PERFORMANCE OF AIRBORNE PRECISION SPACING UNDER REALISTIC WIND CONDITIONS AND LIMITED SURVEILLANCE RANGE

Frederick Wieland, Michel Santos, William Krueger

Air Traffic Management Research
Intelligent Automation Incorporated
Rockville, MD 20855 USA
{fwieland, msantos, wkrueger}@i-a-i.com

Vincent E. Houston

Crew Systems & Aviation Operations Branch
NASA Langley Research Center
Hampton Roads, VA USA
Vincent.E.Houston@nasa.gov

Abstract— **With the expected worldwide increase of air traffic during the coming decade, both the Federal Aviation Administration's (FAA's) Next Generation Air Transportation System (NextGen), as well as Eurocontrol's Single European Sky ATM Research (SESAR) program have, as part of their plans, air traffic management (ATM) solutions that can increase performance without requiring time-consuming and expensive infrastructure changes. One such solution involves the ability of both controllers and flight crews to deliver aircraft to the runway with greater accuracy than they can today. Previous research has shown that time-based spacing techniques, wherein the controller assigns a time spacing to each pair of arriving aircraft, can achieve this goal by providing greater runway delivery accuracy and producing a concomitant increase in system-wide performance. The research described herein focuses on one specific application of time-based spacing, called Airborne Precision Spacing (APS), which has evolved over the past ten years. This research furthers APS understanding by studying its performance with realistic wind conditions obtained from atmospheric sounding data and with realistic wind forecasts obtained from the Rapid Update Cycle (RUC) short-range weather forecast. In addition, this study investigates APS performance with limited surveillance range, as provided by the Automatic Dependent Surveillance-Broadcast (ADS-B) system, and with an algorithm designed to improve APS performance when ADS-B surveillance data is unavailable. The results presented herein quantify the runway threshold delivery accuracy of APS under these conditions, and also quantify resulting workload metrics such as the number of speed changes required to maintain spacing.**

Keywords-airborne precision spacing; weather-winds; surveillance; ADS-B; TMX; fast-time simulation

I. INTRODUCTION

Of the many improvements envisioned by the FAA's NextGen and Eurocontrol's SESAR program, increasing runway throughput without adding to an airport's infrastructure is a key capacity-enhancing goal. Improvements that fall into this category include high-density Metroplex operations, improved surface management techniques, simultaneous closely-spaced parallel approaches, as well as more precisely delivering aircraft to the runway threshold, and many others. Of these improvements, the research herein focuses on high-precision runway spacing through the application of time-based metering. Time-based metering is included in the FAA's High Density Airport component of its NextGen Solution Sets [1], and is addressed in Eurocontrol's SESAR program management plan, Lines of Change 7 (Queue Management Tools) and 10 (Airport Throughput, Safety, and Environment) [2]. This particular application of time-based metering involves assigning a time interval to each pair of aircraft in an arrival stream, one called the *leading aircraft* and the other called the *trailing aircraft*. The trailing aircraft performs speed changes during its approach in order to achieve its assigned time spacing with respect to its leading aircraft at the runway threshold.

Previous research has shown that time-based spacing has several advantages over current procedures [3], [6]. First, because the trailing aircraft is responsible for throttle control, it can manage its fuel burn more efficiently than could a controller on the ground. Secondly, controller workload can be reduced with time-based spacing. This reduction occurs because there is less controller-pilot communication (no need for the controller to relay speed changes to the pilot). Thirdly, by managing to a time interval instead of a distance, controllers can deliver aircraft more precisely to the runway threshold, thereby increasing runway throughput. A modest increase in runway throughput at a busy airport can result in a significant decrease in delay and concomitant increases in system-wide performance. Fourthly, and related to the third point, in heavy headwinds the distance-based approach reduces runway throughput, while a time-based approach can maintain throughput and thereby enhance runway capacity.

This study builds upon a decade of research in the concept of Airborne Precision Spacing, or APS, whose goal is to improve system-wide performance through application of the time-based spacing technique. In particular, this paper studies the APS concept from the Top of Descent (TOD) to arrival at a single runway where multiple arrival streams merge at multiple waypoints. This study uses realistic wind conditions obtained from atmospheric sounding data, and also considers limited surveillance range. Background research is presented in the next section, followed by the APS concept of operation, a description of the experimental design, and a discussion of the results.

II. Previous Research in Airborne Precision Spacing

Airborne Precision Spacing, or APS, is the National Aeronautics and Space Administration's (NASA's) concept of operations for airborne spacing. It is similar to the FAA's Flight Deck Merging and Spacing (FDMS) concept, but has been developed separately [3]. The name "APS" is an umbrella term that describes several different time-based spacing concepts, each more advanced than the previous. An early APS tool, called Advanced Terminal Area Approach Spacing (ATAAS), involved applying time-based spacing to a single stream of arriving aircraft. After successfully investigating this concept, researchers extended it to multiple arrival streams, resulting in the Airborne Merging and Spacing for Terminal Arrivals (AMSTAR) concept. Recently, the AMSTAR concept was expanded to include continuous descent arrivals (CDAs), resulting in a concept called Airborne Spacing for Terminal Arrivals (ASTAR). Much of this history is summarized in reference [3]. The ASTAR concept is the one used in this study, but a brief review of earlier research from ATAAS and AMSTAR helps explain the rationale and design of the current experiment.

In investigating the single-stream ATAAS concept, human-in-the-loop experiments were conducted in a real time simulation laboratory [4]. The study found that pilots were able to meet a time-based spacing behind a leading aircraft to within one second accuracy when the spacing command was coupled to an autothrottle. This level of accuracy in time is equivalent to an accuracy in distance of 220 feet when flying at 130 knots, a typical approach speed for many aircraft. When the throttle was controlled manually by the pilots, the time accuracy degraded to 4-5 seconds within the required spacing (or a distance of 1100 feet at 130 knots). Pilots reported slightly more head-down time and ocular examination showed a slight shift in instrument scan patterns than when using distance-based spacing. The study also showed that the pilots required 5-7 speed adjustments for each approach.

