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AIRBORNE Separation Assurance System (ASAS) applications[1] promise a range of benefits, from improved all-weather situation awareness for flight crews to decreased air traffic controller workload through delegation of separation responsibility to equipped aircraft. In the category of ASAS applications called 'airborne spacing' (ASAS 2), air traffic controllers maintain separation responsibility, but may instruct flight crews to achieve and maintain a spacing interval to a specified reference aircraft using on-board guidance. Delegating spacing responsibility to flight crews of suitably equipped aircraft may reduce controller workload and required air-ground communications.

Airborne spacing fits within the Next Generation Air Transportation System (NGATS) plan undergoing refinement by the Joint Planning and Development Office (JPDO) by providing a capability for "equivalent visual operations"—using cockpit displays of traffic information (CDTIs) and onboard spacing guidance to achieve capacities under Instrument Flight Rules (IFR) formerly possible only under Visual Flight Rules (VFR). Equivalent visual operations would improve the predictability of operations at busy airports by reducing the impact of bad weather. Airborne spacing may also be used in conjunction with Area Navigation (RNAV) routes flown using aircraft Flight Management Systems (FMSs), and is therefore compatible with trajectory-based operations—another important NGATS capability. Trajectory-based operations use four-dimensional (4D) trajectories as the basis for flexible planning and dynamic airspace configuration. In terminal area (TRACON) airspace, related concepts such as Continuous Descent Approaches (CDAs) address the NGATS objective to reduce aircraft noise and emissions. Air Traffic Management (ATM) concepts devoted to phasing in a combination of these elements are under development.[2]

This paper presents a simulation study to investigate flight crew and controller decision support tools (DSTs) to support airborne spacing and FMS operations in the TRACON. The study was conducted as part of NASA Distributed Air Ground Traffic Management (DAG-TM) research to address air traffic management (ATM) concepts for increasing flexibility, efficiency, and capacity by redistributing responsibilities among flight crews, dispatchers, and air traffic service providers. DAG-TM research has been conducted at NASA Langley, Glenn, and

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Ames Research Centers with funding from the NASA Airspace Systems Program Advanced Air Transportation Technologies (AATT) project[3-5]. The simulation described here was performed in the Airspace Operations Laboratory (AOL) and Flight Deck Display Research Laboratory (FDDRL) at NASA Ames Research Center to investigate DAG-TM Concept Element 11 (CE 11): Terminal Arrival: Self-Spacing for Merging and In-trail Separation, which is focused on time-based airborne spacing and merging in terminal radar approach control (TRACON) airspace.

This paper discusses results of the simulation from a ground-side perspective. (Battiste et al. describe the CDTI-based spacing DSTs available to the flight crews along with the results of this study from an air-side perspective.[6]) The paper first presents related research on terminal-area airborne spacing. It then describes the Ames CE11 simulation in detail. The paper relates results from the present study to results achieved in similar studies conducted by EUROCONTROL researchers.

ATM concepts that incorporate airborne spacing have long interested researchers as a means for decreasing reliance on air traffic controllers to maintain safety. Enabling technologies such as ADS-B (Automatic Dependent Surveillance—Broadcast) have reinvigorated these efforts. For example, recent research at NASA Langley Research Center has sought to extend a previously analyzed[7] and flight tested[8] spacing algorithm[9] for use in merge situations by incorporating ADS-B information.[10]

Simulation studies have also demonstrated the effectiveness of airborne spacing operations from both flight deck and controller perspectives. For example EUROCONTROL studies indicate that delegating spacing tasks to the flight deck can improve spacing accuracy and increase controller availability by enabling them to set up traffic flows earlier[11]. That research provides an important basis for comparison with the current simulation, as emphases were placed on different aspects of the concept.

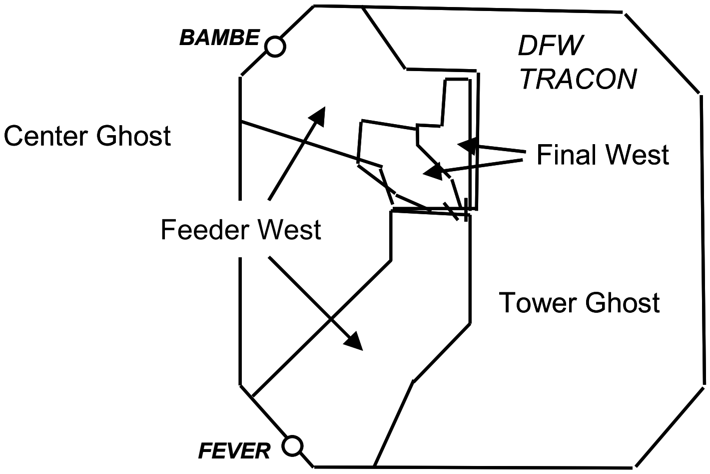
The EUROCONTROL research reported in Grimaud et al.[11] used a three-phase procedure for implementing spacing clearances, with variations for common versus merging trajectories, and for maintaining versus achieving proper temporal spacing. First, the controller specifies a target aircraft for the flight crew to select via their CDTI using the “Secondary Radar Surveillance” code (“XYZ, select target 1234”). After the flight crew verbally confirms that the target is selected, the controller issues the spacing instruction (e.g., “XYZ, heading 270 then merge WPT 90 seconds behind target”). The pilot first flies heading 270, then turns direct WPT when proper spacing is attained. A verbal communication accompanies the turn to the waypoint (“XYZ, merging WPT”). The flight crew then adjusts their speed to maintain the required spacing. The third phase entails termination of the airborne spacing phase (“XYZ, cancel spacing, speed 180 knots”).

Grimaud et al. also identified three problems that could occur if traffic flows are “not organized enough for spacing purposes.” Researchers therefore developed airspace design requirements for spacing operations.[11] For example, legs should be added to standard trajectories to enable controllers to expedite or delay aircraft while keeping the aircraft on FMS trajectories. Routes should be structured so that a range of possible arrival paths are available, segregated from departures and overflights. The difference in path length should correspond at least to the size of a ‘slot.’ In addition, “sequencing legs” should be vertically separated, straight and parallel to afford easy visualization, separated so as not to lose space, and of a length appropriate for avoiding highly diverging merge situations. Taken together, these requirements yielded a very ‘clean’ airspace configuration for flows arriving across two different fixes.

