AIRBORNE PRECISION SPACING: A TRAJECTORY-BASED APRROACH TO IMPROVE TERMINAL AREA OPERATIONS

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Abstract

Airborne Precision Spacing has been developed by the National Aeronautics and Space Administration (NASA) over the past seven years as an attempt to benefit from the capabilities of the flight deck to precisely space their aircraft relative to another aircraft. This development has leveraged decades of work on improving terminal area operations, especially the arrival phase. With APS operations, the air traffic controller instructs the participating aircraft to achieve an assigned inter-arrival spacing interval at the runway threshold, relative to another aircraft. The flight crew then uses airborne automation to manage the aircraft's speed to achieve the goal. The spacing tool is designed to keep the speed within acceptable operational limits, promote system-wide stability, and meet the assigned goal. This reallocation of tasks with the controller issuing strategic goals and the flight crew managing the tactical achievement of those goals has been shown to be feasible through simulation and flight test. A precision of $\pm$ 2-3 seconds is generally achievable. Simulations of long strings of arriving traffic show no signs of instabilities or compression waves. Subject pilots have rated the workload to be similar to current-day operations and eye-tracking data substantiate this result.

This paper will present a high-level review of research results over the past seven years from a variety of tests and experiments. The results will focus on the precision and accuracy achievable, flow stability and some major sources of uncertainty. The paper also includes a summary of the flight crew's procedures and interface and a brief concept overview.

Development of Airborne Spacing Applications

The concept of Airborne Precision Spacing (APS) operations in terminal area arrival flows has evolved from several decades of research into aircraft-managed spacing [1], [2]-[6]. Early research indicated that, by precisely spacing aircraft across the runway threshold, variability in threshold crossing times could be reduced, thereby increasing runway throughput [5]. Further, even a small increase in runway throughput could lead to a significant decrease in landing delays for airports during high-demand conditions [1]. Simulator experiments at NASA established the feasibility of using traffic information displayed on the flight deck to enable airborne-managed spacing [3], [6] from crew workload and acceptability considerations. This phase of research also determined that time-based spacing was superior to distance-based spacing due to the successive speed reductions that are inherent in arrival flows.

Recent improvements in airborne display and computing capabilities, the emergence of Automatic Dependant Surveillance – Broadcast (ADS-B) technology for the sharing of traffic data, and the growing need for capacity-increasing concepts of operation have sparked renewed interest in airborne precision spacing operations. Starting in 1999, NASA researchers developed a preliminary concept of operations for terminal-area precision spacing operations [7]. Under this concept, the terminal-area air traffic controller delegates responsibility for achieving precise spacing at the runway threshold to the aircraft flight crew. Airborne automation assists the flight crew in achieving this goal. The controller retains responsibility for separation and for issuing spacing requirements to the flight crew. The concept accommodates equipped (self-spacing) as well as unequipped (present-day IFR) aircraft within an arrival stream.

Research into this concept of operations is being conducted in three phases, commencing with in-trail precision spacing, progressing to precision spacing in merging arrival streams, and culminating with the limited use of maneuvering to ensure that aircraft can arrive properly spaced at the runway threshold. Prototypes of the onboard automation and operational procedures for the first phase of research (in-trail spacing) were developed and tested at NASA Langley Research Center in the

1999 – 2003 timeframe. A control law to provide flight crews with speed guidance when in-trail behind their lead aircraft [8] was incorporated into the APS on-board automation. The automation and associated operational procedures were evaluated in a piloted simulation at NASA Langley Research Center [9] and in a flight evaluation at Chicago O'Hare [10], successfully demonstrating the operational feasibility of achieving precise spacing between aircraft flying in-trail to a runway.

The second phase of research added the capability to space off another aircraft not on the same route, i.e., merge behind them and then continue with in-trail spacing. The updated tool was tested in several fast-time simulations [11][12] and a piloted study [13].

In Europe, precision spacing operations have been studied through several experiments [14], [15] that have evaluated the performance of exact and approximate time-delay algorithms in a variety of operational conditions, and studied the impact of these new procedures on flight crew and air traffic control (ATC) operations. Although they employ some variations on the technical approach, both European and American research findings affirm the feasibility of the basic concept of airborne-managed precision spacing for in-trail arrival streams.

Approach Spacing Operational Concept

NASA, under the Advanced Air Transportation Technologies Project, developed an operationally viable approach spacing concept. As the concept, tools and procedures were developed and refined the concept went through several name changes. Throughout this paper, Airborne Precision Spacing (APS) will be used when referring to the operation or concept in general. The specific names, introduced below, will be used when referring to a specific intermediate step.

The goal of APS is to achieve system-wide performance improvement by precisely spacing aircraft in a stream and not just focusing on a single pair of aircraft. Performance improvements result from more consistent spacing with the possible expense of occasionally having excess spacing for one pair of aircraft.

The first development stage, called ATAAS, used time-history spacing between pairs of aircraft [8]. ATAAS focuses on in-trail and final approach spacing. The concept includes an extended Standard Terminal Arrival Route (STAR) which includes vertical and speed profiles. When desired, the air traffic controller clears the spacing aircraft to begin spacing relative to an assigned target aircraft (the lead) and an assigned spacing interval to achieve at the runway threshold. APS has always worked with the idea of achieving the assigned goal at the runway threshold instead of achieving it early in the operation and then maintaining the assigned spacing. This allows the spacing aircraft to damp out reactions far from the runway and only tightly manage the spacing where it is necessary.

