AIRBORNE-MANAGED SPACING IN MULTIPLE ARRIVAL STREAMS

Dr. Bryan Barmore[†], Terence Abbott[‡], and Dr. Karthik Krishnamurthy[⋆]
[†] NASA Langley Research Center, Hampton, VA 23669
[‡] Booz Allan Hamilton, Hampton, VA 23669
[⋆] Titan Corporation, Hampton, VA 23669

Keywords: *Terminal Arrival, airborne technology, ADS-B, spacing*

Abstract

A significant bottleneck in the current air traffic system occurs at the runway. Expanding airports and adding new runways will help solve this problem; however, this comes at a significant cost, financially, politically and environmentally. A complementary solution is to safely increase the capacity of current runways. This can be achieved by precise spacing at the runway threshold with a resulting reduction in the spacing buffer required under today's operations. At the NASA Langley Research Center, the Advanced Air Transportation Technologies (AATT) Project is investigating airborne technologies and procedures that will assist the pilot in achieving precise spacing behind another aircraft. This new spacing clearance instructs the pilot to follow speed cues from a new on-board guidance system called Airborne Merging and Spacing for Terminal Arrivals (AMSTAR). AMSTAR receives Automatic Dependent Surveillance-Broadcast (ADS-B) reports from the leading aircraft and calculates the appropriate speed for the ownship to fly in order to achieve the desired spacing interval, time or distance-based, at the runway threshold. Since the goal is overall system capacity, the speed guidance algorithm is designed to provide system benefit over individual efficiency. This paper discusses the concept of operations and design of AMSTAR to support airborne precision spacing. Results from the previous stage of development, focused only on in-trail spacing, are discussed along with the evolution of the concept to include merging of converging streams of traffic. This paper also examines how this operation might support future wake vortex-based separation and other advances in terminal area operations. Finally, the research plan for the merging capabilities, to be performed during the summer and fall of 2004 is presented.

1 Introduction

During the 1990's, air travel increased at an unprecedented rate, placing ever increasing capacity pressures on the National Airspace System (NAS). While the events of 2001 temporarily relieved these pressures, there are already signs of returning demand and possible gridlock. It is important to continue to address these capacity issues so that future U.S air transportation growth is not impeded. As part of this effort, numerous government and industry efforts are underway to develop new procedures for airborne and ground-based concepts to increase the capacity of the NAS. One such venture is NASA's Distributed Air/Ground Traffic Management (DAG-TM) concept under the Advanced Air Transportation Technologies (AATT) Project. The DAG-TM concept involves various levels of collaboration between airborne and ground-based resources to enable less-restricted and more efficient aircraft trajectories throughout all phases of flight.

One aspect of DAG-TM focuses on terminal arrival operations, providing a means for merging multiple inbound streams and delivering precisely spaced aircraft to the runway threshold. A properly equipped aircraft and trained flight crew are able to use speed guidance cues, advanced displays, and lateral path changes to meet these goals. This concept also envisions advanced ground-based decision support tools. These tools and associated procedures are being developed at the NASA Ames Research Center. This paper will focus only on the airborne tools, technologies and procedures.

Previous research investigated the feasibility of using traffic information displayed on the flight deck to enable airborne-managed spacing [1–9]. Simulator experiments conducted at NASA Langley involving the use of Cockpit Display of Traffic Information (CDTI), including a display of the lead traffic's location on the subject aircraft's Navigation Display (ND) found that time-based spacing was the most useful technique. A "time box" was used to represent the position where the subject aircraft ("ownship") should be, and this symbol provided a positional target for the flight crew to achieve in order to be at the right spacing interval behind the aircraft it was following. The spacing interval was assigned by the Air Traffic Service Provider (ATSP). The studies concluded that this concept is feasible from a crew workload and acceptability standpoint. Accurate knowledge of the positions and speeds of the lead aircraft with fast update rates are necessary for concept feasibility. Recent improvements in display and computing capabilities and broadcast of traffic data make the concept more realizable.

This paper discusses the current state of the DAG-TM terminal arrival concept and the airborne tools and proce-

dures being developed to support this concept. Current development is in the second of three planned phases for this terminal area concept. The first was in-trail and final approach spacing. The current phase adds merging capabilities. The final phase will implement limited maneuvering to aid in resolving large errors that may occur at the entry into the terminal area.

2 Time-based Spacing

Terminal area precision spacing has the potential to provide an increase in runway capacity. This increase is possible through improved precision of over-the-threshold times, which can lead to a decrease of the variability of the runway threshold crossing times [10]. While a small percentage increase in throughput may seem insignificant, this small increase in runway capacity can lead to a significant decrease in landing delays for airports during high-demand conditions. For example, if the throughput for a runway with a demand rate (ratio of arrivals to throughput) of 85% could be increased by 5%, the mean delay times for arriving aircraft could be reduced by as much as 29% [1]. To obtain this operational benefit, concepts for self-spacing of aircraft operating in airport terminal areas have been under development by NASA since the 1970's [1, 2, 4]. Interest in these concepts has recently been renewed due to a combination of the continued growth in air traffic with the ever increasing demand on airport (and runway) throughput, the emergence of enabling technology (Automatic Dependent Surveillance Broadcast data link, ADS-B), and the encouragement by the FAA's Safe Flight 21 Program to examine airborne approach spacing concepts.

