Fast-Time Evaluations of Airborne Merging and Spacing in Terminal Arrival Operations

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NASA researchers are developing new airborne technologies and procedures to increase runway throughput at capacity-constrained airports by improving the precision of inter-arrival spacing at the runway threshold. In this new operational concept, pilots of equipped aircraft are cleared to adjust aircraft speed to achieve a designated spacing interval at the runway threshold, relative to a designated lead aircraft. A new airborne toolset, prototypes of which are being developed at the NASA Langley Research Center, assists pilots in achieving this objective. The current prototype allows precision spacing operations to commence even when the aircraft and its lead are not yet in-trail, but are on merging arrival routes to the runway. A series of fast-time evaluations of the new toolset were conducted at the Langley Research Center during the summer of 2004. The study assessed toolset performance in a mixed fleet of aircraft on three merging arrival streams under a range of operating conditions. The results of the study indicate that the prototype possesses a high degree of robustness to moderate variations in operating conditions.

I.   Introduction

Following a system-wide capacity analysis, the FAA projects[1] that demand at the nation's major airports may exceed capacity for several years to come. According to their forecasts, in 2020 more hub airports could experience capacity shortfalls than today, even if currently planned capacity enhancements become operational. As the airlines adapt to shifting market demand and modify their networks, and new business models (on-demand services and fractional ownership, for example) begin to take root, the need for additional capacity may increasingly be felt at non-hub airports as well[1] – a trend that is already becoming evident[2]. Reflecting these factors, the Next Generation Air Transportation System plan[3] states (p. 4) "The uncertainties in the form of future demand call for a highly flexible solution to avoid over-building with the wrong infrastructure or under-building for the pace of expansion".

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This flexibility may be provided in part by new technology-enabled modes of operation that increase the efficiency of arrival operations without large-scale ground infrastructure improvements. At airports operating close to their capacity limits, even a small increase in runway throughput could result in a large reduction in arrival delays[4, 5], and reducing the variability of inter-arrival spacing at the runway threshold could provide this increase in runway throughput[5, 6]. Operational concepts that seek to achieve this goal without negative impacts on controller workload or situation awareness are being investigated by research organizations in the US and in Europe. Several years of NASA research[5-9] have established the feasibility of achieving precision spacing from the cockpit given traffic state data at adequate update rates. Researchers working on NASA's Advanced Air Transportation Technologies (AATT) project have developed a detailed concept of operations for airborne-managed spacing[10] that exploits the emergence of Automatic Dependent Surveillance – Broadcast (ADS-B). The concept of operations is referred to as Airborne Precision Spacing (APS), and NASA Langley Research Center has been developing prototypes of the onboard automation that enables APS.

An early version of the APS toolset[11] that enabled airborne-managed spacing in a single stream of aircraft was successfully tested in simulation[12, 13] and in flight evaluations at Chicago O'Hare airport[14]. The performance of this toolset compares favorably with those investigated by other researchers studying precision spacing operations[12, 15, 16]. The prototype APS system has subsequently been extended to permit time-based spacing across multiple streams of traffic headed to the same runway. The extended toolset and associated operations are referred to as Airborne Merging and Spacing for Terminal Arrivals (AMSTAR). During AMSTAR operations[17], equipped aircraft enter the Terminal Radar Approach Control (TRACON) airspace at a pre-determined time, and follow a standardized arrival route (STAR) to the runway that contains lateral and vertical constraints as well as a nominal speed profile. The entry time may be issued to the aircraft while it is en route, in the form of a required time of arrival (RTA) at the entry fix. Soon after TRACON entry, Air Traffic Control (ATC) issues these arriving aircraft a precision spacing clearance, consisting of the callsign of the "lead aircraft" (which may be on a different arrival route) and the time-based relative spacing to be achieved at the runway threshold. The pilot can enter this data into the AMSTAR avionics via the control display unit (CDU). Using ADS-B data from the lead aircraft, AMSTAR provides the pilot with speed guidance cues, which could be implemented manually or directly through the auto-throttles. By following the AMSTAR speed guidance, the aircraft crosses the runway threshold at the assigned spacing interval relative to the lead aircraft. The AMSTAR speed guidance logic incorporates protection from violating pre-defined minimum separation requirements. The lead aircraft needs only be equipped with an ADS-B out transmitter.

As part of ongoing APS research at NASA Langley, a series of fast-time simulations were conducted to assess AMSTAR performance under a representative range of near-nominal operating conditions. In the next section, we describe the experiment design and the simulation system used to conduct the study. A sample dataset from the baseline condition is then analyzed, and results for different aspects of the study are then summarized. The analysis of these data highlighted some features of the AMSTAR implementation within the simulation that could be enhanced, and representative results from the enhanced simulation are presented. The paper concludes with a summary of the findings and recommendations for follow-on work.

