Simulation Results for Airborne Precision Spacing along Continuous Descent Arrivals

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This paper describes the results of a fast-time simulation experiment and a high-fidelity simulator validation with merging streams of aircraft flying Continuous Descent Arrivals through generic airspace to a runway at Dallas-Ft Worth. Aircraft made small speed adjustments based on an airborne-based spacing algorithm, so as to arrive at the threshold exactly at the assigned time interval behind their Traffic-To-Follow. The 40 aircraft were initialized at different altitudes and speeds on one of four different routes, and then merged at different points and altitudes while flying Continuous Descent Arrivals. This merging and spacing using flight deck equipment and procedures to augment or implement Air Traffic Management directives is called Flight Deck-based Merging and Spacing, an important subset of a larger Airborne Precision Spacing functionality. This research indicates that Flight Deck-based Merging and Spacing initiated while at cruise altitude and well prior to the Terminal Radar Approach Control entry can significantly contribute to the delivery of aircraft at a specified interval to the runway threshold with a high degree of accuracy and at a reduced pilot workload. Furthermore, previously documented work has shown that using a Continuous Descent Arrival instead of a traditional step-down descent can save fuel, reduce noise, and reduce emissions. Research into Flight Deck-based Merging and Spacing is a cooperative effort between government and industry partners.

Nomenclature

ADS-B	=	Automatic Dependant Surveillance-Broadcast
APS	=	Airborne Precision Spacing
ASAS	=	Airborne Separation Assistance Systems
ASTAR	=	Airborne Spacing for Terminal Arrivals
ATOL	=	Air Traffic Operations Laboratory
ATOS	=	Airspace and Traffic Operation Simulation
ASTOR	=	Aircraft Simulation for Traffic Operations Research
CDA	=	Continuous Descent Arrival
CDTI	=	Cockpit Display of Traffic Information
DFW	=	Dallas-Ft. Worth Airport
FDMS	=	Flight Deck-based Merging and Spacing

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TMX	=	Traffic Manager
TOD	=	Top-Of-Descent
TTF	=	Traffic-To-Follow
TTG	=	Time-To-Go

I. Introduction

Fast, efficient air transportation is a fundamental part of the world's economy, moving people and goods rapidly and safely. However, in the United States and Europe, the air transportation system faces two important challenges: reduce the fuel consumption, as well as air and noise pollution generated by aircraft and airports, and increase the capacity at high-density airports and the airspace surrounding them. During the past several years, increased interest in reducing airport community noise and the escalating cost of aviation fuel have led to the use of Continuous Descent Arrival (CDA) procedures to enable lower noise and lower fuel usage than current procedures. To provide these operational enhancements, arrival flight paths into terminal areas are planned around optimized vertical profiles. These profiles are designed to be near-idle descents from cruise altitude to the final approach fix and are typically without any powered, level segments. By staying higher and faster than conventional arrivals, these CDAs also save flight time for the aircraft operator.

However, these benefits do not come without a price. Since the flight crew is optimizing the trajectory for that particular aircraft to maximize fuel and noise efficiency rather than the Air Navigation Service Provider managing for system throughput, more airspace is required around an aircraft on a CDA than on a conventional arrival procedure to accommodate the variance of many different trajectories. This additional space decreases the overall capacity of the destination airport. To maintain the arrival rates required for a very busy airport, different terminal area concepts have been researched over the past 30 years, to include time-based,[1-4] vectors and speed commands from a ground system,[5] Required Time of Arrival procedures for CDAs,[6,7] and speed commands generated on-board the aircraft.[11-16] Required Time of Arrival concepts are being developed to support high throughput for CDA procedures. This paper explores one of those concepts, Airborne Precision Spacing (APS), by using the current instantiation being developed by the FAA, NASA, MITRE, UPS, and other industry partners called Flight Deck-based Merging and Spacing (FDMS). This concept has the flight crew making minor speed adjustments based on cues from on-board software while flying CDAs, and is intended to address both capacity and efficiency issues facing the air transportation system. The algorithm used for generating the speed command for the flight crew to follow has been under development for almost 20 years,[17,18] and was also recently used in several important flight tests. [19-21] The three major changes to the prior concept and supporting technology involved real-time updating of wind forecast data, the support of Mach cruise segments with constant Mach descent capabilities, and support for the use of this technology into a retrofit context. This enhanced capability implementation is described in the next section, and is called the *Airborne Spacing for Terminal Arrivals* (ASTAR) system. Finally, this experiment is closely linked to several experiments by NASA Ames and MITRE that also explore the effects of airborne spacing on system wide effects and how it could be integrated into the current airspace system from a controller's perspective. [22-27]

II. Airborne Precision Spacing during Continuous Descent Arrivals

A. Airborne Precision Spacing Concept

NASA is currently participating in the FDMS Development Group to develop and test an airborne spacing application that is compatible with CDAs.[8,22] In this concept, a ground-based automation tool would provide an arrival schedule and the related aircraft arrival sequence that would ultimately become ATC clearances for aircraft to perform self-spacing during CDAs. In this clearance, the flight crew of the self-spacing aircraft, i.e., the ownship, would receive the flight identification of the aircraft they are to land behind and the inter-arrival landing interval. This aircraft would then "listen" for ADS-B messages from its leading aircraft. In addition to the basic ADS-B state data message, it is assumed that participating aircraft would also be transmitting the name of their arrival routing and their planned final approach speed via an ADS-B Operational Coordination Message.[28] The published routes would include altitude and speed constraints in addition to the lateral path, and could include Area Navigation (RNAV) or Standard Terminal Arrival Routes (STAR) with approach transitions that extend the arrival path to the runway. Prior to receiving ADS-B data from its leading aircraft, the ownship would simply fly the speeds assigned to the arrival route.