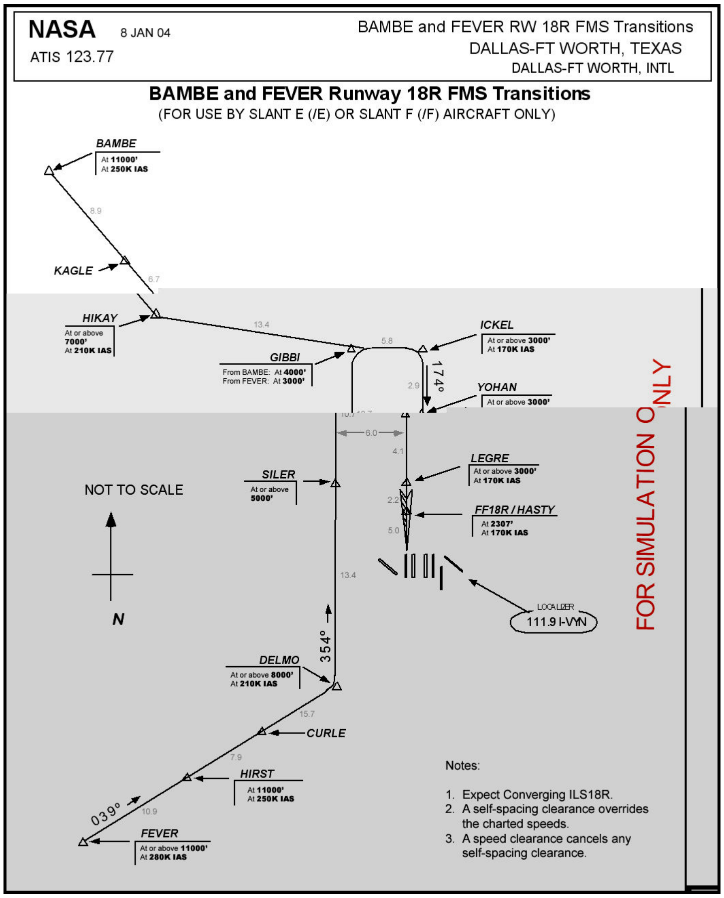
Grimaud et al. simulated two approach sectors under both conventional and spacing operations.[11] Traffic entered each sectored already sequenced. Aircraft spacing guidance was previously analyzed in detail.[12] In trials with spacing operations all aircraft were equipped to space, and controllers used graphical tools that indicated lead aircraft and sequence. Subjects received two weeks of training followed by a week break, then participated in two weeks of data collection. The results show that with airborne spacing the controllers benefited from increased anticipation and issued fewer clearances while spacing accuracy improved. At high traffic levels, however, controllers were concerned about the monitoring aircraft required under spacing operations.[11] The EUROCONTROL experimental conditions and results are revisited below in the course of describing the Ames CE11 simulation and results.

The goal of the August 2004 simulation in the NASA Ames AOL was to evaluate the operational viability and potential benefits of time-based airborne spacing and merging in the TRACON. In addition to workload reduction, potential benefits include increased throughput, decreased excess separation, and reduced losses of wake vortex separation. The simulation was a large-scale, distributed air and ground simulation that provided a rich operational environment. It utilized the same simulation infrastructure as previous DAG-TM simulations in the AOL.[13] This section describes the elements of the simulation in detail.

Figure 1 depicts the simulation airspace. The western portion of Dallas-Fort Worth (DFW) TRACON was configured for south-flow operations to runways 18R (the primary landing runway) and 13R. One controller staffed the 'Feeder West' position, receiving traffic arriving on FMS arrivals across the northwest (BAMBE) and southwest (FEVER) meter fixes from an en route confederate controller ('Center Ghost'). A second controller staffed the 'Final West' position and was responsible for aircraft on approach to both 18R and 13R. The Final West controller handed aircraft off to a confederate tower controller ('Tower Ghost').



Four professional TRACON controllers with between 15 and 20 years experience participated in the study. Two controllers were very familiar with DAG-TM concepts and simulations conducted in the NASA Ames AOL, while other two were novices. Nine commercial pilots participated in the study. All pilot participants had previously taken part in DAG-TM simulation research. Two retired controllers staffed the Ghost controller positions, and six general aviation pilots served as pseudo-aircraft pilots.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BAMBE and FEVER RW 18R FMS Transitions
DALLAS-FT WORTH, TEXAS
DALLAS-FT WORTH, INTL

BAMBE and FEVER Runway 18R FMS Transitions

(FOR USE BY SLANT E (/E) OR SLANT F (/F) AIRCRAFT ONLY)

Notes:

1. Expect Converging ILS18R.
2. A self-spacing clearance overrides the charted speeds.
3. A speed clearance cancels any self-spacing clearance.

All aircraft arrived in the DFW TRACON on FMS arrivals. Feeder West cleared aircraft to continue their descent on an FMS approach transition. Aircraft arriving across BAMBE flew either the HIKAY FMS transition to 18R or the HIKAY FMS transition to 13R, depending on their assigned runway (Figure 2). FEVER aircraft flew the DELMO FMS transition to 18R. The routes merge at the initial base-leg waypoint GIBBI, where northwest and southwest flows had different altitude restrictions to ensure separation. Other altitude restrictions along the routes ensure separation from departure traffic. The routes otherwise follow current-day traffic flow patterns.

