at the same time the AG condition was their favorite. It is possible that a more refined spacing algorithm would have helped to make the controllers more accepting of the A condition.

Reports by working groups in the US and Europe have identified preliminary requirements for the ground system under ASAS operations. These include an indication of ASAS equipage or capability, an indication of ASAS status or assignment, a method to monitor for ASAS clearance compliance, and method to alert the controller of any abnormal conditions (Action Plan 1, 2001; Action Plan 1, 2004; Application Definition Sub-group, 2004b). It is possible that with the proper level of feedback provided by the conformance monitoring tool, a separate design element to alert the controller of abnormal conditions may not be necessary. With this assumption, the ASAS-related tools presented in the AG condition directly addressed all of these requirements, and earned very positive ratings from the controllers. By comparison, the ASAS-related tools presented in the A condition only addressed the recommendations for equipage and assignment status indicators. This environment was least preferred by the controllers, but this finding is likely related to the behavior of the spacing algorithm in conjunction with the controller's responsibility to maintain separation. A near-term implementation of ASAS operations that require minimal changes to the ground system may still be possible, but would require a spacing algorithm that is in close agreement with the mental expectations and common working practices of the controller.

ASAS operations that best facilitate a near-term implementation of the concept would completely avoid any modification to the ground system, specifically the controller's display, in order to minimize cost. In theory this could be accomplished by aircraft filing their flight plans with a unique equipment flag, so that the controller would be informed of their ASAS capabilities. However, controllers are quite sensitive to their workload, and their acceptance of new operating methods, which can be perceived as additional work, can best be earned by providing tools that make their job seem easier, as evidenced in this study by their strong preference for the conditions with ground tools and their reservations about the A condition. Even with an ideal spacing algorithm, such a minimal amount of ASAS feedback may not receive a very positive reaction from controllers, and could result in them using ASAS clearances only in very conservative situations, thereby limiting the potential system benefits. By adding only an ASAS equipage and assignment indicator to the datablock, controllers can more easily coordinate spacing and merging information between sectors, would not need to interrupt their scan pattern to confirm the ASAS equipage and assignment status of their aircraft, and would have a visual reminder of the potential effect maneuvering a lead aircraft may have on an ASAS aircraft following it.

This is not to say that further modifications to the ground system are unnecessary; in fact they would provide system performance and controller workload improvements that would allow for higher traffic densities. Conformance monitoring tools, like the spacing history circles, provide the controllers with the ability to quickly and easily check the current status of an ASAS clearance relative to its goal, and do so without requiring any mental calculation. Because of the sometimes gradual nature in which an ASAS aircraft achieves its target spacing, it can be difficult for the controller to know if the aircraft is progressing toward the goal or not. It is recommended that conformance monitoring feedback include some form of trend information to help the controller quickly judge the current progress of an ASAS clearance, and decide whether or not to intervene. In contrast to a function that would alert the controller of any off-nominal ASAS situations, a function that instead identifies for the controller opportunities to issue ASAS clearances is recommended. The spacing advisory tool used in the current study identified both the lead aircraft and the spacing interval for the controller, and presented them in the datablock of the candidate aircraft. This allows the controller to easily assign the clearance, or modify it if they prefer to, and can easily be ignored. In more far-term implementations, the suggested intervals can be driven by reduced or dynamic wake vortex separation minima, so as to further maximize runway throughput. A real-world implementation of these suggestions would need to thoroughly consider display clutter issues before adding such items to the datablock.