There are two main benefits to delegating the precision spacing task to the flight deck. The first is that the flight crew is able to manage their speed more precisely and with a tighter control loop than a controller. The flight deck automation can have a much quicker reaction time to changes in the aircraft state and spacing and can make finer adjustments to the speed. The second main benefit is that each flight crew is responsible for a single spacing interval instead of a single human, the controller, being responsible for the spacing between several pairs of aircraft. This allows a more tailored spacing interval to be given to the flight crew. They can easily manage an assigned spacing interval while a controller, who is responsible for several different intervals, would naturally start to clump similar values together to reduce the workload associated with remembering and applying these close, but different, values. It is also possible that having the controller issue a single strategic clearance to the flight crew instead of a series of tactical commands reduces the amount of radio communications. The extent of this benefit has not been tested under APS but Eurocontrol has looked at the same issue for the related operation called Sequencing and Merging and found significant reduction in the number of commands issued [16].

ATAAS was then extended to include the ability to merge traffic on different arrival routes. The calculation of the projected spacing interval was changed from a time-history approach [8] to a trajectory-based approach [17]. The later still requires aircraft to be following a published STAR so

that intent information is easily known. The new spacing tool, called AMSTAR, calculates the expected time of arrival (ETA) at the runway threshold for both the ownship and leader and uses the time difference as input to the speed control law. The speed control law remains unchanged from ATAAS. This is a purely internal change, and the pilot interface is largely untouched.

AMSTAR has recently been upgraded again to improve the stability of the trajectory prediction and ETA calculations, improve the internal wind model to accept real-time updates and to enable operations to start at cruise altitudes. Spacing at cruise altitudes enables en route merging as well as Continuous Descent Approaches (CDA). The current version of the spacing tool is called ASTAR for Airborne Spacing for Terminal Arrivals.

This paper will review the past several years of research into Airborne Precision Spacing focusing on key research results. For more information on the operational concepts, the reader is referred to references [18] and [19]. However, a brief review of the concept is included below. A discussion of the flight crew procedures follows.

APS Concept of Operations

The aim of APS is to assist the controller in achieving their goal of maximizing throughput on capacity-constrained runways. To this end, APS enables the controller to issue a single strategic clearance to spacing-capable flight crews to achieve the assigned spacing interval at the runway threshold relative to an assigned lead aircraft. The flight crew then manages their speed along an assigned lateral and vertical path to achieve that goal. The assigned path is generally an established arrival route that ends at the runway threshold. Alternatives to fixed routing are possible but are not explored further in this paper. Speed changes from the nominal speeds on the established routing are limited to ±10% and less than 250 kt when appropriate. The commanded speeds are also limited by the current aircraft configuration. Additional limits and controls are included to increase the system stability [18]. Under normal conditions, speed changes from the nominal are generally 5-10 kt.

If the final approach speeds of the lead and ownship are available, the APS spacing tool in-

cludes these in the ETA calculations, effectively creating an offset to account for the difference in final approach speeds. This ensures that maximum throughput is achieved at the runway threshold. This may cause a different spacing interval at the final approach fix than at the threshold. However, with minimal training on this point, both pilots and controllers seem comfortable with this technique. Finally, to ensure a stable approach the APS spacing tool will command the slow-down to the final approach speed at the appropriate time to be stabilized by 1000 ft above ground level. Any spacing deviation at this point is not actively countered.

Flight Crew Procedures

The flight crew procedures have been well tested and only minor adjustments have been made over several years of studies. The procedures and displays are well documented in references [18], [20]. A brief overview follows. The spacing operation is initiated for the flight crew when they receive a clearance from the controller to begin spacing. The clearance includes the lead aircraft identifier and the assigned spacing interval at the runway threshold. In addition, the spacing tool needs to know the planned final approach speed of the lead aircraft and, if merging, the reference path that the lead is following. These can either be communicated through the controller or, preferably, through an on-condition ADS-B report. Current simulations use the on-condition report. The flight crew then selects their lead from a list of ADS-B targets. This can be via the Multi-function Control and Display Unit (MCDU) or an Electronic Flight Bag (EFB). The flight crew then enters the assigned spacing interval and if needed, the lead's route and final approach speed. If the route and final approach speed are available via ADS-B, they are automatically populated. Once this information is entered, the spacing tool goes into an armed mode and starts calculating the desired speed. In cases where the lead aircraft is not yet within ADS-B range or they are not yet a valid target, the spacing tool will command the nominal published speeds for each leg until it can start actively spacing relative to the lead aircraft. If the system is coupled to the autothrottles, once the pilot is comfortable with the new speed they may make this the new source of speed guidance. If the spacing tool is not coupled to the autothrottles, then the pilot manually

matches the commanded speed. From this point on the flight continues as normal with the only alteration being that speed commands are coming from the on-board tool instead of from the controller.

The spacing tool has several built-in protections to maintain the stability of the operation and the operational acceptability of the speeds. If either the lead or ownship deviates significantly from the planned routing to the point that the ETA calculation is no longer reliable, the tool alerts the pilot and reverts to the published speed profile. This limit is currently set at 2.5 nm and 90° of the expected track. The tool also accepts a minimum protection distance. This would normally be the required radar or wake separation criteria. If the aircraft is projected to encroach on this distance within the next 20 seconds the tool commands the slowest allowable speed and notifies the pilot. This generally will only occur when the pilot has lost attention and missed a speed change.

