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Airborne Evaluation and Demonstration of a Time-Based Airborne Inter-Arrival Spacing Tool

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FLIGHT EVALUATION AND DEMONSTRATION OF A TIME-BASED AIRBORNE INTER-ARRIVAL SPACING TOOL

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Abstract

An airborne tool has been developed that allows an aircraft to maintain a time-based spacing interval from the preceding aircraft. The Advanced Terminal Area Approach Spacing (ATAAS) tool uses Automatic Dependent Surveillance-Broadcast (ADS-B) data to compute speed commands for the ATAAS-equipped aircraft, allowing that aircraft to maintain a required time interval behind another aircraft. The tool was evaluated in an operational environment at the Chicago O'Hare International Airport. Three aircraft participated in the flights: a Piper Chieftain, a Rockwell Sabreliner, and a Boeing 757. The Chieftain functioned as lead aircraft on which the Sabreliner spaced, and the Sabreliner served as lead for the B757. The implementation of the ATAAS spacing tool onboard the B757 included speed management through the autothrottles; both manual and autothrottle speed management were included in the scenarios to demonstrate the ability of ATAAS with either method of speed scenarios. Two basic types of scenarios, differentiated by the type of lateral navigation used, were flown: an "area navigation" (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 these latter scenarios, the other two "spacing " aircraft would follow the lateral path of the first, using an onboard display of the preceding aircraft's path generated by the ATAAS algorithm. Data collected consisted primarily of aircraft state data, algorithm outputs, and pilot subjective comments. 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. Results on the delivery precision of the algorithm, based on a target spacing of 90 seconds were as follows. For all scenarios a mean of 90.8 seconds with a standard deviation of 7.7 seconds was achieved. The results for the RNAV and vector cases respectively were M=89.3, SD=4.9 and M=91.7, SD=9.0. Pilots stated that the task of tracking the lateral path of the leading aircraft (vector scenarios), and following ATAAS-generated speed guidance was manageable and could be integrated into normal flying duties.

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Abbreviations and Acronyms

ADS-B	Automatic Dependent Surveillance – Broadcast
AGL	Above Ground Level
Ant	antenna
ARC	Ames Research Center
ARIES	Airborne Research Integrated Experiment System
ATAAS	Advanced Terminal-Area Approach Spacing
ATC	Air Traffic Control
ATIS	Automatic Terminal Information System
ATSP	Air Traffic Service Provider
BOT	bottom
CDTI	Cockpit Display of Traffic Information
CDU	Control-Display Unit
DAG-TM	Distributed Air/Ground Traffic Management
EADI	Electronic Attitude Director Indicator
EDCP	Experimental Display Control Panel
FMC	Flight Management Computer
FMS	Flight Management System
F/S	Fast/Slow
IAS	Indicated Airspeed
ILS	Instrument Landing System
LaRC	Langley Research Center
MCP	Mode Control Panel
NASA	National Aeronautics and Space Administration
ND	Navigation Display
PDA	Paired Dependent Approach
RNAV	Area Navigation
STAR	Standard Terminal Arrival Route
TTF	traffic to follow
ft	feet
KIAS	knots indicated airspeed
kts	knots
nmi	nautical miles
Xpndr	transponder

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1.0 Introduction

In the years following 9/11 air travel has rebounded and continues to increase, leading to traffic congestion in many of the nation's busiest terminal areas. With this trend expected to continue into the foreseeable future, many government and industry efforts have focused on research programs aimed at alleviating congestion through development of new procedures for airborne and ground-based use with supporting new technologies. To address this problem, the National Aeronautics and Space Administration's (NASA) Advanced Air Transportation Technologies (AATT) Project developed the concept of Distributed Air/Ground Air Traffic Management (DAG-TM). 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, leading to increased airport capacity [1].

The element of the DAG-TM concept that focuses on terminal area operations requires the development of technologies and procedures that allow aircraft to have more flexibility in choosing an efficient route through the terminal area, while arriving at the runway threshold properly and efficiently spaced from the preceding aircraft [2]. The objective of approach spacing is to reduce the excess inter-arrival spacing in the arrival traffic stream (approx. 26 seconds for vectored aircraft) [3]. by increasing spacing precision to achieve nominal spacing intervals at the runway threshold. The concept of approach spacing allows for a safe reduction in the excess spacing in traffic streams from what current procedures generally provide, increasing the precision with which aircraft are spaced, such that they can be delivered at the desired spacing intervals at the runway threshold. This requires the capability to precisely predict and control the spacing intervals between arriving aircraft. To meet this objective, an airborne tool, called the Advanced Terminal Area Approach Spacing (ATAAS) tool, was recently developed at NASA's Langley Research Center (LaRC). The ATAAS tool, a refinement of previous techniques, is based on the idea of an aircraft maintaining a time-based, rather than distance-based, spacing interval from the preceding aircraft [4].

A flight evaluation was conducted by LaRC to evaluate the in-trail spacing tool and associated flight deck procedures in a real-world operational environment, as a follow-on to a piloted simulator study that assessed pilot workload and acceptability of the approach spacing concept. The remainder of this paper provides background on the concept and previous work, and documents the flight evaluation and results.

2.0 Background

2.1 Past Work

Previous research has investigated the feasibility of using traffic information displayed on the flight deck to enable airborne-managed spacing [3, 5-7]. Simulator experiments conducted at LaRC involving the use of Cockpit Display of Traffic Information (CDTI), including a display of the lead traffic's location and other predictors 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 provided a position target for the ownship to achieve to be at the correct spacing interval behind the aircraft it was following, with the spacing interval assigned by Air Traffic Control (ATC). The studies concluded that this concept was feasible from a crew workload and acceptability standpoint, although accurate knowledge of the positions and speeds of the aircraft with fast data update rates are necessary. Recent improvements in display and computing capabilities and broadcast of traffic state data have made the concept realizable.

The ATAAS tool uses Automatic Dependent Surveillance-Broadcast (ADS-B) aircraft state data along with final approach speeds and wind data to compute speed commands for the ATAAS-equipped aircraft to maintain, in order to achieve the required runway-threshold time interval behind the other aircraft. This tool has undergone extensive Monte Carlo analysis to characterize and refine its performance. Although the tool has many potential applications in different types of operational scenarios, including merging routes, en-route, and oceanic operations, the concept of in-trail spacing in the terminal area (i.e., aircraft are spacing longitudinally while following directly behind each other on the same ground track) was the first step in the evolution of the end-state goal of more efficient and flexible maneuvering through the terminal area. Research in this area has continued and a recent study at NASA has addressed the more complex merge problem, where an aircraft arriving into the terminal area is sequenced behind an aircraft arriving from a different direction[8]. Complete result from this study will be available in the near future.

The ATAAS tool was tested with airline pilots in a high-fidelity, full mission engineering B757 simulator, to evaluate workload and pilot acceptability issues associated with its use, and to explore the feasibility of the operational concept (i.e., can the assigned spacing interval be consistently achieved under operationally reasonable conditions)[9]. Results from this study showed that the aircraft was able to consistently achieve the target spacing interval within a mean error of one second (the equivalent of approximately 220 ft at a final approach speed of 130 kts) when the ATAAS speed guidance was autothrottle-coupled. A slightly greater mean error (4.5 seconds), and consistent interval was also achieved with the pilot-controlled speed modes, where the pilot adjusted the aircraft speed by use of manual throttles or manually-controlled speed through the Mode Control Panel (MCP). The subject pilots generally rated the workload level with the ATAAS procedure as similar to that with standard procedures and also rated most aspects of the procedure high in terms of acceptability. Positive results were also obtained from subjective and eye-tracking data used to assess head-down time required for using the ATAAS tool [10]. Using the positive results from the simulator study, some minor enhancements were made to the algorithm and interface, in preparation for implementation on a LaRC research aircraft for the in-flight evaluation and demonstration of the concept in an actual operational environment.

2.2 Approach Spacing Concept

The ultimate goal behind the in-trail approach spacing concept is not to optimize precision spacing for individual pairs of aircraft, but rather to achieve a system-wide improvement in performance. That 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 will be given a speed beyond what would normally be expected in current-day operations in order to achieve a spacing interval. It is readily apparent that increasing the speed of one aircraft excessively in order to "close up the gap" with a preceding aircraft would quickly destabilize the system and would not, in fact, increase system-wide performance. In addition, this destabilization could multiply the effect on the speed required of every aircraft that is in-trail, creating increasingly larger gaps and speeds well beyond acceptable levels by today's standards. In future applications, any reduction in system throughput that could result from this type of limitation could be recovered through other methods, such as adjusting the lateral route in a designated maneuvering area. Flight crew procedures were developed to implement this in-trail concept with a focus on minimal impact to current workload levels.

To develop the concept of in-trail, airborne-managed spacing in the terminal area, a nominal scenario was defined, to include system and operational (crew and controller) procedures, with candidate phraseologies and a crew interface with the ATAAS tool. The concept definition includes the use of a charted Standard Terminal Arrival Route (STAR), similar to those currently in use today. The arrival route is 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. This method is used to provide a common profile that can reduce ATC-pilot communication requirements and provide the flight crew with an understanding of when they can expect speed changes. However, this does not imply that the aircraft must be on this route in order to use ATAAS. The ATAAS tool can also be used in a vectoring environment where the lead aircrafts ground track can be displayed and followed by another aircraft. The basic system procedure is the issuance of an additional clearance from the controller to the ATAAS-equipped aircraft flight crew, which identifies the traffic to follow (TTF) and the assigned time interval for spacing. This clearance could be issued at any time during the arrival. Once the flight crew accepts the spacing clearance and begins following the ATAAS-commanded speeds, no further speed clearances are needed from the Air Traffic Service Provider (ATSP), but other normal communications (frequency changes, approach and landing clearances) take place as usual. Note that after accepting this clearance, the flight crew does not assume responsibility for separation; under this concept, the ATSP retains responsibility for separation, and may cancel the clearance if required to do so in the interest of safety.

Part of this approach spacing concept is the ability for un-equipped aircraft (i.e., those without an ATAAS implementation) to also participate in this operation by means of a charted arrival. Including the nominal routing and speed profile as part of the charted arrival allows an aircraft that can maintain the charted profile to be cleared for and fly 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. This concept can also be extended to lower-density facilities as their traffic levels increase. The procedure allows aircraft to perform approach spacing operations at those facilities, enabling more consistent and reliable spacing of arrivals with minimal changes to infrastructure.

A fundamental issue that is unchanged from current-day procedures is the responsibility for maintaining separation between aircraft. Under the new scenario, that responsibility remains with the Air Traffic Service Provider (ATSP). To assist the controller in fulfilling this role, ground tools have been developed at the NASA-Ames Research Center (ARC). The tools are based on anticipated information requirements and are currently being evaluated. Studies focusing on controller impact of an airborne spacing concept and related procedures have been conducted by EuroControl with positive results [11].

Appropriate flight crew procedures were developed to allow interaction with the ATAAS tool, with minimal impact to current workload levels. Only a subset of these procedures were used in the flight evaluation, since only one member of the flight crew was performing the ATAAS task with the non-flying pilot performing safety pilot duties. Supporting display symbology was developed to augment the basic aircraft displays to provide ATAAS information to the crew. A simple interface was also developed that allowed the crew to select the lead aircraft and enter other appropriate information into the Flight Management Computer Control-Display Unit (FMC-CDU). The CDU pages used for ATAAS data were customized for entering data to the ATAAS tool. These pages and data did not directly interface with the FMC.

2.3 ATAAS algorithm

The ATAAS algorithm is designed to provide pilots with speed guidance which, when properly followed, will result in the target spacing interval behind the lead aircraft at the runway threshold. Supporting pilot interface and display elements provide information on the mode of operation and the state of the ATAAS-equipped aircraft ("ownship") relative to the aircraft it is spacing behind (the "lead" aircraft). In order to achieve the concept goals for system-wide (as opposed to individual aircraft pair) efficiency, the ATAAS algorithm was developed with features and limits on the speed guidance it provides. The commanded speed will not exceed 10% of the nominal (charted) speed for any given segment on the arrival, so as not to take any aircraft significantly off the nominal speed profile that would be used by ATC. Speed is also limited by configuration, so as not to command a speed beyond the current aircraft configuration (flaps and gear) limits.

A trail of "history dots" behind the lead aircraft show its ground track on the ownship's ND, and can be used for lateral navigation. A simple pilot interface with the ATAAS tool allows the crew to select the lead aircraft and to enter other appropriate data required for optimizing the ATAAS tool's performance.

To evaluate the ATAAS spacing tool in a real operational environment, and to provide data for comparison with Monte Carlo analysis and simulator data, several types of scenarios were developed for the flight evaluation. Only a subset of the ATAAS flight deck procedures were used in the flight evaluation, since only one member of the flight crews was performing the ATAAS task (because of the ARIES flight deck configuration, only one pilot can act as research pilot, while the other must act as safety pilot).