The Ames DAG-TM CE-11 simulation investigated airborne spacing and merging operations in the TRACON. The research was done in a rich operational environment with FMS operations and mixed spacing equipage. The DSTs and behavior of the spacing guidance implemented for this study were not as mature as would be required for real-world operations, nor could the controllers be considered experts in their use. However, the results suggest that the concept is feasible even under mixed equipage scenarios and with challenging traffic flows that require vectoring. Based on the results from this study, better spacing algorithms are required that match more closely to controllers' expectations and strategies, and provide increased predictability in off-nominal situations. Additional studies are needed to investigate how ASAS concepts might produce benefits in heavier traffic conditions, with different equipage mixes, or with reduced or dynamic separation minima. Future simulations could staff more of the surrounding airspace with participant controllers to allow for further investigation of inter-sector coordination issues. Capturing metrics for fuel consumption as well as radio frequency transmission times are also desirable, and would provide for additional benefit analyses. The results from this study present a conservative but promising view of what could be achieved in a fielded, more mature version of the concept with an improved spacing guidance, and more experienced flight crews and controllers.

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APPENDIXES

Appendix A

Human Subjects Approval Form

San José State
UNIVERSITY

Office of the Provost
Associate Vice President
Graduate Studies & Research

One Washington Square
San José, CA 95192-0025
Voice: 408-924-2427
Fax: 408-924-2477

E-mail: gradstudies@sjsu.edu
http://www.sjsu.edu

To: Joey Mercer

From: Pam Stacks,
AVP, Graduate Studies & Research

Date: November 11, 2005

The Human Subjects-Institutional Review Board has approved your request to use human subjects in the study entitled:

"Airborne Spacing & Merging in the Terminal Area."

This approval is contingent upon the subjects participating in your research project being appropriately protected from risk. This includes the protection of the anonymity of the subjects' identity when they participate in your research project, and with regard to all data that may be collected from the subjects. The approval includes continued monitoring of your research by the Board to assure that the subjects are being adequately and properly protected from such risks. If at any time a subject becomes injured or complains of injury, you must notify Pam Stacks, Ph.D. immediately. Injury includes but is not limited to bodily harm, psychological trauma, and release of potentially damaging personal information. This approval for the human subjects portion of your project is in effect for one year, and data collection beyond November 11, 2006 requires an extension request.

Please also be advised that all subjects need to be fully informed and aware that their participation in your research project is voluntary, and that he or she may withdraw from the project at any time. Further, a subject's participation, refusal to participate, or withdrawal will not affect any services that the subject is receiving or will receive at the institution in which the research is being conducted.

If you have any questions, please contact me

Cc: Kevin Jordan

Appendix B

NASA Consent Form

NASA Ames Research Center

HUMAN RESEARCH MINIMAL RISK CONSENT

To the Test Subject: Please read this consent form and the attached protocol and/or subject instructions carefully. Make sure all your questions have been answered to your satisfaction before signing.

A. I agree to participate as a subject in the ______________________________ research experiment as described in the attached protocol or subject instructions. I understand that I am employed by ______________________________ who can be contacted at ____________________.

B. I understand that my participation could cause me minimal risk*, inconvenience, or discomfort. The purpose and procedures have been explained to me and I understand the risks and discomforts as described in the attached research protocol.

C. To my knowledge, I have no medical conditions, including pregnancy, that will prevent my participation in this study. I understand that if my medical status should change while a participant in the research experiment that there may be unforeseeable risks to me (or the embryo or fetus if applicable). I agree to notify the Principal Investigator (P.I.) or medical monitor of any known changes in my condition for safety purposes.

D. My consent to participate as a subject has been freely given. I may withdraw my consent, and thereby withdraw from the study at any time without penalty or loss of benefits to which I am entitled. I understand that the P.I. may request my withdrawal or the study may be terminated for any reason. I agree to follow procedures for orderly and safe termination.

E. I am not releasing NASA from liability for any injury arising as a result from my participation in this study.

F. I hereby agree that all records collected by NASA in the course of this study are available to the research study investigators, support staff, and any duly authorized research review committee. I grant NASA permission to reproduce and publish all records, notes, or data collected from my participation, provided there is no association of my name with the collected data and that confidentiality is maintained, unless specifically waived by me.