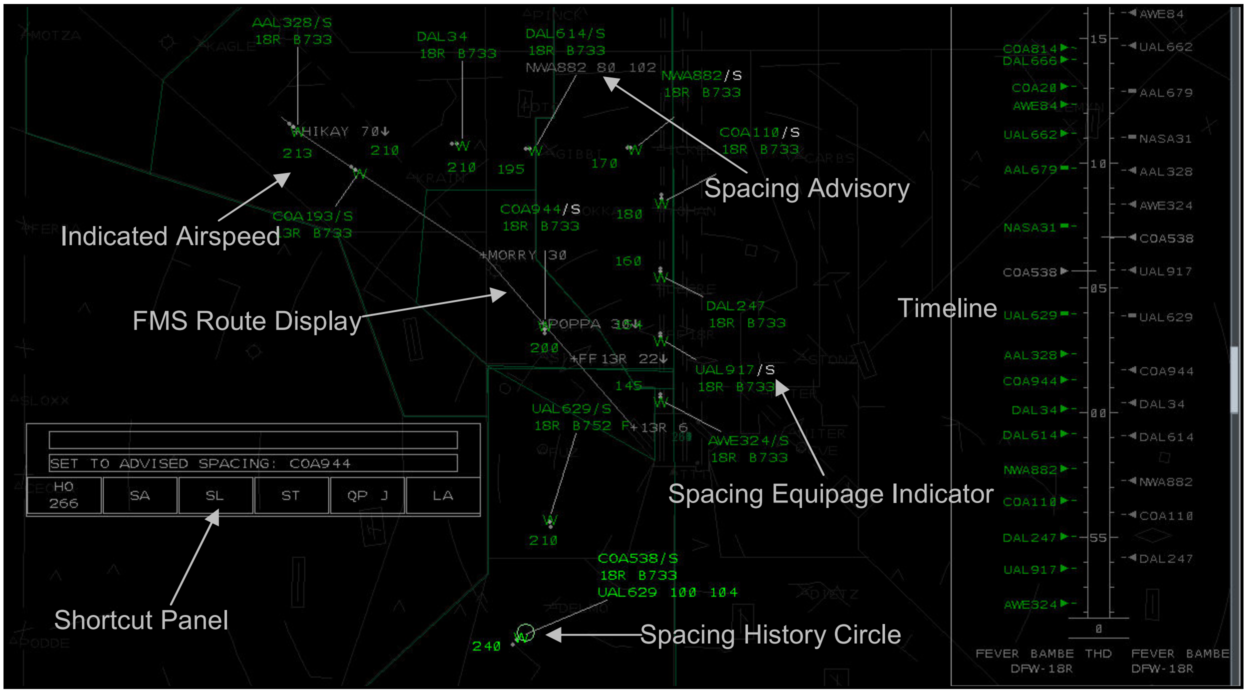
Although the routes were not specially designed to support merging and spacing, they nonetheless meet some of airspace design requirements set forth in the EUROCONTROL airborne spacing research. For example, the merge point GIBBI, as well as the waypoints SILER and ICKEL afford controllers opportunities to issue direct-to clearances to absorb delay. A range of possible routes is created depending upon the timing of the direct-to clearance.

Controllers used the Multi Aircraft Control System (MACS) STARS display emulation (Figure 3).[13] The STARS display was hosted on realistic 2048x2048 large-format displays in the AOL. Controllers could configure the basic STARS display according to their individual preferences (e.g. brightness, map range, range ring center, etc.). The STARS emulation enabled controllers to display aircraft FMS routes in all simulation trials. Indicated airspeed was also displayed just beneath the aircraft target symbol. These enhancements were available as a consequence of having fully FMS- and ADS-B-equipped traffic.

Other DSTs were dedicated to supporting airborne spacing operations. First, an arrival schedule is presented on a timeline display (Figure 3). Given a reference point at the runway threshold and a matrix of temporal spacing intervals (based on weight class), the scheduler computes estimated times of arrival (ETAs) for all aircraft at the runway threshold based on each aircraft's charted route through the forecast wind field. The scheduler also computes a landing sequence and scheduled times of arrival (STAs). The schedule does not include any 'extra' spacing buffers. The timeline displays ETAs on the left side and STAs on the right, enabling controllers to estimate the predicted spacing between aircraft at the runway threshold. The timeline tool also enables controllers to perform slot reassignments and swaps.

Spacing advisory DSTs use the schedule and routings to advise a lead aircraft and spacing interval. The advised spacing interval is that is specified for the weight classes of the lead and trail aircraft. When an aircraft is spaced within 30 seconds of the advised interval, its datablock automatically expands to display a spacing advisory in the third line. For DAL614 in Figure 3, the advised lead aircraft is NWA882, the advised spacing interval is 80 seconds, and the actual current spacing is 102 seconds. The controller has the option to change the advised lead aircraft and/or the advised spacing interval using the shortcut panel shown in Figure 3. The shortcut panel also enables controllers to perform other tasks, such as handoffs and determining the distance between aircraft.

A spacing equipage indicator is included next to an aircraft's callsign. A green '/S' tells the controller that an aircraft is equipped for airborne spacing. If the controller issues a spacing clearance to an aircraft, they can make an entry using the shortcut panel that highlights the spacing equipage indicator in white as a reminder that the aircraft should now be complying with a spacing clearance (Figure 3).



SET TO ADVISED SPACING: COA944

When a controller dwells on an aircraft that has received a spacing clearance, or has a spacing advisory available, a ‘history circle’ appears. The center of the circle indicates where the lead aircraft was x seconds ago, where x is the advised spacing interval. History circles have a radius of ten seconds. An aircraft directly following its lead aircraft at the correct spacing interval appears centered in the history circle. In Figure 3, COA538 appears slightly behind the circle that shows where UAL629 was 100 seconds ago. This graphical information complements information displayed in the spacing advisory.

EUROCONTROL research likewise included spacing DSTs for controllers that consisted of circles around spacing aircraft and links between them, together with range rings centered on merge points.[11] In the present simulation, controllers were free to select the location of range rings and, indeed, often centered them at the merge point GIBBI. The EUROCONTROL research did not investigate the role of scheduling automation in spacing operations and the DSTs did not include equipage cues, since all aircraft were equipped for spacing.