One of the easiest spacing concepts to understand and implement is the fixed-distance concept. In this concept, each aircraft maintains a fixed-distance behind the aircraft it is following. The problem with this concept is that terminal area operations involve successive speed reductions by the landing aircraft. With a fixed-distance concept, when the in-trail spacing is obtained, the following aircraft then continually matches the current speed of the aircraft it is following. With multiple aircraft in-trail, the last aircraft will be speed matching with the very first aircraft, resulting in following aircraft performing speed reductions at distances continually further from the airport [9]. This may result in increased aircraft fuel consumption and higher generated noise. It should be noted, however, that traditional Air Traffic Control operations successfully use fixed-distance spacing by changing (reducing) the spacing interval as they reduce the in-trail speed.

3 In-trail and Final Approach Spacing

In 1999, renewed work at NASA Langley was initiated to support an operationally viable approach spacing concept. The eventual product of this effort was called the Advanced Terminal Area Approach Spacing (ATAAS) concept and was based on a following aircraft maintaining a time-based, rather than distance-based, spacing interval from the preceding aircraft [11]. It should be noted that the ultimate goal behind this concept was not to accurately and precisely space individual pairs of aircraft, but rather to achieve a system-wide improvement in performance. This improvement will be realized by obtaining better consistency in spacing from a system-wide standpoint, sometimes at the expense of having excessive spacing between individual aircraft pairs. As such, no single aircraft would be given guidance to aggressively achieve a spacing interval beyond what would normally be expected in current-day operations. It should be readily apparent that increasing the speed of one aircraft excessively in order to "close up the gap" with a preceding aircraft could quickly de-stabilize the system by multiplying the effect on the speed required of every aircraft that is in-trail, creating increasingly larger gaps and speeds well beyond acceptable operational standards.

To develop this concept of in-trail, airborne-managed spacing, system and operational (crew and controller) procedures were defined. The concept included the use of a charted Standard Terminal Arrival Route (STAR), similar to those currently in use today. This arrival route was extended to include a complete lateral path to the runway, plus a vertical profile (speed and altitude), all of which become part of the nominal arrival clearance. The basic system procedure was the issuance of an additional clearance from the controller to the flight crew of the ATAAS-equipped aircraft, which identified the traffic to follow and the assigned spacing interval. Theoretically, this clearance could be issued at any time during the arrival. Once the flight crew accepts the spacing clearance, no further speed clearances are needed from the ATSP.

A fundamental issue that is unchanged in ATAAS operations from current-day procedures is the responsibility for maintaining separation between aircraft. Under the new scenario, this responsibility remains with the ATSP. With this in mind, the clearance to conduct the approach-spacing operation is then a clearance to follow the ATAAS provided speeds, since the aircraft is already in the arrival phase. The clearance phraseology used reflects this procedure. Additionally, in keeping with a design goal of operational viability, part of the concept vision is the ability for unequipped aircraft (i.e., those without an ATAAS system) to also participate in this operation by means of the charted arrival. Including the nominal routing and speed profile as part of the charted arrival would allow an aircraft to be cleared for this arrival. By broadcasting its position and the appropriate data, it can also serve as a lead aircraft for the ATAAS-equipped aircraft sequenced behind it.

The ATAAS tool uses ADS-B aircraft state data plus final approach speeds and wind data to compute a speed command for the ATAAS equipped aircraft to follow. Although the tool has many potential applications in different types of operational scenarios, including en-route and