II.   Fast-time evaluations

A. Experiment design

The fast-time simulations focused on the effect of five specific operational variables on APS performance, namely: ADS-B range; TRACON entry-time inaccuracies; wind prediction errors; aircraft type diversity; and merge frequency. The airspace modeled for the study was the Dallas Fort-Worth (DFW) TRACON, a symmetric four-cornerpost airspace well suited to parametric studies of environmental and operational effects. Three standardized arrival routes were designed based on existing STARs for use in APS operations (Fig. 1).
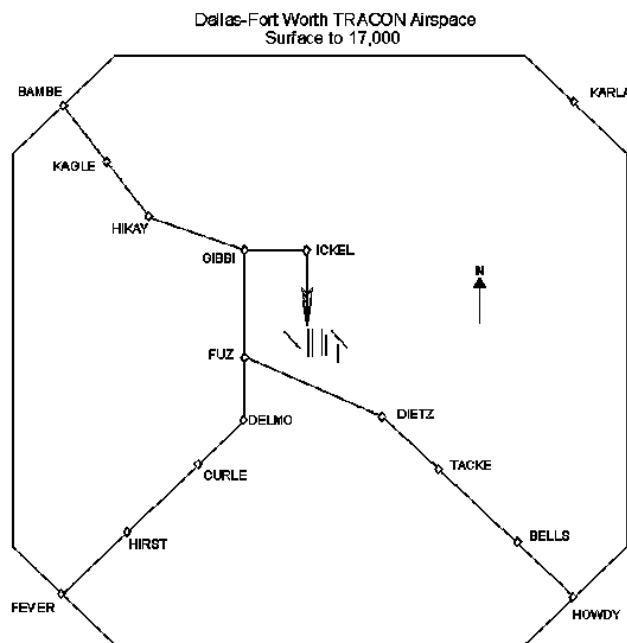

Figure 1. Experiment airspace and arrival routes.

The range of values considered for each of these five variables are listed in Table 1, with the nominal conditions indicated in *italics*. The nominal truth wind-field ranged from 10 knots/155° at Sea Level to 40 knots/170° at 15000 feet. Test conditions were defined by maintaining nominal values for all parameters and varying only the independent variable of interest. When evaluating the effects of wind-prediction errors, an extra truth wind-field condition was also tested (10 knots/110° at Sea Level to 40 knots/125° at 15000 feet), resulting in a test matrix containing 14 unique test conditions. The arrival time errors were randomly selected from a normal distribution, and each test condition was repeated 40 times in order to adequately sample the normal distribution. Each such data collection run corresponded to a unique "scenario" in the simulation. Each scenario featured a sequence of 100 AMSTAR-equipped aircraft entering the TRACON through the three meter-fixes, and following the pre-defined arrival routes to runway 18R at DFW. The long arrival streams were modeled to detect any undesirable behaviors that could arise from the use of AMSTAR in extended operations.

Table 1: Nominal and test values of independent variables

Independent Variable	Test Values
ADS-B range	*90 NM* 30 NM
RTA error	Normal distribution, bounded at *±15 seconds* ±60 seconds
Wind prediction errors	No error Mean direction error of 5° *Mean direction error of 20°* Mean magnitude error of -10 knots Mean magnitude error of +40 knots
Aircraft types	*Diverse mix of types* Single aircraft type
Merge complexity	*1 arrival / merge* 5 arrivals / merge

B. Simulation system

The study was performed on simulation software called the Traffic Manager (TMX), which was developed by the National Aerospace Laboratory (NLR) of the Netherlands in cooperation with NASA. TMX[18] is a multi-aircraft desktop simulation that includes medium-fidelity aircraft models, airspace models and navigation databases, the ability to model truth and predicted wind-fields, and the ability to execute, in fast-time, scripted scenarios with specific aircraft creation times and flight routes. TMX was enhanced for this study[19] to incorporate AMSTAR software, improve waypoint constraint adherence, refine aircraft models, augment the ADS-B range model, and increase the scope of data recording.

A custom-designed scenario generator (SG) was developed to create the large number of TMX-formatted scenarios required for this study. For each test condition, the SG first creates a landing schedule by randomly assigning an aircraft type to each arrival and determining the spacing required between successive aircraft given the type sequence. The spacing interval depends upon the wake-turbulence category of the aircraft and that of its lead, and is not constant when a mix of aircraft types is being simulated. For this study, the time-based spacing required between arrivals was calculated by converting current-day distance-based wake-vortex minima into time-based minima using representative final approach speeds for each category (Table 2). Once the landing schedule is determined, the SG back-calculates the appropriate

Table 2: Time-based Separation Minima (in seconds)

		Category of Trailing Aircraft			
		Small	Large	757	Heavy
Category of Leading Aircraft	Small	100	90	80	90
	Large	130	90	80	90
	757	170	120	100	110
	Heavy	200	150	100	110

initialization time for each aircraft by computing the TRACON transit time using the predicted winds and adding a randomly selected RTA error. By repeating the above process with repeated random selections of RTA error, the SG creates 40 scenario files per test condition.

III. Results and Discussion

Analysis of the data focused primarily on the precision with which the assigned spacing was achieved at the runway threshold. The primary metric was the pair-wise spacing error (difference between actual and assigned spacing). The spacing error data for different test conditions were compared both qualitatively and through statistical analysis to determine which test conditions caused noticeable differences in the spacing errors. Results from the analysis of a representative set of conditions are presented below.