G. I have had an opportunity to ask questions and have received satisfactory answers to all my questions. I understand the P.I. for the study is the person responsible for this activity and that any pertinent questions regarding the research will be addressed to him/her during the course of the study. I have read the above agreement, the attached protocol and/or subject instructions prior to signature, and understand the contents.

* Minimal Risk means that the probability and magnitude of harm or discomfort anticipated in the research are not greater, in and of themselves, than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests.

Signature of Test Subject Date	Signature of Principal Investigator Date
Printed/Typed Name of Test Subject/Evaluation Pilot	Printed/Typed Name of Principal Investigator
Address	Telephone Number of Principal Investigator
City, State, Zip Code	Subject Signature: Authorization for Videotaping
Telephone Number of Test Subject	Subject Signature: Authorization for Release of Information to Non-NASA Source(s)

Appendix C

NASA Human Subjects Approval Form

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Ames
Research
Center

APPROVAL OF HUMAN RESEARCH

Distributed Air Ground Research 2003
Title of Protocol

Vernol Battiste and Nancy Smith
Principal Investigator

IHH/IHI
Org Code or Affiliation

Phone | Mail Stop | E-mail

NASA Point of Contact (if P.I. Non-NASA) | Org Code

Phone | Mail Stop | E-mail

See reverse/page 2 for definition of "exemption" and "minimal risk." If the PI, Branch and Division Chief **all** agree that the research satisfies the definition of exemption and does not impose greater than minimal risk, an exemption may be requested.

1. Attach a copy of your research protocol. Refer to Ames Procedures and Guidelines, APG 7170.1, "Human Research Planning and Approval" for details and format.
2. Route through management, obtaining appropriate signatures.

Exemption Requested: yes	Exemption Requested: no	Minimal Risk: yes	Minimal Risk: no	Signature	Date
☐	☒	☒	☐	Vernol Battiste — Principal Investigator	8/27/03
☐	☒	☒	☐	Chief Branch/Office	8/27/03
☐	☒	☒	☐	Chief Division/Organization	8/27/03

3. Send this form with original signatures, protocol, consent form and attachments to the Office for the Protection of Research Participants (OPRP), M/S 243-2.
NOTE: Signatures also indicate that this protocol has been reviewed and has been determined to have significant merit.

The Principal Investigator will be notified by the OPRP
A. If the request for exemption is approved, or
B. Following disposition/approval of the protocol by the Human Research Institutional Review Board (HRIRB)

I understand I may not proceed with any research until I have received notification either in terms of "A" or "B" and the requirements of APG 7170.1 have been met.

Initials of Principal investigator | Date: 8/27/03

For OPRP use only:

Assigned HR number HRII-03-39
(continuation of HRII-02-47)

Requested Exemption Approved ☐ Disapproved ☐

Protocol Approved ☐ Disapproved ☐

Chief, Office for the Protection of Research Participants | Date | Chair, Human Research Institutional Review Board | Date

Appendix D

Human Participant Protections Education for Research Teams Completion Certificate

Human Participant Protections Education for Research Teams

National Cancer Institute
U.S. National Institutes of Health | www.cancer.gov

NCI Home | Cancer Topics | Clinical Trials | Cancer Statistics | Research & Funding | News | About NCI

Human Participant Protections Education for Research Teams

Completion Certificate

This is to certify that

Kevin Jordan

has completed the **Human Participants Protection Education for Research Teams** online course, sponsored by the National Institutes of Health (NIH), on 09/16/2005.

This course included the following:

- key historical events and current issues that impact guidelines and legislation on human participant protection in research.
- ethical principles and guidelines that should assist in resolving the ethical issues inherent in the conduct of research with human participants.
- the use of key ethical principles and federal regulations to protect human participants at various stages in the research process.
- a description of guidelines for the protection of special populations in research.
- a definition of informed consent and components necessary for a valid consent.
- a description of the role of the IRB in the research process.
- the roles, responsibilities, and interactions of federal agencies, institutions, and researchers in conducting research with human participants.

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