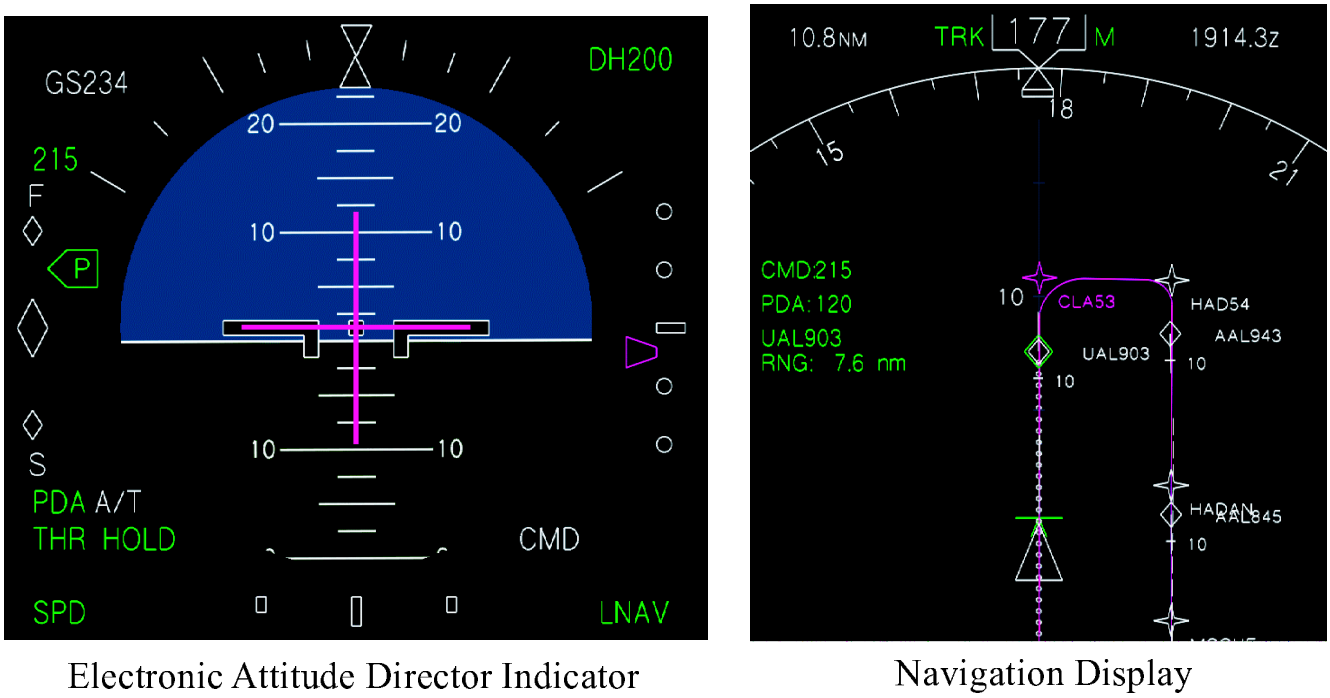

Fig. 1 Sample cockpit displays from the Boeing 757 showing ATAAS symbology. The left side shows the Electronic Attitude Director Indicator with the green PDA annunciation and commanded speed. The right side shows the navigational display with traffic displayed along with the history dots, green spacing indicator and green text block.

oceanic operations, the concept of in-trail spacing in the terminal area (i.e., aircraft are spacing longitudinally while following directly behind each other) was the logical first step in the evolution of the end-state goal of more efficient and flexible maneuvering through the terminal area.

The flight crew of a properly equipped aircraft manages their speed in real-time, thus allowing for finer control over the inter-arrival spacing between aircraft. Early research showed that flight crews are able to achieve the assigned spacing interval with a standard deviation of approximately two seconds [12]. This increased precision can eliminate excess spacing between aircraft, thus allowing for increased runway throughput.

From this new procedure and traditional operational considerations (e.g., the requirement for a stable speed segment prior to touchdown), the supporting ATAAS flight deck tool was developed using the nominal speed profile associated with the charted procedure as a basis around which the ATAAS algorithm would build the speed commands. Key features of the ATAAS tool are: (1) to provide speed commands to obtain a desired runway threshold crossing time or minimum distance, one aircraft relative to another; (2) to compensate for dissimilar final approach speeds between aircraft pairs; (3) to include wake vortex minima requirements; and (4) to provide guidance for a stable final approach speed.

Appropriate flight crew procedures were developed for crew interactions with the ATAAS tool. These procedures were designed to minimize the impact to crew workload levels. Supporting display elements (see figure 1) were designed to provide information to the crew on the mode of operation and the current state of the ATAAS-equipped ownship relative to the lead aircraft it is spacing behind. A trail of “history dots” behind the lead aircraft show its ground track on the ownship’s ND, and can be used instead of an area navigation (RNAV) route for lateral navigation. To allow the crew to select the lead aircraft and enter other appropriate data, a simple pilot interface with the ATAAS tool was provided via two custom Control Display Unit (CDU) pages.

The ATAAS tool has undergone extensive Monte Carlo analysis to characterize and refine its performance. Studies of this and another final approach spacing tool showed the possibility for runway throughput improvements of 15 – 20% [13].

In order to evaluate pilot workload, pilot acceptability, and to explore the feasibility of the operational concept (i.e., can the assigned spacing interval be consistently achieved with the algorithm implemented on real-world equipment), in-trail arrival scenarios were tested in a high-fidelity, B757 full mission simulator with eight airline subject pilots [12]. Aircraft and ATAAS state and mode data were collected, and pilots provided subjective ratings of perceived workload levels and various other aspects of the concept through questionnaires. The results of this simulation study showed that the ATAAS guidance