A. Nominal Operations

To introduce the discussion, a sample scenario for the nominal test condition is first examined. The distribution of RTA errors with which aircraft were initialized at the three entry fixes is presented in Fig. 2. Soon after TRACON entry, each aircraft was assigned its lead aircraft and the required spacing interval. AMSTAR on-board each aircraft then provided speed guidance to achieve the assigned spacing at the threshold. The sample scenario included wind direction prediction errors that averaged 20 degrees. Upon scenario completion, the spacing error for each aircraft was computed as the difference between the actual spacing interval (the time interval between threshold crossings for each arrival and its lead aircraft) and the spacing interval assigned during initialization.
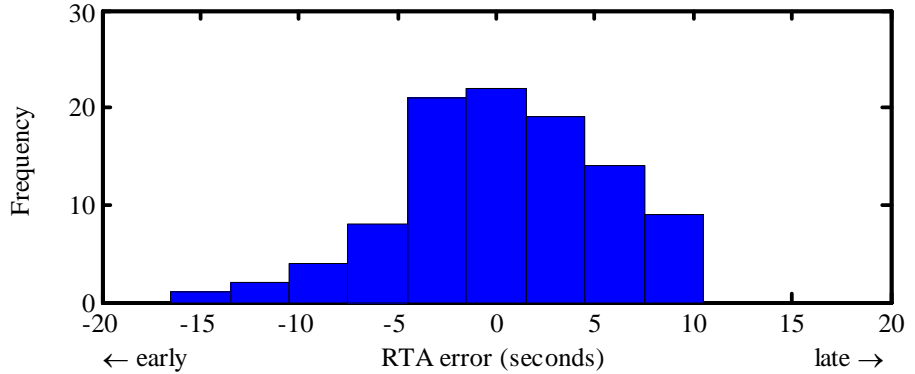

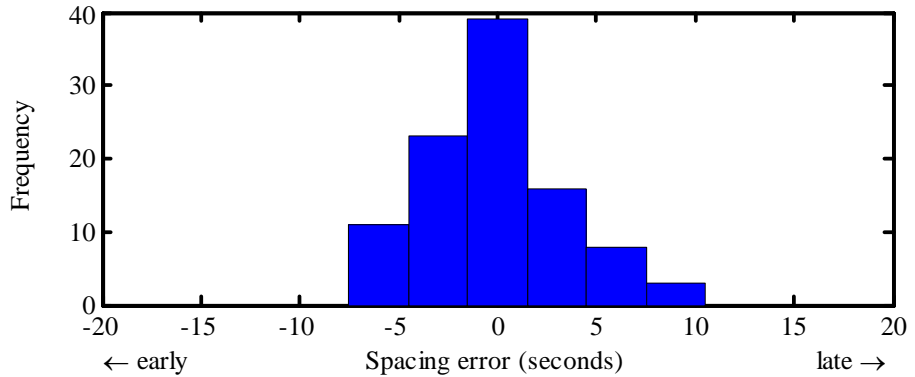**Figure 2. RTA error distribution in a sample scenario**

Figure 3 presents the resulting spacing errors, where a positive error implies that the aircraft was spaced further from its lead than required (that is, it arrived late). It can be seen that aircraft in this scenario achieved their assigned spacing intervals to well within 10 seconds.

These inter-arrival spacing errors accumulate with successive arrivals, and the cumulative spacing error determines how well the planned landing schedule was adhered to by the use of APS opera-
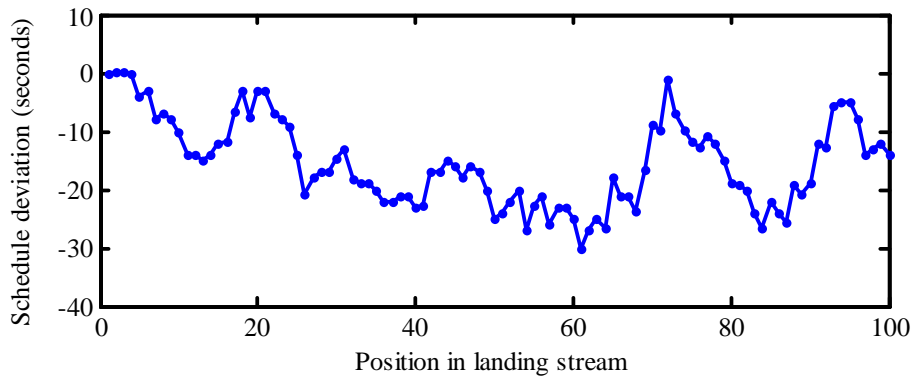

Figure 3. Spacing error data for a sample scenario

Figure 4. Cumulative spacing errors for sample scenario

tions. Figure 4 presents the cumulative error (i.e., the schedule deviation) as a function of position in the landing sequence. A schedule deviation that grows without bounds would indicate instability in the arrival stream; however, these data indicate no such trend. The maximum magnitude of the schedule deviation is 30 seconds. Considering

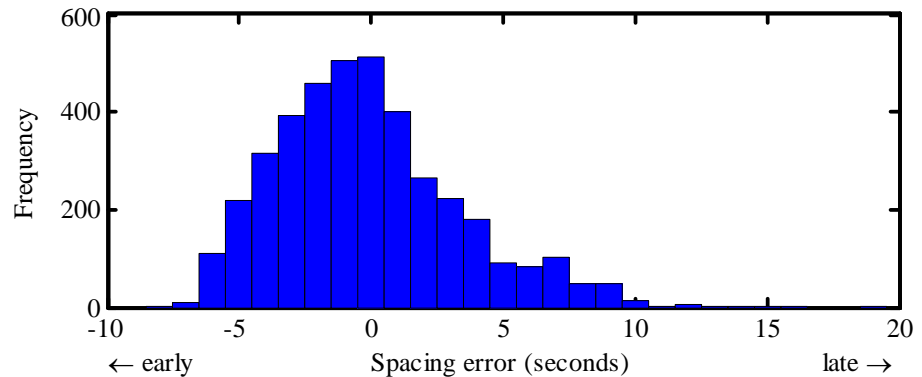American Institute of Aeronautics and Astronautics

that the time elapsed in the course of a hundred arrivals is more than 3 hours, overall schedule deviation appears insignificant in this scenario.