If there is a system error or unexpected deviation, such as the route deviation mentioned above or loss of ADS-B data, the spacing tool reverts to the published speed for that segment. If the flight crew is no longer able to follow the speed command, or experiences one of these system errors, they are instructed to contact the controller to terminate spacing operations and revert to current-day controller mechanisms. At any time the controller can intervene with either a speed or vector clearance; this procedurally cancels the spacing operations clearance.

Key Research Results

This section will focus on several key research issues that impact the operational feasibility or benefits of Airborne Precision Spacing operations. It will draw on results from several fast-time, human-in-the-loop and flight activities.

Presentation of Data

Much of the data presented below will be in the form of a modified box plot. This form will present a large quantity of data in a compact form. The standard Tukey box-and-whisker plot shows the median value of a population along with the first and third quartiles (inter-quartile distances) [21]. This demarcates the central 50% of the popu-

lation and is the box. Whiskers then extend out one and a half times the inter-quartile distance in each direction. Any additional data points beyond the ends of the whiskers are shown explicitly as extreme values. If no extreme values exist in a given direction, the whisker is terminated at the extreme value in that direction. In many cases, the central peak of the data distribution will approximate a normal distribution; therefore, a thin box is superimposed that shows the mean and standard deviations. An example is shown below in Figure 1 with a histogram of spacing data along with the same data shown as a modified box plot.
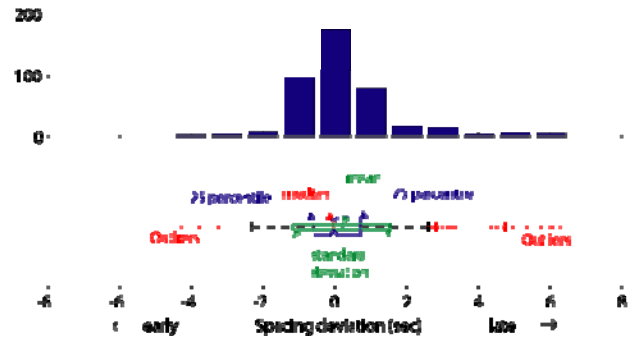

Figure 1: Explanation of the box-plot format.

Overall Spacing Performance

The first key question in airborne spacing is does it offer the proposed benefit mechanism of precisely and accurately spacing aircraft at the runway threshold and what are the effects of various disruptive conditions. Many possible disruptive conditions have been studied so far and those with the largest impact are discussed below. These include: limited surveillance range; wind forecasting accuracy; and, the preconditioning of traffic before spacing operations start. The effects of having a range of final approach speeds representative of normal traffic make-up will also be discussed. While not a disruptive condition, it has a significant impact on how well the aircraft are spaced and the traffic flow behavior near the runway.

For the assigned spacing interval the required wake turbulence separation criteria were converted into time-based separations using the expected slowest final approach speeds based on wake category [12]. These numbers were then rounded upward approximately 10 seconds to add a safety buffer between spacing the aircraft and separating

them. In the APS concept of operations, the flight crew is only responsible for spacing relative to the other aircraft; separation remains the responsibility of the controller.

All of the studies have looked at the accuracy and precision of the interarrival spacing. A series of fast-time studies [11], [12], [25], [26] have found accuracies of less than one second and precisions of less than three seconds in the non-disruptive cases. The disruptive cases are discussed in more detail below. A human-in-the-loop study in the NASA Integration Flight Deck [9],[22] focused on the in-trail spacing only and found that pilots could achieve an accuracy of less than one second off the assigned value with a standard deviation of 1.7 seconds when the spacing tool was coupled with the autothrottles. When the pilot was in the loop for speed control the precision remained the same but the accuracy decreased with a mean deviation of 4-5 seconds. This is caused by the pilots making the deceleration to the final approach speed more quickly than the spacing tool predicted; therefore, flying longer at a slower speed.

A human-in-the-loop study conducted in NASA's Air Traffic Operations Laboratory (ATOL) tested the merging, as well as in-trail, operations [13]. The ATOL was used to study strings of 9 aircraft arriving to one of three modeled airspaces. Six of the nine aircraft were piloted by subject pilots while the remainder were flown by confederate pilots. Subject pilots were able to achieve a mean spacing deviation at the runway threshold of -0.8 seconds with a standard deviation of 4.7 seconds. The larger standard deviation was largely attributed to training errors with the simulation environment instead of errors with the spacing tool itself. Several pilots made mistakes with the vertical navigation modes and hence had significant deviation from the reference vertical profile. The same types of errors occurred with the same frequency during baseline runs that did not include spacing operations. There were no significant differences seen between the merging and in-trail operations or between the different airspaces.

A flight trial of the ATAAS tool was conducted at Chicago O'Hare in September 2002 [10],[20],[23]. The NASA Boeing 757 aircraft was third in line and achieved a mean of +0.8 seconds and a standard deviation of 7.7 seconds. These re-

sults suffered from additional filtering that was incorporated to overcome errors with the ADS-B data. This was an artifact of the flight test hardware of a non-deployed system and would be corrected before any system went into operational use.

