AUTOMATED ARRIVAL MANAGEMENT: EFFECTS OF DESCENT TRAJECTORY PREDICTION ERRORS ON METERING CONFORMANCE

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Abstract

The effects of descent trajectory prediction errors on the performance of an "Arrival Manager" algorithm are explored. Errors in descent calibrated airspeed and wind speed are modeled in order to assess their impact on the baseline performance of the Arrival Manager algorithm in terms of arrival time performance, airborne delay and the number of losses of separation. These data were obtained by simulating in fast-time two streams of arrival traffic merging at the northeast metering fix at Dallas/Fort Worth International Airport. A simple arrival schedule is imposed with uniform spacing between aircraft. Given the modeled error in descent speed or wind, the Arrival Manager's ability to deliver each aircraft to meet its crossing-time constraint with no loss of separation from other aircraft is assessed. Results indicate that both metrics—airborne scheduled delay and the number of separation losses—are more sensitive to the modeled descent speed errors than the modeled wind speed error. Wind speed error resulted in no losses of separation.

Introduction

Separation management automation holds the promise of increasing throughput by reducing workload for en-route air traffic controllers; workload is known to be a key constraint on capacity in en-route airspace. En-route workload generally is highest in busy transition airspace, where aircraft are climbing and descending and where arrivals are vectored to comply with metering constraints. It is in this type of airspace where separation management automation offers the greatest potential benefit in terms of workload reduction and throughput increase. However, this same airspace, with its high concentration of climbing and descending flights, is where trajectory prediction errors are most significant and potentially most hazardous. This trajectory uncertainty is a critical challenge for designers and eventual users of separation management automation, as it has the potential to undermine the benefit case.

The Advanced Airspace Concept (AAC) is an integrated approach to trajectory-based automation for separation management in the presence of weather and metering constraints [1]. The AAC function that sequences and schedules arrival traffic to conform with metering and separation constraints is called the Arrival Manager. This paper documents a study to assess the effects of descent trajectory prediction error on the performance of the AAC Arrival Manager.

Several studies have evaluated AAC algorithms in an automated separation management configuration (i.e., no controllers in the loop). Farley and Erzberger found AAC performed soundly (no losses of separation) under high traffic demand in high-altitude Cleveland Center airspace when there was no trajectory uncertainty [2]. When a transition of airspace was included, some losses of separation did occur, even with perfect trajectory prediction, this was due to the algorithm level of sensitivity of choosing a less efficient trajectory prediction [2]. Lauderdale documented the sensitivity of AAC to six different sources of trajectory uncertainty; the study did not, however, include arrival metering operations, where the effects of trajectory uncertainty are expected to be more disruptive [3].

The present work explores the effects of descent trajectory prediction errors on the performance of the AAC Arrival Manager in a simplified time-based metering environment. The goal of this study is to characterize the impact of errors in predicted descent calibrated airspeed (CAS) and wind speed on the performance of the Arrival Manager algorithm in terms of metering conformance, airborne delay and the number of losses of separation. Every loss of separation can be traced to one of these errors in trajectory prediction; therefore, it is crucial to understand how robust this system performs. The next section highlights the most relevant prior work and provides a basic description of the AAC Arrival Manager. The experimental approach and design is presented in experimental procedure, followed by the analysis of results in terms of the two different types of prediction errors: descent speed and wind. A short discussion talks about the importance of this data while conclusions and future work are defined.

Article Under Test: The AAC Arrival Manager

The Advanced Airspace Concept (AAC) is an operational concept and trajectory-based automation prototype that integrates separation assurance with weather avoidance and arrival metering [2-5]. The Arrival Manager function operates exclusively on arrival aircraft, executing three main tasks: sequencing, scheduling and conflict resolution. Using its real-time trial-planning capability, the Arrival Manager generates a four-dimensional descent trajectory (horizontal position, altitude, and meter fix time) for each arrival aircraft; the trajectory is projected to conform to metering and weather constraints while preserving safe separation [4, 5].

The AAC Arrival Manager can operate as a stand-alone algorithm, or it can be coupled with an external scheduling or metering system like the Traffic Management Advisor (TMA), which is deployed throughout the NAS. TMA is a system used at major airports that aids the Terminal Radar Approach Control (TRACON) airspace to increase arrival traffic efficiencies by sequencing and merging arrival traffic while increasing the airports capacity and maintaining safety [5].