As indicated earlier, each test condition was repeated 40 times with a different set of RTA errors randomly chosen from a normal distribution. The spacing error data from these 40 data runs were analyzed to determine the aggregate behavior of AMSTAR operations under the nominal test condition. The average spacing errors were within ± 10 seconds, as was the case with the sample scenario. The distribution of the spacing error data (presented in Fig. 5) suggests that these data loosely approximate a zero-mean normal distribution, but with an extended tail on the positive side.
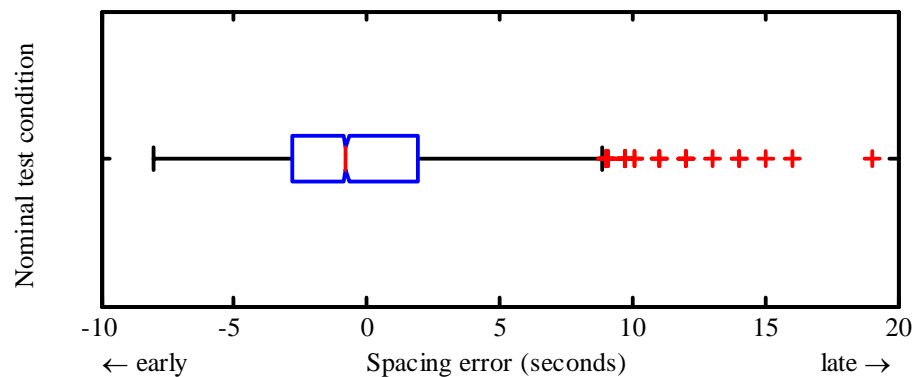
Further insight into these characteristics can be obtained from a box-plot[21] of these data, presented in Fig. 6. The median spacing error is marked by the vertical red line in Fig.6 and has a value of –0.8 seconds for this test condition. Half the data samples are contained within an interval extending from –3 to +2 seconds (the inter-quartile range, indicated by the blue box in the figure). The bulk of the remaining data lies within the range of values spanned by the dashed-black "whiskers" extending to –8 seconds on the negative side and +9 seconds on the positive side. Data points that are more than 1.5 times the inter-quartile range away from the blue box are considered statistical outliers. There are no outliers among the negative spacing error data in this case, but a few of the data samples on the positive axis (indicated by the red symbols in excess of 9 seconds in Fig. 6) do meet the criterion to be labeled as outliers.

Figure 5. Spacing error distribution for the normal test condition

Even though these outliers are only a small portion of the data set of 3960 data points, they still contribute to lost arrival throughput, and understanding their causes may help in devising methods to prevent a loss of throughput. Further analysis of these data points indicates that some of these outliers are the result of dissimilar final approach speeds within an aircraft pair. When aircraft with lower final approach speeds follow aircraft with higher final approach speeds, the minimum spacing is achieved near the Final Approach Fix, following which point the lead speeds away from the follower. This results in larger than desired spacing at the threshold[#]. Other causes for larger-than-desired spacing errors include aircraft speed-change limitations (inability to speed up sufficiently to close a gap), and arrival route limitations (such as the BAMBE arrival route, which is shorter and steeper than the other two routes).

Figure 6. Box-plot of spacing error data for the nominal test condition

The spacing error data also indicate that several of the arriving aircraft crossed the threshold closer to their lead than assigned (negative values for spacing errors). Significant negative spacing errors are generally unacceptable, since they imply that aircraft were closing in on the wake-turbulence minima. In such situations, the follower aircraft would typically be taken out of the landing stream and re-sequenced in the interests of safety, but creating extra workload and unpredictability in arrival operations. These undesirable outcomes could be pre-empted in regular operations by including a buffer in the assigned spacing intervals. The magnitude of this additional buffer could be

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[#] Subsequent analysis of the final approach speed effects on spacing errors resulted in a change to the AMSTAR implementation that improved spacing performance significantly, as described later in this paper.

chosen so that the number of these ATC interventions does not exceed a desired rate. Following the methodology in Credeur[4], the additional spacing buffer required to reduce the minimum spacing violation rate to 5% can be estimated from the mean value and standard deviation of the spacing error distribution. For these spacing error data, the mean value is –0.131 seconds, and the standard deviation is 3.44 seconds. Therefore, an additional spacing buffer of at least 5.81 seconds would be required to lower the number of spacing minima violations to 5% of the total airplane count. However, this approach works best for a normal distribution of spacing errors. If the spacing error distribution deviates from a normal distribution (as in this case), this estimation technique may provide misleading values of the spacing buffer.