For airborne surveillance we have assumed ADS-B functionality. Since ADS-B is a broadcast link instead of an addressed link, there is no guarantee of reception. If multiple messages arrive simultaneously, one or more of them may be lost to the interference. This effectively reduces the range for reliable reception. This range can be particularly small within a busy terminal environment where there are a high number of 1090 MHz signals (ADS-B, secondary surveillance radar, TCAS and others) to interfere.
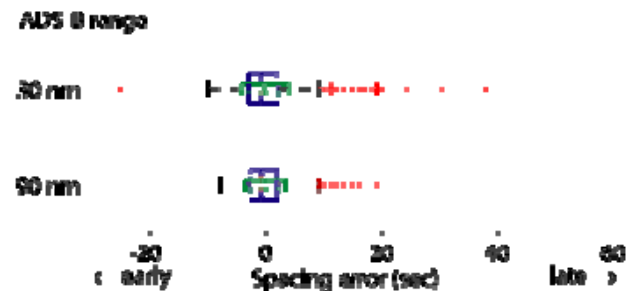

Figure 2: ADS-B range effect on spacing.

As seen in Figure 2, limiting the reception range to 30 nm, from a more realistic 90 nm, had little impact on the overall performance (mean and standard deviation moves from -0.13 ± 3.42 seconds to -0.20 ± 4.03 seconds) but does introduce more extreme values. The extreme values arise when two conditions are met. First, the aircraft are approaching their merge point from opposite sides of the airfield so that they are close to it when they entered ADS-B range. Second, there is a significant spacing deviation that needs to be overcome. The farther from the runway active spacing can be started, the greater the spacing deviation that can be overcome. When initiation is delayed due to limited ADS-B range, the deviations that can be overcome are necessarily smaller. As ADS-B technology has improved since the first standards were published, the likelihood of such small ranges has decreased. A range of 90 nm covers the extent of most terminal areas and is a reasonable expectation. Limited ADS-B range becomes a concern again when spacing operations start well outside the terminal area as

would be the case for doing CDAs. A possible solution to this problem is discussed below in response to wind forecasting errors.

The most significant disruptive effect seen in the fast-time studies so far is from wind forecasting errors. It is assumed in the concept that the aircraft would have a wind forecast that it would use in calculating the ETAs at the threshold. The same, or different, forecast would have been used by the sequencing tool that assigned the landing sequence. Both of these could differ from the actual winds encountered. These two sets of differences lead to prediction errors in the sequencing or ETA calculations. For our studies we have focused on the difference between the aircraft's forecast and the truth winds and considered both magnitude and directional errors. For the baseline case, we assumed an accurate forecast so there is no difference between the forecast and the truth winds. For directional errors, we assume accurate magnitude but directional errors of 5° and 20° off of the truth winds. For the magnitude errors we assume accurate direction but −10 kt and +40 kt mean error. The wind field varied in both direction and magnitude with altitude. For the magnitude error cases, the error scaled with the baseline magnitude and was characterized by the averaged error.

For the +40 kt case, the errors were large enough that the traffic flow was seriously disrupted with aircraft unable to achieve the assigned spacing. However, current wind forecast products have accuracies on the order of 10 kt [24]. Therefore, the failure to handle 40 kt errors is not considered to be operationally relevant. As Figure 3 shows, the remaining wind forecast error conditions introduced a larger spread in the data and more extreme values.
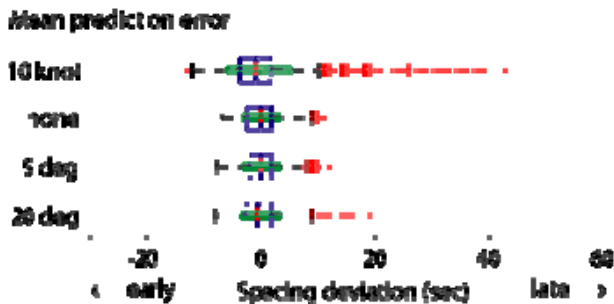

Figure 3: Spacing deviation due to wind forecast errors.

Work is currently underway to improve the performance under wind uncertainties. The current version of the APS spacing tool takes the air reference velocity ADS-B report, if available, plus ownship wind information to continually update the internal wind model. This allows the tool to continually improve the accuracy of the wind model. The wind forecast problems are greatest when the lead aircraft is not yet within ADS-B range. In those cases, there is currently no mechanism to correct for the forecast errors until the lead is within ADS-B range. We are exploring ways to detect the forecast errors and adjust to them before the lead is within ADS-B range. At that point, the spacing tool should be able to overcome most realistic forecast errors.

One of the reasons for several of the improvements to the current generation spacing tool, ASTAR, is to enable Continuous Descent Approaches (CDA) from cruise altitude to the runway threshold. The goal is to combine spacing operations with the energy and noise efficiency of CDAs to maintain capacity. In order to maintain the optimal descent profile, once an aircraft is on a CDA, controllers do not make adjustments to the aircraft. The aircraft are therefore given a wide berth and excess spacing. This leads to a decrease in capacity. By allowing the aircraft to make minor changes to their speed to maintain relative spacing, much of the CDA benefit may be obtained while maintaining the tighter spacing of current operations. Being able to decrease the environmental impact of flights while maintaining or increasing capacity is a significant challenge for the Next Generation Air Transportation System (NGATS) and being able to precisely space along CDAs is seen as a key capability in reaching that goal.