Encouraged by these findings, ATAAS research was extended to actual flight trials using three research aircraft at Chicago O'Hare (ORD). The first of the three flew an approach as-published, while the second and third aircraft were assigned a time-based spacing of 90 seconds behind their respective leaders. The test was subject to actual wind conditions as well as other variables and consisted of both RNAV and vectored approaches. All tests showed that the second and third aircraft were able to achieve an actual spacing of 0.8 ± 7.7 seconds within the target spacing of 90 seconds [5]. In a subset of those test flights, the pilots encountered actual wind conditions that included a 180-degree reversal of winds during final approach, and yet in those extreme conditions the pilots were still able to maintain the required spacing to within 4 seconds of accuracy [5 p. 7].

With the Flight Deck Merging and Spacing (FDMS) working group, MITRE/CAASD performed a set of HITL laboratory experiments to investigate time-based spacing. They found many benefits of the concept, including a reduction in controller workload, reduced controller-pilot interactions, zero impact on pilot situational awareness, and no impact on overall safety [6].

Recent research has focused on the ASTAR concept, in which multiple arrival streams adhere to a time-based spacing while executing CDAs. The concept (explained in more detail in section III) assigns the time interval and identifier of the leading aircraft just prior to the trailing aircraft's TOD, and when properly executed, all merge points and the final approach is flown without further controller intervention.

In one ASTAR experiment, an 80-second gap was inserted after the 25th arriving aircraft (in a 50-aircraft arrival stream), simulating a lapse in the delivered arrival stream from the enroute airspace. Although the ASTAR concept achieved its overall timing goal in the presence of the gap, the timing errors at the runway threshold were much larger than without the 80-second gap [7]. Another experiment showed that, with an artificially generated wind forecast error of 5-15 knots, the number of ASTAR speed adjustments increased only 3% over the same scenario but with a perfect wind forecast [7].

These results led researchers to study in more detail the impact of wind forecasts on APS performance. Errors in the wind forecast have a larger effect on pre-merge operations than on post-merge operations, because the forecast errors double when aircraft are entering the merge point from opposite directions. For example, a 10-knot headwind error for one aircraft becomes a 10-knot tailwind error for an aircraft in the opposite heading, resulting in a 20-knot wind forecast error when those two aircraft are merged [8]. Even if the wind forecast errors are being updated by aircraft and broadcast, for example, through ADS-B to other aircraft in the vicinity, small errors in an aircraft's computed heading or ground track can lead to noticeably larger errors in its estimation of wind speed and direction [8]. Further research revealed that APS performance is not impacted as much by wind direction errors of up to 20 degrees as it is by wind speed errors of 10 knots or larger [9]. Recent research shows that forecast errors for wind speed lie between 10 and 15 knots, which is within the range of expected degradation of APS performance [9]. Furthermore, fast-time simulation studies show that extreme wind forecast errors of 40 knots (which can occur for two opposite-headed merging aircraft, each of which has a 20-knot error) cause a very serious degradation of APS performance [3].

These and other results lead to several outstanding questions, for which the current study is designed to answer. First, what is the actual impact of *realistic* wind forecast errors on APS performance? Furthermore, given that APS depends upon information broadcast from ADS-B, what is the impact of limited ADS-B range on APS performance?

III. Concept of Operation

In this section we will explain concept of operation used in this study, which is further explored in [3], [7], and [8]. This study is based on the ASTAR concept, consisting of a ground-based scheduling algorithm and avionics-assisted self-spacing on the flight deck. Throughout the arrival procedure, the controller maintains responsibility for safe separation of aircraft at all times; responsibility for safe separation is *not* delegated to the flight deck. The ground-based scheduling algorithm computes the aircraft arrival sequence and then the controller sends a clearance to each aircraft indicating its required time of arrival (RTA) at a coordination point just prior

to the aircraft's TOD, about 150 nm from the airport. Next, the controller issues each flight a second clearance consisting of the identifier of its leading aircraft and the assigned time spacing behind its leader, as well as its arrival procedure identifier. This second clearance becomes active immediately after the aircraft reaches its coordination point. If the aircraft is the first in a chain of flights, and therefore lacks a leading aircraft, then this second clearance consists of its required time of arrival at the runway threshold. After these two clearances are issued, no further clearances are needed and merging at all waypoints becomes automatic.

After receiving the clearances and after meeting the required time of arrival at the coordination point, a trailing aircraft then "listens" for the Automatic Dependent Surveillance—Broadcast (ADS-B) signal of the leading aircraft. The leading aircraft may be directly in front of the trailing aircraft on the same approach, or it may be dozens to hundreds of nautical miles away if it is on a different approach to the airport. The APS concept assumes that the ADS-B signal includes the leading aircraft's basic state (call sign, airspeed, heading, direction) but is further enhanced to include its planned arrival route as well as its final approach speed. The published arrival routes are assumed to include all altitude and speed restrictions as well as lateral path restrictions and transitions from STARS to published approach procedures. These route parameters are critical because, prior to actually receiving the ADS-B signal, the trailing aircraft flies the arrival route as published.

The minimum time-based spacing is determined by using the published wake vortex distance-based spacing for each aircraft type, and applying the final approach speed of the leader to determine the minimum required time based spacing of the trailing aircraft. To this minimum spacing the controller (perhaps aided by a decision support tool) will add a safety buffer to determine the final assigned spacing interval. In this study, a safety buffer of ten seconds is added. The ten second safety buffer incorporates the natural variability in aircraft performance found by the ATAAS and ASTAR research reviewed in section II. In an actual APS implementation, that safety buffer may be larger or smaller depending upon the results of future research as well as the controller's preference.

Avionics in the flight deck computes the speed adjustments necessary to meet this required spacing. The speed adjustment is computed by using the leading aircraft's time-to-go (TTG). The leading aircraft's TTG is computed based upon its broadcast information (current speed, approach path, final approach speed). The controller-assigned spacing interval is then added to the leading aircraft's TTG. The net result is the assigned TTG of the trailing aircraft, which is then compared to its current TTG. If its current TTG is less than its assigned TTG then the aircraft must slow down, else if it is greater it must speed up. The actual speed command is issued as a change to the current speed, i.e. increase speed by ten knots.