It is necessary for the Arrival Manager to have consecutive arrivals crossing a meter fix with a minimum time interval. A sequencing conflict can happen if a predicted minimum time interval is violated at the meter fix. The Arrival Manager resolves the conflict using both conventional distance separation and sequencing simultaneously while trying to meet its minimum time interval arrival meter fix requirement [4, 5]. Figure 1 shows a predicted sequencing conflict between two flights that are merging to the same arrival fix.

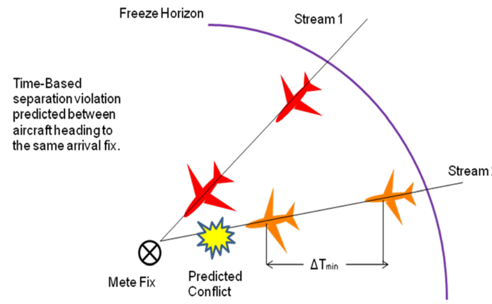

Figure 1. Predicted Sequencing Violation for Meter Fix Spacing

Experimental Procedure

Goal of the Study

The goal of this exploratory study is to characterize the impact of certain errors (not realistic) in predicted descent calibrated airspeed (CAS) and wind speed on the performance of the Arrival Manager algorithm in terms of metering conformance, airborne delay and the number of losses of separation (LOS).

Scenarios & Assumptions

The same traffic scenario and modeling assumptions were used to probe the effects of CAS uncertainty and wind uncertainty. A 200 flight scenario simulated 3½ hours of arrival traffic to the northeast meter fix for Dallas/Fort Worth International Airport (DFW). Each aircraft flew a nominal airspeed of 290 kts before applying the CAS & wind speed errors. Each arriving flight had a CAS error that was randomly sampled using a uniform distribution between -10kts and 15ts. Two arrival streams were modeled merging at the meter fix (see Figure. 2). No other arrival traffic nor crossing traffic was included in the traffic scenario.

For this study, traffic in each arrival stream was uniformly spaced and had identical planned four-dimensional (i.e., horizontal, vertical, and time) trajectories. Arrival slots at the meter fix were scheduled at uniform time intervals. Winds and temperature were modeled using archived Rapid Update Cycle (RUC) data. Two streams of merging flight arrivals were modeled to see the effect of wind fields as depicted in Figure 2. A wind error magnitude in the along-track direction was applied to the predicted wind field. Splitting the streams brings the flights in from two different directions, so for each given flight a different wind speed error will be obtained than for the aircraft ahead of it. No convective weather was modeled.

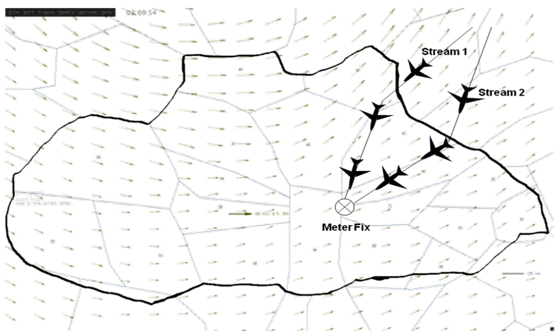

Figure 2. Two Streams of Arrival Flights Merge at the Northeast Meter Fix to DFW

Table 1 shows all required parameters used to simulate this experiment. Separation standards were assumed to be the same as today: 5 nmi laterally and 1000 ft vertically. The AAC horizontal and vertical conflict detection criterion of 5 nmi and 1000 ft resolution detection algorithm was programmed to identify aircraft pairs that were projected to violate both of these standards simultaneously. A violation was defined as a loss of separation. Inter-arrival spacing of less than 60 sec at the meter fix was also defined as a loss of separation. The freeze horizon—the point along an arriving aircraft's trajectory at which its scheduled time of arrival (STA) at the meter fix is set, or "frozen," by the Arrival Manager—was set at 20-min flying time from the meter fix.