3.0 Flight Evaluation Method

3.1 Flight Test Facilities Used

3.1.1 Participating Aircraft, Onboard Equipment, and Flight Crews

Three aircraft participated in the ATAAS flight evaluation, and represented performance characteristics of a high-performance general aviation aircraft, an executive jet-type aircraft, and a transport category aircraft. These aircraft were a Piper Chieftain from Aviation, Navigation, Satellite Programs, Inc. (Figure 1), a Rockwell Sabreliner from Rockwell Collins (Figure 2), and a Boeing 757, NASA's Airborne Research Integrated Experiments System (ARIES), shown in Figure 3, respectively. The sequence of aircraft remained the same on all three aircraft scenarios: the Chieftain was first, followed by the Sabreliner, and ARIES last. Two- aircraft sequences were flown when either of the first two aircraft was grounded for refueling or maintenance. Two levels of onboard equipment were used for this flight activity: broadcast-only and spacing-capable. Since the role of the Chieftain was to act solely as a lead aircraft, it was only required to broadcast aircraft state information. Equipment required for this task is a Mode-S transponder (broadcasting the basic ADS-B message) and a GPS receiver. In this regard, the Chieftain represented the non-ATAAS equipped aircraft described in the operational concept. Both the Sabreliner and the B757 required capabilities that allowed them to space on another aircraft. In addition to the Mode-S transponder and GPS receiver, this also required an ADS-B receiver unit and the spacing algorithm and associated display capability. A description of the avionics implementation to support approach spacing operations is provided in Appendix A.

Of the four flight crew members flying the spacing tools (the Sabreliner and ARIES crews), one was a former airline pilot, two were former transport category cargo aircraft pilots and the fourth was an experienced research test pilot. No subject pilots were used in the ATAAS flight activity. The pilots were given oral briefings on the Approach Spacing concept and the spacing tool, as well as training time in the simulator as needed to develop proficiency in flying the scenarios. The flight crew members flying the non-spacing aircraft had military flying experience, as well as civilian experience with the flight test of avionics.

Figure 1. Aviation Navigation Satellite Programs (ANSP) Chieftain

Figure 2. Rockwell-Collins Sabreliner aircraft

Figure 3. NASA LaRC ARIES research aircraft

3.1.2 Air Traffic Control Facility

Air traffic control services were provided by Chicago Tower and Chicago TRACON (C90). Services provided by these facilities to ATAAS flight participants were solely to facilitate the flight evaluation. Dedicated project controllers were used during both the planning and conduct of the flight evaluation. Their specific role during the flight evaluation is described in Section 3.3.

3.2 ATAAS Pilot Interface

3.2.1 ARIES pilot interface

Electronic Attitude Director Indicator (EADI) Display

Output from the ATAAS system was shown in various locations and forms on the pilots' displays. Pilots obtained ATAAS guidance from these displays, and additional status data from the Flight Management Computer FMC-CDU pages (described below). The ATAAS symbology on both electronic attitude director indicator and navigation display appeared only after a lead aircraft and spacing interval were selected from the CDU page.

The EADI used for this flight evaluation was the standard B757 EADI, which is currently in use in most aircraft of this type (Figure 4). It includes a Fast/Slow (F/S) indicator on the left side of the display, which is normally used with the speed guidance mode. For example, when the crew is flying the aircraft in "Speed" mode (meaning speed is controlled by dialing the ATAAS command speed into the Mode Control Panel (MCP) Speed window), the red "command airspeed bug" on the airspeed indicator moves to point to the speed matching what is displayed in the window, and the F/S indicator reflects the relationship of the current aircraft speed with this target speed. If the current speed is faster than the target speed in the MCP window, the pointer on the F/S indicator moves towards the "F"; if the current speed is slower than the MCP window speed, the pointer moves towards the "S".

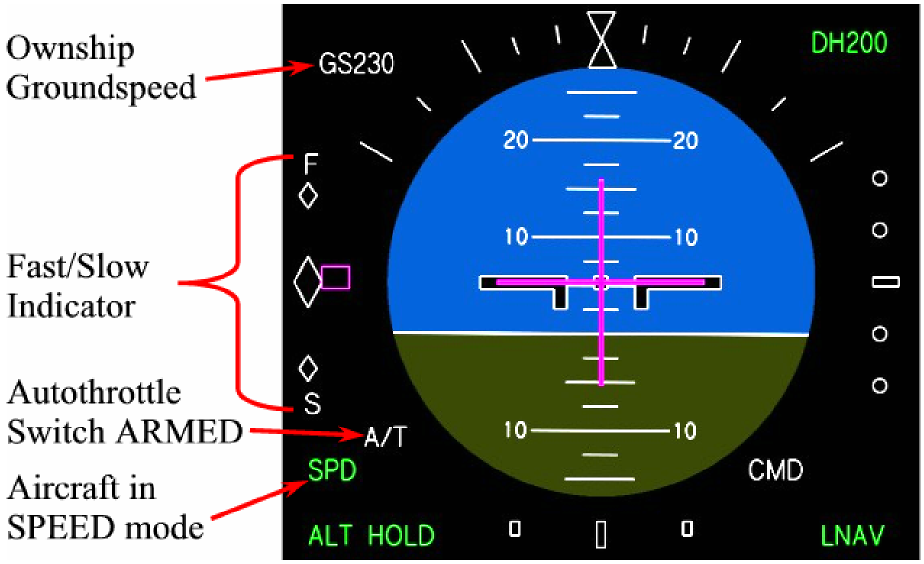

Figure 4. EADI with Normal Symbology

The ATAAS implementation on the EADI (Figure 5) made use of the F/S indicator to reflect the relationship between the current aircraft speed and the ATAAS command speed. The command airspeed bug on the electromechanical airspeed indicator also tracked the ATAAS speed guidance, giving the pilots another reference. In addition, the commanded speed appeared in digital form next to the pointer on the F/S indicator, in green font. The displayed readout, the pointer on the F/S Indicator, and the bug on the airspeed indicator all reflected the commanded speed from the ATAAS algorithm.

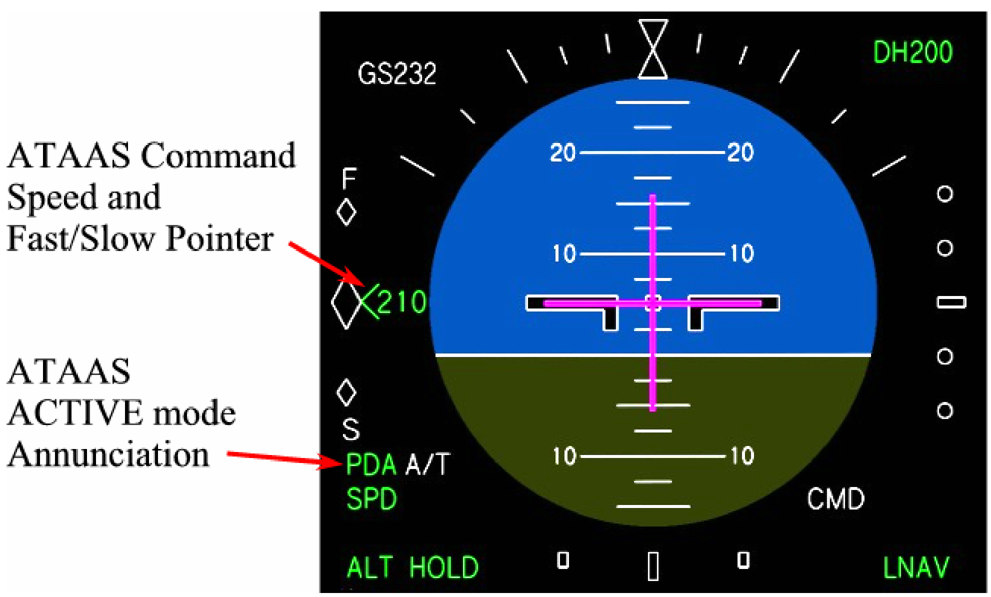

Figure 5. EADI with ATAAS Symbology

A feature of the ATAAS algorithm is its ability to provide a smooth transition from the commanded speed required for achieving the spacing interval, to the final approach speed entered on the ATAAS Approach Data CDU page. The algorithm is automatically switched to this approach mode near the final approach fix to allow enough time to achieve a stabilized final approach. When the algorithm transitions to this mode, it is no longer actively "spacing" on the lead aircraft, and an "APPR" message is provided above the F/S indicator to inform the pilot of the change.

The Mach/airspeed indicator on the ARIES (Figure 6) is a standard electromechanical dial type of display, with a pointer and digital readout of the current indicated airspeed, and a red command airspeed bug that is driven in the autoflight speed mode to indicate the commanded (target) airspeed. With the aircraft in speed mode, and a command speed showing in the MCP speed window, this pointer would be positioned at the command speed. With the ATAAS tool active, the pointer is positioned at the ATAAS command speed. During a change in ATAAS command speed, the pilot could closely match the deceleration profile of the ATAAS algorithm by using this pointer as a guide to make speed adjustments.

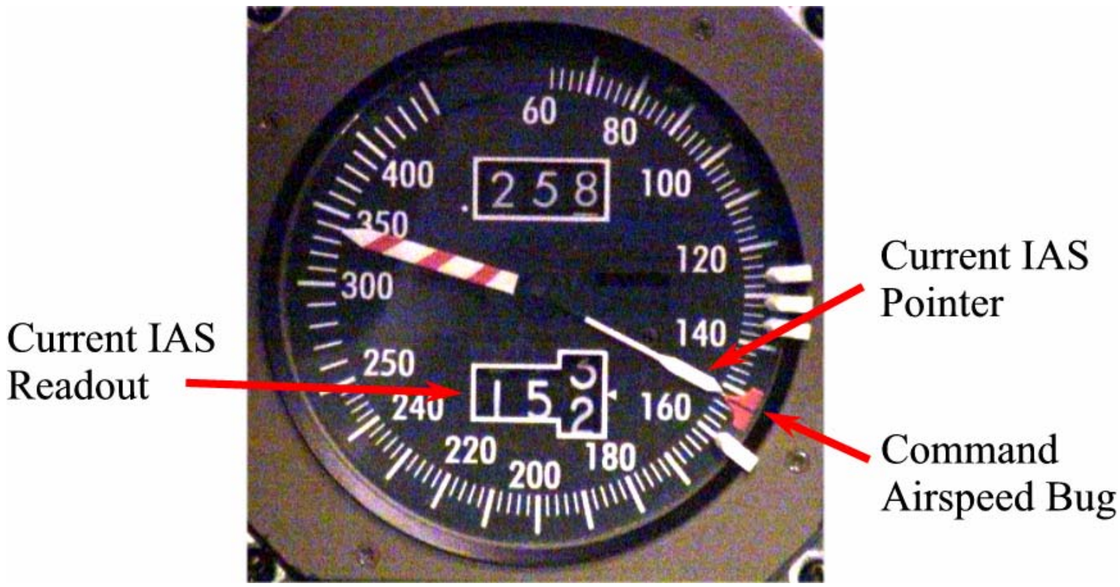

Figure 6. Mach/Airspeed Indicator

Navigation Display
Symbology was added to the ND to provide additional information on the ATAAS guidance and aircraft spacing status (Figure 7). Three main pieces of information were provided: 1) a data block that included the identification of the currently selected ATAAS lead traffic, and its current range in nmi from the ownship, 2) a spacing position indicator, which provided the pilot with a reference of ownship's position, relative to the optimal position based on the entered target interval, and 3) lead aircraft highlighting and position history dots. This symbology and data were updated as the distance between the aircraft or any other factors changed (e.g., selection of a new lead aircraft).

The spacing position indicator was provided to show the position where the ownship would be if the predicted spacing interval at the runway matches the desired interval (based on the current speeds and anticipated speeds for remaining flight-path segments). The indicator consisted of a short green line perpendicular to the ownships's ground track, with an inverted "V" attached to the midpoint of the line. When the predicted and desired intervals match, the spacing position indicator fit exactly of over the apex of the white triangular ownship symbol. If the spacing position indicator was behind the apex of the ownship symbol, the predicted spacing was less than the target interval. Conversely, if the spacing position indicator was ahead of the ownship symbol, then the predicted spacing was greater than the target interval. This indicator was intended to simply provided a simple visual reference of the spacing interval predicted form current conditions relative to the desired spacing interval.

The position history dots showed the previous ground track of the currently selected lead aircraft. This history trail feature allows an ATAAS-equipped aircraft to maintain spacing behind an aircraft that is not on the RNAV route, such as one that is being radar-vectored or is on a visual approach, by following its history dots. The spacing of the history dots was displayed in proportion to the range selected on the ND, such that they had a consistent appearance at any range.