Airborne self-spacing is an operational concept where the control of the aircraft's speed is delegated by ATC to the flight crew in order to precisely achieve an assigned inter-aircraft spacing. If several aircraft are arriving in sequence to the same runway, the controller can assign each following aircraft in the stream to arrive at the runway threshold at a set interval, either time or distance, behind an assigned lead aircraft. The flight crew then uses onboard automation to determine the optimal speed to achieve this assigned interval. Because this spacing operation is pair-wise, two aircraft arriving via different routes will merge onto the common route without the need for any additional flight crew intervention or change in the spacing guidance. Numerous arriving aircraft can be strung together in this fashion. The finer speed control available onboard the aircraft allows for more precise control of the inter-arrival spacing. By combining airborne spacing with CDAs, the benefits of reduced noise pollution and fuel consumption can be realized while maintaining or increasing capacity relative to current-day levels.

B. Calculation of the Speed Command

A system on the ownship would use both its route and the leading aircraft's route to generate a 4-D trajectory for each aircraft, noting that the aircraft do not initially need to be on the same route. The nominal spacing time is then computed by adding the leading aircraft's calculated Time-To-Go (TTG) to the runway, based on its current position on the trajectory, to the spacing interval. The difference between this nominal spacing time and the calculated TTG to the runway for the ownship is the spacing error (Figure 1). Because the aircraft may be using different final approach speeds and because airborne spacing must terminate at a point on approach prior to landing to allow for a stable final approach segment, the nominal spacing time may also include an offset to account for different landing speeds. For example, if the ownship has a faster planned final approach speed than its leading aircraft, then this offset would provide a larger spacing interval for the ownship, knowing that this offset will be eliminated during the final approach segment.
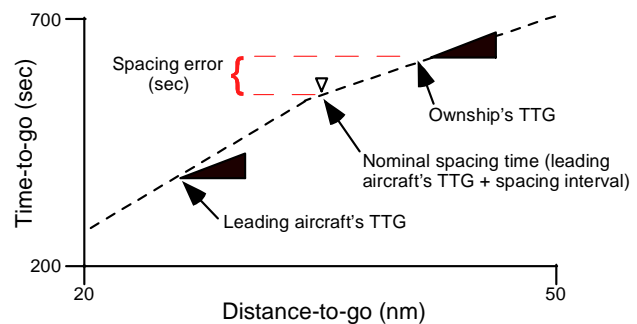

Figure 1: Spacing error calculation.

Since the goal of the self-spacing system is to deliver the aircraft properly spaced at the runway threshold while maintaining arrival stream stability, gains are applied to the spacing error so that the resulting speed commands are less aggressive far from the runway and become more aggressive as the aircraft approaches the runway. This technique has been shown to aid in providing stability to the arrival stream.[11] The computed speed command that would be provided to the flight crew would be a speed error value, based on the spacing error, added to the published arrival route speed associated with the position of the ownship 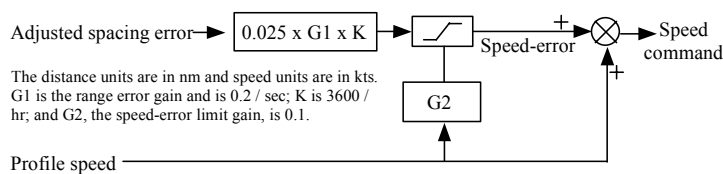on this route (Figure 2). This method of using the published speed as the nominal speed command also enhances arrival stream stability and eliminates excessive excursions from the published arrival speeds, where these excursions can otherwise become operationally problematic when successive spacing aircraft are attempting to overcome large spacing errors. Lastly, speeds are limited to be within 10% of the published speed and are also limited by other operational limitations, e.g., a maximum of 250 kt below 10,000 feet. If current aircraft configuration limits are provided, the command speed would be further limited by those values.

Figure 2: Speed control law.

With a larger focus on pre-merge operations, real-time forecast updating was added to the self-spacing technology using inertial and air reference data obtained via ADS-B from the surrounding aircraft. Wind forecast error can have a much larger, detrimental impact on pre-merging self-spacing operations than on post-merge, in-trail operations. This is because the wind forecast error can have a doubling effect in opposite-direction, pre-merge situations, even in the presence of the same wind environment. That is, with a 20 knot forecast error, one aircraft could have a 20 knot headwind error while the other a 20 knot tailwind error; yielding a 40 knot relative error between the two aircraft. The current algorithm for wind forecast updating uses the correlated inertial and air reference data to determine the wind speed and direction at each aircraft's current position. This wind data is then used to modify the vertical wind profile that is associated with each point on the trajectory. This modification uses

3

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linear interpolations relative to both the difference in the horizontal position between the aircraft and the waypoint and the difference between the aircraft's altitude and the vertical profile of the wind forecast data at that waypoint. A weighting value is used that determines the effect of each aircraft's contribution toward adjusting the original wind profile. This weighting value is based on the aircraft's position relative to each point in the wind forecast profile.

For the initial airborne implementations of the FDMS concept, the technology was not planned to be forward-filled into the aircraft systems, especially the auto-flight system, but was planned to be an almost independent add-on. Because of this, a large effort was undertaken to minimize pilot workload during the self-spacing operation. The technology was extensively redesigned to minimize the number of speed command changes made by the self-spacing system. As part of this redesign, the most significant change from the previous implementation was to limit the speed changes to 5 knot increments. Also, in addition to the gain scheduling used to reduce the magnitude of the speed commands at increasing distances from the runway, a spacing error notch filter, also based on the distance to the runway, was employed. The spacing error gain and notch values were set to 0.25 and 1 NM, respectively, for distances greater than 130 NM from the runway and 1.0 and 0 NM, respectively, for distances less than 30 NM. These values were changed linearly between these two distances. Examples of the resulting, adjusted spacing error are shown below for distances to the runway of 30 and 130 NM (Figure 3).
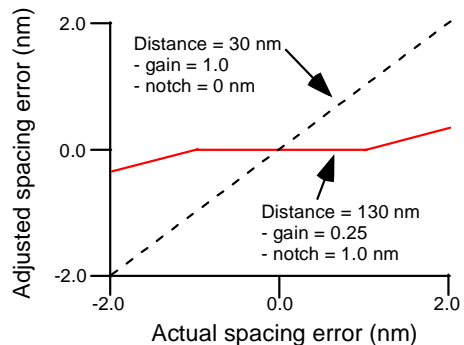
Figure 3: Gain and notch filtering.