provided a means for achieving a target threshold arrival interval within ±5 seconds (this equates to approximately 1100 ft at the approach speed of 130 kt) across all test conditions. When autothrottles were used to track the ATAAS guidance, a mean error within ±1 sec, equivalent to 220 ft., was achieved. The standard deviation was 2 seconds. For comparison purposes, a simulator study conducted at Langley in 1990 using conventional air traffic control methods and ground-based automation resulted in a delivery precision of approximately 12 seconds [7]. With the pilot controlling the speed by either the Mode Control Panel or manual throttle inputs, the mean spacing interval was slightly greater than the ±1 sec (5 sec); but the consistency (standard deviation) was approximately the same as with the autothrottles tracking the ATAAS guidance. This mean difference was most likely a display or training issue, which resulted in the pilots not following the ATAAS speed guidance during the final deceleration. With respect to workload, the subject pilots generally rated the level of workload with the ATAAS procedure as similar to that with standard air traffic control procedures. They also rated most aspects of the procedure high in terms of acceptability. Oculometer data obtained from the subject pilots indicated slight changes in instrument scan patterns, but no reduction in the amount of time spent looking out the window (a concern with terminal area operations) [14].

A follow-on flight evaluation of the ATAAS concept was conducted at the Chicago O'Hare International Airport and in its surrounding terminal area [15]. Three aircraft participated in these flights: a Piper Chieftain, a Sabreliner, and a Boeing 757. The Chieftain functioned as the lead aircraft on which the Sabreliner spaced, and the Sabreliner served as lead for the B757. The implementation of the ATAAS spacing tool on-board the B757 included speed management through the autothrottles, and both manual and autothrottle speed management were included in the scenarios. Two basic types of scenarios, differentiated by the type of lateral navigation used, were flown: an RNAV based path which transitioned onto the final approach course, and vector scenarios in which headings were assigned to the first aircraft in the sequence. In the vector scenarios, the Chieftain was vectored off path by the controller and the other two aircraf were able to stay in-trail by following the history dots displayed on their CDTI by the ATAAS tool. Data collected consisted primarily of aircraft state data, algorithm outputs, and pilot subjective data. All flight crews were research pilots. During the course of the flights, the aircraft were exposed to varying wind conditions, occasional firmware problems, and other challenges. The delivery precision of the algorithm, based on a target spacing of 90 seconds, were similar to the simulation results and resulted in a mean error of 0.8 sec with a standard deviation of 7.7 sec.

Although the evaluations of the ATAAS concept have been relatively limited, some important conclusions can be drawn from this study. Consistent airborne-managed approach spacing is easily achievable with the ATAAS tool used on real-world equipment. Use of simple pilot and controller procedures to accompany the tool can result in a highly acceptable system from the pilot's standpoint. Proper training, including fixed-base simulator time is necessary to provide pilots with the knowledge and capabilities needed to perform this type of procedure. Use of this tool can result in slight changes to the pilots' scan patterns, however a well-designed interface can minimize the amount of head-down time needed to interact with the tool.

4 Merging and Spacing Operations

Following the successful flight evaluation of the ATAAS tool, the DAG-TM research team at NASA Langley commenced work on extending the ATAAS concept to accommodate the second phase of research – airborne spacing in merging arrival streams. Where ATAAS was intended for use only when the lead and following aircraft were in-trail, this extension of ATAAS would permit time-based spacing between any two aircraft headed for the same runway, even if they were not yet physically in-trail. This situation would occur if arrivals entered the terminal area through different entry points or were separated on to different approach routes to the runway for performance reasons (for example, jets and turboprop arrival routes).

This new concept, called Airborne Merging and Spacing for Terminal Arrivals (AMSTAR), is a direct descendant of the ATAAS concept and implementation. AMSTAR extends the capabilities of ATAAS to provide spacing guidance prior to merging behind a lead aircraft. Arriving traffic, as with ATAAS, will follow a charted STAR, similar to those in use today, but extended to include a complete lateral path to the runway, a vertical path, and a speed profile.

The new capability offers two benefits: (1) it would increase the time available for aircraft to achieve the desired spacing, notionally to the entire time they are within the terminal area, and (2) it could be used to ensure proper merging of arrival streams, potentially reducing the controller's task from active vectoring for the merge, to monitoring the progress of an airborne-managed merge.

As with the in-trail concept, a named arrival route is part of the nominal arrival clearance (see figure 2 for examples used in simulation); the arrival clearance could be supplemented by a spacing clearance that would designate a lead aircraft and an assigned spacing interval to be achieved at the runway threshold. This clearance could be issued at any time after entry into the terminal area.