The Ames CE 11 traffic scenarios represent traffic consistent with DFW traffic mixes. Arriving traffic flows were comprised of mostly ‘large’ and some ‘B757’-class aircraft. In the study, the spacing matrix was configured such that aircraft should be spaced 80 seconds behind large aircraft and 100 seconds behind B757s. These values were selected to ensure 3 and 4 nm at the final approach fix, respectively, even if aircraft are spaced slightly closer (i.e. five seconds or less) than the assigned temporal interval. Twenty-one aircraft split between two flows across the BAMBE and FEVER meter fixes were assigned to runway 18R. Additional BAMBE arrivals assigned to runway 13R arrived in slots that became available to FEVER 18R aircraft when the 13R aircraft diverged from the primary BAMBE 18R flow (around waypoint HIKAY). Thus, an open slot in a flow from one direction would typically be filled by an aircraft coming from the other direction. The traffic level to runway 18R could therefore be characterized as ‘high,’ similar to the traffic levels investigated by Grimaud et al.[11] Traffic to runway13R, on the other hand, was very light.

The traffic scenarios were partitioned into ‘coordinated’ and ‘uncoordinated’ flows. The first twelve aircraft arrived at the meter fixes within fifteen seconds of their meter fix STAs, as if they had been delivered using en route DAG-TM concepts. The meter fix STAs for these aircraft reflected the runway 18R arrival sequence. The next nine aircraft represented the uncoordinated flow intended to test the CE 11 concept in a situation where the merging traffic sequences were not well synchronized. These aircraft instead arrived as if a miles-in-trail criterion had been applied. In conditions when air-side DSTs were available, seventy-five percent of all piloted simulators and pseudo-aircraft assigned to runway 18R were equipped for airborne spacing. Partitioning traffic flows in all scenarios to include coordinated and uncoordinated portions and including aircraft unequipped for spacing are two key differences with the research reported in Grimaud et al.[11]

One DST-enabled strategy that emerged as attractive during the CE 11 simulation development process involved first using the timeline display to assess how closely aircraft would meet their assigned STA at the runway. Speed clearances could be used in conjunction with the charted FMS routes to adjust aircraft toward their assigned STAs. For example, controllers could issue a slower speed—or a speed prior to the nominal FMS slowdown region—to aircraft that need to absorb delay. Aircraft behind schedule could be held fast or sent direct to a downpath waypoint (in some situations, given FMS functionality and route geometry, this would also effectively cancel a deceleration). Merging badly coordinated flows might require heading vectors, but in general, aircraft could remain on the lateral FMS routes. Once aircraft were reasonably close to (perhaps within ten seconds of) their STA, controllers could use spacing clearances to effect a merge (“American 123, merge behind and follow United 345 80 seconds in trail”), or ‘lock in’ the required temporal spacing behind a lead aircraft (“United 123, follow American 345 80 seconds in trail”).

In a typical scenario Feeder West would issue the descent transition clearance (“American 123, continue your descent on the HIKAY 18R FMS transition”) upon accepting aircraft from Center Ghost. Feeder West would then issue an ‘adjustment’ clearance—either a speed or a shortcut to a downpath waypoint. For aircraft already well spaced in-trail behind their eventual leads, Feeder West would simply issue the ‘follow’ spacing clearance. Aircraft requiring significant adjustment might be handed to Final West, who would then issue the merging or spacing clearance and clear the aircraft for the approach. Final West would monitor and ensure proper spacing for the handoff to Tower Ghost. If a spacing clearance was not working out as planned, controllers would cancel it by issuing a speed clearance. Controller DSTs would support the process throughout by facilitating spacing assessment, helping select adjustment clearances, and aiding in conformance monitoring of spacing aircraft. Unequipped aircraft in the flow would be handled primarily through the use of speed clearances—first to establish spacing, then to match lead aircraft speeds.

Aside from the presence of unequipped aircraft in the traffic flows, these operations differ from those used in the EUROCONTROL research[11] in four ways. First, the spacing clearances explicitly include the callsign of the lead aircraft, rather than some other unique identifier. Second, a single spacing instruction and pilot readback is sufficient; flight crews did not first confirm selection of the lead aircraft. Third, the clearances neither specified the merge point nor a heading vector to fly prior to engaging spacing; controllers were responsible for issuing appropriate heading or direct-to clearances before issuing spacing clearances. Finally, controllers only cancelled spacing if it was not working out; the approach clearance was otherwise assumed to cancel the spacing clearance.

Table 1 summarizes each of the four conditions of a 2x2 repeated-measures experimental design intended to test the value of air and ground-side DSTs to support airborne spacing. 75% spacing equipage was selected to afford controllers ample opportunities to issue spacing clearances and use DSTs when they were available. On the other hand, it ensured that enough aircraft were unequipped for spacing that controllers needed to check that aircraft were equipped, and devise ways to manage unequipped aircraft. In all conditions, controllers were free to issue any FMS trajectory modifications or tactical clearances they deemed necessary via voice communication.

		Flight Deck DSTs	
		No	Yes
Controller DSTs	No	“No Tools” • No aircraft were equipped for airborne spacing • Controllers could issue FMS trajectory modifications or tactical clearances	“Air Tools” • 75% of aircraft assigned to primary landing runway equipped for airborne spacing (both CDTI-equipped piloted simulators and pseudo-aircraft) • Controllers could issue spacing commands, FMS trajectory modifications, or tactical clearances
	Yes	“Ground Tools” • No aircraft were equipped for airborne spacing • Controllers had DSTs available • Controllers could issue FMS trajectory modifications or tactical clearances	“Air & Ground Tools” • 75% of aircraft assigned to primary landing runway equipped for airborne spacing (both CDTI-equipped piloted simulators and pseudo-aircraft) • Controllers had DSTs available • Controllers could issue spacing commands, FMS trajectory modifications, or tactical clearances

The study was conducted during a two-week period that consisted of two travel days and two training days, followed by six days of data collection. The two days of training covered the DST functionalities, exploration of controller strategies, and general familiarization of the airspace and traffic scenarios. During data collection, however, the only firm rule constraining controller behavior was that the first aircraft in the flow could not be ‘short cut’—an attractive option given the FMS route geometry, but one that would invalidate some of the performance metrics across conditions. Training was therefore in marked contrast to the detailed two-week controller training regimen used by Grimaud et al.[11]