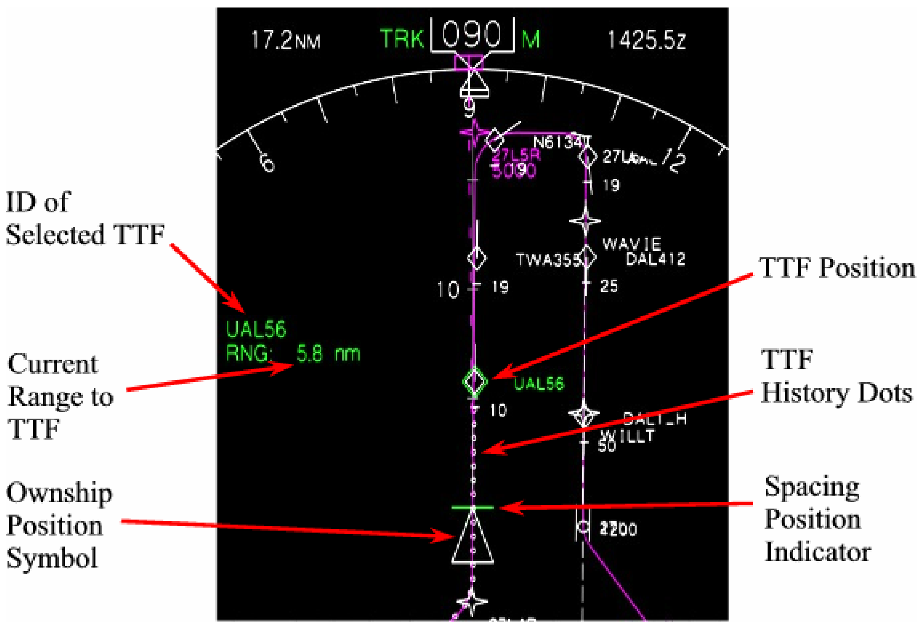

Figure 7. ND with ATAAS Symbology

FMC-CDU pages

The flight crew interface with the ATAAS system was accomplished through customized FMC-CDU pages, accessed through a re-mapped function key on the CDU, which was labeled "ATC". Pilot inputs to the custom CDU pages that were required prior to activation of the ATAAS system were: selection of the traffic-to-follow (TTF), entering the assigned spacing interval, entering airport winds, final approach speeds of ownship and lead aircraft, and minimum allowable spacing interval. Because the current standard configuration for the ARIES aircraft allows only one pilot to interact with the research systems, and the other to act as safety pilot, this essentially leaves only one research pilot available. Thus, the ATAAS interface tasks that would normally be done by the non-flying pilot, which is to make the required inputs to the research CDU, were performed by a research engineer situated on the flight deck . Although the research pilot could observe this CDU interaction, his active role was to perform the tasks associated with the flying pilot, and the opinions and ratings provided by the research pilots were obtained with this in mind. It should be noted however, that the workload associated with the CDU, i.e. pilot not flying duties, was evaluated in the previous simulation study.

Figure 8 shows what the ATAAS custom CDU page looked like when the ATC function key was depressed. The other nearby aircraft are listed on the right side of the display, in this case the Chieftain (ANSP1) and the Sabreliner (N50CR).

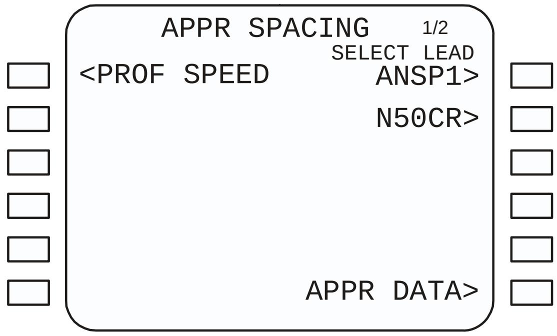

Figure 8. ATAAS CDU page on ARIES prior to selecting TTF

After line-selecting the Saber and entering the required spacing interval (90 seconds), the page updated (Figure 9) to show the current spacing interval (91 sec), current distance (6.8 nmi), and lead groundspeed (230 kts). These data were updated continuously, as long as the TTF was not selected off.

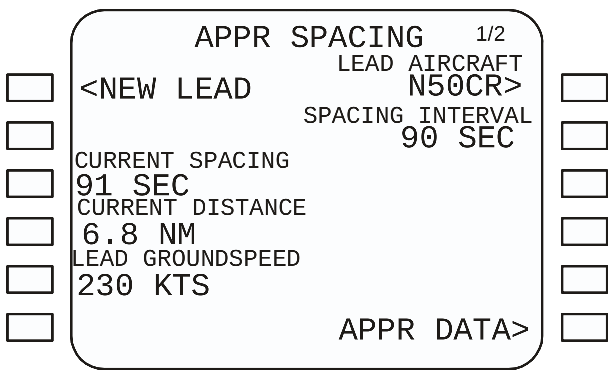

Figure 9. ATAAS CDU page on ARIES with TTF selected and spacing interval entered

The rest of the approach data were entered on the Approach Data page, accessed from bottom right line-select key. Figure 10 shows what this page looked like after entering data for a typical run.

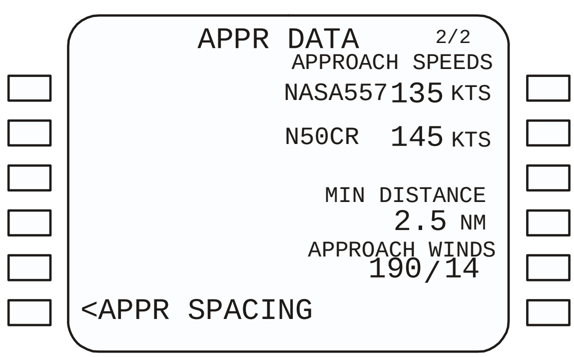

Figure 10. ATAAS CDU Approach Data page on ARIES with all data entered

3.2.2 Sabre pilot interface

The ATAAS symbology onboard the Sabreliner was all displayed on the TCAS display (Figure 11), rather than split across two displays as on ARIES. Figure 12 shows the Sabre TCAS display with ATAAS symbology. The selected spacing interval was displayed in the upper left corner, under the label “APP SPG”. The ATAAS command speed was displayed in the middle of the left side of the display, next to the label “REQ” (for required speed), above the ownship indicated airspeed (IAS). The history trail of the lead aircraft can be seen behind both the lead aircraft and the ownship symbol, which is the blue triangular symbol in the center of the compass rose. The call sign for the lead aircraft is shown on the lower left side of the display. In the example provided in Figure 12, the lead aircraft has passed the final approach fix, hence the relatively slow groundspeed (116 kts.) of the lead aircraft.

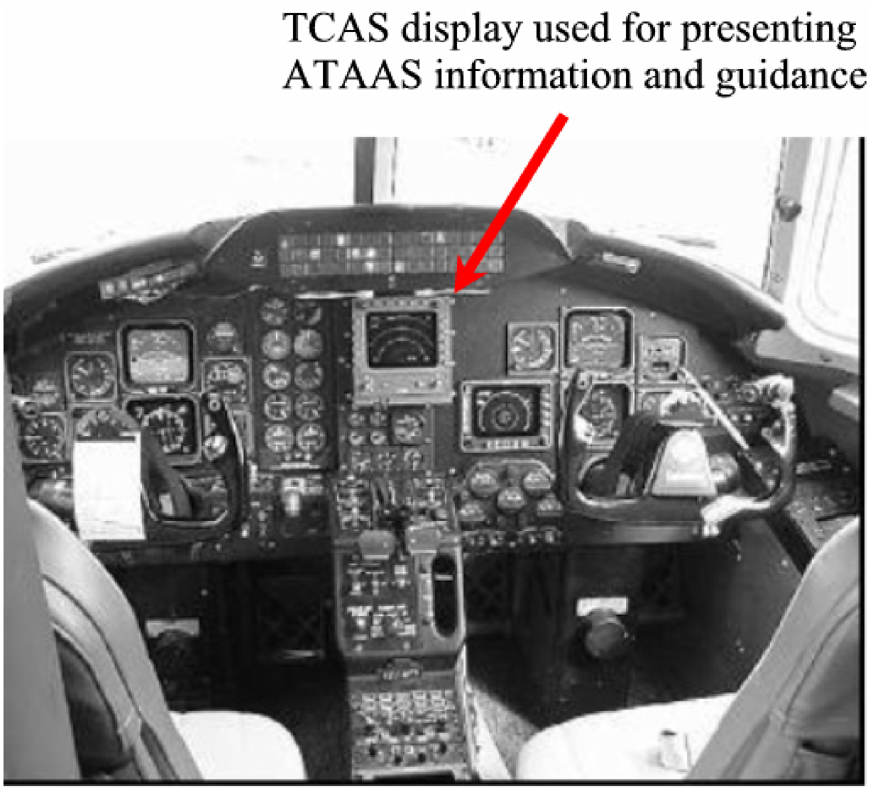

Figure 11. ATAAS Display Location on Rockwell-Collins Sabreliner

3.3 Flight Environment

The flight activity was conducted at the Chicago O’Hare International Airport and the surrounding terminal airspace. As this was not an evaluation of air traffic control procedures, the tasks for the controller were (1) to provide control instructions that would position the aircraft for the start of each run and (2) in the case of the vector scenarios, to provide vectors and speeds as appropriate for the selected run. In positioning aircraft for the start of each run, the controllers did not employ a greater degree of precision than they normally would in day-to-day operations. No special accommodations were made to provide other than normal services.

Conducting the flights in an operational environment presented several challenges not normally encountered in a day-to-day operational environment. For safety reasons, one of the three aircraft (ARIES) was limited to operations in VMC conditions, and as such a lower altitude than that used for the other two aircraft was sometimes required to avoid cloud ceilings. The net effect of this was to have aircraft subject to wind fields that, at times, were significantly different. A second challenge was responding to spurious errors in the ADS-B equipment (a situation which would not occur in a production ADS-B unit), which occasionally transmitted production ADS-B

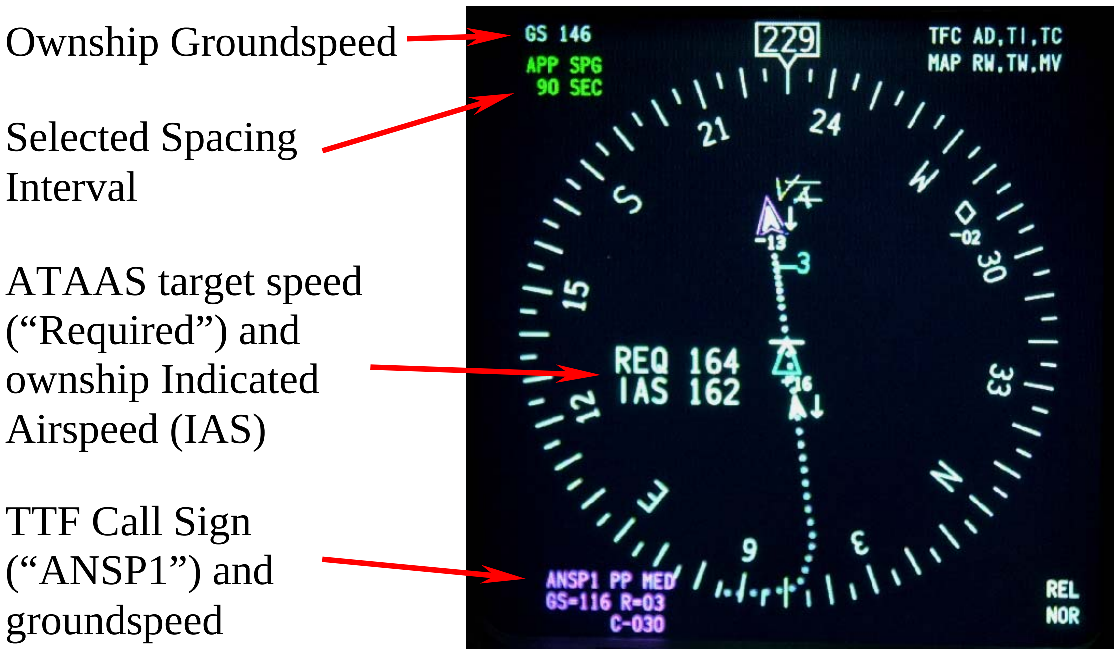

Figure 12. Rockwell-Collins Sabreliner TCAS Display with ATAAS symbology

unit), which occasionally transmitted erroneous groundspeed data to the ATAAS algorithm. This required modification of the onboard processing to include additional filtering to the groundspeed data. The filtering was designed to minimize the effect erroneous data might have on the algorithm, which could have resulted in inappropriate speed commands. Finally, due to traffic conditions, there were several runs in which a significant tailwind was present on final approach. Although the algorithm had been tested in simulation with winds, the effect of the type of winds encountered in flight were not previously studied.

In order to not adversely affect itinerate traffic, the flights were conducted at night. As this was an operational environment, the assignment of runways and direction of traffic patterns (left or right) was subject to change with minimal notice. It was anticipated that any of seven runways with either left or right traffic patterns could be assigned. Thus, Area Navigation or “RNAV” routes were developed to accommodate any of these possibilities.

3.3.1 Scenarios and Test Procedures

The ATAAS flight participants flew paths representative of those normally flown by arrival aircraft. Two basic types of scenarios were flown: an RNAV path that represented a pre-defined lateral route and a vector path scenario. Three variations of the vector scenario were flown, a nominal (downwind-base-leg routing), a "weather" case representative of an aircraft being vectored around weather on the downwind leg, and a re-sequence case (using a nominal vector path). A depiction of the RNAV path and the weather vector case is shown in Figure 13. The tracks for the nominal vector case and the re-sequence case were basically the same as the RNAV path.