Table 1. AAC Parameters

Horizontal separation standard	5 nmi
Vertical separation standard	1000 ft
Meter-fix crossing time sep. std.	60 sec
Horiz. conflict resolution std.	5 nmi
Vert. conflict resolution std.	1000 ft
Freeze Horizon (ref. to meter fix)	20 min

Test Bed

The simulation test bed is the Advanced Concept Evaluation System (ACES). ACES is a four-dimensional simulation environment that models National Airspace System (NAS) operations in non-real time [6]. The aircraft performance models are derived from the Base of Aircraft Data (BADA) [7]. The wind forecast (RUC data) is provided by the National Oceanic & Atmospheric Administration (NOAA) and is the same as that used by the Federal Aviation Administration (FAA) [8].

Test Matrix

The study assessed the effects of descent CAS error and the effects of wind error. These error sources and magnitude constituted one of the independent variables in the study. The other independent variable was the inter-arrival spacing requirement being enforced by the arrival scheduler. The inter-arrival spacing requirement at the meter fix was always greater than the inter-arrival spacing between aircraft as they crossed the freeze horizon and became eligible for scheduling. This forced the Arrival Manager to delay aircraft in order to conform to the arrival schedule. Table 2 shows how these independent variables were represented in the test matrix.

Table 2. Test Matrix

Scheduled inter-arrival spacing at the meter fix	CAS error, [-10 kts, +15 kts] (random seed)				Wind error (10 kts)
	A	B	C	D	
70 sec					
80 sec					
90 sec					

The descent CAS error for each arriving aircraft was randomly sampled from a uniform distribution between -10 kts and 15 kts. Four descent CAS error test cases were executed, each with a different random CAS-error seed, to verify that the random seed did not cause significant variability in the results.

Once established on descent inside the freeze horizon, the constant descent CAS error for each flight was applied to the constant CAS segment of the Mach/CAS descent as shown in Figure 3. The error range between -10 kts and 15 kts was selected based on operational data measured by Stell [9]. Figure 3 illustrates how the constant descent CAS prediction error was applied.

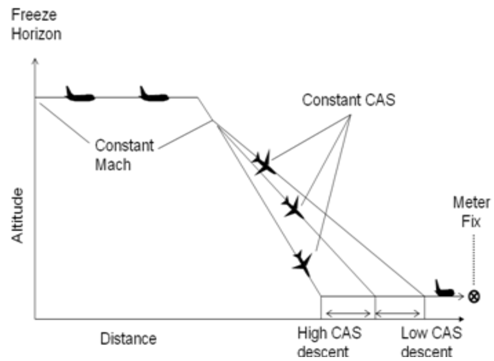

Figure 3. Schematic CAS Prediction Error

A wind field, with magnitude and direction, was used to simulate wind prediction errors. A constant wind field error of 10 kts was used to propagate each aircraft along its trajectory [10].

The second independent variable was the inter-arrival spacing requirement enforced by the arrival scheduler at the meter fix. A 60-sec slot at the meter fix was used as a base value. It was then tested with 70-sec, 80-sec, and 90-sec scheduled inter-arrival times at the meter fix. It was the role of the Arrival Manager to amend each arrival aircraft's trajectory to conform with the meter-fix schedule and to resolve any detected traffic conflicts. All aircraft trajectories were then analyzed for any losses of separation and airborne delay in the presence of the modeled descent CAS and wind errors.

Analysis of Results

Results of the experimental procedure described above are presented in this section. For each test case, four dependent variables are presented: number of LOS, arrival time accuracy and precision, arrival time conformance, and airborne delay.

Losses of Separation

For this study, a loss of separation is defined as either (a) less than 5 nmi lateral separation and less than 1000 ft vertical separation, or (b) less than 60 sec inter-arrival spacing at the meter fix.

Descent CAS Error

Descent CAS errors produced a relatively high number of separation losses at the meter fix when the scheduled (or target) inter-arrival spacing at the meter fix was small (i.e., 70 sec). These losses were of type (b) above, where the 10-second buffer between the target spacing and the LOS threshold was consumed by the induced error in descent CAS. However, as the required spacing at the meter fix was increased, the number of LOS's decreased, because the time buffer between the target spacing and the LOS threshold was large enough to accommodate the modeled errors in descent CAS. Table 3 shows the number of LOS for each inter-arrival spacing target and seed.