Given the exploratory nature of the current study and the limited fidelity of the simulation, we use a simpler approach to compare the different test conditions in terms of the spacing buffer requirement – we use the time interval that would eliminate minimum separation violations from the data set. With this approach, the nominal test condition would require a buffer of about 8 seconds. To put these required buffers into perspective[**], experimental data from observations of landing rates at DFW suggest that a spacing buffer of the order of 12 seconds is applied by experienced air traffic controllers during rush periods in current operations[5].
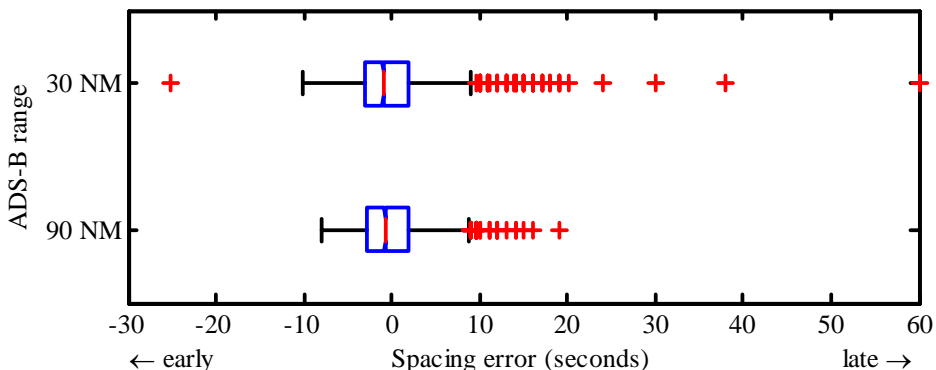
The discussions that follow compare the results of the different test conditions investigated in the batch study with those from the nominal test condition. We examine the spacing error distributions and the spacing buffers that would be required to avoid minimum spacing violations, and point out data trends that warrant further investigation. The box-plot format is used for these comparisons, since it provides greater insights into comparative behavior of the data than does a traditional histogram.

B. ADS-B range effects

The distance at which ADS-B signals can be received and interpreted is a function of several factors, including the power levels of transmitter and receiver, and the number of transmitters proximate to the receiver. A crowded TRACON airspace may be a high interference region, reducing the effective range of ADS-B reception from its nominal value of 90 NM[20], which is comparable in magnitude to the size of the DFW TRACON. Since AMSTAR operations rely on the timely reception of ADS-B data from the lead aircraft, APS performance may suffer if aircraft have to wait for active spacing guidance until relatively late in the arrival route.

To ascertain the effect of reduced ADS-B range on the precision of APS operations, data for the nominal condition was compared with that for nominal test conditions but with the ADS-B maximum range reduced from 90 to 30 NM (Fig.

Figure 7. Effect of reduced ADS-B range on spacing error distributions

7). Even with this drastic reduction in ADS-B range, it can be seen that the bulk of the data (blue boxes and whiskers in Fig.7) exhibit similar characteristics under both test conditions. However, there are several more outliers with the reduced ADS-B range, the extremes being one aircraft that was 25 seconds closer than it should have been to its lead aircraft, and one spaced 60 seconds in excess of its required interval. Closer examination of the data reveals that both these aircraft were "small" jets spacing behind "small" jets.

In actual operations, aircraft experiencing the extreme negative spacing error would have been pulled out of the stream and re-sequenced. Ignoring the one outlier on the negative side on this basis, the data suggest that the spacing buffer required to achieve at least minimum separation in the remaining airplanes is about 10 seconds. On the other side of the scale, the airplanes that experience substantially high spacing errors contribute to a significant loss of throughput for the runway. Since these cases are unique to the reduced ADS-B range test condition, the cause of this behavior is interpreted to be the limited time available for active spacing. This suggests that operational procedures

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[**] Direct comparison of this observed spacing buffer with the present results is not possible since several operational variables were not adequately addressed in the current study, and no effort was made to model the environmental conditions or aircraft type mix of the referenced study.

may need to be designed that limit the extent to which aircraft may wait for the lead aircraft ADS-B data to be received. Such procedures would permit near-nominal performance to be attained for the majority of arrivals.