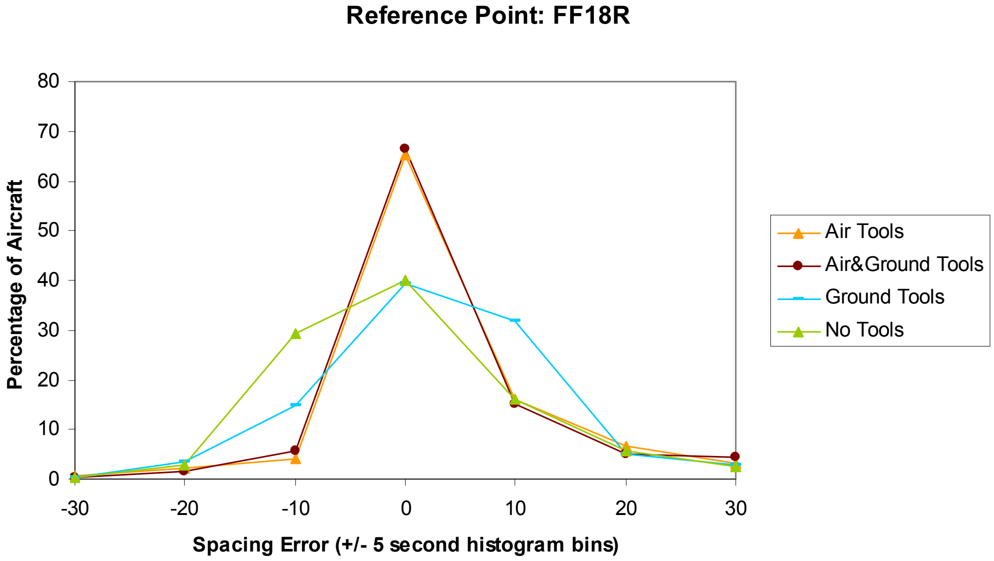
To obtain data for sixteen trials in each treatment combination, two parallel simulations were conducted simultaneously under the same conditions. The four controllers rotated in forming two-person teams. A given team stayed together during the course of a day. Pairs of trials in the four conditions were conducted in randomized order each day, with each team member serving as Feeder West and Final West in the test condition before moving to the next condition. Individual trials lasted thirty-five minutes with a short break between trials and a longer break between conditions. A trial ended after thirty-five minutes regardless of whether all the aircraft had been handed off to Ghost Tower.

System performance data were collected from each controller, pilot, and pseudo-pilot MACS station, as well as from dedicated data collection stations and networking hubs. Task data, such as pilot and controller interface actions, were also collected via MACS. Voice communications were recorded and overall traffic patterns were captured as movies. Workload Assessment Keypads (WAKs) probed controller workload at five-minute intervals during simulation trials. Workload questionnaires followed each trial, and participants completed usability/acceptability questionnaires and debrief sessions at the conclusion of the study.

This section presents the results of the Ames CE 11 study from an ATM perspective. The results address spacing accuracy, efficiency, and clearances, as well subjective controller workload, safety, and acceptability measures. Some results concerning flow coordination and its effect on clearance selection and location are also presented.

Figure 4 depicts a histogram of time spacing errors measured at the final approach fix for runway 18R (denoted FF18R). The results show that accuracy improves when aircraft are capable of airborne spacing in conditions when flight deck DSTs are available. The addition of controller DSTs in the Air & Ground Tools condition does not improve spacing accuracy beyond that obtained in the Air Tools condition. Ground Tools did, however, help controllers err on the conservative side relative to No Tools, suggesting an improved awareness of the required spacing that may help minimize go-arounds.

Grimaud et al. report slightly better results, with seventy-five percent of aircraft in the ‘center’ histogram bin under airborne spacing.[11] If the results in Figure 4 reflect a performance decrement due to the twenty-five percent unequipped aircraft in the present study, then the performance decrement due to the presence of unequipped aircraft may be characterized as small. However, further research is needed to confirm this.



Throughput measured at FF18R is not significantly different across conditions (p = .10), despite better spacing accuracy in the Air Tools conditions. The main reason was the efficient delivery of aircraft in the No Tools condition, which left little room for improvement with the addition of air and ground tools. In future studies, traffic scenarios that result in inefficient delivery of aircraft (e.g. bad weather) should be examined to maximize potential benefits of airborne spacing DSTs and procedures. In addition, throughput measurements do not consider potential go-around situations. Such situations arose most often in the No Tools condition. Also, temporal spacing criteria corresponded conservatively to current day wake vortex spacing requirements. The study did not examine airborne spacing using reduced or dynamic spacing matrices.

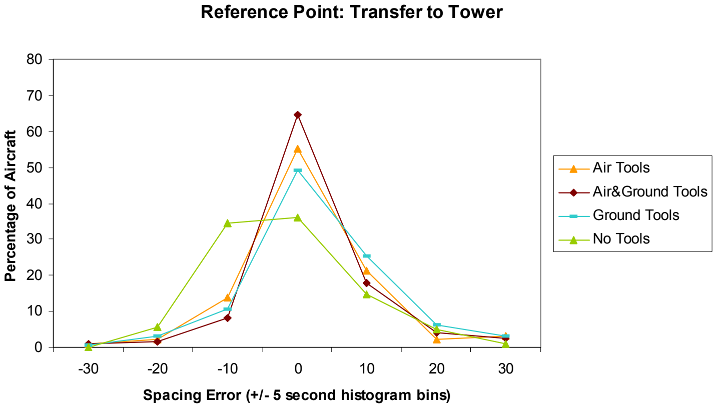
As in previous DAG-TM simulations (e.g. [1]), flight time and distance are used as surrogate metrics for fuel efficiency. Average flight time and flight distance were measured from each metering fix to FF18. No significant differences in either flight time or flight distance between conditions were found for aircraft arriving from a given metering fix. This consistency is likely due in large part to the use of the same FMS procedures in all conditions; aircraft flew coupled to the FMS an average of approximately 90 percent of the time in all conditions. Grimaud et al., on the other hand, report reductions in both flight time (10%) and distance (5%) in airborne spacing conditions—perhaps because FMS routes figured less prominently in trials with conventional operations.11

Flight distance from BAMBE was significantly longer (p < .05) in the Ground Tools condition when measured at point when Final West transferred control to Tower Ghost. Flight time from both BAMBE and FEVER was also significantly longer in the Ground Tools condition (p < .05). These results may indicate that with DSTs available and no aircraft equipped for airborne spacing, Final West maintained control of aircraft longer in order to monitor and ensure proper spacing before transferring control to Tower Ghost.