III. Experiment Design Overview

A. Experiment Objectives

This FDMS research was conducted in 2006, using a fast-time TMX simulator to address the three objectives listed in this paragraph, and using higher-fidelity simulators to validate the results of the fast-time experiment runs.

The FDMS fast-time experiment objectives were designed to answer the following questions:
1. Will the spacing speed cues maintain the required aircraft-to-aircraft separation from Top-Of-Descent to runway threshold?
2. Will the spacing algorithm deliver aircraft to the runway threshold with an average deviation of no more than 5 seconds and a standard deviation of no more than 20 seconds?
3. Will the spacing operation exhibit stability over a 40 aircraft stream?

B. General Experiment Description

Three aircraft simulation systems were used in this experiment: the Traffic Manager (TMX) low-fidelity, traffic simulator/traffic manager; the medium-fidelity Aircraft Simulation for Traffic Operations Research (ASTOR) aircraft simulation; and the high-fidelity, full-workload, Integration Flight Deck (IFD) simulator. The TMX and ASTOR simulators are in the Air Traffic Operations Laboratory (ATOL) at NASA Langley Research Center. The experiment design and results of a fast-time aircraft in TMX using a software pilot model are described in Sections IV and V. Validation of those results using a software piloted model in ASTOR and human pilot-in-the-loop in the IFD is described in Section VI.

Within the FDMS concept, there will be a scheduling and sequencing tool that determines the preferred arrival sequence and spacing between each pair of aircraft. At a point approximately 150 to 300 NM from the Top-Of-Descent (TOD), the sequence is finalized and the spacing instruction given to the aircraft. The sequencing and scheduling tool is expected to deliver aircraft to the transition zone with an accuracy of approximately 60 seconds. For this evaluation, the aircraft were introduced at the 350 NM point on an assigned route within 60 seconds ($\sigma = 30$ s; 2σ cut-off) of the assigned schedule. Shortly thereafter, they receive their spacing instruction. For the TMX and ASTOR simulations, a simulation pilot model responds by entering the data into the spacing tool and then follows the speed guidance generated by the airborne spacing tool. The pilot model also reacts to updated speed guidance cues, controls the vertical descent, and configures the aircraft as necessary for the arrival.

C. Routes and Continuous Descent Arrivals

Four routes were loosely designed for the Dallas-Ft. Worth (DFW) airspace, and represent the expected descent profiles and speeds of a typical CDA. DFW was chosen so that the lateral arrival routes modeled in previous studies could be used.[10, 11] The previous routes were extended to 350 NM from runway 18R at KDFW (Figure 4). All four

4

routes have the same altitude and speed profiles. The TOD is approximately 120 NM from the threshold; however, the initial descent segment from cruise to 11,000' MSL is unconstrained. Therefore, each aircraft's flight management computer chooses the optimal descent point based on the aircraft performance and weight as well as the forecast winds. The first constrained waypoint is at 11,000' MSL and 240 kt. After this point the flight path angle is designed to be 2.4° until ILS-intercept. This is a low-power descent that allows for some speed control.

The two routes from the southwest (CME, INK) merge at a point approximately 190 NM from the runway and 70 NM from the expected TOD. The southeast route, AEX, merges abeam the field approximately 25 NM from the threshold and at 7000' MSL. The fourth route from the northwest, BGD, merges at the turn to base.

A key component of airborne spacing is the pre-conditioning of traffic at the start of the operation by a ground system. Consecutive aircraft are not allowed to pass a preceding aircraft as this would allow for separation violations. If the aircraft are at different altitudes and vertical separation is ensured, then a faster aircraft could be sequenced ahead of a slower aircraft that was geometrically in front of it. However, the aircraft pair was only allowed to do this if they were predicted to be in the correct order and adequately separated before merging onto a common lateral and vertical path.
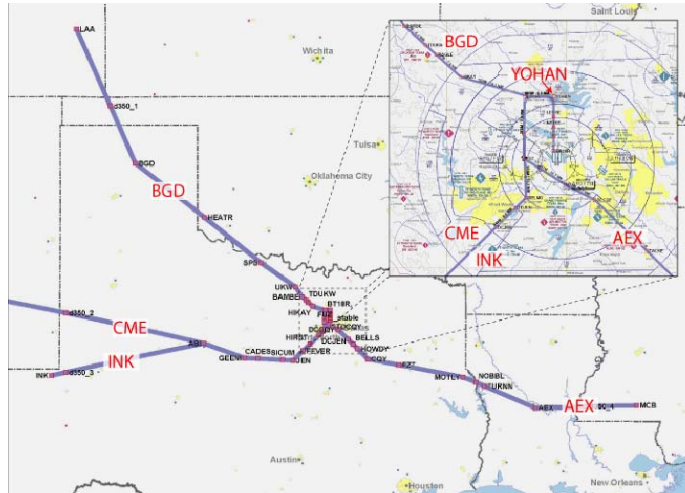

Figure 4: Four arrival routes used in the simulation.

IV. Fast-Time Experiment Overview

A. Simulation Environment

This fast-time experiment used the Traffic Manager (TMX) simulation platform. TMX is a low-fidelity, traffic simulator/traffic manager that can be used in either a standalone mode for real-time or fast-time simulations or networked with one or more flight simulators to provide a realistic traffic environment for these simulators. TMX can represent over 80 different aircraft types using a 6 degree of freedom model. The performance data for the TMX aircraft come from the Eurocontrol Base of Aircraft Data with enhancements derived at NASA Langley Research Center. Each aircraft has representative auto-flight and auto-throttle models that include basic altitude, heading and speed modes plus lateral and vertical navigation modes. The ASTAR speed guidance has been incorporated into TMX and can be used directly by the autothrottles or via a pilot model following commanded speeds. The pilot model simulates delays in stimulus-to-control response time using a normal distribution with the mean and standard deviation as controllable parameters. TMX also includes both truth and forecast wind fields that can vary in both horizontally and vertical position,vertically; an ADS-B model that includes realistic report content and a configurable distance-based reception probability, and airspace infrastructure such as navigation aids. The simulation can run in both real-time and fixed time-step, fast-time modes. TMX was developed by the National Aerospace Laboratory of the Netherlands and enhanced by the National Institute of Aerospace and NASA Langley Research Center.