To prevent over-controlling the aircraft, two factors are considered before the avionics issues a speed command to the pilots. First, speed commands are generally less aggressive farther from the runway and more aggressive closer to it,

leading to stability in the arrival stream. The aggressiveness factor is controlled by the threshold at which speed changes are issued, which is five knots until final approach, at which point the threshold is lowered to one knot. A five knot threshold means that speed changes are issued only if they are at least five knots in magnitude. A second factor that prevents over-controlling is that the resulting speed must be within 10% of the published speed, and the resulting speed must adhere to any speed restrictions, such as the 250-knot speed limit below 10,000 feet.

There are three off-nominal procedures included in the APS concept. First, if either the leading or trailing aircraft deviate from the air traffic controller's clearance such that the estimated time of arrival at the runway threshold becomes unreliable, then the controller is notified and the flights revert to flying the published speeds. Secondly, if a trailing flight encroaches on the minimum protection interval from the leading flight by twenty seconds or more, then the pilot is alerted and the trailing aircraft flies its slowest safe speed until the minimum protection interval is reestablished. Finally, in the case of a system error, for example, an ADS-B outage, pilots fly the published speed and, if unable, alert the controller and current-day procedures are then followed. In the studies conducted herein, none of these off-nominal procedures are invoked.

IV. EXPERIMENT DESIGN

The research question concerns the performance of APS with actual winds and actual wind forecasts, as well as limited ADS-B range and the impact of an ADS-B signal loss mitigation algorithm (explained later). The hypothesis is that APS performance will degrade as the effective ADS-B range decreases, and its performance will vary as the wind forecast error varies. It is also expected that the ADS-B signal loss mitigation algorithm will enhance the performance of APS when the ADS-B signal range is low. The verification and quantification of these hypotheses is the goal of this experiment.

This experiment involves fifty different aircraft arriving at Dallas Ft. Worth (DFW) airport. The fifty aircraft include six aircraft in the "large" wake vortex category and forty-four in the "heavy" wake vortex category, and consists of a mix of Airbus 300, 310, and 319 aircraft with Boeing 757, 767, and 777 aircraft. There is also one Boeing 727 and one 707 aircraft among the fifty.

Aircraft are generated at a freeze horizon just prior to TOD (about 150 nm from the airport), at a scheduled time that includes a randomized schedule variation of ±40sec from the default start times (uniformly distributed). Traffic from the four different arrival routes merges onto a single runway, runway 18R, at DFW. All but the first aircraft is instructed to execute time-based merging and spacing along the various routes as they approach the single runway. The first aircraft is instructed to fly a nominal flight profile along its particular arrival route. A picture of the four arrival routes to DFW used in this study is shown in Figure 1.

Figure 1. Depiction of the four arrival routes used in this study. All routes are to DFW runway 18R.

The independent variables for this experiment are the actual and forecasted winds which, when combined, lead to a realistic wind prediction error. In addition, the range of the ADS-B signal is varied in discrete quantities: 25 nautical miles (nm), 40 nm, 90 nm, and an unlimited range. Finally, the ASTAR algorithm contains a mitigation feature which attempts to compute the TTG of the leading aircraft before its ADS-B signal is received by the trailing aircraft. This algorithm uses the scheduled time of arrival (STA) of the leading aircraft as well as the current wind forecasts to estimate the leading aircraft's current position, and is denoted the "STA mitigation" algorithm. STA mitigation can either be enabled or disabled during initialization. When disabled, the trailing aircraft flies the approach as published until the leading aircraft's ADS-B signal is acquired. When enabled, the trailing aircraft spaces itself using the STA mitigation algorithm's estimate of the leading aircraft's position until its ADS-B signal is acquired. To eliminate the effect of pair-wise interaction of particular aircraft, the landing order of the fifty aircraft is randomized seven times, producing seven distinct landing sequences. The resulting test matrix is shown in Table I.

The fast-time simulator used in this experiment is Traffic Manager (TMX), first developed by the National Aerospace Laboratory of the Netherlands and subsequently enhanced by both the National Institute of Aerospace and NASA Langley Research Center [7], [11]. TMX is a fast-time low to medium fidelity traffic simulator that can be configured for standalone mode (as used herein) or networked with other traffic simulators. It has a modular structure. Developers can add new modules by identifying the existing modules with which it needs to interact and then studying their interface specification. It contains a six degree-of-freedom aircraft model with auto-flight functions and a pilot model, and can handle up to 1,000 distinct flights at any given simulation time. Aircraft performance information is derived from Eurocontrol's Base of Aircraft Data for over two hundred different aircraft types [12]. Aircraft state in TMX is available for its true state, its perceived state (i.e. after sensor errors are introduced), and its ADS-B state. The latter is the perceived state transmitted at the ADS-B update rate, and includes a lost message algorithm, transponder failure algorithm, and degradation of the ADS-B signal with distance. The ADS-B model is fully parameterized and is configurable by the analyst.

TABLE I.   THE EXPERIMENTAL RUN MATRIX.

Wind-Wind Forecast Error Combinations	ADS-B Range	STA Migration	Landing Sequence
None	25 nm	Enabled	1
January 7, 2009,6PM local	40 nm	Disabled	2
January 11, 2009, 6 PM local	90 nm		3
March 2, 2009, 6 PM local	Unlimited		4
March 6, 2009, 6 PM local			5
May 17, 2009, 7 PM local			6
June 23, 2009, 7 PM local			7
June 25, 2009, 7 PM local			

TMX contains both truth and forecasted wind fields that can vary both horizontally and vertically, although in this study the wind field varied only vertically due to data availability issues discussed later. An ASTAR speed guidance module has been added to TMX, and its speed guidance is used directly by the autothrottle. TMX logs all pertinent variables at one minute simulation time intervals for each active flight in a text file format easily parsed by databases and other standard analysis tools.

A. Selection of the Seven Realistic Wind Days

Because one of study's goals is to confirm the relationship between wind forecast error and APS performance, it is necessary to select appropriate wind data for the experiments. The use of *realistic wind data* derived from atmospheric soundings and *realistic wind forecasts* derived from Rapid Update Cycle (RUC) model predictions set the current experiments apart from previous experiments described earlier. We will briefly discuss the method by which wind days were selected. In this discussion, the term "truth winds" refers to the winds the aircraft actually fly through, i.e. the winds used to compute simulated aircraft trajectories. The term "forecasted winds" refers to the predicted winds used by the ground scheduling system as well as the aircraft's avionics to compute predicted trajectories.