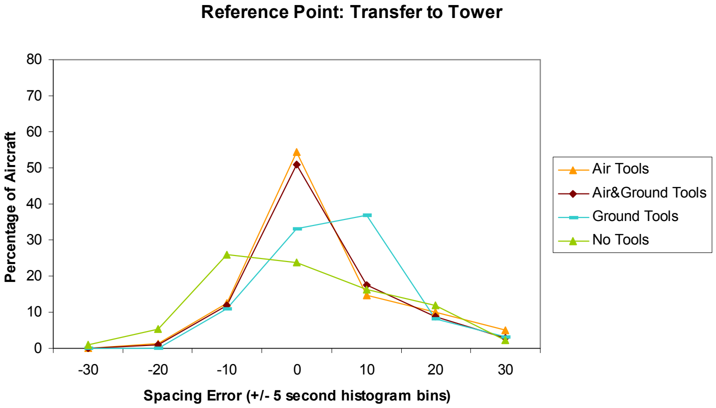
Airborne spacing and merging clearances issued by voice used the voice callsign of the target and the voice callsign of the lead aircraft (e.g. "United 123, merge behind and follow American 345 80 seconds in trail," or "American 123, follow United 345 80 seconds in trail"). An important result of this study was that, out of 323 airborne spacing or merging clearances, neither controllers nor pilots misidentified a target or lead aircraft. This indicates that another way of identifying the lead aircraft in a voice clearance is not necessary.

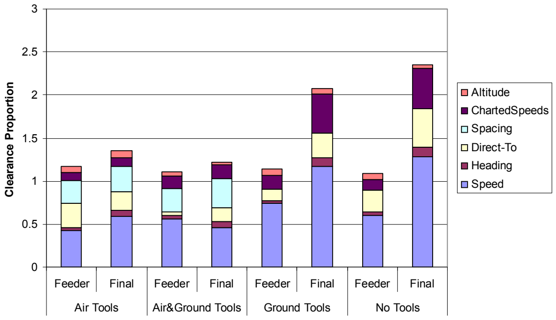
Clearance data also provide insights about the impact of spacing clearances. The data presented here are preliminary in that they are inferred from MACS pilot logs, not directly transcribed from communication recordings. However, a strong correlation exists between MACS p

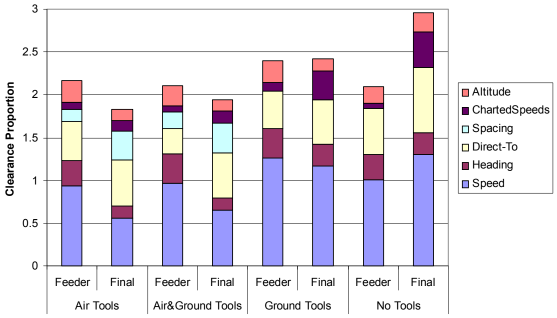
Spacing accuracy and clearances are both affected by how well the merging flows to 18R are initially coordinated. Accuracy measures for the coordinated flows measured at FF18R strongly resemble the overall measures shown in Figure 4; uncoordinated-flow aircraft are under-represented in Figure 4 because all trials stopped after thirty-five minutes when many of the had not yet reached FF18R. Figure 6 depicts spacing accuracy histograms for the coordinated flows in each condition instead measured at 'transfer to tower,' when Final West transferred control of the aircraft to Tower Ghost. The coordinated flows exhibit greatest accuracy for the Air & Ground Tools conditions, followed by Air Tools, then Ground Tools. Figure 7 shows accuracy measures for aircraft in uncoordinated flows. These results suggest that with airborne spacing, controllers can achieve better spacing accuracy even when merging flows are not well coordinated. Ground tools produced more conservative spacing, whereas No Tools showed broad variation in spacing accuracy.



Flow coordination also affected the clearances controllers issued. Figures 8 and 9 separate the clearances issued to aircraft in coordinated and uncoordinated flows, respectively. The results are again expressed as proportions. The data show that both Feeder West and Final West issued a greater proportion of clearances to aircraft in uncoordinated flows. For the coordinated flows, spacing clearances comprised a greater proportion of the clearances issued, and both controllers used smaller proportions of heading vectors and temporary altitudes, which translates into fewer