B. Independent Variables

Previous research identified the accuracy of the wind forecast used by the ground-based scheduling tool and the airborne spacing tool as being important to the stability of the overall operations. Because these arrivals are much longer than previously studied and have reduced speed authority, it was expected that wind forecast errors would provide a challenging environment for airborne spacing. Pilot responsiveness to speed cues may also affect individual operations and overall system stability. Delays in entering the new speed, coupled with the slow responsiveness of the aircraft during a near-idle descent, may cause the spacing tool to be continually "behind," resulting in decreased performance or increased pilot workload. The third disturbance studied was changing the spacing between aircraft after the aircraft had started the spacing operation. Such adjustments might occur to accommodate a late entrant into the flow or changing atmospheric conditions. The FDMS concept allows the

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controller to vector an aircraft off the published arrival in order to delay the aircraft and then return it to the CDA and restart spacing. For this fast-time study, we examined the size of spacing interval change that could be achieved by speed changes alone.

The three independent variables and their parameters are described below, while the combination of parameters to create eight distinct conditions is listed in the test matrix in the next section.

1. Wind prediction accuracy

Either accurate (no error) or inaccurate (error) prediction of the wind field. The wind field used in this study was isotropic with an altitude dependence and is based on the Joint Aviation Requirements All Weather Operations (JAR-AWO) auto-land certification process:

$$V(h) = V_{30}(h/30)^{1/7}.$$

V_{30} is the only adjustable parameter and represents the winds measured at 30' AGL. The wind direction is taken to be a direct headwind at 1000' on final rotating smoothly to 90º clockwise by 10000' and then constant above 10000 ft. The predicted wind field will always use V_{30} = 10 kt. For the conditions with no wind prediction errors the truth wind field is identical. For the wind prediction error cases the truth wind is based on V_{30} = 20 kt.

2. Response time

Either auto-throttle (no delay in implementing ASTAR speed cue and follow commanded deceleration rates) or normal pilot response (8 seconds < 10,000'MSL; 30 seconds > 10,000'MSL and decelerate as quickly as the aircraft will allow). The speed change will be presented to the flight crew who will need to manually enter the speed either into their flight management computer or via the mode control panel. In either case, there would be a delay between the time the algorithm commands a change and the aircraft begins to react.

3. Disruption

Either no disruption or disruption in arrival stream (30 second variation of initial conditions). Since there was no human intervention in this study, this was done by assigning one aircraft a spacing value twice the planned value. For example, a B767 would be initialized at a spacing of 115 seconds but assigned a spacing of 230 seconds shortly after the run begins. This effectively created a new slot in the arrival stream.

C. Experiment Design and Test Matrix

The ASTAR fast-time evaluation used a 2 × 2 × 2 full factorial design matrix with ten repetitions for each condition as shown in Table 1 (results described in Section V). The same set of ten scenarios were used for each of the test conditions to allow for direct comparisons where desired.

Table 1. Test Matrix

Parameters	Condition							
	1	2	3	4	5	6	7	8
Wind error	no	yes	no	yes	no	yes	no	yes
Delayed response time	no	no	yes	yes	no	no	yes	yes
Disruption	no	no	no	no	yes	yes	yes	yes

D. Test Conditions

Three causes of disturbances to the traffic flow were identified as Independent Variables in paragraph IV B. While there was interest in looking at the disturbance interactions, the primary effects dominated any interaction effects. Therefore only the condition without any error (#1, or Baseline) and three single disturbance conditions (#2, #3, and #5) will be reported in Section V. Each scenario consisted of 40 aircraft with randomly assigned airframe types, routes, altitudes, and weights. The initial aircraft speed was consistent with the type, weight, and altitude of the aircraft. There were an additional ten aircraft at the front of the arrival stream that provided sensed wind data via ADS-B datalink but were not part of the data analysis. The same set of ten aircraft were used in all repetitions. The ownship spacing algorithm would update its internal wind model based on reported winds from all aircraft within ADS-B range. Performance data are presented in this paper on the 40 aircraft, and spacing results for the 39 pairs of aircraft (390 pairs of spacing aircraft for the 10 runs of each condition).

The assigned spacing intervals were based on the aircraft wake-vortex category and the average final approach speed plus an approximately 10-second buffer to ensure the aircraft maintained appropriate separation. The range for aircraft-to-aircraft surveillance (AD-B) reception limit was set to 120 NM with the probability of reception

falling from 100% to 0% between 110 NM and 130 NM. Aircraft that started beyond that range flew the published speed until they were within surveillance range of their lead aircraft, at which time the spacing tool automatically started providing speed guidance to achieve the assigned spacing interval.

E. Initialization parameters
The following variables were randomized in the experiment:
- Arrival sequence (list of origins appearing with equal numbers in each scenario)
- Aircraft type (this and the sequence will determine the assigned spacing interval)
- Initial cruise altitude, speed, and weight (based on direction of flight and aircraft type)
- Initial spacing error (normal distribution with 0 mean and 30 second standard deviation)

For the test scenarios, a landing sequence was designed, including the desired spacing interval between aircraft. The spacing interval was based on the aircraft's weight category, which determines the wake vortex separation requirement, converted to a time based on a slow but reasonable final approach speed. The final approach speed was aircraft type and weight dependent. The time-based spacing matrix is given below.