Knowing the arrival route assigned to the ownship, and that assigned to the designated lead (via ADS-B), the AMSTAR tool computes the estimated time of arrival (ETA) for each aircraft at the runway threshold (incorporating the effects of predicted wind fields). By comparing the difference between ETAs with the assigned spacing at the runway, the algorithm computes any required speed change

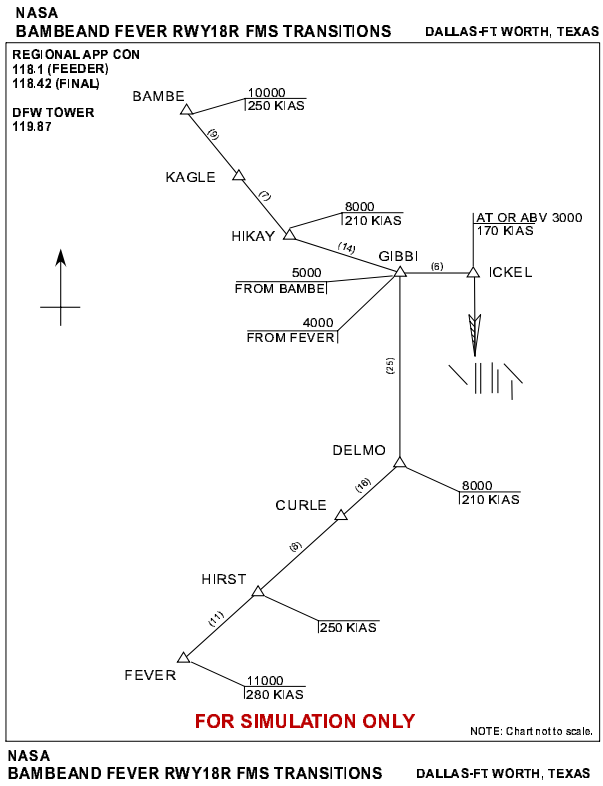

Fig. 2 Simulation approach routes for arrivals from the west landing at DFW runway 18R. Traffic merges laterally at GIBBI and vertically at ICKEL. Past ICKEL all aircraft intercept the 18R ILS.

relative to the profile speeds being flown. In keeping with the ATAAS philosophy of not aggressively commanding spacing corrections for any one pair of aircraft, the speed changes are limited at 10% of the profile speeds for that segment of the approach path. Other considerations that limit the speed change include the 250 KIAS / 10000 feet restriction, and a check on violating wake turbulence separation criteria. These criteria could reflect traditional regulatory spacing requirements, or could reflect wake-vortex separation requirements for the given aircraft types. The new speed-to-fly is annunciated on the flight deck and (optionally) input to the autoflight system for speed guidance, thereby gradually and progressively reducing the error in the assigned arrival spacing, while ensuring that the ownship merges in a stable and safe fashion behind the lead aircraft.

Responsibility for maintaining separation between aircraft remains with the ATSP (as in present day operations). Operations are similar to the ATAAS operations in that the approach spacing clearance is now to follow the AMSTAR provided speeds. As such, the basic procedure is the issuance of a new clearance from the controller to the flight crew of AMSTAR-equipped aircraft, identifying the traffic to follow, the named route to fly, and the assigned spacing interval. Once the flight crew accepts the spacing clearance, no further speed clearances are needed from the ATSP. For operational viability, unequipped aircraft (i.e., those without an AMSTAR tool) can also participate in this operation by flying the charted arrival. As long as such aircraft (or a ground-based system) broadcast the appropriate data, they can serve as the lead aircraft for AMSTAR-equipped aircraft.

Compared to ATAAS operations, AMSTAR operations require some extra information to be available from the lead aircraft, namely the identifier for the standardized arrival route being flown by that aircraft. A new on-condition ADS-B report, to be transmitted by all participating aircraft in the terminal area, is proposed as the broadcast mechanism for this new information. In addition to the named arrival route, each aircraft would broadcast its final approach speed and weight / wake-vortex class. Also, if the transmitting aircraft is itself performing AMSTAR operations, it transmits the ID of its lead aircraft and the assigned spacing, as well as information on the AMSTAR operational mode. These latter data could provide ground-based systems with information for conformance monitoring and error checking.

The commencement of active spacing in AMSTAR operations is dependent upon ownship acquiring the ADS-B messages of the lead aircraft, which may not be initially within reception range (given the combination of high traffic and large distances between entry points at typical terminal areas). Therefore, the AMSTAR tool is designed to accept a pilot-entered lead aircraft as well as the assigned spacing interval, and to fly the charted speed profile, while waiting to acquire the lead's ADS-B transmissions. This is called a "Profile" mode. The aircraft can also be assigned to fly in profile mode by the ATSP in instances where there is no lead aircraft to follow. If the lead is not acquired within a pre-specified time interval, the tool will advise the pilot of this fact. Once the lead is acquired, the tool transitions into a "Paired" mode, when it actively spaces relative to the lead. Since traditional operational considerations dictate a stabilized speed prior to touchdown, AMSTAR also transitions into a "Final" mode once ownship has crossed the Final Approach Fix.

In summary, the AMSTAR tool is initialized by crew input of ATSP-provided spacing information, and then (1) provides speed commands to obtain a desired runway threshold crossing time or minimum distance, relative to the lead; (2) compensates for actual final approach speeds of own and lead aircraft; (3) respects wake vortex minima requirements; and (4) provides guidance for a stable final approach speed.

The tool has been implemented in a batch-capable airspace and air traffic simulation system developed by the NLR with support from NASA [16], where its robustness to a variety of operational variables (such as wind prediction errors, ADS-B range limits, meter-fix arrival time errors, and variations in aircraft type) are being evaluated.