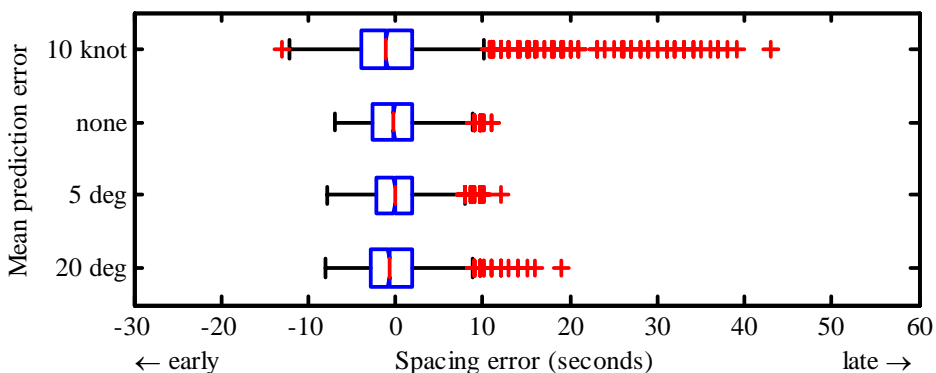### C. Wind Prediction Error Effects

A given wind-field may have different effects on AMSTAR performance for aircraft flying along different arrival routes. For example, winds from the south would consistently be experienced as headwinds for aircraft arriving from BAMBE, but as tailwinds for a portion of the arrival routes from HOWDY and FEVER (see Fig. 1). Therefore, an aircraft from BAMBE may be limited in its capability to close a gap in spacing relative to aircraft from either of the other fixes, and this effect could be compounded by wind prediction accuracy. To investigate these effects, data obtained with the nominal truth wind condition (sea-level winds are 10 knots from 155 degrees) were compared with spacing error data for three different kinds of wind prediction errors. These three conditions were: a mean 5-degree error in predicting wind direction; a mean 10-knot error in predicting wind magnitude; and no wind prediction errors at all. The nominal case included a mean 20-degree error in predicting wind direction. The resulting data are compared in Fig. 8.

These data suggest that an error in predicting wind magnitudes has more effect on the spacing error distribution than errors in predicting wind direction. These effects are noticed both in the main body of the data (increased extent of the box and whiskers) as well as in the number and extent of outliers. If the solitary outlier on the negative side for the magnitude prediction error condition is ignored as before, the spacing buffer required to ensure no

Figure 8. Effect of wind prediction errors under the nominal test condition

separation violations with this error in predicting wind magnitude is of the order of 12 seconds. Even then, significant throughput loss is suggested by the wide-ranging outliers, with some airplanes experiencing as much as 40 seconds of excessive spacing.
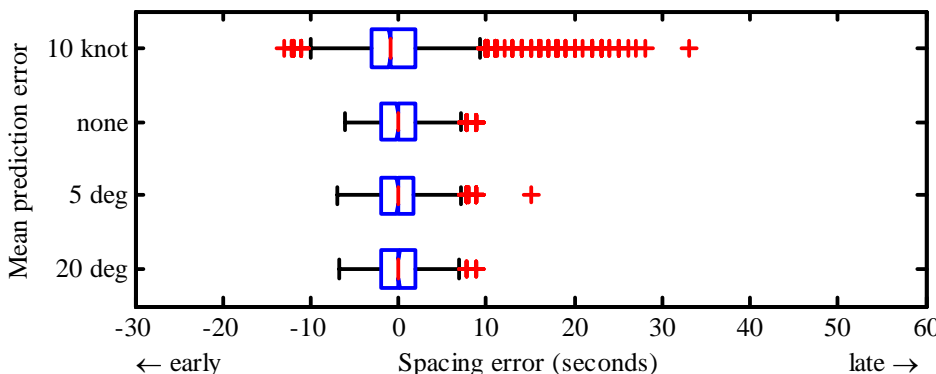
On the other hand, if wind magnitudes are accurately predicted, errors in predicting wind direction alone have comparatively minor influence on the spacing error distribution. As the prediction error decreases, the spacing buffer goes from about 8 seconds for the nominal (20 degree prediction error) case to about 7 seconds for the no error case. The number and extent of the outliers on the positive side also reduces as the wind prediction error is reduced.

Since aircraft on the three arrival routes experience different headwind components for any given wind-field, spacing error data were also compared for a different truth wind-field (the 70-degree crosswind condition, where sea-level winds are 10 knots from 110 degrees) with the same prediction error cases (see Fig. 9). It is seen that this

Figure 9. Effect of wind prediction errors under the 70-degree crosswind condition

wind condition results in similar spacing error distributions than the nominal condition, and that the influences of the different kinds of prediction errors are similar to those noted with the nominal test condition.

Recent research[22] suggests that errors in predicting wind magnitudes at TRACON altitude ranges may be about 10 to 15 knots, although new technologies may further improve these predictions. The results presented in Fig. 8 and 9 indicate that the performance of APS operations may indeed suffer – perhaps significantly – under such conditions. To overcome this sensitivity and optimize the landing rate, the AMSTAR toolset could be enhanced to

estimate current wind magnitudes from the data broadcast by proximate traffic, rather than relying solely on ground-uplinked wind predictions. The effectiveness of such a modification will be the subject of future research.

D. Arrival time inaccuracies

In the APS concept, aircraft are required to enter the TRACON at a specific time, pre-calculated by a ground-based scheduler. However, some error is inevitable in meeting this time in the presence of real-world environmental and operational conditions. Therefore, it is of interest to determine whether precision spacing at the runway is significantly impacted by the magnitude of arrival time errors at the TRACON boundary.

Figure 10 presents a comparison of the spacing error data of the nominal condition with those generated with RTA errors expanded to lie within ± 60 seconds. These data indicate that the majority of arrivals are not adversely affected by the greater inaccuracy in meeting RTAs, and that poor metering performance at the TRACON
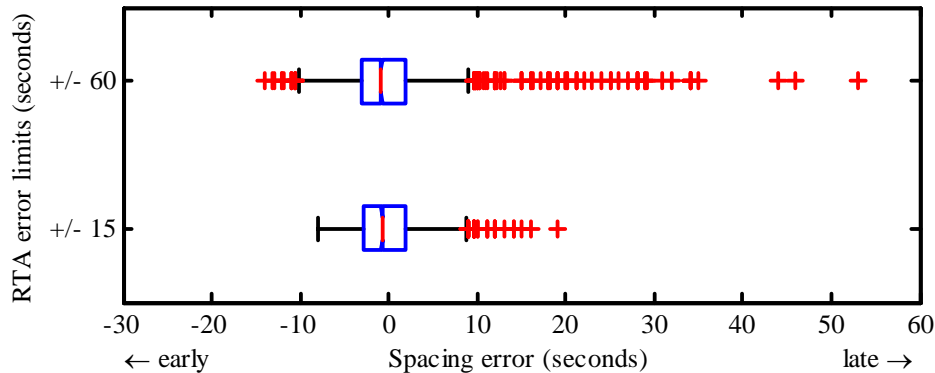