Early simulations have just been completed and initial results are promising. Under nominal conditions, including good wind forecast, uniform fleet and reasonably accurate preconditioning, overall spacing performance (a mean of 0.2 sec and standard deviation of 1.4 sec) is consistent with previous studies (see Figure 4). More detailed analysis of these simulations will be reported in the near future [25].
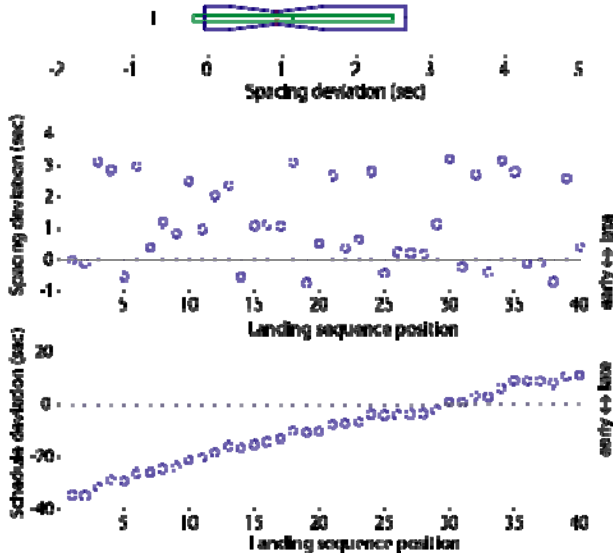
Figure 4: Spacing and schedule deviation for a CDA run.

The next issue of interest is the requirements for preconditioning the traffic flow. Preconditioning involves properly scheduling and delivering aircraft to the starting point of the spacing operation so that the aircraft is able to compensate for any initial spacing deviations and uncertainties that occur during the remainder of the flight. These uncertainties include the wind forecast errors, differences in aircraft conformance to the reference trajectory and the spacing needs of the lead. The spacing aircraft only has so much control of the relative spacing when using only speed changes. The requirement for preconditioning would be lessened if the aircraft were able to make minor route modifications as part of the spacing operations; however, that has not been included in the operational concept as of yet.

In simulation, the preconditioning was modeled by assigning the aircraft with a scheduled time of arrival (STA) at the start of operations. The aircraft would enter the simulation at that time with some given spread around the STA. A normal distribution with a zero mean was used. The preconditioning was controlled by adjusting the standard deviation of the distribution. Figure 5 shows the results for distributions with $2\sigma = 15\,\mathrm{sec}$ and $2\sigma = 60\,\mathrm{sec}$.
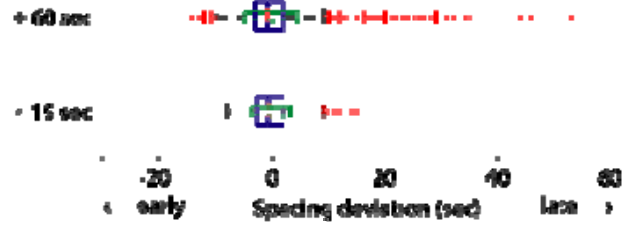

Figure 5: Spacing deviation based on preconditioning.

As in the surveillance range study, the major effect of decreasing the initial delivery precision is to create more extreme values and not to substantially move the mean and standard deviation (–0.13±3.42 seconds to –0.12±4.73 seconds). The large number of extreme values for the $2\sigma = 60\,\mathrm{sec}$ case suggests that a delivery precision of less than 60 seconds is needed[1]. The aircraft that had the most trouble were those arriving along the shortest arrival route with a large initial spacing deviation. The short flight distance and steep descent limited their ability to adjust the spacing. There were also problems for aircraft arriving from opposing entry points and following an aircraft on the shortest route. In the operational concept, an aircraft would not start spacing until both it and their lead were within the terminal area, so once the lead aircraft entered the terminal area there was not much time remaining to correct for any significant spacing deviation.

Some of these cases could be controlled by including a feasibility test by either the controller or the flight crew before starting operations. If it is

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[1] The preconditioning requirement is expected to depend more on flight time than on airspace design. However, that has not been verified.

unlikely that the aircraft could achieve the assigned spacing in time, then alternate control methods could be used until the spacing was achievable. This would most likely include path stretching or shortening. Initial spacing deviations much beyond 60 seconds opens the possibility of resequencing (the spacing intervals were generally between 90 and 150 seconds) and were not considered in the simulations.

Final Approach Speed Effects

As discussed above, the APS spacing tool makes use of the ownship's and lead's final approach speed (FAS) in the ETA calculations, if it is available. Currently, final approach speed is not part of the ADS-B state report so if it is a desirable piece of information, it would have to be added. Two of the fast-time studies have looked at the benefits and behavior of knowing the final approach speed. To test the benefit of knowing the final approach speed we tested four conditions: the lead's FAS was known; the lead's FAS was assumed to be the same as the ownship's; the lead's FAS was assumed to be a generic value based on wake category; and the lead's FAS was assumed to be a generic value of 130 kt regardless of wake category. The ownship's FAS was always taken as the planned FAS. Figure 6 shows the spacing performance for these four conditions.
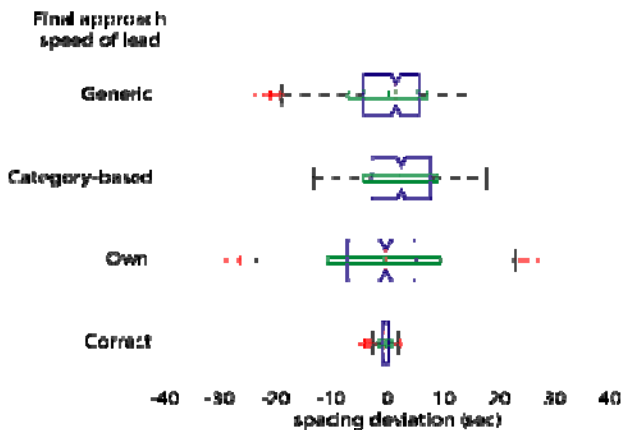

Figure 6: Spacing results for various FAS assumptions.