To begin a scenario, the controller provides vectors to establish the aircraft on the "inbound leg" (this simulated aircraft entering the terminal area). Altitudes for initiation of the scenarios varied nominally between 5000' and 7000' depending on other traffic. The initial speeds were 200 knots indicated airspeed (KIAS) for the Chieftain and 210 KIAS for both the Sabreliner and ARIES. The spacing between each pair of aircraft was approximately six miles. The controller

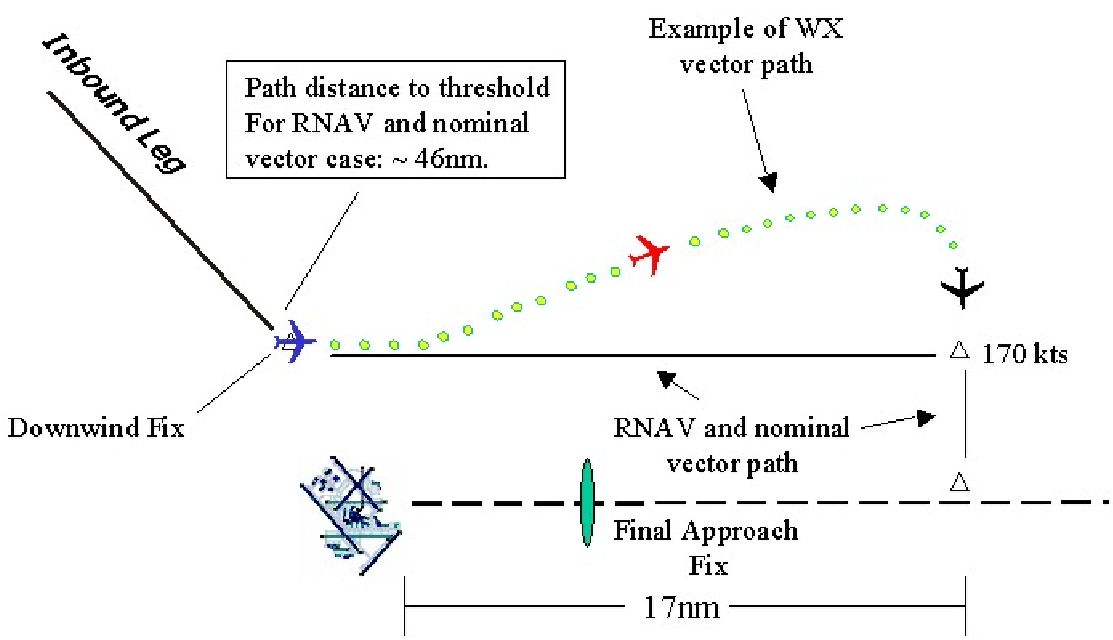

Figure 13. ATAAS flight paths

was asked to provide reasonable spacing, but not to a greater degree of precision than would normally be expected in day-to-day operations. As aircraft #2 and #3 in the sequence were established on their inbound routes, they were to assume that an approach spacing clearance was issued and to follow ATAAS guidance cues accordingly.

For all the runs, each aircraft intercepted and tracked the ILS to 200' AGL, where they would level off and maintain speed and track until crossing the threshold. At that point, a go-around and climb-out was initiated, followed by vectors from ATC to position for the next test run.

RNAV Scenario. The 14 possible RNAV flight paths for ATAAS operations in the KORD terminal area were designed to accommodate FMS or VOR/DME lateral path guidance on the outbound and inbound legs, a 45° intercept to a nominal downwind leg, and a base leg 17 nm from the runway threshold which provided a desired 15 nm ILS final approach leg. RNAV paths (left and right traffic) developed for Runway 27L (identified in the flight test as A27L12) is shown in Figure 14. The outbound legs were established on radials from the ORD VORTAC ±15° from the runway headings with an initial waypoint 4 nm DME (up to 6 nm depending on geometry) and a second waypoint at 20 DME. The next leg is ±105° from the outbound track to intercept the inbound track beginning at 20 DME, displaced 30° from the outbound track, and intersecting a nominal downwind leg approximately 22 nm in length that is parallel to, and 5 nm from, the corresponding ILS localizer centerline. The outbound and inbound legs were based on VOR radials to aid the TRACON controllers whose video maps were relative to ORD. The computer programs Jeppesen FliteMap® and Garmin MapSource® were used to design the flight paths and determine the LAT/LON coordinates for input to the FMS and GPS databases. For ARIES, the paths were implemented as Standard Terminal Arrival Routes (STARs) by Honeywell in a custom database load for the research and ship FMS computers. Printed documentation of the waypoint definitions and graphics were provided to all parties involved in the flight test.

Figure 14. RNAV Paths for Runway 27L

All participating aircraft flew the RNAV route through the transition onto the final approach course. The lead aircraft (Chieftain) was reduced to 170 KIAS at the turn to base leg, as charted. The two spacing aircraft (Sabre, followed by ARIES) followed their respective ATAAS command speed cues.

Vector Scenarios. Three variations of the vector scenario were flown, a nominal (downwind-base-leg routing) and a “vectors for weather” case representative of an aircraft being vectored around weather on the downwind leg, and a “re-sequence case.

Upon intercept of the “inbound leg” the first aircraft tracked inbound until receiving vectors from the controller for turns to downwind. In the nominal vectoring case, the controller issued vectors to the Chieftain that would approximate the RNAV path, with a speed reduction issued at the downwind-to-base turn. Each of the two trailing aircraft followed the lateral path of the aircraft ahead, as depicted on its ND, and the ATAAS speed guidance. The weather vector case differed slightly, in that the controller issued off-nominal route vectors to simulate the presence of a weather cell on the downwind leg. Figure 15 shows the display of a lead aircraft vectored off the downwind leg as indicated by the history trail. It should be noted that weather was used only as one example of why the capability to follow the lateral path of a leading aircraft was useful. This type of “follow-the-leader” scenario could also be useful during runway changes and in instances where delay absorption strategies are required.

The re-sequence case was used to demonstrate the ATAAS algorithm’s flexibility in allowing the flight crew to change the lead aircraft, on which they were spacing, an additional variation on the vectored scenario was developed. This scenario began with two aircraft only, with twice the normal interval between them, to allow for the third aircraft to be inserted between them. The controller initially vectored the lead and following aircraft (Chieftain and ARIES, respectively) to stage them with essentially twice the normal spacing between them (i.e., ARIES was positioned at an interval of 180 seconds behind the Chieftain).

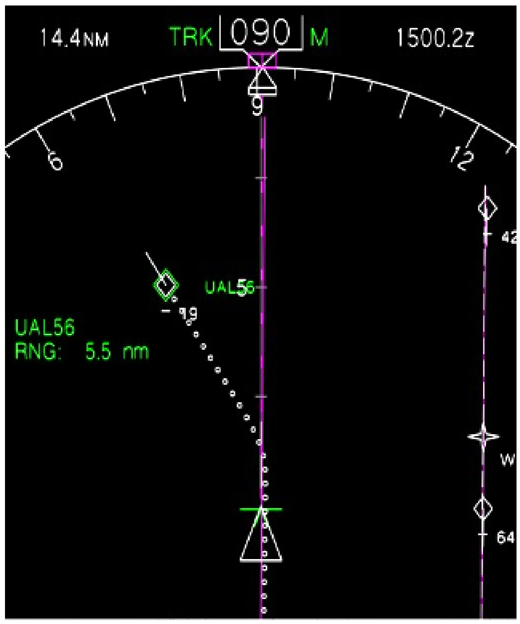

Figure 15. ARIES ND ATAAS display during a "vectors for weather" run

The Sabreliner was then vectored to a position between the two aircraft, and then would begin spacing on the lead (Chieftain) at the nominal 90 second interval. ARIES would then de-select the original lead, and select the new lead (Sabreliner), and begin spacing on it at the nominal 90-second interval.

3.3.2 Flight Deck Procedures for Spacing Aircraft

General flight deck procedures for both spacing aircraft (ARIES and Sabre) involved selection of the appropriate traffic to follow (TTF) and entering the spacing interval (spacing interval was always 90 seconds between aircraft, except for the previously-mentioned re-sequence case). Ownship and TTF final approach speeds, airport wind speed and direction, and minimum allowable ATAAS separation distance were also entered. Note that TTF final approach speed was known by the trailing aircraft; in an operational system, this information could be broadcast via data link or provided by ATC who could solicit the speed from the lead aircraft. At the designated initial point, the ATAAS algorithm was activated, and the crew was responsible for following the ATAAS command speeds. Laterally, the two spacing aircraft either followed the pre-loaded RNAV route, or the history dots of the lead aircraft, depending on the scenario being flown. Altitudes and other required clearances were issued by ATC, as appropriate.

ARIES Flight Deck Procedures

Pilot procedures for the flights were a subset of those used for the simulation experiment. The pilots followed the overall procedures they would normally use for flight in a terminal area, except as described in this section.

Onboard ARIES, a member of the research team was situated in the jumpseat at the "maintenance" CDU (on the aft end of the aisle stand) to enter data needed to activate the ATAAS system. During climb-out to the assigned altitude, the aircraft designated as the TTF was selected on the CDU. This initiated the ATAAS algorithms and the accumulation of TTF position history data. The ownship final-approach speed (verified with the safety pilot), TTF approach speed, airport wind velocity, and minimum allowable ATAAS separation distance were then entered in the research CDU. After the flight path of ARIES was stabilized in-trail of the TTF on the in-bound leg, or no later than just after the turn onto the downwind leg, the safety pilot requested clearance to follow the lead traffic from ATC. The desired spacing interval time was then entered on the ATAAS CDU pages, which initiates the algorithm in a speed advisory mode (Figure 16). The cyan color for the ATAAS symbology (command speed, F/S pointer, and mode annunciation on the EADI, and spacing position indicator on the ND) indicates that the algorithm is in this mode. The advisory mode indicates that the guidance being provided by the algorithm is valid, but the system is not yet activated.

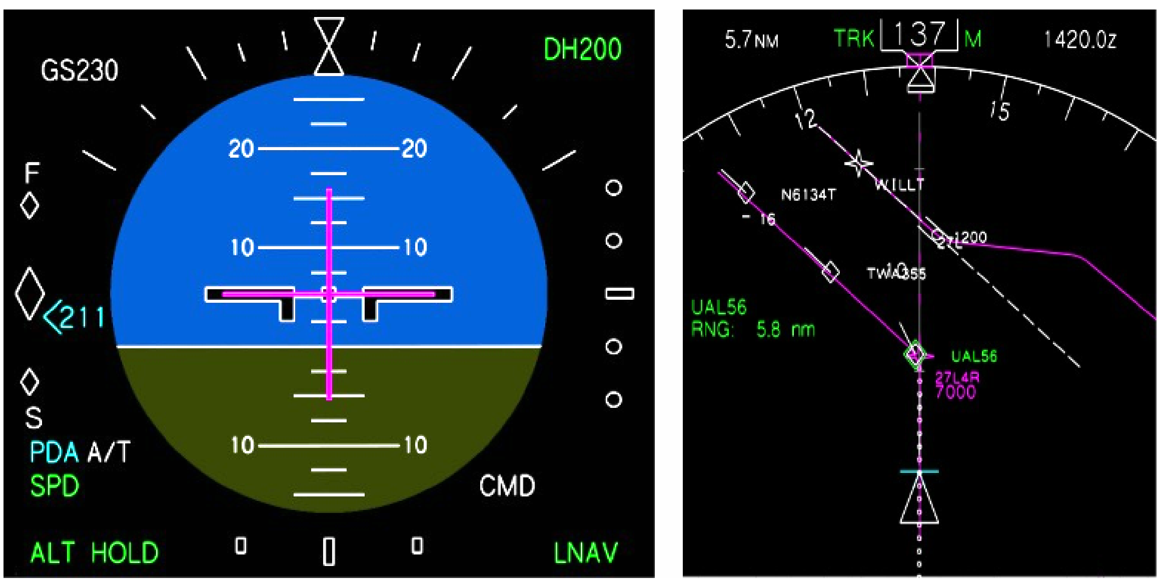

Figure 16. ARIES EADI and ND with ATAAS in "Advisory" mode

After concurrence among the cockpit crew that ATAAS was providing reasonable speed advisories, the ATAAS speed guidance was activated by engaging a designated push button switch on the Experimental Display Control Panel (EDCP), which is a control panel unique to the ARIES aircraft. Subsequent control of airspeed was then relegated to the research pilot or to the autothrottles through the thrust management computer, depending on the test scenario being flown, to maintain the ATAAS commanded speeds for the remainder of the approach. For the scenarios in which the autothrottles were not engaged, the pilot was to simply follow the displayed ATAAS speeds using manual throttle settings. If the current indicated airspeed was less than the ATAAS command speed, the guidance was initiated in an "armed" state, indicated by a symbology color change to white (see Figure 17), until the current IAS was equal to or greater than the ATAAS command speed.

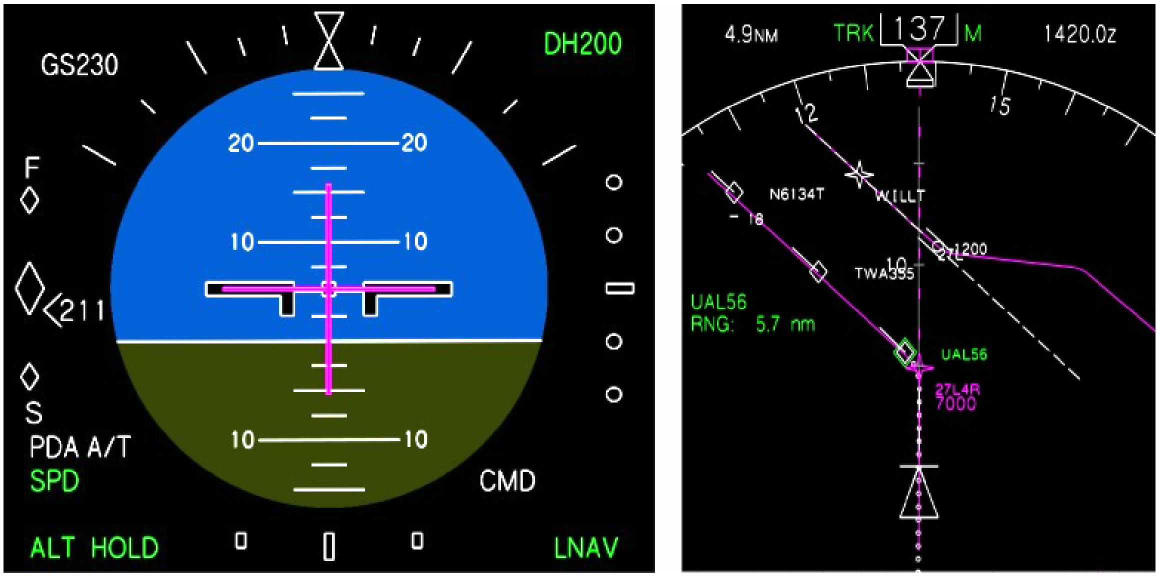

Figure 17. ARIES EADI and ND with ATAAS in "Armed" mode

The displays reflecting ATAAS in the "active" mode are shown in Figure 18. Active mode as indicated by the symbology color change to green. In this state, the command speed would be followed automatically if the autothrottle was on or manually with pilot inputs to the throttles if the autothrottle was off.