Figure 10. Effect of arrival time inaccuracy limits on spacing errors

boundary may lead to a spacing buffer requirement of about 12 seconds. However, several aircraft experience unacceptably high spacing errors, unlike under the nominal test condition. It was found that the positive spacing error outliers are often associated with "small" aircraft following other "small" aircraft, while the negative spacing error outliers are largely associated with "large" aircraft following "heavy" aircraft. It is not yet clear whether this behavior was due to the performance characteristics of the different types or the different spacing requirements for these combinations, and further analysis is required to understand and remedy these trends.

E. Aircraft type mix

AMSTAR operations require aircraft to follow a pre-defined arrival route to the runway. As in current-day operations, these routes would be defined in terms of nominal speed profiles, lateral paths and vertical constraints that suit an entire class of aircraft, resulting in separate routes for jets and turboprops. However, aircraft in an all-jet arrival stream would exhibit differences in the actual descent profiles and constraint-meeting behavior, depending on the type of aircraft. These variations from a nominal profile may give rise to undesirable behaviors in the arrival stream. The aircraft type also effects the wake separation requirements and the final approach speeds, both of which may have performance effects on the spacing precision and stream stability.
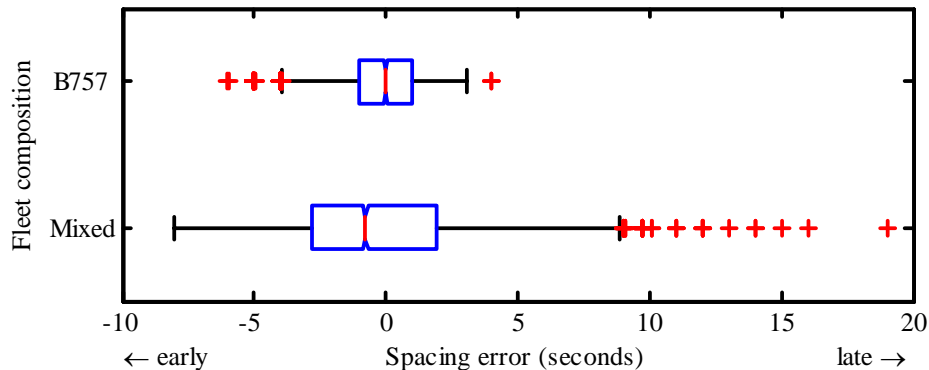

Figure 11. Effect of aircraft type variations on spacing errors
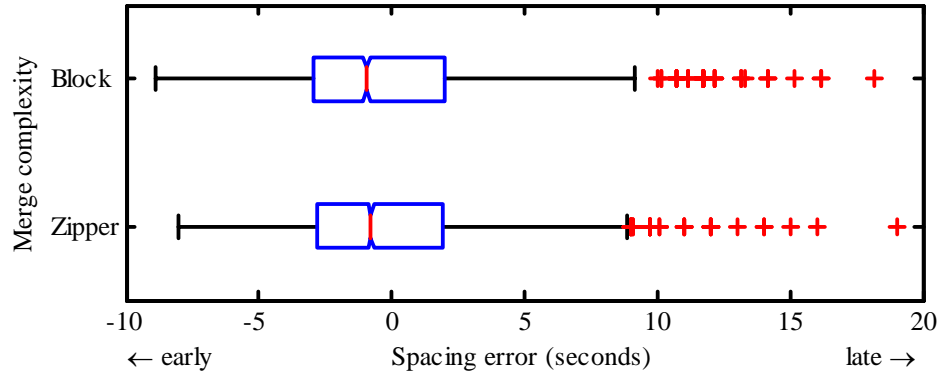
Figure 11 compares the spacing errors obtained with the nominal aircraft type mix (approximately equal numbers of Boeing 757s and small, large and heavy category aircraft types) with those obtained with a completely homogenous stream (in which all aircraft were 757s). Data for the homogenous stream exhibits a significantly narrower range in spacing errors. Perhaps because all arrivals had the same final approach speeds, these data also exhibit no tail of positive spacing errors. The significant reduction in spacing error range compared to the nominal test condition, and the consequent reduction in the required spacing buffers (6 seconds in place of 8) motivate further investigation of the intra-stream effects of aircraft type diversity.

F. Merge complexity

While the AMSTAR tool is designed to enable safe and precise merges of arrival streams, it is not intuitively evident what frequency of merges is preferable in nominal operations. Operational and environmental conditions may dictate that different arrival routes have different traffic densities, and frequent merges may adversely affect the precision spacing performance of the landing stream.