It is clear that there is a significant performance benefit in threshold spacing for knowing the lead's FAS. Figure 7 shows the inter-arrival spacing as measured at the final approach fix and the threshold for the nominal case of knowing the lead's planned final approach speed. The black solid lines show the range in spacing deviation at the final approach fix and the red, dotted lines show the range at the threshold. For large differences in final approach speeds, there is a significant difference between the spacing at the final approach fix and the threshold. As long as the spacing and sequencing is such that this offset is not a separation concern, it delivers the desired threshold crossing performance.
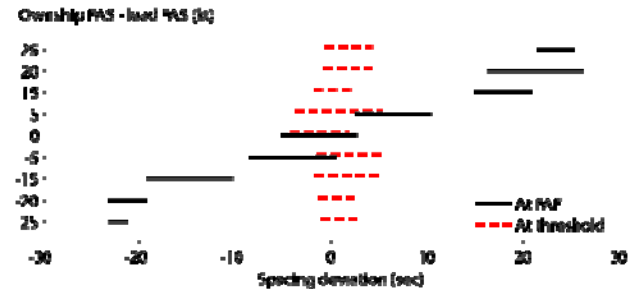

Figure 7: Spacing at Final Approach Fix and runway threshold.

Stability of Operations

The final key point to be discussed in the paper is the stability of spacing operations. As discussed earlier, the goal of Airborne Precision Spacing is not to space one pair of aircraft precisely but to use precision spacing to gain system-wide benefits. To this end we are concerned with introducing instabilities into a long string of spacing aircraft either through over-aggressive speed changes or disruptive behavior. The fast-time studies are particularly well suited to investigate this question. The initial set of studies performed in 2004-5 looked at strings of 100 aircraft. The recently completed studies that included CDAs used strings of 40 aircraft. The ATOL study involved strings of 9 aircraft and also produced some useful data on stability.

The metrics used to judge stability are the overall schedule deviation and string position effects on the precision or number of speed commands issued. Schedule deviation is defined as the difference in the actual time of arrival and the initially projected time of arrival at the threshold by the sequencing tool. If this continues to diverge the further back in the string an aircraft is, then that suggests some instability in the system. Likewise,

the later aircraft achieving a lower level of precision or working harder to achieve the spacing also indicates instability. Figure 8 shows the spacing deviation (upper left), schedule deviation (upper right), and speed changes (lower right) for one run of the nominal test condition in the 2004 studies. The lower left panel of Figure 8 also shows the speed profile for the reference trajectory as well as several aircraft in the string. The spacing deviation and the number of speed changes show no sign of a string position effect. The schedule deviation requires a deeper look since there appears to be a transient and a possibly periodic peak.
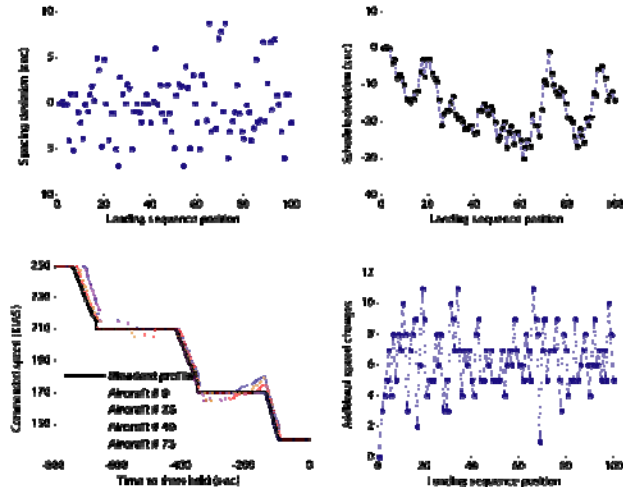

Figure 8: Stability data from nominal condition for fast-time studies.