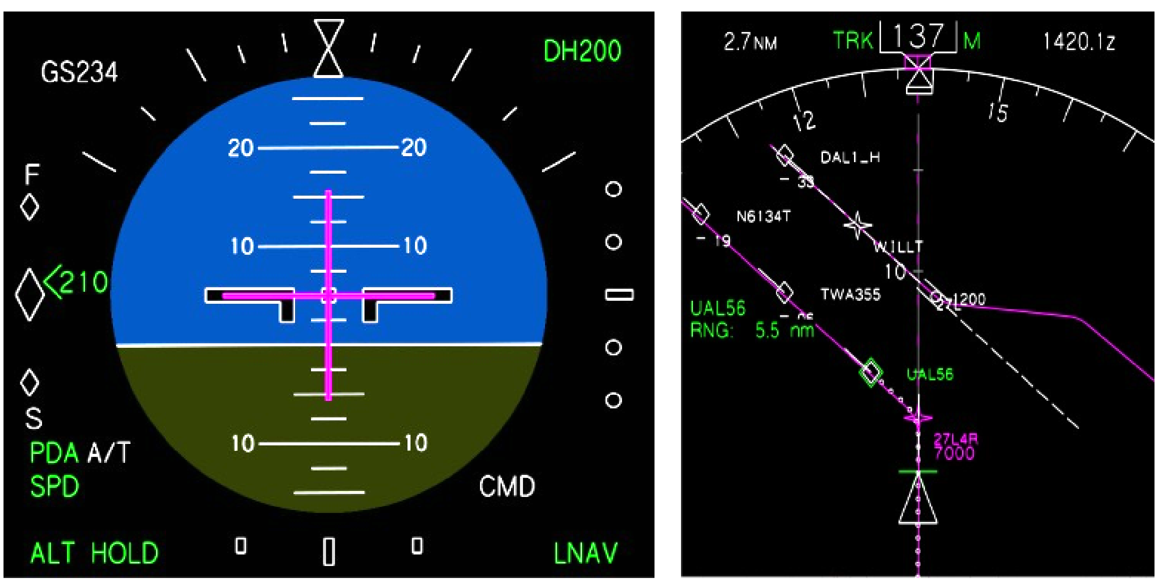

Figure 18. ARIES EADI and ND with ATAAS in "Active" mode

When the ATAAS guidance initiated the deceleration to the final approach speed entered on the Approach Data page, the EADI display changed to show the label “APPR” above the F/S indicator (Figure 19). At this point, the algorithm was no longer attempting to maintain or achieve the required time interval, but rather was slowing the aircraft to its final approach speed, thus the history dots emanating from the TTF symbol disappeared. ATAAS speed guidance was deactivated on the EDCP and the TTF deselected after crossing the runway threshold in preparation for the next run.

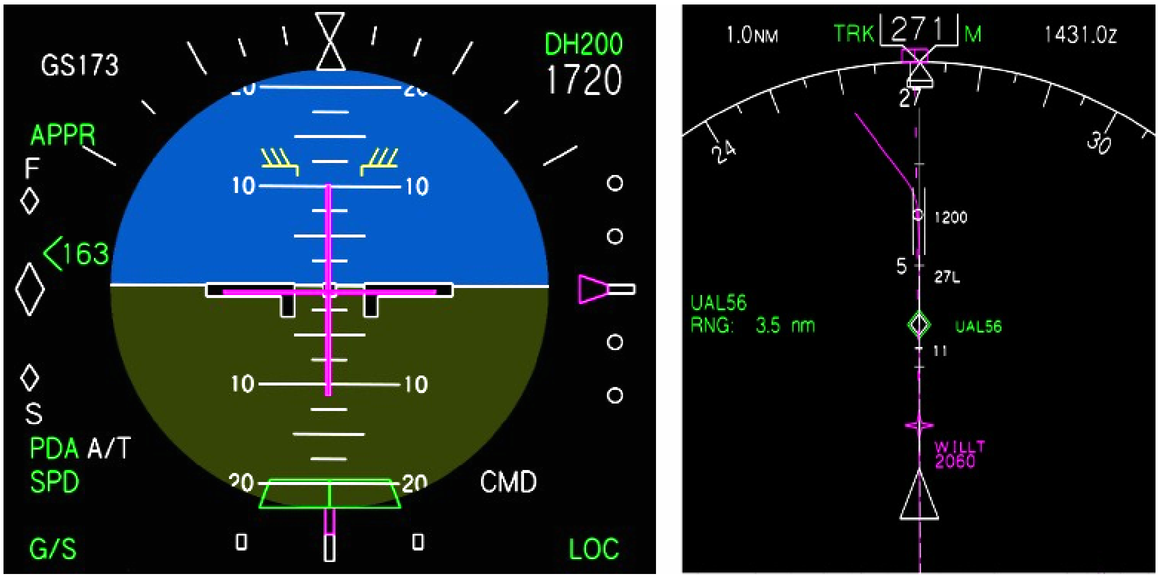

Figure 19. ARIES EADI and ND with ATAAS in “Approach” mode

In the event that the algorithm predicted a future encroachment of the minimum distance (entered by the crew on the Approach Data CDU page, or a default value), an alert was displayed on the ND, and amber limit bars appeared above and below the command speed on the EADI (Figure 20).

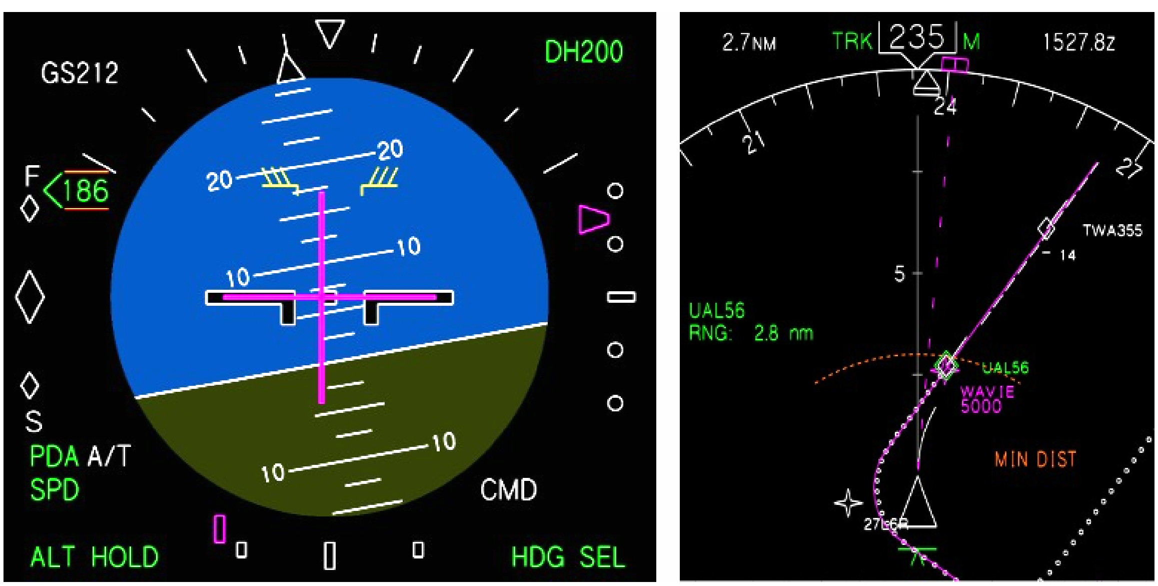

Figure 20. ARIES EADI and ND with ATAAS “Active” and approaching Minimum Distance

If this occurred, no further action was required of the pilots, other than to continue to closely follow the ATAAS command speeds, which would slow appropriately to prevent violation of this minimum distance.

A variation of the limit bars seen in the minimum distance case were also used in other less-critical situations, but were displayed in green, rather than amber. One of those situations is in the case where a speed reduction is required beyond the flap or gear speed for the current aircraft configuration. In these cases, the limit bar would appear below the ATAAS command speed on the EADI (if the command speed was required to go below the minimum flap speed for the current flap setting) or above the command speed readout (if the command speed was required to go above the current maximum flap speed). When the aircraft configuration was changed appropriately, the limit bar disappeared. Another situation where the limit bar appeared was when it was necessary to limit the amount of speed variation from the nominal profile (or from the maximum or minimum previously commanded speed) during any particular segment of the approach. This issue arose during some of the runs, and is addressed in more detail in a later section.

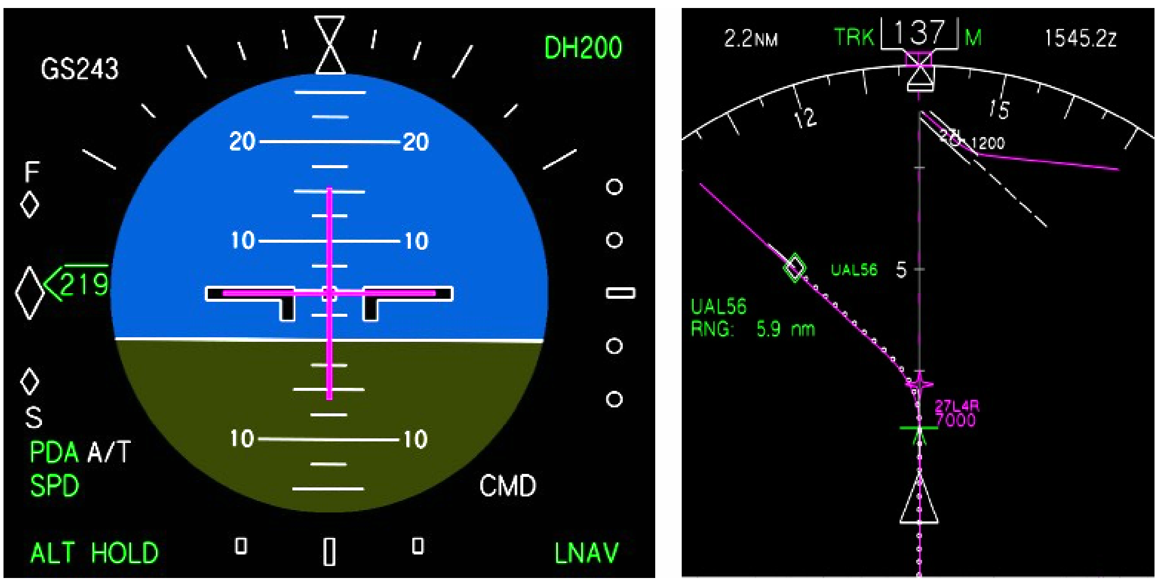

Figure 21. ARIES EADI and ND with ATAAS "Active" and speed upper limit capped

Figure 21 shows an example of the situation where the ownship was "behind" the assigned interval, but the algorithm was limited from commanding a higher speed because it would be more than 10% higher than nominal profile speed. This example illustrates the design feature mentioned previously, that is used to control system-wide stability by not allowing any single aircraft to exceed a reasonable level of variation in speed. In this example, it can also be seen that the ownship on the ND is far behind the spacing position indicator.

Sabre Flight Deck Procedures

Flight deck procedures on Sabre were similar to those on ARIES, but there were some differences due to the slightly different ATAAS implementation. The Saber ATAAS implementation did not include the elements on the ARIES EADI, but rather incorporated the speed guidance on the Navigation Display. Also, since the Saber is not equipped with autothrottles, all the runs were conducted as manual throttle runs. As with the ARIES, the pilot interaction for the ATAAS algorithm on the Saber was not incorporated such that it could be conducted as a two-crew procedure. A researcher situated at a research pallet in the aircraft cabin performed the non-flying pilot data entry duties.

3.3.3 Scenario Run List

A list of possible flight test data runs was developed based on operational, rather than experimental, considerations (see Table 1). The target number of runs was seven per flight period (maximum of four hours each night), but not necessarily one repetition of each of the runs listed in the table. The list includes two RNAV runs, two nominal vectoring runs, and two weather-vectoring runs. For each type of run, ARIES could fly one pattern with manual throttles and the other with autothrottles. Finally, one "re-sequence" run scenario was included for each flight period. No attempt was made to counter-balance the runs. During the actual flights, some of the runs had to be re-ordered for logistical reasons, or to complete at least four total repetitions of each of the runs listed during the course of the flight test. After it was determined that the Sabre could complete four runs before having to refuel, the re-sequence scenario was sometimes moved to later in the run ordering, in order to be able to complete the maximum number of runs in one night.