The selection of truth winds used atmospheric wind soundings available from the University of Wyoming [13]. The data used in this experiment contain wind speed and direction observations for a range of altitudes corresponding to a point location in the Dallas-Ft Worth area (station latitude: 32.83 degrees North, station longitude: 97.30 degrees West). The observations are available at two times: 0Z and 12Z (Zulu time). We chose 0Z for this experiment because it better corresponded with operating times at DFW. We considered twenty-eight different weather days distributed in the year 2009 for the weeks of January 7-13, March 1-7, May 15-21, and June 23-29. To down-select the weather days to a more reasonable but analytically interesting subset, a *k-Medoids* clustering algorithm was performed along with a standard silhouette technique to determine the optimal number of clusters [14], [15]. The algorithm helps select a subset of data with maximum variability between the days for the metrics of interest (wind speed and direction) and eliminates data that are potentially redundant (i.e. it chooses only one day when there are multiple comparable days with similar wind speed and direction characteristics).

The *k-Medoids* algorithm was performed for values of k between 2 and 14. At $k = 8$, we found the silhouette value reaches 0.95 (out of a maximum possible 1.0), after which there are diminishing returns with increasing k. Therefore, the clustering of size 8 is a good compromise between the goals of maximizing the silhouette and maximizing the average number of data objects per cluster. Based on this clustering, and also eliminating those clusters that represented a tailwind at the DFW runway, the set of wind days shown in Table II was selected.

B. Wind Forecast Selection

To answer the research questions associated with the current study, it was necessary to select wind forecast data that correspond in time and location to the truth wind data already selected. Truth winds derived from the University of Wyoming sounding data correspond to the lat-long location 32.83 degrees North, 97.30 degrees West; therefore, forecasted winds were chosen from the nearest RUC-20 grid cell: 32.817 degrees North, 97.369 degrees West [16]. RUC wind vectors were rotated and unit-transformed appropriately to be consistent with TMX input formats. Both the truth and forecasted wind data used in these experiments expressed altitude in units of geopotential meters.

The APS experiments performed herein each required about 2.5 hours of simulated time for all fifty aircraft to complete their path from TOD to the runway, and the simulation time was chosen to be centered on the times associated with the truth winds. Furthermore, one-hour RUC forecasts were chosen such that the "valid" times of the one-hour predictions corresponded to the truth wind times. The selection depended on the time of year, as daylight savings needed to be considered.

TABLE II.   SELECTED WIND DAYS AND THEIR CHARACTERISTICS.

Wind-Wind Forecast Error Combinations	Wind Direction			Wind Strength	Wind Inflections
	Headwind	Crosswind	Tailwind		
January 07	Low			High	Minimal
January 11	Low			High	Minimal
March 02		Medium		High	Moderate
March 06	High			Medium	Large
May 17			Medium	Medium	Moderate
June 23		Low		Low	Large
June 25		Medium		Low	Moderate
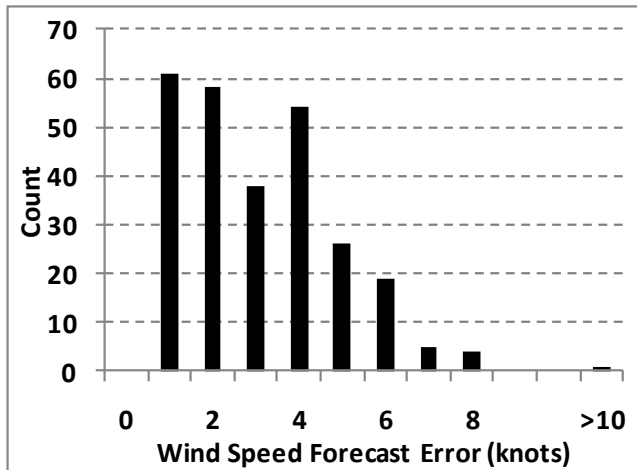
Figure 2. Wind speed forecast error histogram, absolute value of the truth−forecast speed

Figure 4. Truth and forecasted wind speed and direction for January 7, 2009 (pSpeed = forecast speed, pDirection = forecast direction).
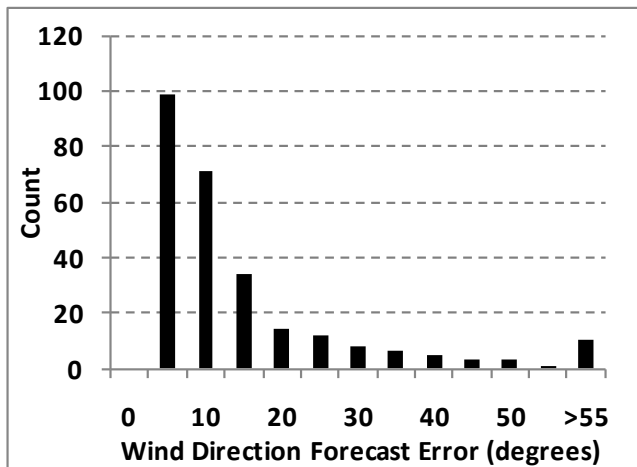

Figure 3. Wind direction forecast error histogram, absolute value of the truth−forecast direction.

The winds used in the experiments do not vary with respect to time or horizontal (lat-lon) location; however, they do vary with respect to altitude. The wind forecast errors for the realistic data are fairly low, the average absolute difference being 2.6 knots. A histogram of the wind speed forecast errors for the seven selected wind days is shown in Figure 2.