Under nominal conditions for this study, every arriving aircraft encountered exactly one merge situation on its route to the runway. Therefore, successive aircraft across the threshold came into the TRACON from different entry fixes (zipper merge condition). To gain insight into merge complexity effects, a landing sequence composed of groups of five aircraft from each meter fix was studied under nominal conditions. Under this test condition, only every sixth arrival encountered a merge situation, and the next four arrivals all flew in-trail to the runway (block merge condition). The resulting inter-arrival spacing errors are compared with the nominal test condition in Fig. 12. It

Figure 12. Effect of merge frequency on spacing errors

can be seen that the range of errors under the block merge condition slightly exceeds that experienced under the nominal zipper merge condition, and the spacing buffer requirement is very slightly higher with the block merge condition (9 seconds instead of 8). Except for these minor differences, the reduced merge frequency appears to have no effect on APS performance under the nominal test condition.
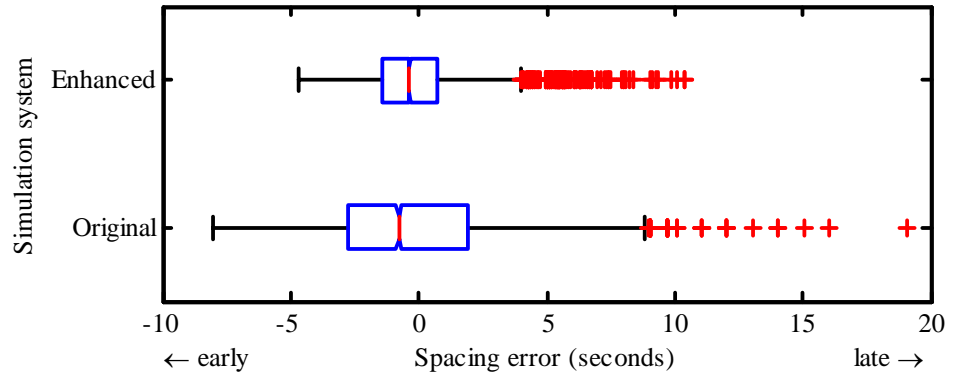
G. AMSTAR performance with enhanced simulation system

Further analysis of the results for the nominal test condition revealed that there was scope to improve the fidelity of the simulation system. The aircraft models used for the simulation were upgraded to BADA version 3.6[23], resulting in changes to the Final Approach Speeds of several aircraft types. Aircraft performance modeling was modified so that aircraft would decelerate at a reduced rate when they were descending compared to when they were in level flight. Analysis of the effects of final approach speeds (alluded to earlier) led to a modification of the ADS-B message reception logic for the AMSTAR implementation. Without the change, certain sequences of AMSTAR initiation and ADS-B message reception could result in AMSTAR using a default final approach speed for the lead, rather than the actual broadcast value. These results have motivated a closer examination of the effects of different levels of knowledge of the lead aircraft's Final Approach Speed, and this analysis will be discussed in a forthcoming paper[24].

Figure 13. Effect of simulation enhancements

Together, these enhancements to the simulation of APS operations resulted in significant improvements to AMSTAR performance, as can be seen from Figure 13. The overall range of errors shrank from 27 seconds to 15 seconds, and the required spacing buffer for the nominal test condition reduced from 8 seconds to about four. The magnitudes of the high positive spacing errors observed with the original simulation have also reduced significantly. Further data collection and analysis with the improved simulation under other test conditions indicated that while data trends across these conditions remained the same, overall performance was significantly improved in all cases[25].

IV.   Summary and Conclusions

A new concept of operations for terminal arrivals was evaluated in a series of fast-time simulations. Under the new operation, flight crews of appropriately equipped aircraft could be cleared by ATC to achieve precision spacing relative to a designated lead aircraft, using new onboard automation for speed guidance. The fast-time evaluations used a high-fidelity prototype of the new toolset, and the study was performed using an airspace and air-traffic simulation that modeled several different aircraft types. The evaluations explored the sensitivity of AMSTAR to variations in environmental and operational conditions. Five topics were considered for the study: the range of reception of ADS-B signals, wind prediction errors, arrival time inaccuracies, aircraft type diversity, and the frequency of merging aircraft in the arrival stream.

The results of the study indicate that the AMSTAR concept and prototype onboard systems possess a high degree of robustness to moderate variations in environmental and operational conditions. APS operations were not noticeably impacted by errors averaging up to 20 degrees in predicted wind direction. Wind magnitude prediction errors averaging 10 knots had some undesired effects on APS performance, as did increased RTA errors and degraded ADS-B range. In all these cases, however, the undesired effects were confined to a few outliers in the data sets of 3960 spacing errors, while the bulk of the data continued to demonstrate good APS performance. Therefore, it may be possible to mitigate these efforts by suitable operational procedures without sacrificing overall spacing performance. Aircraft type diversity contributes to increased spread in the spacing errors, and further analysis is underway to determine the causes of this behavior. Merge frequency did not appreciably affect inter-arrival spacing accuracy.

Ongoing research has already indicated that careful refinements of the AMSTAR and ADS-B implementation logic could improve spacing performance even further. Research into the APS concept at NASA Langley is further investigating the interdependence of aircraft type diversity and spacing error behavior as well as evaluating the importance of lead aircraft final approach speed data to precision spacing. Further research is required to better understand the limits of the concept and the effects of off-nominal APS operations, such as the downstream effects of an aircraft departing the assigned route, or modifications to an active spacing assignment.

V.   References

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