Table 2. Initialization Altitude, Speed, and Assigned Spacing Interval

Aircraft Type	Altitude (FL)	Speed (Mach)	Behind an A300-600	Behind a B757-300	Behind a B767-400
A300-600	330-370	.80	135 sec	135 sec	135 sec
B757-300	330-370	.80 - .82	145 sec	120 sec	145 sec
B767-400	330-370	.80 - .82	115 sec	115 sec	115 sec

Each aircraft was randomly assigned a route and appropriate cruise altitude and speed. The gross weight of the aircraft was varied to ensure a spread of final approach speeds. For each aircraft, an ideal starting time was determined based on its sequence and spacing as well as the wind forecast. The actual starting time was then varied around the ideal time as a normal distribution with a standard deviation of 30 seconds. A final check was made to ensure adequate separation if the leading aircraft was on the same route and altitude. If there was not adequate separation then the initiation time offset of the trailing aircraft was resampled.

V. Fast-Time Experiment Results

A. Baseline Test Condition (no error)
The Baseline test condition (#1) had no wind forecast error, no additional delay in implementing commanded speed changes, and no arrival stream disturbance.

Since the spacing algorithm is not actively managing the merge point it is interesting to see what the actual separation is at that point. The spacing algorithm is controlling to the ETA difference at the threshold, but due to the higher speeds and beginning to manage the spacing at least 60 NM (half of the 120 NM ADS-B range) prior to the merge, it was expected that there would not be any separation violations at or near the merge point. In full operations, there would also be a controller watching the aircraft and intervening in any case that might evolve into a loss of separation. However, in this study that layer of protection was not present so these results are what would be seen if there was no controller intervention. The merging cases are divided into five categories: those that started in-trail on the same altitude (always in-trail); those that were on the same cruise altitude but merged en route on CME and INK (in cruise); those that were in-trail but on different altitudes and merged at the top-of-descent (at TOD); those that merged from AEX and CME/INK at the point abeam the airfield (on downwind); and
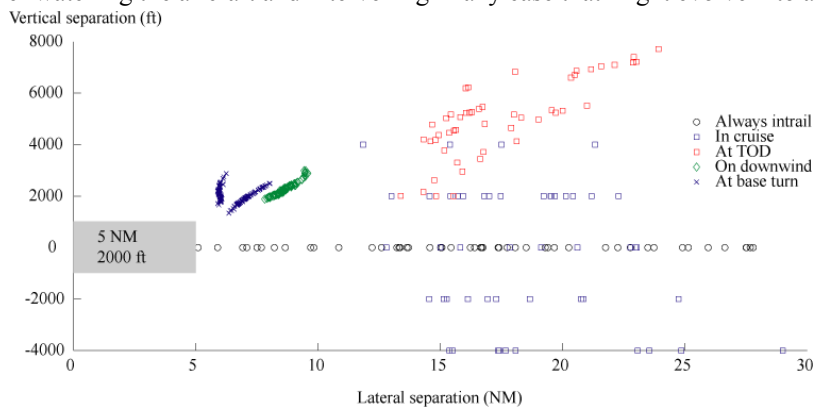

Figure 5: Lateral and vertical separation at the merge points.

those merging at the turn base involving BGD and CME/INK/AEX (at base turn). As shown in Figure 5, this assumption held up during the experiment runs. The spacing algorithm maintained or improved the spacing created by the ground system, and all aircraft were approximately 90 to 120 seconds laterally separated when they merged onto a common path. At cruise altitude (the blue squares) that approximated 15-25 NM, around 11,000' MSL (the green circles) about 7-10 NM, and merging in the traffic pattern (the blue crosses) about 6-8 NM.

Figure 6 shows the timing for a single scenario run. The open circles show the initial spacing deviation which is a function of the initialization offset for the lead aircraft and ownship. The solid blue circle is the ETA difference when the ownship first comes within surveillance range of its lead. In some cases the spacing deviation improved, such as aircraft #11. These usually occurred because the lead aircraft attempted to correct its own spacing deviation. However, sometimes there is negative change, such as #28. The red box marks the achieved spacing deviation at the runway threshold. Even initial deviations of 100 seconds were able to be corrected by the time the aircraft arrived at the threshold.
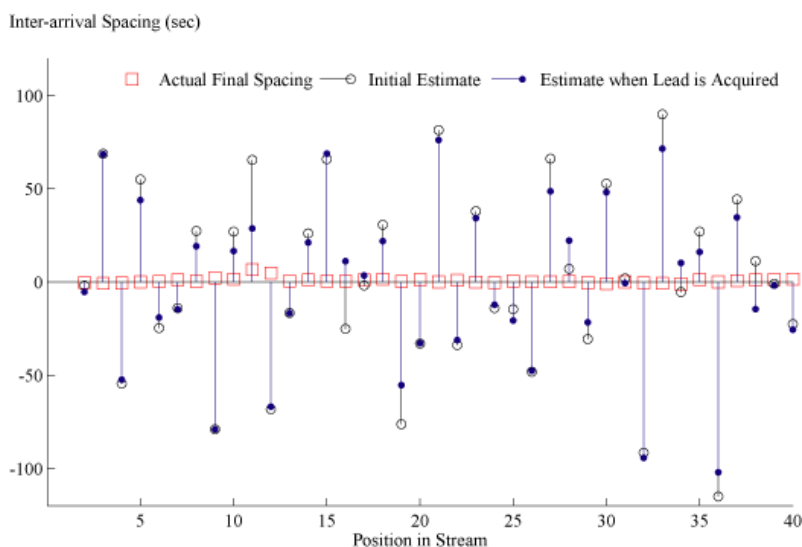

Figure 6: Spacing of arrivals during baseline condition. Since the first aircraft was not spacing, there is no data for it.

For all 390 pairs of aircraft in the nominal test condition, the achieved spacing error was 0.2 seconds with a standard deviation of 1.2 seconds. All aircraft were within 7 seconds of their assigned spacing. The distribution is normal except for the tails beyond 2σ. There was an average of 10 speed changes in addition to the five that are part of the profile. That is approximately one change every 5 minutes.