The wind direction forecast errors have an average absolute difference between truth and forecast of 14 degrees. As noted in Section II, earlier research has shown that APS can handle wind speed forecast errors up to 10 knots and wind direction forecast errors of up to 20 degrees. Because these realistic wind forecast errors generally fall within these bounds (with a few exceptions), it would be expected that the results shown later would show only minor performance degradation of APS in the presence of these realistic forecast errors. A histogram of the wind direction forecast errors is given in Figure 3.
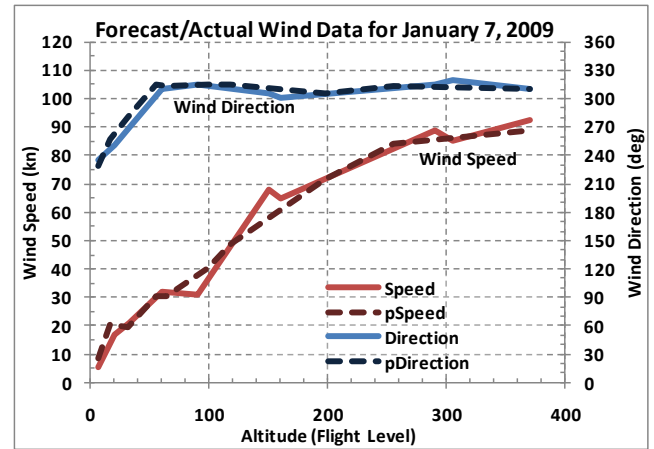
One reason the realistic forecast errors are low is that this experiment utilized wind forecasts an hour before the truth winds were encountered. The one-hour forecast time is realistic because the ground and avionics systems in APS only require weather about an hour ahead of time for estimating flight paths from TOD to the runway. To further illustrate the types of truth and forecasted data used in this experiment, an example of the data for one of the seven selected wind days, January 7, 2009, is shown in Figure 4.

V. RESULTS

In the first set of results we computed the percent of flight time elapsed before the ADS-B signal from the leading aircraft is acquired, for each of the forty nine trailing aircraft (the first aircraft has no leading aircraft, and hence no ADS-B signal to receive). This metric is computed from the TMX output as a function of the ADS-B signal range supplied as the input to the TMX run. The "percent of time elapsed" metric is defined as

$$\% \text{ Time Elapsed} = \frac{(\text{Time Signal Acquired} - \text{TOD Time})}{\text{Flight Time}},$$

where TOD is top of descent (the point at which the aircraft is initialized in these runs), and "flight time" includes only the time from initialization at TOD to exiting the runway. For unlimited ADS-B ranges, the percent of time elapsed should be low, and high when the ADS-B range is limited. The results are shown in Figure 5.

Note that the percent of flight time steadily decreases as the ADS-B range increases, but even at an unlimited range it requires nonzero time to acquire the ADS-B signal. The latency at the unlimited range is due to the fact that the ADS-B signal cannot be acquired until a flight has been assigned a leading aircraft. For some flights, that assignment occurs after some number of minutes has elapsed subsequent to TOD, at which point the leading aircraft's signal is acquired immediately for unlimited ADS-B range.
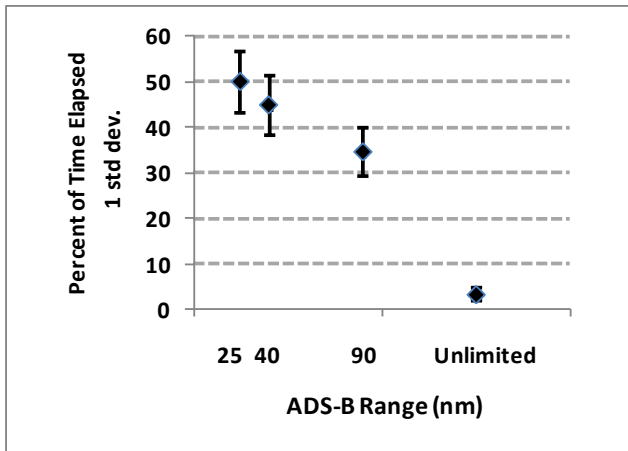
Figure 5. Percent of flight time elapsed before trailing aircraft acquired leading aircraft's ADS-B signal.
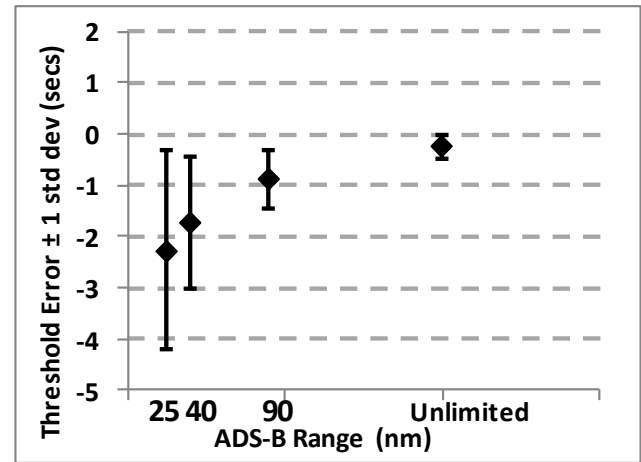

Figure 6. Threshold error metric for zero winds.

A. Threshold Error Metric

The main metric analyzed below is called the "threshold error," defined as the error in spacing that is achieved at final approach just as the leading aircraft lands. Because APS is a time-based spacing algorithm, this metric is particularly sensitive to any problems in APS performance and is a particularly good at determining whether APS has achieved its goal. If this error is negative, then the spacing is closer than assigned by the controller, while a positive error indicates that the spacing is further away than assigned. Although a negative error can suggest safety violations, because there is a ten-second safety margin added by the ground scheduler (as discussed earlier), a negative error must have a magnitude greater than ten before safety issues occur.

The threshold error for those runs with no winds at all is a baseline for which to compare the APS performance with the actual winds. There are fifty-six runs that occur without any winds, during which the wind forecast error is perfect (i.e. forecasted winds are zero). The threshold error metric for the no wind case is shown in Figure 6.