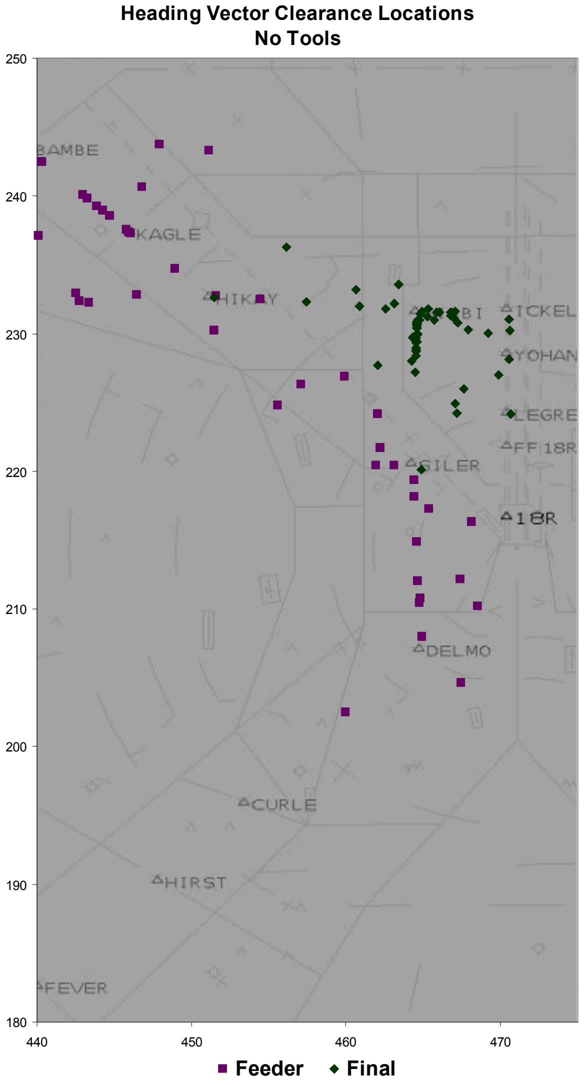


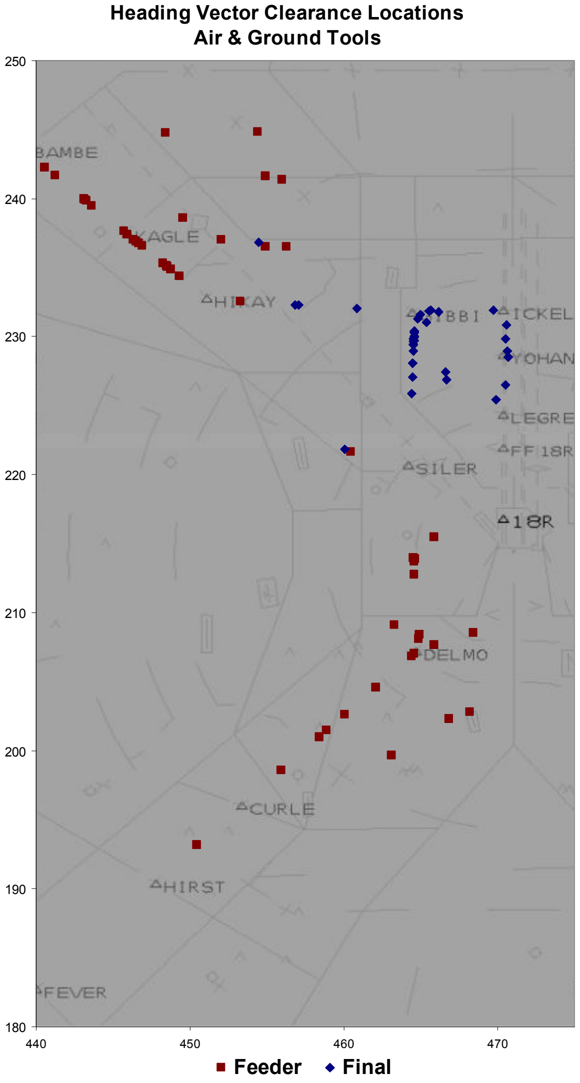


disruptions to FMS operations. The relative proportions of clearances issued by Feeder West and Final West in the Ground Tools and No Tools conditions are much closer for the uncoordinated flows.

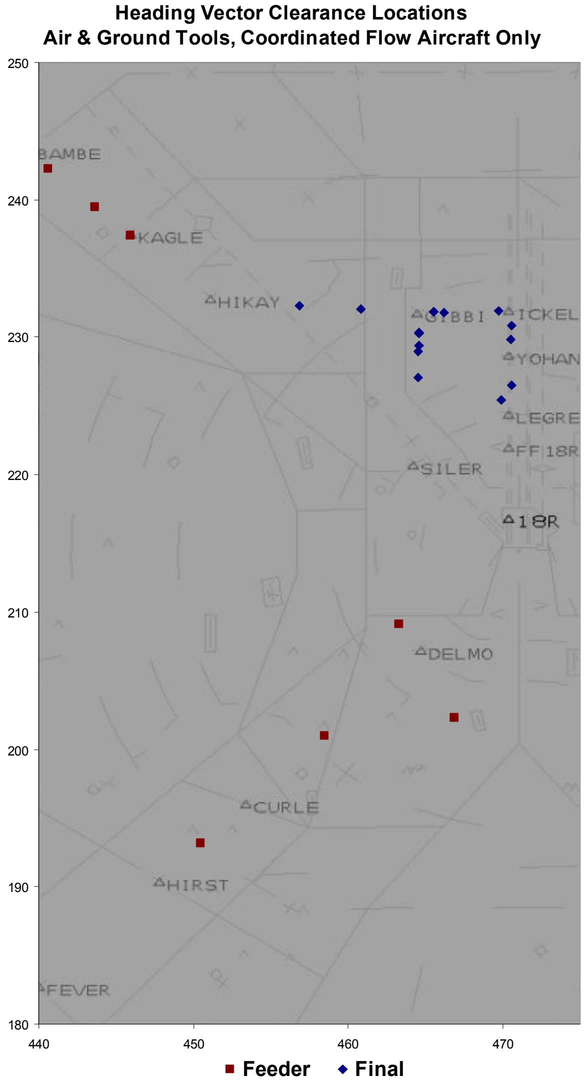
These results show reductions in heading vectors under spacing conditions similar to the results of Grimaud et al.[11] Another key finding of Grimaud et al. was that, with airborne spacing, it appeared that controllers could integrate the merging flows earlier and rely less on late vectoring. Their controller subjects reported better anticipation under airborne spacing conditions, a result they confirmed by examining the locations at which controllers issued clearances of various types. Figures 10 and 11 depict the geographical locations of heading vector clearances controllers issued in the present study in the No Tools and Air & Ground Tools conditions, respectively. Although controllers were free to use vectoring as they saw fit in all conditions, Figure 11 suggests a trend toward earlier vectoring by the Feeder controller (e.g, before rather than after DELMO) in the Air and Ground Tools condition when airborne spacing was available, in possible agreement with the EUROCONTROL results.