The transient is actually a result of a systematic shift between the calculated transit time used for sequencing and the actual transit time for the lead aircraft. This shift results from using a simplified, generic trajectory calculator in the sequencing tool, wind forecast errors and final approach speed effects. The sequencing tool assumes a generic final approach speed for all aircraft of a given wake category. Subsequent studies looking at this transient have verified these effects. Therefore, in Figure 8 the initial drop from 0 to -15 seconds is actually the first aircraft in the string landing 15 - 20 seconds early and then the rest of the string relaxing toward the planned schedule. The peaks result from particular pairings of arrival routes and aircraft types where certain combinations have a strong bias to being early. This is explained in more detail in ref. [26].
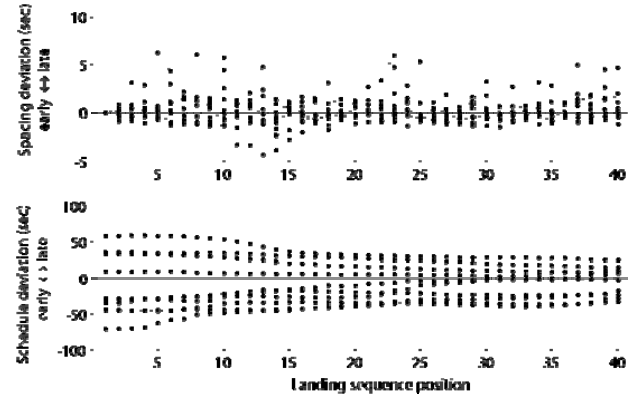

Figure 9: Spacing and schedule deviations for CDA tests.

Figure 9 shows similar results from the recent 2006 study with CDAs. Ten repetitions were performed for this condition and the spacing and schedule deviation for all ten runs are shown. The schedule deviation now includes the initial offset and the recovery towards the initial schedule can be seen.

The human-in-the-loop (HITL) study further supports the claim that spacing operations will be stable. This time with humans interacting in the system we again see no effect based on position in the string. The results are shown in Figure 10.
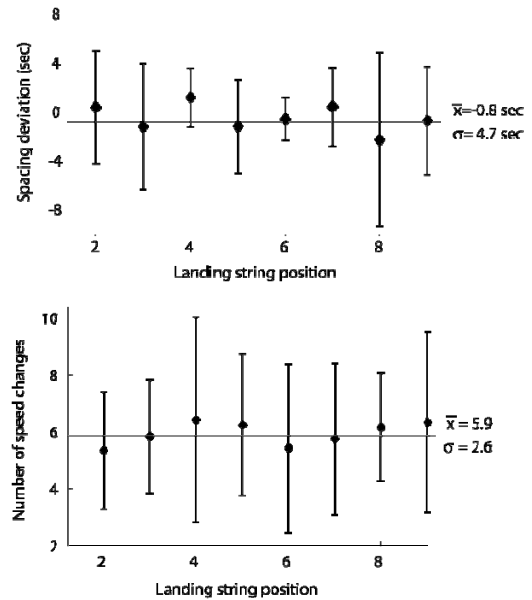

Figure 10: Spacing deviation and speed changes from HITL experiment.

Future of Airborne Precision Spacing

Airborne Precision Spacing has been shown, through simulations of various fidelity and flight testing, to be able to deliver aircraft to the runway threshold with high precision. The standard error is generally less than 1 second with a standard deviation of 2-3 seconds. Unfortunately, two of the higher-fidelity, human-in-the-loop studies, the flight test and the multi-person ATOL test, have had confounding effects attributed to non-spacing aspects of the test. This, however, leaves open the question of the influence of the human in the operation. The full-mission simulation with active line pilots showed that pilots were able to deliver the aircraft with the same precision as the fast-time simulations. Nonetheless, further testing with pilot subjects would help solidify this conclusion.

In both human-in-the-loop and fast-time simulations, there have not been any signs of destabilizing effects over long strings of spacing aircraft. The affects of non-spacing aircraft in the traffic flow have not been adequately tested to date and could cause additional difficulties.

Pilot workload is expected to be minimally impacted by the spacing operations. Subject questionnaires from the Integration Flight Deck (IFD) and ATOL studies show that pilots feel that the overall workload when spacing was not significantly different than the workload without spacing [9][13]. Eye scan data collected during the IFD tests also show minimal change to the pilots scan pattern and dwell time when spacing compared to non-spacing [22].

Recently the APS concept has been extended to work along Continuous Descent Approaches in support of the FAA Merging and Spacing Working Group. This working group is focused on the airborne and ground technologies and procedures to enable environmentally-friendly arrivals while maintaining capacity. Initial testing and implementation is planned by UPS at their Louisville, KY hub. This is seen as a first step toward the NGATS vision for super density operations (SDO) where increased demand must be handled in an environmentally sound manner. Some early results of simulations in support of the Merging and Spacing Working Group have been presented above and more detailed analyses will be presented in the near future [25]. Future studies under more demanding conditions are being planned.

In addition, APS is seen by NASA as one of the key capabilities for an ATM-friendly Flight Management System. This future flight management system would leverage the capabilities of the aircraft to fly precise trajectories and to self-optimize under constraints to become a useful resource for managing the changing demands on the air traffic system. One of the significant capabilities that will need to be added is the ability to modify the planned route in real-time and to continue to space along it. This would apply for the planned route of both the lead aircraft and ownship. Whether the route modification would be done by a centralized system and uplinked to the aircraft or onboard the aircraft and transmitted to other aircraft and the controller, or some combination, is an open research issue that we plan to address in the future.

References

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

[2] Abbott, T.S.,. Moen, G.C, 1981, *Effect of Display Size on Utilization of Traffic Situation Display for Self-Spacing Task*, NASA TP-1885, Washington, DC, NASA .

[3] Abbott, T.S., 1991, *A Compensatory Algorithm for the Slow-Down Effect on Constant-Time-Separation Approaches*, NASA TM-4285, Washington, DC, NASA.