The threshold errors decrease significantly as the ADS-B range increases. The high variance at the low ADS-B range (25 nm) indicates that some trailing aircraft acquired the leading aircraft's signal immediately (most likely because the leading aircraft was directly in front of it on the same flow), while other trailing aircraft had to wait for the leading aircraft's signal (most likely because their leaders were on a different approach). Without the leading aircraft's signal, the trailing aircraft either flies the published approach (mitigation algorithm disabled) or estimates where it is with respect to the leading aircraft (mitigation algorithm enabled). Either case is likely to be inaccurate, even with no winds, although with the mitigation algorithm the inaccuracy should be less. When the ADS-B signal is acquired, the trailing aircraft can more accurately adjust its spacing, subject to the constraints on speed adjustments mentioned earlier. Sometimes the spacing differential cannot be closed in the time remaining in the trailing aircraft's flight, leading to a larger than expected

threshold error. Therefore, the large variance at the low ADS-B signal range is caused by some aircraft acquiring its leading aircraft's state early while others acquire the leading aircraft's state late. For high ADS-B signal ranges, all aircraft acquire the leading aircraft's state early.

The underlying data show that the minimum threshold spacing for all these no-wind runs was −6.6 seconds, occurring for an aircraft pair at an ADS-B range of 25 nm. Because this threshold error is within the 10 second safety tolerance, it poses no concern for the safety of the procedure.

B. Threshold Error with Realistic Winds

Interestingly, the magnitude of the threshold error when realistic winds are introduced to the system is *less* than the magnitude with no winds, although the difference in means is less than the variance, suggesting that this difference is statistically insignificant. The threshold error metric with realistic winds is shown in Figure 7.

The data here reveal that the mean threshold error metric lies within two seconds of the target spacing for all runs, even at limited ADS-B range. Similar to the no-wind case, the variance is larger at lower ADS-B ranges, although there is still
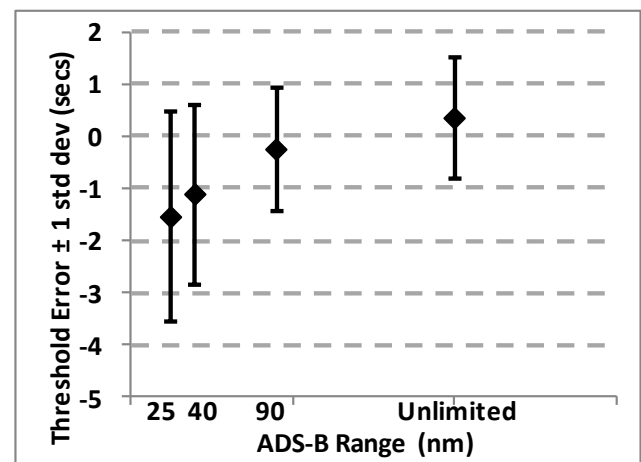

Figure 7. Threshold error metric for realistic winds.

a significant variance at the unlimited ADS-B range. The underlying data show that the minimum threshold error is −5.9 seconds, occurring for an aircraft pair operating at an ADS-B range of 25 nm, and the largest threshold error is 3.1 seconds, occurring for an aircraft pair operating at an unlimited ADS-B range. The data reveal that realistic winds produce threshold errors closer to zero (i.e. better) than the earlier results with no winds. The reason lies in the fact that the flights land into the wind, and the wind tends to naturally slow the aircraft, causing the resulting spacing to increase slightly over a no-wind situation. Despite this explanation, the difference in mean threshold error between the no-wind and the realistic wind runs is in the range of 0.6-0.7 seconds, which is practically insignificant. In both cases (no winds and realistic winds) the minimum errors observed are well within the allotted ten second threshold, and thus safety issues are avoided.

C. Effect of Scheduled Time of Arrival (STA) Mitigation

When the ADS-B range is 25 nm, the data show that, on average, the trailing aircraft will not receive the ADS-B signal until 50% of its flight time has elapsed from TOD to the runway (see Figure 5). When the trailing aircraft does not immediately acquire the leading aircraft's ADS-B signal, the APS concept contains a scheduled time of arrival (STA) mitigation algorithm that uses the leading aircraft's scheduled arrival time to determine its current position. This STA mitigation algorithm has been enabled and disabled in this experiment, and the results are shown in Figure 8.

Figure 8 reveals that the STA mitigation algorithm significantly improves the performance of the system at low ADS-B signal range. At an ADS-B range of 25 nm, the mitigation algorithm improves the average goal time error from about −3 seconds to +0.5 seconds. For an unlimited ADS-B range, not surprisingly, the data show no difference in performance with and without the STA mitigation algorithm.
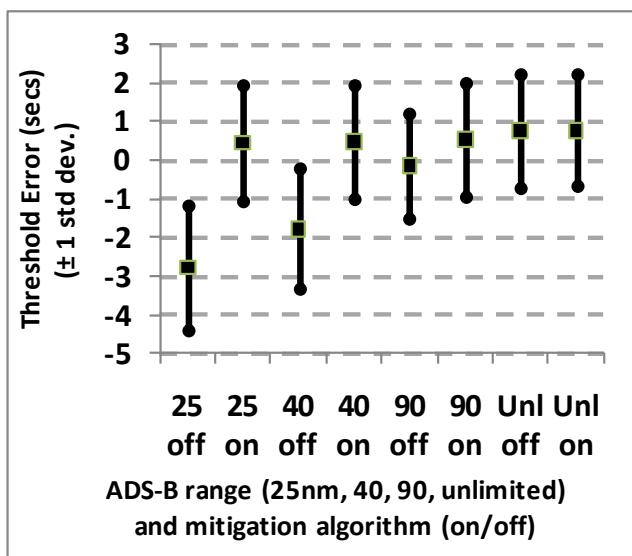

Figure 8. Threshold error with and without the STA mitigation algorithm

D. Number of Speed Changes Issued

Another metric to assess the performance of APS is the number of speed changes that are issued to the aircraft. This metric is related to the overall workload that the algorithm requires, and can also be viewed as the number of communications that a controller avoids when delegating speed control to the flight deck during a time-based spacing procedure. The number of speed changes is ascertained from the TMX data by checking when the target speed is changed by the on-board avionics. The target speed is logged by TMX during its one-minute logging cycle. Using that metric, Figure 9 shows the number of speed changes when there is no wind (and hence a perfect forecast).