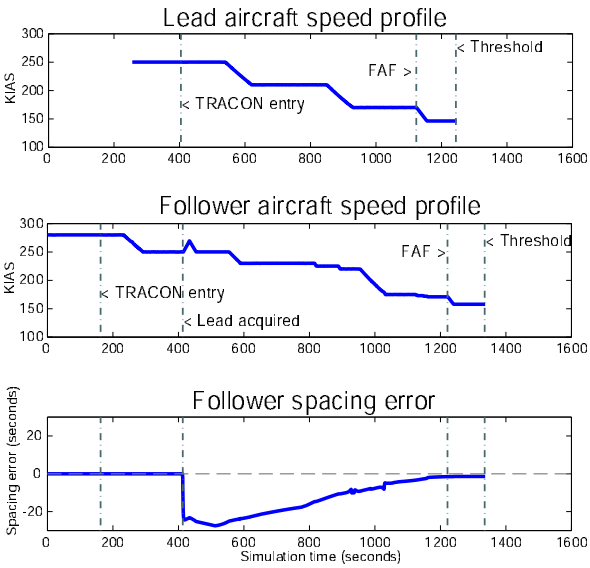

Fig. 3 Sample results of AMSTAR fast-time simulations with no winds. The top block shows the lead aircraft's current indicated airspeed while in profile mode. The middle block shows the trailing aircraft's indicated airspeed. The trailing aircraft starts in profile mode until the lead aircraft is acquired, it then transitions to paired mode. The bottom block shows the current spacing errors as calculated by the trailing aircraft.

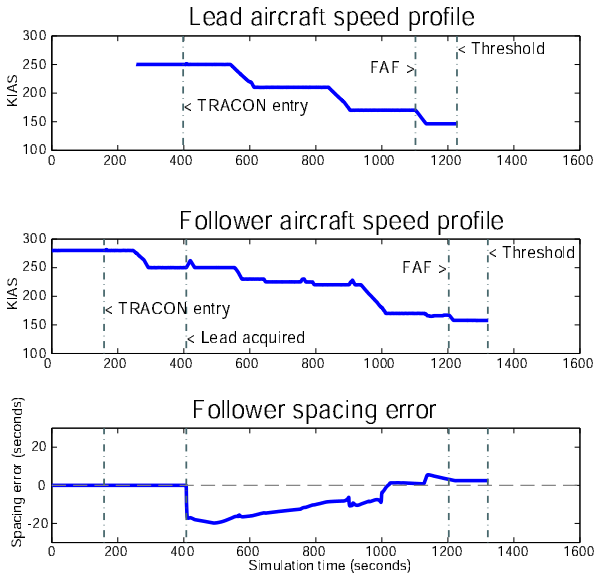

Fig. 4 Sample results of AMSTAR fast-time simulations with different truth and predicted wind fields. The top block shows the lead aircraft's current indicated airspeed while in profile mode. The middle block shows the trailing aircraft's indicated airspeed. The trailing aircraft starts in profile mode until the lead aircraft is acquired, it then transitions to paired mode. The bottom block shows the current spacing errors as calculated by the trailing aircraft.

Figures 3 and 4 represent sample data collected from the fast-time simulations and show the actual airspeed for a lead and trailing aircraft along with the calculated spacing error from the trailing aircraft. This is a sample of the behavior expected from the fast-time and human-in-the-loop experiments. In both cases, the upper figure shows the indicated airspeed of the lead aircraft flying in profile mode. The lead aircraft was flying the DFW BAMBE arrival route shown in figure 2. The trailing aircraft arrived via the FEVER arrival route. When the trailing aircraft entered the terminal area, it went into profile mode since its lead was not yet in the terminal area. Once the lead aircraft entered the terminal area, the trailing aircraft went into paired mode. This is seen by the vertical line near 400 seconds. The third graph shows the calculated spacing error for the trailing aircraft. Notice the slow, monotonic decrease in the error. The goal of the concept is to nullify the spacing error at the runway threshold and not to aggressively achieve the assigned spacing and then maintain it. This is more acceptable to the operators and passengers and enhances system-wide stability.

There are just minor differences between figure 3, with no winds, and figure 4 which has a mild wind field along with a wind prediction error. As can be seen, the wind prediction error causes more speed adjustments; however, the spacing error is satisfactorily nullified. The wind prediction errors cause a little more uncertainty in the "time to go" calculations that appear as small changes in the flown speed and the spacing error.

In a parallel effort, flight crew procedures and cockpit interfaces have been prototyped with the overall objective of supporting crew interaction with the AMSTAR tool without increasing crew workload. Prototypes of the AMSTAR tool, flight deck displays and pilot interfaces have been implemented in a medium-fidelity aircraft simulation housed at NASA Langley's Air Traffic Operations Laboratory (ATOL) [17], where they will be tested and evaluated in piloted simulations (see figure 5). Since the pilot's actions are largely unchanged, the displays are very similar to those used for ATAAS. The major changes are an advanced set of advisories and announcements on the EICAS and changes to conform to the Boeing 777-like cockpit displays used in the ATOL. As part of this integration, a new speed guidance mode was created called Pair Dependent Speed (PDS). If the pilot chooses this mode, the source of speed guidance becomes the AMSTAR tool. A full description of the displays and the CDU pages can be found in Ref. [18].