Table 1. List of Run Conditions Used

	Lateral Path	Auto-throttle configuration (ARIES)	Aircraft ordering, front to back
Run 1	RNAV	Autothrottle-coupled	Chieftain, Sabre, ARIES
Run 2	RNAV	Manual Throttles	Chieftain, Sabre, ARIES
Run 3	Vectors for weather	Manual Throttles	Chieftain, Sabre, ARIES
Run 4	Vectors to nominal path	Autothrottle-coupled	Chieftain, ARIES
Run 5	Re-sequence	Manual Throttles	Chieftain, Sabre, ARIES*
Run 6	Vectors to nominal path	Autothrottle-coupled	Chieftain, Sabre, ARIES
Run 7	Vectors for weather	Autothrottle-coupled	Chieftain, Sabre, ARIES

*Begin with Chieftain, ARIES, then re-sequence to Chieftain, Sabre, ARIES

A complete table of valid data runs is provided in Appendix B. Included in this table is flight number, the type of scenario, speed management mode (ARIES), the aircraft sequence, the runway, the traffic pattern and the separation times.

3.4 Data Collection

Comparable data (qualitative and quantitative) were collected onboard both ARIES and the Sabreliner. Time-stamped latitude, longitude, altitude, ground speed, and ground track data for the three aircraft were recorded. In addition, many other parameters relating to the mode of operation of the autoflight system were also recorded for ARIES. Recorded data from the ATAAS system included the state in which the system was operating, and the commanded speed, time interval, and distance between the ARIES and the lead aircraft, as well as numerous other parameters used for verification of system operation.

Limited subjective data were obtained by administering a verbal questionnaire to the pilots. Questions centered around the acceptability of the ATAAS tool, the acceptability of the amount of head-down time required for using the system, confidence in the guidance provided by ATAAS, and the pilot's comfort level in using the tool. The post flight questionnaire is provided in Appendix C. Each of the four questions was rated on a 7 point scale.

4.0 Results

4.1 Spacing Interval

A total of 36 runs were completed during the five days encompassed by the flight test. Of those, a subset of 28 runs was selected as being the most representative of nominal conditions. This judgment was based primarily on the fewest number of anomalies in the broadcast state data, or other procedural/operator errors. The data anomalies were characterized by large spikes in groundspeed (of 30-40 kts, over less than a second in duration), and caused problems for the ATAAS algorithm. As mentioned in Section 3.3, data filters were employed to mitigate the effects of erroneous spikes in ground speed. However, prolonged or numerous spikes could have resulted in variations of ATAAS command speed that would not have been generated had the groundspeed data been correct. The cause was determined to be an ADS-B firmware problem, which would not be present in a production system. To mitigate any errors resulting from this, additional filtering was incorporated into the ATAAS algorithm.

Delivery precision at the runway threshold, although not as precise as demonstrated in the simulator study, were still generally good. The inter-arrival times are provided in Table 2 for the 28 valid runs (11 RNAV and 17 vector scenarios). The minimum time separation recorded during the data runs was 79.5 seconds; the primary cause of the significant arrival time error was due to incorrect lead aircraft final approach speed input into in the FMS. Even with this error, the minimum distance set for alerting, 2.5 nmi was not violated.

Table 2. Runway Threshold Crossing Times

	Mean (sec)	Standard Deviation
RNAV Case	89.3	4.9
Vector Cases	91.7	9.0
All Cases	90.8	7.7

For comparison, the simulator study (in which all the runs were RNAV runs) resulted in a mean crossing interval of 92.2 seconds with a standard deviation of 2.3 seconds, for all the autothrottle-coupled and manual runs taken together (a total of 32 runs). Comparing this result with the RNAV results in the table above indicates that, although the mean interval in the flight test was closer to the nominal target interval of 90 seconds, the variation was about twice that seen in the simulator study. This is consistent with the notion that the quality of the data was essentially flawless in the simulator study (due to the controlled, no wind conditions), versus the wider variations in conditions seen in the flight test. In the simulator study, the major cause of the variations from the mean crossing interval were determined to be due to piloting technique, particularly in the final approach segment.

A single-factor analysis of variance, with alpha = 0.05, of delivery precision for the manual throttle (93.9 sec average) and autothrottle coupled (88.4 sec average) cases does not show a statistically significant difference ($p = .06$). However, it was noted that threshold crossing times were generally early when autothrottles were engaged and late when manual throttle control was used. Research pilots that flew both cases stated that the workload was lower when autothrottles were engaged.

Two major factors were identified as having adversely affected runway delivery times for this flight test. The first one is the additional filtering that was incorporated into the algorithm to address the ADS-B groundspeed problem. Due to very large wind changes on final approach, this filter would sometimes mask the wind change, with the resulting spacing intervals being off from the nominal interval. It is reasonable to say that in an operational system, these shortcomings with the firmware would be resolved; and therefore, this particular filtering in the algorithm would not be required. Secondly, actual aircraft deceleration varied somewhat from the ATAAS-generated deceleration schedule, and also resulted in delivery errors. Finally, it is not clear what effect pilot technique may have had on the results. Although the ATAAS algorithm was implemented to provide speed guidance, the additional situation awareness information it provided the pilots sometimes led them to make adjustments to the route flown, in an attempt to “help” the algorithm along. This issue is discussed further in the next section. It is felt that additional training and parameter tuning can resolve these issues.

In general, the spacing algorithm performed well when not artificially constrained by additional filtering. Of particular note is the performance of the algorithm in response to changes in wind velocity. Surface winds were received from the Automatic Terminal Information System (ATIS) broadcast. Several cases were noted where a shift in wind direction of greater than 180 degrees (with speeds of 10 to 25 knots) occurred while ARIES was on final. Inter-arrival spacing times for three of the four cases, in which wind shifts of greater than 180 deg occurred on final, were within 4 seconds of the goal time of 90 sec. Figures 22 and 23 show data for a run in which a wind shift in excess of 230 deg was encountered. Figure 22 shows the wind and Figure 23 shows commanded vs. actual airspeed. The data shown represent the last ten minutes (approximately 25 nm) of the approach. For perspective, this approach was conducted to Runway 4R and the wind shift occurred shortly before the turn onto final approach. Note that in the wind data shown in Figure 22, the scale for wind direction is located on the left and the scale for magnitude is on the right. The vertical line in the middle of the wind direction indicates a shift through 360 degrees true North.

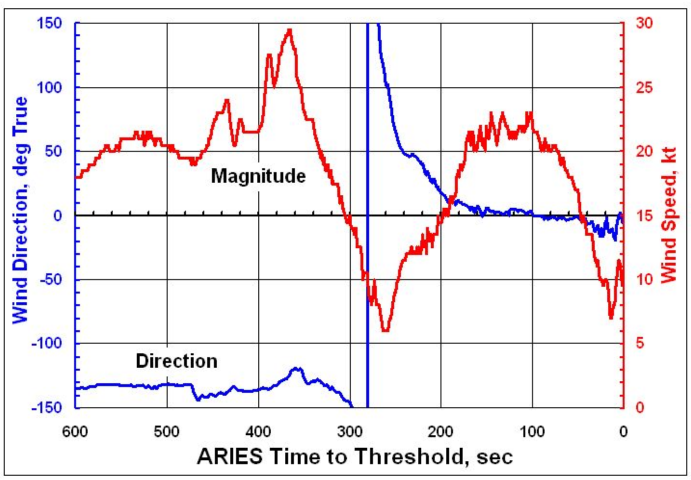

Figure 22. ARIES recorded wind velocity, RNAV scenario, 230-degree wind shift

Figure 23 shows the airspeed tracking performance (with autothrottles coupled) verses ATAAS commanded speeds. The performance with manually controlled airspeed shows, in general, more variability but still conformal with ATAAS speeds.

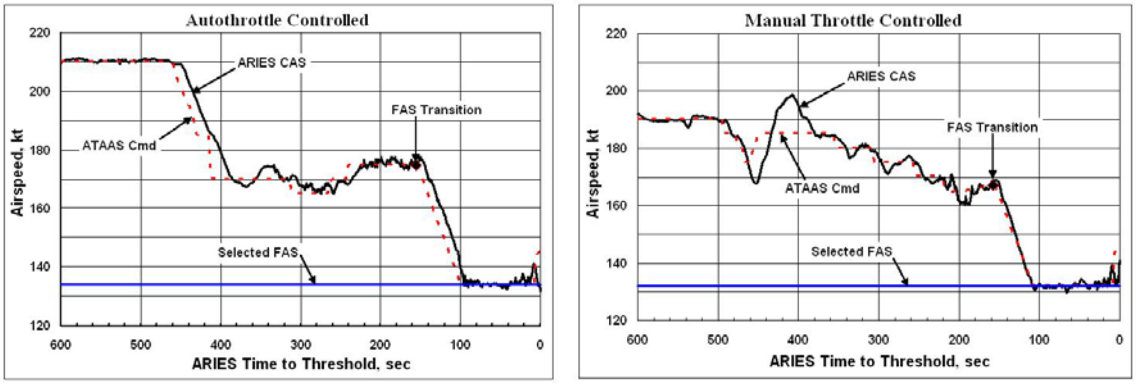

Figure 23. ARIES Calibrated Airspeed and ATAAS command speed, RNAV scenario, consecutive approaches

Figure 24 is an example of the actual tracks of two aircraft for a weather vector scenario. The lead aircraft was provided vectors from the controller and the following aircraft was tracking the lateral path of the lead. Most of the vectored scenarios had similar tracking results.
For the vectoring scenarios, the pilots of the aircraft using the ATAAS guidance were required to track the lateral path of the aircraft ahead. Although quantitative data on lateral path tracking performance is not available, generally it was good for both the Sabreliner and ARIES.

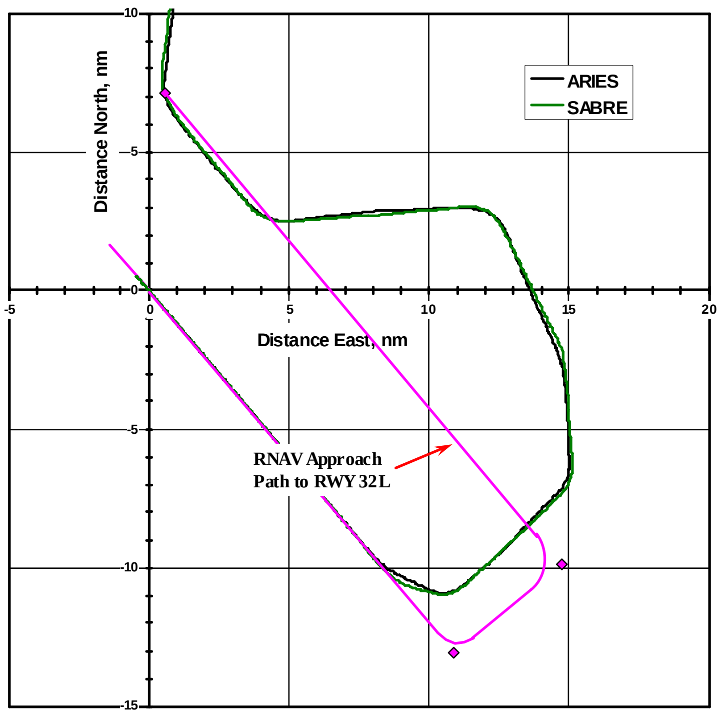

Figure 24. Flight paths of Sabre (lead) and ARIES (following) aircraft, "vectors for weather" scenario

One of the runs demonstrated the utility of displaying the ground track of the lead aircraft, even though all the aircraft were instructed to follow the RNAV lateral path. In that case, the lead aircraft inadvertently overshot the turn to the final approach course, and the following aircraft followed its time history (instead of the RNAV path), thereby alleviating a potential loss of separation. In an operational system, this maneuver would have to be approved by ATC, but could be beneficial.

4.2 Subjective Data

Subjective data measurements were primarily collected in the simulator study. A copy of the complete questionnaire is included in Appendix C. For the flight evaluation subjective data was collected in the form of questionnaires and pilot comments. To collect this data, researchers flew onboard both of the ATAAS-equipped aircraft on the flight deck, to enable communications with the research pilots and observe flight deck operations. Generally, the time for eliciting responses from the pilot for the questionnaire was limited to that available from the completion of the low approach through positioning on the inbound leg. Pilots did, however, provide comments throughout the flight paths as workload permitted and a final debrief was conducted at the conclusion of each day's flights. Encounters with weather during several of the runs added to the crew workload and further limited access for a structured administration of questionnaires. The net result of the aforementioned constraints resulted in only approximately 60% of the questionnaire data being gathered for ARIES and slightly less than 40% for the Sabreliner. In considering the subjective results of the flight evaluation, it should be recalled that a single pilot was performing the ATAAS flight related tasks, a researcher assisted with the CDU interactions, and that the performance monitoring functions envisioned for the pilot not flying were not performed because of safety pilot duties. From the data gathered, the pilots provided responses indicating the following: the ATAAS tool was acceptable, the heads down time was acceptable, they were confident in the guidance provided, and they were comfortable using the tool. A better understanding of ATAAS related pilot workload is provided in Oseguera-Lohr, et al., 2002.