The average number of speed changes is between six and nine with no winds. Figure 9 illustrates the number of speed changes as a function of the ADS-B range. The data for ADS-B ranges of 25, 40, and 90 nm have means within 0.8 "speed changes" of each other and variances that are much larger, suggesting that the results are statistically identical. The data at an unlimited ADS-B range, however, are distinctly higher in mean and lower in variance. This trend might be due to the earlier acquisition of the leading aircraft's position when the ADS-B range is unlimited. That earlier acquisition implies that
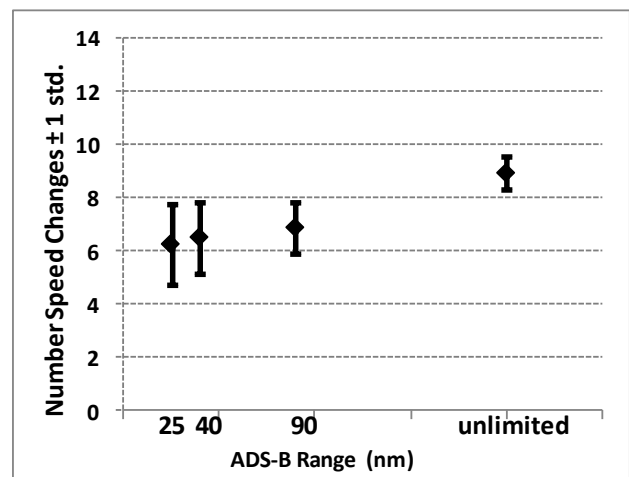

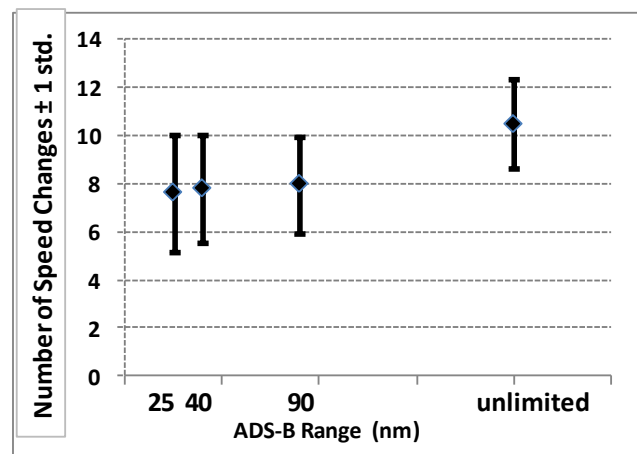Figure 9. Number of speed changes with zero winds.

Figure 10. Number of speed changes with realistic winds

there is more time to make speed adjustments between the acquisition of the signal and final approach. If so, the results suggest that very early acquisition of the leading aircraft's state might cause more workload for the system than if the acquisition is deferred, and therefore another potential study would be a more detailed exploration of the workload issues as a function of ADS-B signal acquisition distance.

The number of speed changes with the realistic winds is shown in Figure 10. With realistic winds, the average number of speed changes increases compared to the no-wind case, to a range between seven and eleven per flight, with the highest number occurring at an unlimited ADS-B range. Thus the effect of realistic winds, in these experiments, increases the number of speed changes per flight by 16%-22% compared to the no-wind case. The maximum number of speed changes observed was 17, from a pair of aircraft with an unlimited ADS-B range.

VI. CONCLUSIONS

The overall conclusion is that the performance of APS is robust with respect to actual wind forecast errors, but degrades as the ADS-B range decreases. The robust performance with respect to wind forecasts is due to the fact that the forecasts are, at most, one hour before the actual winds are encountered. A one-hour forecast is generally accurate, producing speed forecast errors generally less than 10 knots and direction forecast errors generally less than 20 degrees. With forecast errors of this magnitude, the adjustments required by APS avionics when actual winds are encountered are easily made. This conclusion is valid because the APS performance with and without realistic winds are statistically identical.

With respect to safety concerns, the ten-second buffer is sufficient to deal with the uncertainties found in the wind forecast errors and with ADS-B signals ranges as low as 25 nm. However, because the threshold error grows larger as the ADS-B range decreases, the data suggest that ADS-B ranges of 10 nm or less might require an adjustment to the ten-second safety buffer.

This study considered ADS-B ranges down to 25 nautical miles. The ADS-B signal, in the 1090 MHz range, exists in a crowded signal environment that includes transponder returns, radar, and ADS-B signals from other arriving and departing aircraft. In some ADS-B tests in dense Metroplex environments, effective ADS-B ranges below ten nautical miles have been observed. The results here show that at a range of 25 nm, threshold errors as low as −6.6 seconds can occur. At 10 nm, those threshold errors might be even lower. Future studies that consider realistic ADS-B ranges down to 10 nm or less should be conducted to determine the appropriate safety buffer in a realistic signal environment.

Analysis of the number of speed changes shows that the workload of the system is reasonable, as an average of ten speed changes are observed for flights at an unlimited ADS-B range. Among all the runs, a maximum of 17 speed changes are observed. Because the flights require about thirty minutes to fly from top-of-descent to the runway threshold in these experiments, even as many as 17 speed changes implies only one speed adjustment every 105 seconds on average, a manageable workload for the on-board avionics, especially if the speed changes are coupled to the autothrottle (as they are in this experiment).

These results also support that it is beneficial for the trailing aircraft to estimate the leading aircraft's position prior to receiving its ADS-B signal. The results clearly show a reduction in the threshold error when the trailing aircraft computed an estimate of the leading aircraft's position, as opposed to the trailing aircraft merely flying its approach as published until the leading aircraft's state is received. The STA mitigation algorithm is one technique to recover from poor ADS-B signal reception, or perhaps overcome missing information in the ADS-B signal definition.

Although not unique to this study, another conclusion that is worth underscoring is that the APS concept relies upon an enhanced ADS-B standard that includes transmission of an arriving aircraft's approach path as well as its final approach speed in addition to its basic state information. Although such enhancements to the ADS-B message have been considered [17], it has not yet been decided whether future ADS-B standards will include these enhancements.

REFERENCES

[1] Federal Aviation Administration. NextGen Solution Sets. [Online] [Cited: December 20, 2010.] http://www.faa.gov/nextgen/portfolio/sol_sets/.