A human-in-the-loop experiment is being planned for the summer of 2004 in the ATOL. The experiment will focus on the flexibility of the concept and tool by having the pilots fly arrivals into three simulated airspaces based on Chicago O'Hare (ORD), San Francisco (SFO) and LaGuardia (LGA). One of the design goals for airborne

Fig. 5 Primary Flight Display (PFD) and Navigation Display (ND) of the Boeing 777-like simulator with AMSTAR/Pair Dependent Spacing symbology. The PFD shows the PDS annunciation in the upper right corner under the Flight Mode Annunciator and the commanded speed on the speed tape. The ND shows the lead aircraft highlighted in green along with history dots. Note that the aircraft is approaching a merge point with the lead aircraft.

precision spacing was to use existing flow patterns and airborne tools and procedures to develop a concept that operates in the same manner at nearly all airports. This experiment will look to validate that flexibility. It will also provide insight into crew use of these interfaces. In addition, we will gather information on controller acceptability and concerns with these operations.

5 Limited Maneuvering for Precision Spacing

The AMSTAR tool and its predecessor, ATAAS, only make use of the speed degree of freedom to achieve the desired spacing interval. Limiting adjustments to speed help meet the operational goals of stabilizing the entire stream of aircraft and working within current airspace design and ATSP procedures. However, there are limits to how large of an error in spacing that a speed adjustment can correct. Part of the fast-time studies, currently under way at NASA Langley, is investigating the conditions where speed is no longer sufficient to correct for spacing errors.

Large errors in spacing would generally occur near the beginning of the operation. This could be the result of one or more aircraft missing their scheduled time at the entry point or an unexpected shift in the weather or winds. In current AMSTAR-enabled operations, the controller would need to vector the offending aircraft to a proper spacing in the arrival stream before being able to issue the spacing clearance. Since other aircraft could not space off of this aircraft, such maneuvers would disrupt the overall spacing operations with a resulting decrease in runway throughput. An alternative would be to allow the flight crew to use an additional degree of freedom to compensate for the large spacing error. This is where limited maneuvering comes into play.

As envisioned as part of DAG-TM, each arrival route would be surrounded by a corridor of “reserved” airspace. The flight crews could maneuver within these corridors when needed to correct large spacing errors. The role of maneuvering is to make gross adjustments in spacing. The finer adjustments would be made by speed alone. While limited maneuvering concept has not been developed, some early thoughts on its application are presented below.

Due to the limited amount of airspace within a busy terminal area and the large number of operations trying to use that airspace, lateral maneuvering should be minimized. This can be done by allowing AMSTAR-enabled operations to occur whenever the spacing error is not “too large.” This would be the nominal case. In cases where the spacing error is large, the flight crew would be able to modify their arrival route within the pre-defined corridors to minimize the spacing error. Thereafter, they would continue to operate as envisioned for AMSTAR, using only speed variations to correct any additional spacing error that might arise. This one-time path adjustment is designed to minimize the impact of changing routes on the stability of the overall stream.

The trailing aircraft would need to know the path that their lead aircraft is now following in order to properly

determine their spacing. Therefore, information on the new lateral path would need to be broadcast via the ADS-B data message. The details of how this information is shared still need to be determined but must conform to the limited message size available through ADS-B and must allow the trailing aircraft, and ATSP, to adequately reconstruct the new route the aircraft will be following. Again, once this new route is established, the aircraft would continue to follow the speed guidance provided by their on-board tool.

6 Conclusion

A new operation for terminal area arrivals is being proposed that would allow for increases in runway throughput by increasing the precision with which aircraft are spaced at the runway threshold. This precision spacing operation uses on-board speed guidance to obtain an assigned inter-arrival spacing. This prototype concept and supporting tool is called Airborne Merging and Spacing for Terminal Arrivals (AMSTAR), and it allows for spacing operations to commence before the aircraft are physically in-trail, i.e. allows the merging of different streams of traffic. These operations are enabled by the advent of advanced surveillance and datalink capabilities such as ADS-B.

In addition to improved precision at the runway threshold, these operations allow for more dynamic and optimized spacing for each pair of arriving aircraft. This optimal spacing interval could be a combination of wake turbulence avoidance, runway occupancy times and final approach and landing speeds. For example, if one pair of aircraft needs to space at 85 seconds and a second pair needs 95 seconds, these different intervals could be met by airborne precision spacing. If a single human, such as a controller, was responsible for a string of several aircraft, each with slightly different spacing requirements, they would naturally adjust everyone to a common, or a few common, safe intervals. While this keeps their workload at an acceptable level and maintains safety, there is a decrease in throughput due to excess spacing for those pair that could have been safely spaced more precisely. In addition, precision spacing operations could result in fewer speed clearances being issued to equipped aircraft, thus decreasing radio traffic and the associated workload for both the controllers and the pilots.