4.2.1 Questionnaire Data

The total number of runs for which questionnaire data were collected onboard ARIES is shown in Table 3.

Table 3. Data runs for which Workload Ratings were collected on ARIES

Run Type	Number of Manual runs	Number of Autothrottle runs	Total number of runs
RNAV	4	3	7
Vectored	0	10	10

The questionnaires were based on a seven point scale; the end point descriptors were as follows: 1 was defined as "Not At All Acceptable", and 7 was defined as "Very Acceptable.

The first question asked of the pilot was to rate the workload level for the approach, as compared to an approach with current-day procedures. For the RNAV cases, the comparison to be made was with managing speed only, since the pilot was not required to manage the lateral path. For the vectored cases, the comparison to be made was with managing speed and path, compared to receiving speed and heading changes from ATC. The results of the workload ratings are summarized in Table 4.

The second question asked the pilot to rate the acceptability of the ATAAS tool, with a separate rating for each of the three segments of the approach (downwind, base, and final). The third question asked the pilot to rate the acceptability of the amount of head-down time, again separately for each of the three segments of the approach.

Table 4. Mean Workload Ratings

Run Type	Mean	Std. Deviation
RNAV (7 runs)	4.6	1.3
Vectored (10 runs)	3.6	1.0

For the RNAV runs, the workload ratings for the manual vs. autothrottle-coupled runs taken separately did not appear to be significantly different than the aggregate shown in Table 4. It should be noted that a rating of ‘4’ means that the workload level is the same, these results indicate that the pilots felt that the workload level was slightly lower for the vectored runs, and slightly higher for the RNAV runs, versus current-day procedures. Since the primary measure for determining workload in the RNAV runs was the management of speed, this would suggest that the additional speed changes required by ATAAS were perceived by the pilots as slightly higher workload over what they normally would expect in today’s environment (without ATAAS). Although all the vectored runs compiled in Table 4 were with autothrottle coupled to ATAAS, the lower workload rating could also be partially due to a perceived improvement in situation awareness, since the pilots could see the track being flown by the lead aircraft, which they could then follow. The results of the pilot ratings for the acceptability of the ATAAS tool are shown in Table 5.

Table 5. – Mean Ratings for Acceptability of ATAAS tool

Run Type	Mean	Std. Deviation
RNAV	5.4	1.1
Vectored	6.0	0.6

Recalling that a rating of ‘4’ is borderline acceptable, and ‘7’ is very acceptable, the mean overall rating of 5.4 for the RNAV cases indicates a general acceptability of the tool, with some room for improvement. This interpretation is consistent with verbal comments from the pilots. Although they made suggestions for display and algorithm performance changes, generally they felt that the tool was very useful and provided better situation awareness as it was implemented for the flight test. The results of the pilot ratings for acceptability of head-down time with the ATAAS tool are shown in Table 6.

Table 6. – Mean Ratings for Acceptability of head-down time with ATAAS tool

Run Type	Mean	Std. Deviation
RNAV	5.2	0.8
Vectored	5.8	0.8

Generally, the pilots did not have major complaints about the amount of head-down time required for this type of operation. They acknowledged that more head-down time was required to track the commanded speed, but indicated that it was not unacceptable. This result is consistent with the simulator study.

4.2.2 Pilot Comments

Research pilot comments were generally positive regarding the concept and the interface implementation for the flight activity. The pilots found that flying the ATAAS-generated speed commands was easily managed. Even with minimal exposure, pilots exhibited an understanding of the logic behind the algorithm and were able to anticipate generated speed commands. Several strong comments were made regarding the spacing position indicator on the ND, and the urge to take action to minimize the position difference immediately, even though the pilots realized that following the ATAAS generated speed commands would result in the proper spacing interval. This issue is expanded upon in the following section. Comments were also made regarding display clutter due to the additional symbology. A suggestion was made to have the capability to momentarily switch off the other traffic symbols on the ND, except for the selected traffic, as a way of highlighting it. Other methods of highlighting the selected traffic might be preferable, so as to not have to turn off any of the traffic symbols. For example, the selected traffic symbol could be filled in solid green, rather than merely outlined in green. A rigorous human factors evaluation of the ATAAS displays would be required to address this and other display or training issues.

4.2.3 Other display / training issues

Two other important issues were noted by researchers, from stated observations made by the pilots performing the spacing task, and by their actions, and are discussed here.

The first issue involves the training time needed to understand the ATAAS tool. The pilots of both aircraft did not appear to require a significant amount of time to understand the basics of the ATAAS concept and spacing tool. Though training was provided in the Langley Integration Flight Deck (IFD) simulator prior to the flight tests, the Sabreliner pilots were not able to take advantage of it to the same degree as the ARIES pilots. The Sabreliner pilots were provided with a classroom briefing on the concept, algorithm and flight procedures, and familiarization time in the simulator. Also, the Sabreliner interface for the ATAAS algorithm was slightly different than the ARIES implementation, requiring different crew interactions. Based on observations of their use of the tool during training and in the initial pre-test flights, they appeared to have a good working knowledge of the procedures. However, situations arose during the flights that indicated that more formal and structured training, as was used in the previous simulation study, would have been beneficial. As the test flights progressed, the pilots' actions and comments indicated that there might have been too much information displayed. This issue is described next.

As previously mentioned in section 4.1, it that was noted that pilots attempted to apply compensation strategies when the current spacing was different from the assigned interval. This typically occurred shortly after the ATAAS system was activated. This was contrary to instructions from the researchers during training; to follow the ATAAS commanded speed on the display, and to only use the spacing position indicator as a reference. It was also contrary to the ATAAS pilot procedures that were provided in the checklist form. The strategies used by the pilots consisted of either slightly altering the turns (making them either shorter or longer), in order to expand or contract the spacing interval, or varying the speed (holding a speed slightly higher than the ATAAS commanded speed, in order to shorten the current spacing interval). These observations are supported by pilot comments that "there is an almost irresistible urge" to position the ownship symbol "in the notch" created by the spacing position indicator on the ND (see Figure 25). The spacing indicator symbol was intended to be a reference to let the pilot know where the aircraft was relative to the target spacing interval, in order to better understand variations in the ATAAS commanded speed. Thus, if the ATAAS algorithm was commanding a speed slightly higher than the nominal speed expected by the pilots, they could see on the ND that it was to correct an actual spacing interval that was slightly behind the target interval, or conversely a lower than expected ATAAS speed would be commanded if the spacing interval was shorter than the target interval.

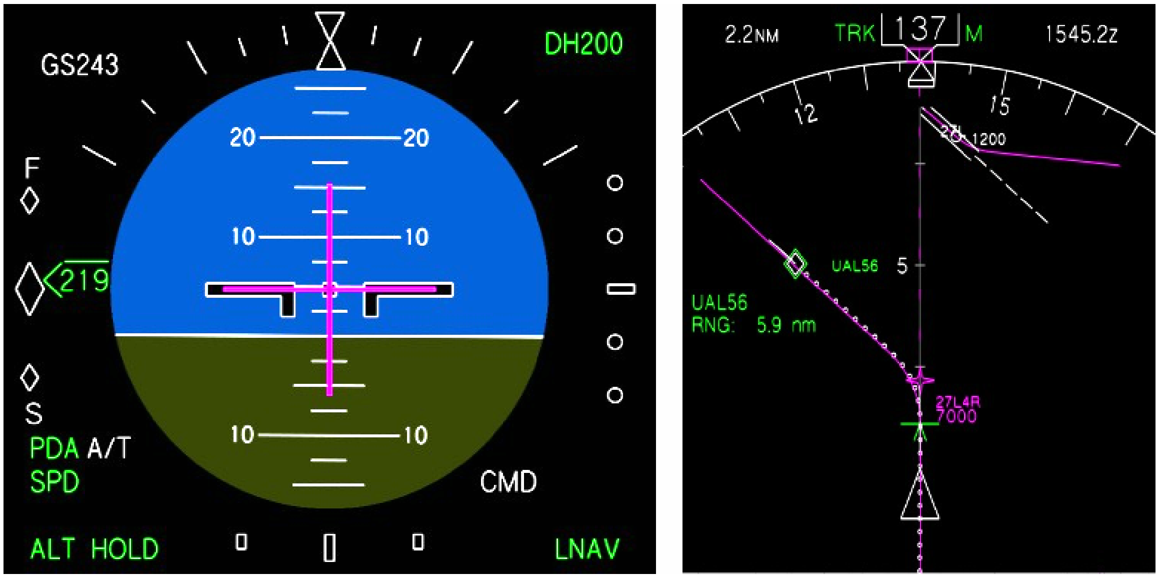

Figure 25. EADI and ND ATAAS display with actual spacing interval longer than target interval

Although the spacing position indicator could be used to adjust the speed to maintain the correct spacing interval, this resulted in more throttle activity (and in turn, higher pilot workload) than by following the ATAAS commanded speed. Also, since the algorithm allows for longer distances and the natural slowing of speed that occurs as the approach progresses to manage the spacing interval, the more immediate actions of the pilots to “correct” these errors ahead of the algorithm’s prediction could have unwanted effects later in the approach which would require further corrective actions that would not have been necessary had the pilots followed only the speed guidance.

5.0 Concluding Remarks

A flight evaluation and demonstration of a tool developed to support the Approach Spacing concept was conducted at the Chicago O’Hare International Airport and in the surrounding terminal area. The objective of the flight activity was to evaluate the ATAAS tool in an operational environment and to demonstrate various applications of the tool. Over 30 approaches were flown during five flying periods. The primary evaluation metric was delivery precision at the runway threshold. In general, delivery precision was good. However, expected improvements in areas mentioned in the previous section (e.g., reliability of the ADS-B data received by the algorithm and wind data) would improve performance.

Four research pilots flew the approaches for the flight evaluation. All pilots felt that the task of flying the ATAAS-generated speed guidance could be integrated into a pilot’s normal duties. It was also noted that the task was easier with the use of auto throttles. Pilots also stated that the task of tracking the lateral path of the leading aircraft was manageable and could be integrated into normal flying duties.

Although not evaluated in this flight activity, it should be noted that use of the ATAAS tool could reduce the required number of voice communications in the terminal area. Unburdening the controller from issuing speed instructions, and in some cases, limiting the number of vectors required could reduce congestion on the voice channels.

Based on the results of this flight activity, these recommendations are made for further research and improvements to the ATAAS tool and procedure:

- Addition of wind data to the ADS-B message to support better accuracy and consistency of the algorithm's performance for the following aircraft in the presence of changing winds.
- Conduct further evaluations to refine the ATAAS symbology and displays and assess the factors for potentially misinterpreting the displayed information.
- Additional equipment testing in an operational environment to ensure data integrity and identify the potential for further algorithm modifications.

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Appendix A. ATAAS System Architecture

The basic avionics configuration of the NASA B-757 includes an Allied Signal (now Honeywell) TPA-81 Traffic Collision Avoidance System (TCAS) system which is made up of two TRA-67A Mode-S transponders, one TPA-81A TCAS Computer, three omni-directional transponder antennas, two (top/bottom) TPR-920 TCAS directional antennas, and one CTA-81A control panel. The TCAS system is illustrated in Figure A-1. The TCAS system was modified to provide the ADS-B capability using Rockwell-Collins modified TCAS equipment. The modifications included replacing the Allied Signal TCAS Computer with a Rockwell-Collins TTR-901 unit with internal modifications for receiving Automatic Dependent Surveillance – Broadcast (ADS-B) signals from other Mode-S transponders. The left Allied Signal transponder was also replaced with a Rockwell-Collins TPR-901 unit modified to transmit ADS-B signals. A Rockwell-Collins Model GNLU-930 Multi-Mode (Global Navigation Satellite System (GNSS) Receiver was also installed to provide the Global Positioning System (GPS) position and timing information to the transponder for ADS-B. The top and bottom TCAS directional antennas were also replaced due to the incompatible technologies used between the Allied Signal and Rockwell-Collins antennas. Other than the directional antennas, the ARINC 429 signals passed between the TCAS sub-systems were compatible since they all comply with ARINC 735 TCAS specifications. The modified TCAS configuration is shown in Figure A-2. Wiring modifications were also made to provide signal outputs from the GNSS, TCAS, and Transponder units to external computers. The internal modifications that Rockwell-Collins made to the TCAS computer allowed the ADS-B outputs to be sent to an external computer for further data processing before being sent to the primary research flight computer (ONYX) where the self-spacing algorithms reside. The primary outputs from the TCAS computer were the DF17 and DF18 messages. The Fieldworks PC shown in Figure A-3 used for the ADS-B processing was a 750 MHz Pentium III with 128 MB RAM, a 6 GB hard drive, and the Microsoft Windows NT 4.0 operating system. The computer was configured with a Condor Engineering CEI-520 ARINC 429 PCI interface card. The Condor card was capable of receiving 16 ARINC 429 channels and 8 transmit channels. The Condor card was configured to receive the DF17/DF18 messages from the TCAS computer as well as inputs from the Left Inertial Reference System (IRS), the Left Air Data Computer (ADC), and the GNSS data. Data from all of these systems was used in the Fieldworks computer to process the ADS-B data. Additionally, a DCM-1 timing card was installed in the Fieldworks to take a timing signal from the GNSS receiver and provide timing for the ADS-B processing. A Systran Inc. ScramNet+ reflective memory card was also installed in the Fieldworks PC. This card provided the means to pass the processed ADS-B data to the Onyx flight computer. The reflective memory is basically a block of common memory shared by all connected nodes and is updated by high-speed fiber optic data transfer.