[4] Sorensen, J.A., Hollister, W., Burgess, M., Davis, D., 1991, *Traffic Alert and Collision Avoidance System (TCAS) - Cockpit Display of Traffic Information (CDTI) Investigation*, DOT/FAA/RD-91/8, Washington, DC, FAA.

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

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

[7] Koenke, E., Abramson, P., 2004, *DAG-TM Concept Element 11, Terminal Arrival: Self Spacing for Merging and In-trail Separation*, Advanced Air Transportation Technologies Project, Washington, DC, NASA.

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

[9] Osaguera-Lohr, R.M., Lohr, G.W., Abbott, T.S., Eischeid, T.M., 2002, *Evaluation Of Operational Procedures For Using A Time-Based Airborne Interarrival Spacing Tool,* AIAA-2002-5824, Reston, VA, AIAA.

[10] Lohr, G.W., Osaguera-Lohr, R.M., Abbott, T.S., 2003, *Flight Evaluation of a Time-based Airborne Inter-arrival Spacing Tool*, Paper 56, Proceedings of the 5th USA/Europe ATM Se-minar at Budapest, Hungary, http://atm2003.eurocontrol.fr

[11] Krishnamurthy, K., Bussink, F.J.L., Barmore, B., 2004, *Fast-Time Evaluations of Airborne Merging and Spacing for Terminal Arrivals (AMSTAR)*, Advanced Air Transportation Technologies Project, Washington, DC, NASA

[12] Krishnamurthy, K., Barmore, B., Bussink, F.J.L., Weitz, L., Dahlene, L., 2005, *Fast-Time Evaluations Of Airborne Merging and Spacing In Terminal Arrival Operations*, AIAA-2005-6143, Reston, VA, AIAA.

[13] Barmore, B.., Abbott, T.S., Capron, W.R., 2005, *Evaluation of Airborne Precision spacing in a Human-in-the-Loop Experiment,* AIAA-2005-7402, Reston, VA, AIAA.

[14] Hoffman, E., Ivanescu, D., Shaw, C. Zeghal, K., 2003, *Analysis of Constant Time Delay Airborne Spacing Between Aircraft of Mixed Types in Varying Wind Conditions,* Paper 77, Proceedings of the 5th USA/Europe ATM Seminar at Budapest, Hungary, http://atm2003.eurocontrol.fr

[15] Ivanescu, D., Powell, D., Shaw, C., Hoffman, E., Zeghal, K., 2004, *Effect Of Aircraft Self-Merging In Sequence On An Airborne Collision Avoidance System*, AIAA 2004-4994, Reston, VA, AIAA

[16] Grimaud, I., Hoffman, E., Rognin, L., Zeghal, K., 2005, *Spacing Instructions in Approach: Benefits and Limits From an Air Traffic controller Perspective*, Proceedings of the 6th USA/Europe ATM Seminar at Baltimore, Maryland, USA.

[17] Weitz, L., Hurtado, J. E., Bussink, F.J.L., 2005, *Increasing Runway Capacity for Continuous Descent Approaches Through Airborne Precision Spacing*, AIAA 2005-6142, Reston, VA AIAA.

[18] Barmore, B.E.,. Abbott, T.S, Krishnamurthy, K., 2004, *Airborne-Managed Spacing in Multiple Arrival Streams*, Proceedings of the 24th Congress of the International Council of Aeronautical Sciences, Stockholm, Sweden, ICAS Secretariat.

[19] Baxley, B., Barmore, B. Bone, R., Abbott, T.S., 2006, *Operational Concept for Flight Crews to Participate in Merging and Spacing of Aircraft.* submitted to 2006 AIAA Aviation Technology, Integration and Operations Conference, Wichita, Kansas 25-27 September, 2006.

[20] Lohr, G.W., Oseguera-Lohr, R.M., Abbott, T.S., Capron, W.R., Howell, C.T., 2005, *Airborne Evaluation and Demonstration of a Time-Based Airborne Inter-Arrival Spacing Tool,* NASA/TM-2005-213772, Washington, DC NASA.

[21] Tukey, J. W., 1977, *Explanatory Data Analysis,* Addison-Wesley, Reading, MA, pp. 39-43.

[22] Oseguera-Lohr, R.M., Nadler, E.D., 2004, *Effects of an Approach Spacing Flight Deck Tool on Pilot Eyescan,* NASA/TM-2004-212987, Washington, DC, NASA.

[23] Lohr, G.W., Oseguera-Lohr, R.M., Abbott, T.S., Capron, W.R., 2005, *A Time-Based Airborne Inter-Arrival Spacing Tool: Flight Evaluation Result,* ATC Quarterly, Vol 13 no 2.

[24] Benjamin, S.G., at al., 1999, *Aviation Forecasts From the RUC-2,* 8th Conference on Aviation, Range, and Aerospace Meteorology, Dallas, January 1999.

[25] Barmore, B., Krishnamurthy, K., Capron, W., Baxley, B., Abbott, T.S., 2006, *An Experimental Validation of Merging and Spacing by Flight Crew* submitted to 2006 AIAA Aviation Technology, Integration and Operations Conference, Wichita, Kansas 25-27 September, 2006.

[26] Krishnamurthy, K, Barmore, B., Bussink, F.J.L., 2005, *Airborne Precision Spacing in Merging Terminal Arrival Routes: A Fast-time Simulation Study,* Proceedings of the 6th USA/Europe ATM Seminar at Baltimore, Maryland, USA.