Figure 7 shows the behavior of a pair of spacing aircraft consisting of the lead aircraft, "CME15" (an Airbus A300), arriving via the CME arrival (west route) cruising at 35000' at 0.80 Mach, and a trailing aircraft, "BGD16" (a Boeing 757), arriving via the BGD arrival (northwest route) at 37000' and 0.80 Mach. The lead aircraft is spacing behind aircraft "INK14." The trailing aircraft, or ownship, is first within ADS-B datalink range of CME15 at approximately the TOD.

The top graph of Figure 7 shows the profile speed for all aircraft (green line), the speed of ownship "BGD16" (black line), and the speed of the lead aircraft "CME15" (red line). The graph shows that between acquiring the lead aircraft and reaching the 11,000' MSL constraint, "BGD16" was projected to be too far behind and hence was commanded speeds 10-15 kt faster than the profile speed. Below 11,000' MSL, "CME15" flew above the profile speed in order to manage its spacing with "INK14."
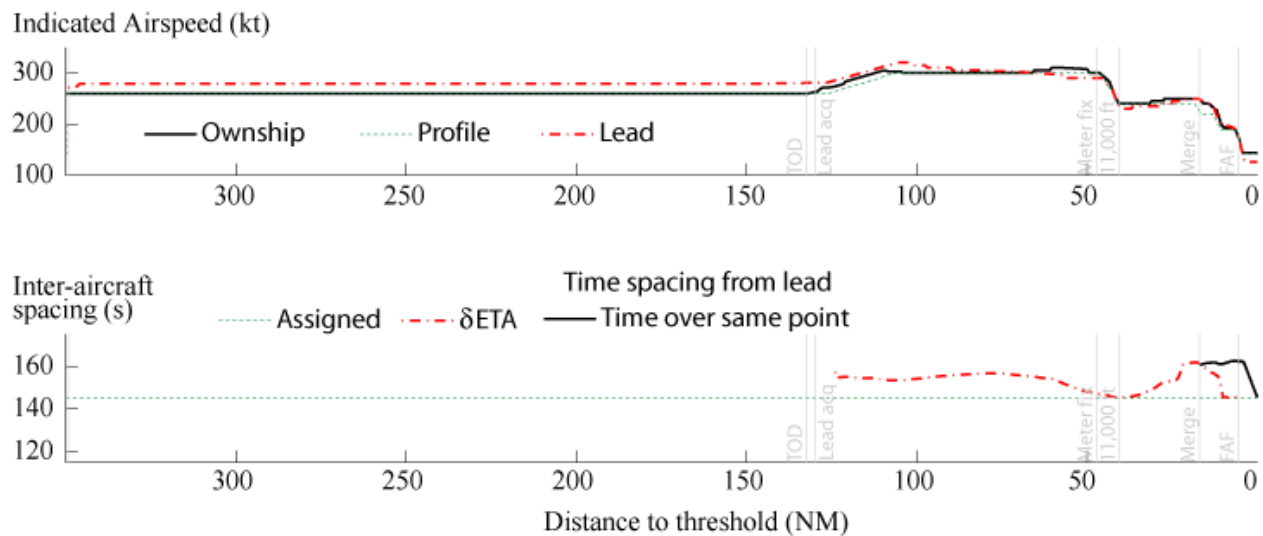
Figure 7: Speed, distance, and spacing of aircraft pair during Baseline run.

The lower graph shows the calculated time difference at the runway threshold (δETA) as well as the measured time difference over common points ("time over same point"). The former is continually calculated as soon as the lead aircraft is within ADS-B range. The latter is only defined once the two aircraft are on the same lateral path, that is, post-merge. The initial spacing error of 15 s was nullified by the 11,000' crossing. However, the lead aircraft, CME15, had to increase its speed to achieve its spacing behind INK14; hence, increasing the spacing error back to 15 s at the merge point. Inside the merge point, BGD16 was again able to nullify the spacing error by the final approach fix.

At the final approach fix, the spacing algorithm stops calculating the estimated times of arrival at the threshold and commands the ownship's selected final approach speed. The lead aircraft landed at 127 kt while the ownship landed at 143 kt. This final overtake was calculated in the δETA calculations and can be seen in the "time over same point" which shows an approximate 15 second differential at the final approach fix which closes to near zero at the threshold. The final spacing interval for this pair was 145.6 seconds.

B. Error Test Conditions (Wind, Pilot, Disruption)

1. Pilot Delay

Simulating the manual entry of the commanded speeds had very minimal impact on the aircraft and system performance. There were no losses of separation and the overall spacing performance went from $\mu = 0.2$ s, $\sigma = 1.2$ s for the nominal case to $\mu = 0.4$ s, $\sigma = 1.8$ s for the manual entry case. Since the spacing algorithm is constantly recalculating the expected spacing and a speed to null that deviation, any reasonable delay early in the flight would be corrected later. The largest impact on overall performance comes from any delay in implementing the final slowdown to the final approach speed. The aircraft is effectively open-loop on speed after this point so any deviation would be uncorrectable. But, since the distance traveled is small, the impact is small.

2. Disruption

Attempting to create a gap in the flow caused a reduction in the system performance. The distribution of inter-arrival spacing has a significant tail on the early side. The aircraft before the gap performed as in the nominal condition. Six of the ten aircraft that created the gap arrived within one second of the assigned interval which was twice the scheduled interval. The four that failed to achieve their assigned spacing did so because they acquired their lead aircraft late in the arrival. The procedure, if the ownship was outside ADS-B range of their lead, was to follow the nominal speed profile. This caused the aircraft to not attempt to increase the spacing until after they were within ADS-B range of their lead. If this came late in the arrival, for example, the turn to base, there was not enough time remaining to create the additional space using speed alone. Even for the runs where the first aircraft after the gap could achieve their spacing goal, there were often later problems. For example, if the second aircraft after the gap was outside ADS-B range of their lead (the first aircraft after the gap) for a long time, the same effect was seen. Based on the combinations of routing, it took until the 10th aircraft after the gap before all of the spacing deviations at the threshold were back to within 6 seconds of the assigned values. For the final 25 aircraft in each run the

9

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spacing performance was μ = -1.2 s, σ = 1.3 s. There was still a small bias towards being early but the precision was close to the nominal condition.