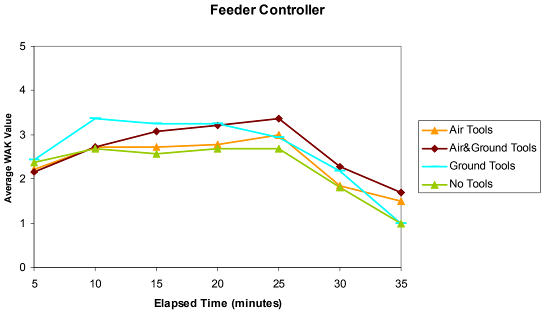
The effects of flow coordination on spacing operations can be understood through a similar examination of geographical clearance locations. Figure 12 depicts the approximate clearance locations of heading vectors issued to aircraft in coordinated flows in the Air & Ground Tools condition. Figure 12 reveals that controllers issued the

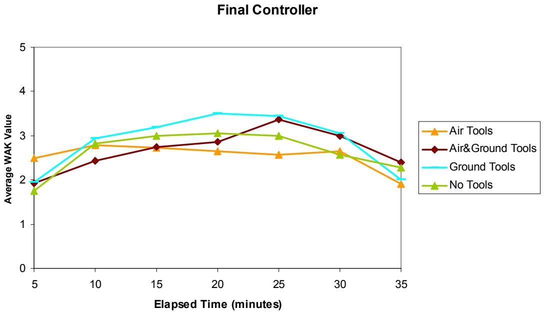


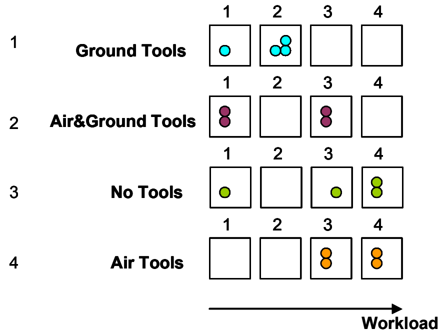


majority of heading vectors shown in Figure 11 to aircraft in uncoordinated flows. Similar effects are revealed for other clearances that disrupt FMS operations, such as temporary altitudes. Positive effects of flow coordination are also not limited to the Air & Ground Tools condition; indeed, flow coordination is helpful regardless of whether airborne spacing is used or whether controllers have DSTs.









Workload measures were assessed via Workload Assessment Keypads (WAKs) at five minute intervals during each trial. The average WAK scores for Feeder West show the lowest workload in No Tools conditions, with slightly higher workload in Air Tools conditions. Ground Tools conditions registered the most workload at the beginning of trials, whereas Air & Ground Tools conditions registered the most workload at the end (Figure 13). Final West average WAK scores were mostly lowest in Air Tools conditions, and mostly highest in Ground Tools conditions. Final West average WAK scores for Air & Ground Tools conditions exceeded scores for No Tools conditions toward the end of trials (Figure 14). On average, workload remained in an acceptable range for all conditions and the differences between conditions were small, indicating that airborne spacing operations with DSTs are feasible and do not result in any unreasonable workload increases for the traffic loads in this simulation.

Subjective workload rankings of the conditions were also included as part of the post-simulation questionnaire (Figure 15). Interestingly, the subjective workload rankings rate Ground Tools as the lowest workload condition and Air & Ground Tools as the second lowest. Controllers ranked the Air Tools condition as the highest workload. These rankings are essentially reversed from the average WAK scores. These results may reflect a desire on the part of controllers to have as much information as possible, as well as a perceived workload increase from maintaining responsibility for aircraft separation even after delegating spacing tasks to aircraft.

Controllers found the operations safe for all conditions. However, when asked to rank the conditions by safety, controllers ranked safety highest for Ground Tools condition, followed by No Tools, Air & Ground Tools, and Air Tools (Figure 16—note: one controller described all conditions as equally safe). These results are similar to the subjective workload rankings. Any behavior on the part of airborne spacing guidance or DSTs that controllers found unpredictable could have contributed to these rankings.

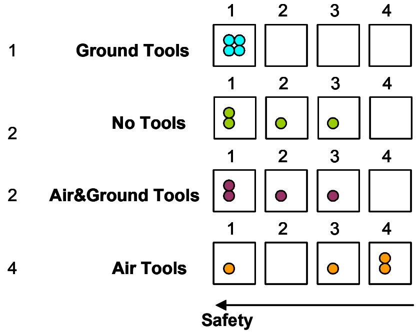
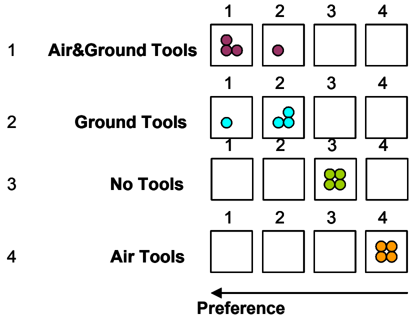


Figure 17 depicts how controllers ranked the conditions in the post-simulation questionnaire according to their preference for use. A majority of controllers preferred the Air&Ground Tools condition. The Air Tools condition was least preferable. Controller comments generally mirrored these preference rankings. The DSTs and 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, these results suggest that controllers would likely accept a mature implementation of airborne spacing operations with appropriate DSTs.



During the debrief discussions, controllers commented on their concerns with the self spacing aircraft. In a mixed equipage situation in which controllers had to manage an unequipped aircraft behind a self spacing aircraft, they had problems issuing speeds to maintain proper separation because the lead aircraft was flying variable speeds to maintain a targeted spacing. They felt in general that the concept would work better if they were relieved of the distance-based separation requirements (e.g. 3 nm) to self spacing aircraft.

The Ames DAG-TM CE 11 simulation study investigated TRACON merging and spacing operations in a rich operational environment with FMS operations with mixed spacing equipage. This paper has presented results that suggest the concept is feasible and improves spacing accuracy. Although workload always remained within an acceptable range, clearance data indicate that airborne spacing in the TRACON works best when linked to en route concepts capable of delivering aircraft in coordinated flows. Although the study differed from the airborne spacing research reported in Grimaud et al.[11] in several ways, the findings can be viewed as complementary. Taken together, the studies cast terminal area airborne spacing operations in a positive light.

The results in this paper present a conservative view of what could be achieved in a fielded version of the concept with mature spacing guidance and DSTs, and experienced flight crews and controllers. Further analysis is needed to isolate and study particular situations and characterize effects unequipped aircraft may have had. Analyses should also address when particular clearance types are used (cf. [6]). Additional studies are needed to investigate how such concepts might produce benefits in heavier traffic conditions, or with reduced or dynamic separation minimums. Future studies should also include en route and tower controller participants, as well as more realistic feeder controller positions, to investigate how these controllers function together.

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[1] EUROCONTROL/FAA, "Principles of Operation for the Use of Airborne Separation Assurance Systems,"