[2] Eurocontrol. *European Air Traffic Management Master Plan, Edition 1.* s.l. : Eurocontrol, March 30, 2009.

[3] B. Barmore, "Airborne Precision Spacing: A Trajectory-Based Approach to Improve Terminal Area Operations." 25th Digital Avionics Systems Conference, Portland, OR : IEEE, October 2006..

[4] R. M. Oseguera-Lohr, G.W. Lohr, T. S. Abbott, and T. M. Eischeid, "Evaluation of Operational Procedures for Using a Time-Based Airborne Inter-Arrival Spacing Tool" Digital Avionics Systems Conference, Irvine, CA USA 2002.

[5] G. W. Lohr, R. M. Oseguera-Lohr, T. S> Abbott, and W. R. Capron, "Flight Evaluation of a Time-Based Airborne Inter-Arrival Spacing Tool", 5th USA/Europe Air Traffic Management Seminar, Budapest, Hungary, June 2003.

[6] W. J. Penhallegon and R. S. Bone, "Evaluation of a Flight Deck-Based Merging and Spacing Concept on En-Route Air Traffic Control Operations," 7th USA/Europe Air Traffic Management Seminar Barcelona, Spain, July 2007..

[7] V. E. Houston and B. Barmore, "An Exploratory Study of Runway Arrival Procedures: Time-Based Arrival and Self-Spacing", 9th AIAA Air Traffic Integration and Operations Conference, Hilton Head, SC, September 2009.

[8] B. Barmore, T. Abbott, W. R. Capron, and B. T. Baxley, "Simulation Results for Airborne Precision Spacing Along Continuous Descent

Arrivals", 26th International Congress of the Aeronautical Sciences, Anchorage, AK, September 2008.

[9] K. Krishnamurthy, B. Barmore, F. Bussink, L. Weltz, "Fast-Time Evaluations of Airborne Merging and Spacing in Terminal Arrival Operations", AIAA Guidance, Navigation, and Control Conference, San Francisco, CA, August 2005..

[10] K. Krishnamurthy, B. Barmore, and F. Bussink, "Airborne Precision Spacing in Merging Terminal Arrival Routes: A Fast-Time Simulation Study", 6th USA/Europe Air Traffic Management Seminar, Baltimore, MD, June 2005..

[11] B. Heesben, J. Hoekstra, and M.V. Clari, "Traffic Manager Traffic Simulation for Validation of Future ATM Concepts", AIAA Modeling, Simulation, and Technology Conference, Austin, TX : August 2003..

[12] Eurocontrol Experimental Centre**.** User Manual for the Base of Aircraft Data Revision 3.6. Bretigny-sur-Orge, France, July 2004.

[13] University of Wyoming College of Engineering, Department of Atmospheric Sciences. Atmospheric Soundings. [Online] [Cited: December 20, 2010.] http://weather.uwyo.edu/upperair/sounding.html. .

[14] J. Han and M. Kamber, Data Mining: Concepts and Techniques. San Francisco, CA, Morgan Kaufmann Publishers, 2001. pp. 351-353.

[15] P. J. Rousseeuw, "Silhouettes: A Graphical Aid to the Interpretation and Validation of Cluster Analysis", Computational and Applied Mathematics,. 1987, Vol. 20(1), pp. 53-65.

[16] National Oceanic and Atmospheric Administration. NOAA National Operational Model Archive and Distribution System - Data Access. [Online] [Cited: December 20, 2010.] http://nomads.ncdc.noaa.gov/data.php?name=access.

[17] RTCA Special Committee 186, Minimal Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependence Surveillance-Broadcast (ADS-B), Change 1. RTCA, 2006. document number RTCA DO-260.

AUTHOR BIOGRAPHIES

Frederick Wieland holds a Ph.D. in information technology/applied mathematics from George Mason University, Fairfax, VA USA (2000), an M.S. in computer information systems from The Claremont Graduate School, Claremont, CA USA (1988), and a B.S. in astronomy from Caltech, Pasadena, CA USA (1983).

He is currently the Director of Air Traffic Management Research at Intelligent Automation, Inc. in Rockville, MD. Previously he worked as the Chief Technologist at Sensis Corporation Reston Technology Center, and also has held various positions at MITRE/CAASD. He has over twenty seven years' experience in modeling, simulation and analysis, including seventeen specifically in aviation analysis and is the author or co-author of over sixty different papers and reports

Dr. Wieland is a member of AIAA, AOPA, and other professional societies. He is also an adjunct faculty member in George Mason University's System Engineering and Operations Research department.

Michel Santos earned a BSc in mechanical engineering from Cornell University, Ithaca, NY, USA in 1996; an MEng in aerospace engineering from Cornell University, Ithaca, NY, USA in 1999; and, a PhD in aerospace engineering from the University of Maryland, College Park, MD, USA in 2007.

Since 2007, he has been a Research Scientist at Intelligent Automation, Inc in Rockville, MD, USA. In 2005, he was an Aerospace Engineer at the Air Force Research Laboratory's Space Vehicles Directorate. His prior research included the maneuvering of satellite constellations in order to improve coverage of selected targets on the Earth. He currently researches various NextGen concepts including airborne merging and spacing.

Mr. Santos is also an officer of the AIAA National Capital Section council.

William Krueger received his B.S. with majors in both computer science and mathematics from University of Maryland, Baltimore County (UMBC), Baltimore, MD USA in 2002 and has completed the coursework for the Ph.D. degree in computer science from the same institution.

He has been a Research Engineer at Intelligent Automation, Inc., in Rockville, MD USA since 2005. He previously held professional internships with Northrup Grumman Corporation, Eagan McAllister Associates Incorporated, and Juxtopia as well as graduate research assistant positions at UMBC.

Vincent E. Houston received his B.S. in Computer Engineering from Old Dominion University, in Norfolk, VA; with a minor in Modeling and Simulation in 2004 and is completing his graduate studies in Modeling and Simulation from the same university.

He has been a research engineer with NASA since 2005; prior to that he was an implementation Engineer with NASA developing new software and hardware designs for NASA Langley's Aries B757 aircraft.

Mr. Houston served 8 years in the United States Navy, during which time he was involved in Operation Desert Shield/Desert Storm.