3. Wind Prediction Errors

The poor spacing performance when there was a disturbance and the aircraft were delayed in acquiring their lead, was even more pronounced in the wind forecast error condition since it affected every aircraft and was a larger disturbance. In nearly every case where the lead aircraft was on a different arrival route than the ownship, the achieved spacing was unacceptable. During the time the lead is outside ADS-B range, the ownship is flying the profile speed which is presented in terms of indicated air speed, not ground speed. Therefore, the along-track wind component is either increasing or decreasing the ownship's ground speed. This adds an unaccounted-for deviation to the spacing interval. By the time the lead is within ADS-B range, there is not enough time to correct this additional spacing deviation. The impact of the wind forecast error can be seen in Figure 8.

Aircraft #2, the first spacing aircraft, is an

Figure 8: Spacing of arrivals during wind forecast error condition. Since the first aircraft was not spacing, there is no data for it.

excellent example of what happens. It is initialized 32 seconds too late based on the forecasted winds. During the cruise segment, it had a tail wind resulting in predicting 215 seconds too early by the time it acquired the lead aircraft's ADS-B signal. The aircraft then slowed as much as possible, but was unable to achieve acceptable spacing. In fact, in this case the trailing aircraft landed *before* its lead.

In an operational environment, the controller would be able to identify this issue as the aircraft started to get close to the merge point and would have resequenced the aircraft or maneuvered the ownship to ensure separation and flow stability. Both of the problems identified by the disruption conditions ultimately relate back to the behavior of the aircraft before they are within ADS-B range 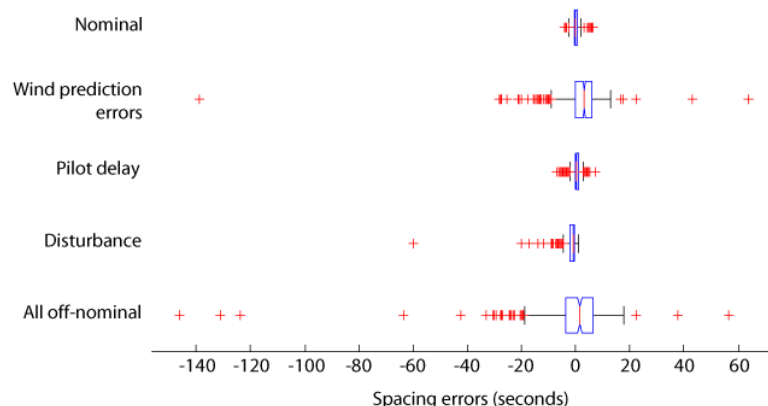where they made no adjustments. What is needed is for the aircraft to be able to detect and correct such problems before they become insurmountable. Several approaches to solve these problems are being considered and will be tested in the future.

Figure 9: Overall spacing performance for all conditions.

In summary, the pilot delay case had a minimal impact on the spacing precision or system performance. Both the gap creation and wind forecast error cases had significant spacing deviations at the runway. These resulted from situations where there was a significant initial deviation and the lead aircraft was well beyond surveillance range. In those cases, the initial spacing deviation remained, or even worsened, for a significant part of the flight before it could be corrected. The interaction effects between the different test conditions were found to be small compared to the surveillance range effect. Figure 9 shows the relative impact the different types of error had on the ability of the FDMS procedure to accurately deliver aircraft to the runway threshold at the assigned spacing interval.
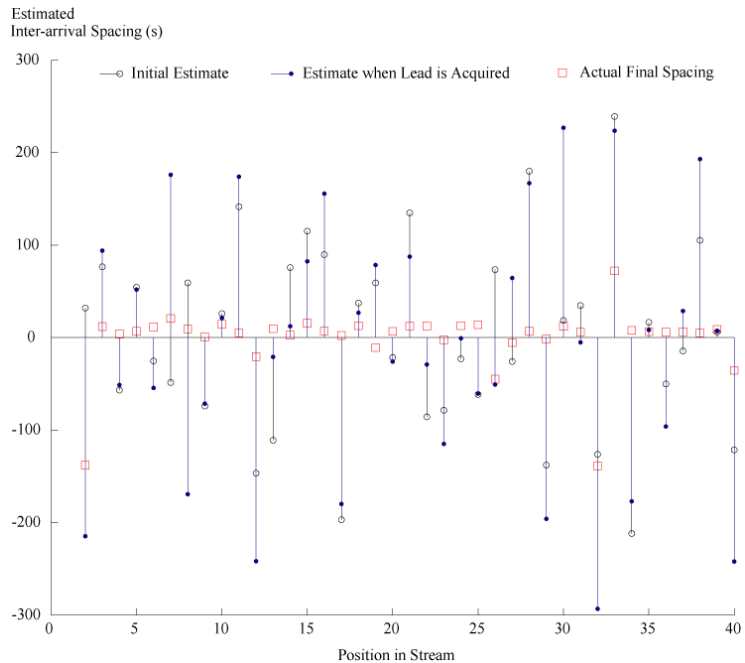
10

VI. Validation of the Fast-Time Experiment Results

A. Simulation Environment

A comparative evaluation of performance between the TMX data runs and the higher fidelity simulators was conducted to validate the fast-time results.

1. Airspace and Traffic Operations Simulation

The Airspace and Traffic Operations Simulation (ATOS) is a part-task, medium-fidelity, distributed simulation designed to explore future concepts in a rapid-prototyping environment. The ATOS system for the validation experiment consisted of twelve workstation-based Aircraft Simulation for Traffic Operations Research (ASTOR) aircraft simulations networked together through High Level Architecture. Also on this network are TMX traffic generation tools and a simulation manager that controls time, events, and simulation system modes. The ASTOR was developed in compliance with existing and advanced avionics system specifications to verify research concept benefits in a realistic onboard Communication, Navigation, and Surveillance system environment. The ASTOR models current aircraft components including: aircraft and engine models, autopilot and auto-throttle systems, flight management computer, multi-function control display unit, mode control panel, and electronic flight instrumentation system control panel. The ASTOR is a six degrees of freedom airplane simulation with a medium-fidelity auto-flight simulation.