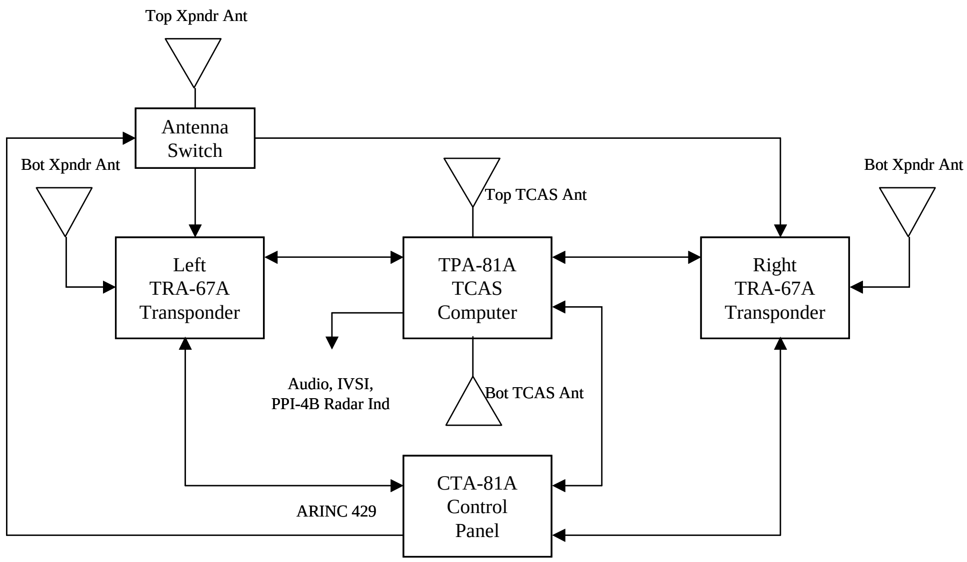

Figure A-1. B-757 ALLIED SIGNAL TPA-81 TCAS SYSTEM -Un-modified

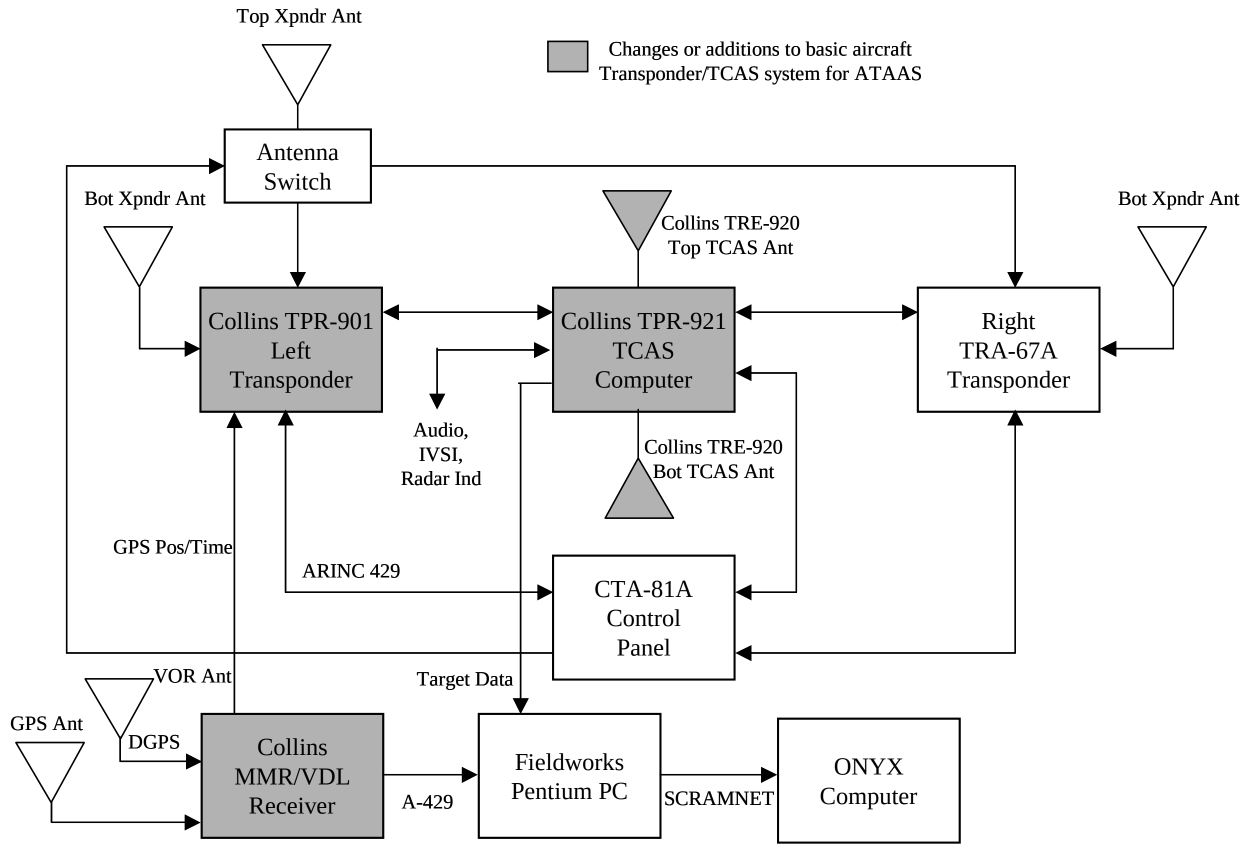

Figure A-2. B-757 ALLIED SIGNAL TPA-81 TCAS SYSTEM - Modified For ATAAS with Collins Equipment

Figure A-2

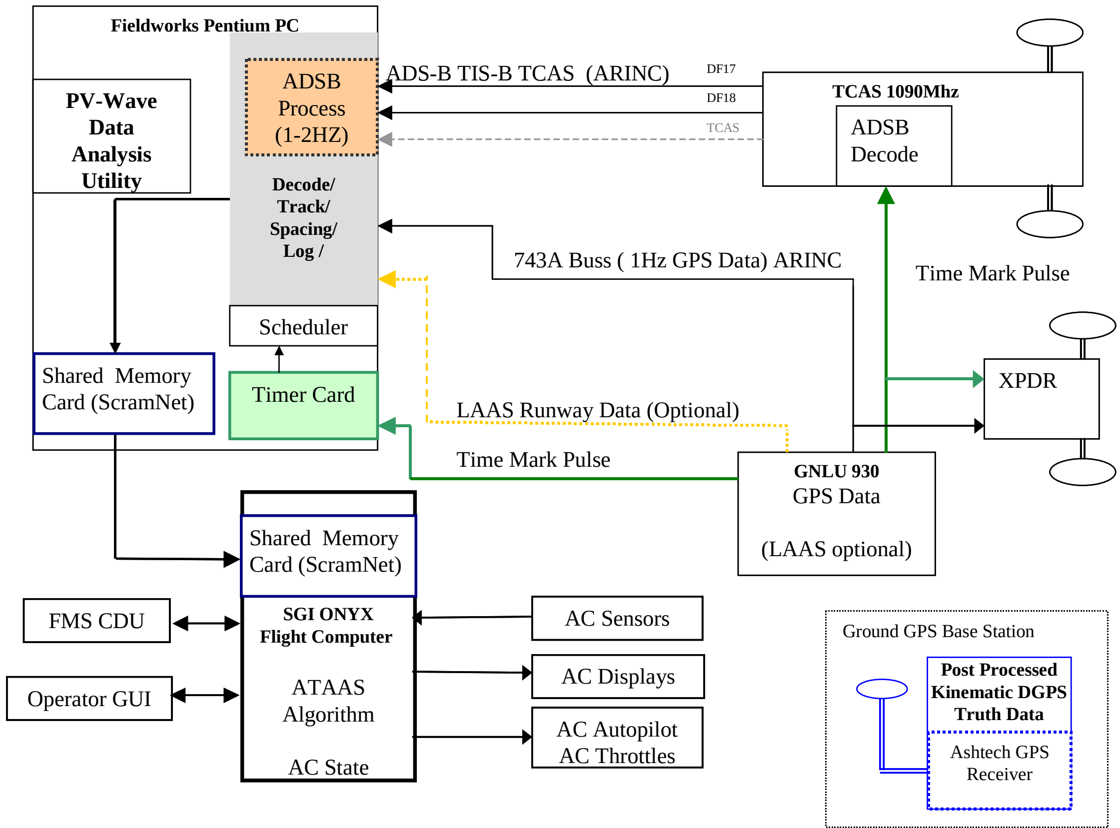

Figure A-3. B-757 ATAAS SYSTEM ARCHITECHURE

Appendix B. Run Conditions for the 28 Valid ATAAS Approaches

Flt	Scenario	Throttles	Seq	Runway	Traffic	Sep Time
249R1	RNAV	AT	C-S-A	09R	Left	90.4
249R2	RNAV	MT	C-S-A	09R	Left	89.7
249R3	Vect-Wx	MT	C-S-A	09R	Left	83.9
249R4	Vect-Nom	AT	C-A	09R	Right	86.4
249R5	Vect-Nom	AT	C-A	09R	Left	81.5
249R6	Vect-ReSeq	MT	C-S-A	09R	Left	101.4
250R1	RNAV	AT	C-S-A	22L	Left	84.8
250R2	RNAV	MT	C-S-A	22L	Left	86.4
250R3	Vect-Wx	MT	C-S-A	22L	Left	90.2
250R4	Vect-Nom	AT	C-A	22L	Left	88.2
250R5	Vect-ReSeq	MT	C-S-A	22L	Left	90.5
250R6	Vect-Nom	AT	C-S-A	22L	Left	82.7
250R7	Vect-Wx	AT	C-S-A	22L	Left	79.5
251R6	Vect-Nom	AT	C-A	22L	Left	84.6
252R1	Vect-Wx	AT	C-S-A	14R	Right	107.9
252R2	Vect-Nom	AT	C-S-A	14R	Right	92.4
252R3	RNAV	AT	C-S-A	14R	Right	83.7
252R4	RNAV	MT	C-S-A	22L	Left	95.2
252R5	Vect-Wx	MT	C-S-A	22L	Left	111.9
252R6	RNAV	AT	C-A	22L	Left	85.2
252R7	Vect-ReSeq	MT	C-S-A	22L	Left	94.2
252R8	RNAV	AT	C-S-A	22L	Left	88.7
252R9	RNAV	MT	S-A	22L	Left	86.0
253R1	Vect-Nom	AT	C-S-A	04R	Right	91.7
253R2	Vect-Wx	AT	S-A	04R	Right	94.0
253R3	RNAV	AT	S-A	04R	Right	93.1
253R4	RNAV	MT	S-A	32L	Right	99.6
253R5	Vect-Wx	MT	S-A	32L	Right	97.5

Appendix C. Post-Run Questionnaire for ATAAS Flights

Note to researchers: ensure that you have discussed this questionnaire with your pilots prior to beginning flights on the first flight day. Query the crew to let you know when is the best time to administer the questionnaire.

1. Rate the overall workload level as compared to current-day procedures (complete either “A” or “B”):

A. RNAV Case – Rate your overall workload level in following the ATAAS speed guidance cues versus following speed control instructions provided from ATC.
B. Vector Cases – Rate your overall workload level in following the ATAAS speed guidance cues tracking the lateral path of the lead aircraft versus following comparable ATC instructions for speed control and vectors.

Much Lower			The Same			Much Higher
1	2	3	4	5	6	7

2. How acceptable was the ATAAS tool during the following phases of the approach procedure:

	Not at all Acceptable			Border-line			Very Acceptable
	1	2	3	4	5	6	7
Downwind							
Base							
Final							

3. How acceptable was the amount of head down time for the following phases of the approach procedure?

	Not at all Acceptable			Border-line			Very Acceptable
	1	2	3	4	5	6	7
Downwind							
Base							
Final							

4. How confident were you with the guidance provided by the ATAAS tool during the following phases of the approach procedure:

	Not at all Acceptable			Border-line			Very Acceptable
	1	2	3	4	5	6	7
Downwind							
Base							
Final							

5. How comfortable were you with using the ATAAS tool during the following phases of the approach procedure:

	Not at all Acceptable			Border-line			Very Acceptable
	1	2	3	4	5	6	7
Downwind							
Base							
Final							

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14. ABSTRACT
An airborne tool has been developed that allows an aircraft to obtain a precise inter-arrival time-based spacing interval from the preceding aircraft. The Advanced Terminal Area Approach Spacing (ATAAS) tool uses Automatic Dependent Surveillance-Broadcast (ADS-B) data to compute speed commands for the ATAAS-equipped aircraft to obtain this inter-arrival spacing behind another aircraft. The tool was evaluated in an operational environment at the Chicago O'Hare International Airport and in the surrounding terminal area with three participating aircraft flying fixed route area navigation (RNAV) paths and vector scenarios. Both manual and autothrottle speed management were included in the scenarios to demonstrate the ability to use ATAAS with either method of speed management. The results on the overall delivery precision of the tool, based on a target spacing of 90 seconds, were a mean of 90.8 seconds with a standard deviation of 7.7 seconds. The results for the RNAV and vector cases were, respectively, M=89.3, SD=4.9 and M=91.7, SD=9.0.

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