Two studies are underway at NASA Langley Research Center to characterize the performance and usability of the AMSTAR concept. A fast-time simulation is looking at performance under varying conditions to identify situations where speed intervention is not sufficient for precision spacing. Under these extreme conditions the concept might need to be augmented to include limited maneuverability by the aircraft to meet the operational goals. A human-in-the-loop study will also be conducted to determine the flight crew and ATSP acceptability of the concept.

References

[1] Credeur, L. *Basic Analysis of Terminal Operation Benefits Resulting from Reduced Vortex Separation Minima.* NASA/TM-78624, 1977.

[2] Abbott, Terence S. and Moen, Gene C. *Effect of Display Size on Utilization of Traffic Situation Display for Self-Spacing Task.* NASA/TP-1885, 1981.

[3] Abbott, Terence S. *Simulation of a Cockpit Display for Increased Airport Capacity.* Presented at the 27th Annual Meeting of the Human Factors Society. In Proceedings, Volume II, p.777-781, 1983.

[4] Williams, David H. *Time-Based Self-Spacing Techniques Using Cockpit Display of Traffic Information During Approach to Landing in a Terminal Area Vectoring Environment.*, NASA/TM-84601, 1983.

[5] Kelly, James R. and Abbott, Terence S. *In-Trail Spacing Dynamics of Multiple CDTI-Equipped Aircraft Queues.* NASA/TM-85699, 1984.

[6] Williams, David H. and Douglas C. Wells *Jet Transport Flight Operations Using Cockpit Display of Traffic Information During Instrument Meteorological Conditions, Simulation Evaluation.*, NASA/TP-2567, 1986.

[7] Credeur, L., J. A. Houck, W. R. Capron, and G. W. Lohr *Delivery Performance of Conventional Aircraft by Terminal Area, Time-Based Air Traffic Control, A Real-time Simulation Evaluation.* NASA/TP-2978, 1990.

[8] Abbott, Terence S. *A Compensatory Algorithm for the Slow-Down Effect on Constant-Time-Separation Approaches.* NASA/TM-4285, September 1991.

[9] Sorensen, J. A., et al *Traffic Alert and Collision Avoidance System (TCAS) - Cockpit Display of Traffic Information (CDTI) Investigation.* DOT/FAA/RD-91/8, April 1991.

[10] Swedish, W. J. *Evaluation of the Potential for Reduced Longitudinal Spacing on Final Approach.* FAA-EM-79-7, 1979.

[11] Abbott, T. S. *Speed Control Law for Precision Terminal Area In-Trail Self Spacing*, NASA TM 2002-211742, July 2002.

[12] Oseguera-Lohr, Rosa M., Lohr, Gary W., Abbott, Terence S., and Eischeid, Todd M. *Evaluation Of Operational Procedures For Using A Time-Based Airborne Interarrival Spacing Tool* AIAA-2002-5824.

[13] Wang, Ganghuai; and Hammer, Jonathan *Analysis of an Approach Spacing Application.* 4th USA/Europe ATM2001 R&D Seminar, Sante Fe, NM, USA, Dec. 3 - 7, 2001.

[14] Oseguera-Lohr, Rosa M., Eric Nadler. *Effects of an Approach Spacing Flight Deck Tool on Pilot Eye Scan.* NASA/TM-2004-212987.

[15] Lohr, Gary W., Oseguera-Lohr, Rosa M., Abbott, Terence S., and Capron, William R. *Flight Evaluation of a Time-Based Airborne Interarrival Spacing Tool.* 5th EUROCONTROL / FAA ATM R&D Seminar, Budapest, Hungary, June 23-27, 2003.

[16] Hull, J., B. Barmore, K. Krishnamurthy and T. Abbott. *Technology-enabled Airborne Spacing and Merging.* submitted to 23rd Digital Avionics Systems Conference, Salt Lake City, Utah.

[17] Peters, Mark E., Mark G. Ballin and John S. Sakosky. *A*

Multi-Operator Simulation for Investigation of Distributed Air Traffic Management Concepts. AIAA Guidance, Navigation, and Control Conference & Exhibit, Monterey, California, AIAA 2002-4596, August 5-8, 2002.

[18] Palmer, Michael T., Bryan E. Barmore, Terence S. Abbott. *Integration of Paired-Dependent Speed Guidance into Current-Generation Glass-Cockpit Commercial Aircraft*. 24th ICAS Congress, Yokohama, Japan, August 29 - September 3, 2004.

[19] Bussink, F.J., N. Doble, B. Barmore, S. Singer. *A Fast-Time Simulation Environment for Airborne Merging and Spacing Research*. submitted to 23rd Digital Avionics Systems Conference, Salt Lake City, Utah.