2. Integration Flight Deck

NASA Langley's Integration Flight Deck (IFD) simulator was used to verify the results of the TMX and ASTOR data. The IFD is a full-workload commercial transport category aircraft research flight simulator, operating in fixed-base mode. Because it is used for research, there are some non-standard components installed in the IFD that are used to support the experimental systems. The main difference is the location of the control panel for the ND, which is located further back on the aisle stand than in the standard configuration. This panel also contains the push-switch that is used to couple the ASTAR and auto-throttle systems after the self-spacing guidance becomes valid.

B. Validation Results

For comparative evaluations of performance between the TMX fast-time data runs and the medium-fidelity ASTOR and high-fidelity IFD simulations, the first 12 aircraft were chosen from six of the nominal test condition scenarios used in the fast-time study. The six subset scenarios were run using networked ASTOR machines and the IFD. The IFD was initialized coincident with, and at the same weight and cruise conditions as the fifth ASTOR aircraft in each of the scenarios. Both of these aircraft were given the same spacing instructions. Their lead aircraft was either on the same route or on the merging route in various combinations of the CME and INK routes.

Analyses of the inter-arrival times at the runway threshold show that the TMX aircraft inter-arrival spacing was nearly equal to the assigned interval of 150 seconds. The mean interval for the 66 cases (11 spacing conditions per scenario) was 150.03 seconds with a standard deviation of 0.38 seconds. The corresponding values for the ASTOR aircraft were a mean of 149.15 seconds and a standard deviation of 2.82 seconds. For the six arrivals flown in the IFD, the average spacing interval was 143.52 seconds with a standard deviation of 2.82 seconds.
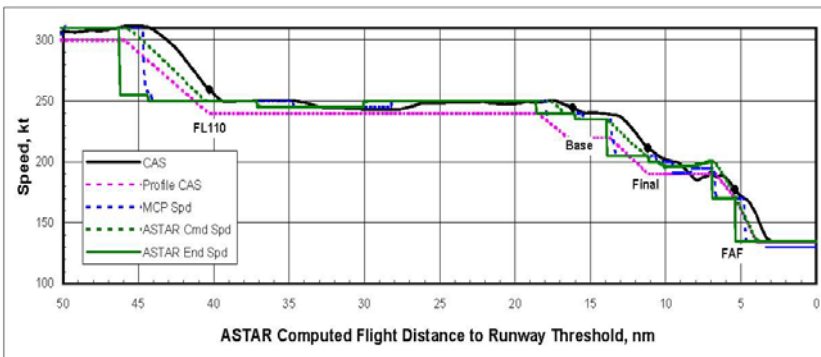

Figure 10: Comparison of profile speed (red dashed), ASTAR provided speeds (discrete in green, continuous in green dashed), pilot commanded speed (blue dashed) and actual speed (black).

The differences in average spacing times between the TMX and ASTOR aircraft and the IFD can be attributed to the differences in pilot technique. The pilot models in both the TMX and ASTOR are programmed to minimize speed and vertical path deviations with rather aggressive use of spoilers and throttles. With the human-in-the-loop (HITL) IFD simulation, deceleration rates were generally less than the rates assumed by the spacing tool. The discrepancies can be seen in Figure 10, which show airspeeds assumed by the spacing tool and

achieved by the IFD during the terminal area flight phase. The differences result in somewhat higher actual ground speeds during the deceleration phases and about six-second deterioration in the spacing interval during the final approach to landing. Subsequent evaluations of IFD flight data have resulted in refinements in assumed performance rates used for trajectory predictions. The differences in the standard deviations of the inter-arrival spacing times reflect what might be expected between low, medium, and high fidelity simulations.

VII. Conclusion

These evaluations verify that it is reasonable and beneficial to combine airborne spacing with CDAs, which supports research findings conducted over the past two years by NASA Ames and MITRE. The aircraft are able to fly low-power descents and still precisely manage their inter-arrival spacing. The Flight Deck-based Merging and Spacing (FDMS) procedure to enable airborne spacing while performing CDAs addresses the challenges of reducing air and noise pollution of aircraft operations while maintaining separation standards and maximum capacity throughput.

Probably the most significant issue facing the deployment of any viable trajectory-based system, whether it is a ground system for aircraft scheduling or an airborne system such as ASTAR, is the elimination of the effect of wind forecast error. With large starting distances from the airport and multiple routes, even relatively small wind forecast errors can result in aircraft arriving out of sequence, assuming the arrival schedule is not modified during the operation and that active spacing does not start until late in the arrival.

Several techniques have been considered that could minimize this problem, with the continuous updating of the arrival schedule being the first and most obvious technique. This technique, however, introduces its own issues, the most significant being that if an aircraft's arrival schedule is changed at or after the TOD, the aircraft may not be able to continue on a CDA. Another obvious alternative would be to provide very frequent updates to the forecast data via a data link from the ground to the aircraft. A technique that was used in the ASTAR implementation was to derive current wind information from data obtained via ADS-B from proximate traffic. While this seems to work well in simulation, it is questionable if it will work correctly in an actual operational environment because small errors in the aircraft's reported heading and ground track can introduce large errors in the estimation of the wind speed and direction. Additional research is planned to further examine this data quality issue. An additional technique that is also being evaluated is to begin the operation with aircraft flying speeds to maintain a Scheduled Time of Arrival to the runway and then switch to airborne spacing once the leading aircraft's ADS-B data are received by the ownship. While this will not correct the wind forecast error, it may reduce the effect of that error on the aircraft's relative position in the arrival stream. In all likelihood, some combination of these techniques may be necessary to overcome errors in the wind forecast data.

Acknowledgments

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