Table 3. Number of LOS per Seed

Scheduled inter-arrival spacing at the meter fix	CAS error, [-10 kts, +15 kts] (random seed)			
	A	B	C	D
70 sec	3	4	1	4
80 sec	0	0	0	0
90 sec	0	0	1	0

The number of separation losses for the 70-sec case was expected be high. The root cause of these failure cases is depicted in Figure 4. In each LOS case, at the bottom-of-descent point, the leading aircraft immediately decelerated to meet a 250-kt speed restriction for the meter fix. At the same time, the trailing aircraft continued its nominal descent. The speed differential between the two aircraft was exacerbated by a relatively high speed error in the descending aircraft. This speed differential coupled with the short inter-arrival spacing requirement resulted in a loss of separation as shown in Figure 4.

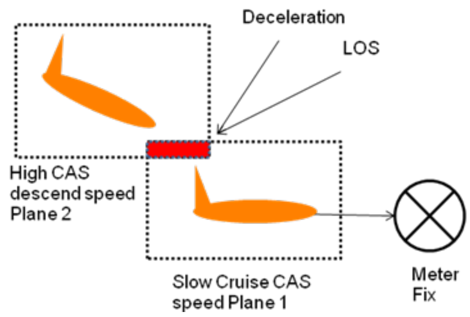

Figure 4. A Vertical LOS Between Two Aircraft

The LOS in the 90-sec occurred not near the meter fix but at an altitude of 25,000 ft. In this LOS, two different descent CAS error speeds and flight trajectories were flown between aircraft. A path stretch trajectory with a much higher descent CAS error speed was flown by the leading aircraft while the trailing aircraft flew a straight path but with a much slower descent CAS error speed. Therefore, by having two different flight trajectory paths and CAS error descent speeds the aircraft flew too close to each other upon arriving at the merging point hence a LOS occurred due to the aircraft's horizontal space distance violation of less than 5nmi. Figure 5 shows the leading & trailing aircraft's descent trajectories.

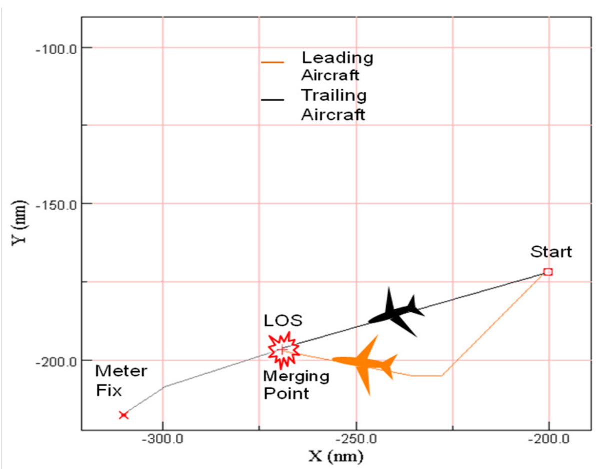

Figure 5. Aircraft LOS Path Trajectories

Wind Error

The modeled wind errors produced no separation losses in either flight stream for any of the three inter-arrival spacing requirements at the meter fix. This is not a surprising result since a fixed wind error value was applied to the entire wind field. Accordingly, aircraft in each arrival stream experienced roughly the same head wind and head wind error, resulting in little to no drift between flights and, hence, no losses of separation.

Arrival Time Accuracy and Precision

To characterize the accuracy and precision with which the AAC Arrival Manager delivered aircraft to the arrival schedule, histograms were generated of the arrival-time error for all arrival flights. Arrival time error was measured as the difference between the scheduled time of arrival (STA) and the actual time of arrival (ATA) for each aircraft.

Descent CAS Error

Figure 6 depicts the arrival-time error histogram for the 70-second inter-arrival spacing constraint at the meter fix. The mean error was 2.5 seconds, and 98% of flights conformed to their STA to within 6 seconds. These promising results are more accurate and more precise than expected, although the distribution does not have the expected normal distribution form because each CAS error speed was randomly sampled using a uniform distribution between -10 kts and 15 kts. The histograms for the 80- and 90-second inter-arrival spacing constraints were similar to Figure 6.

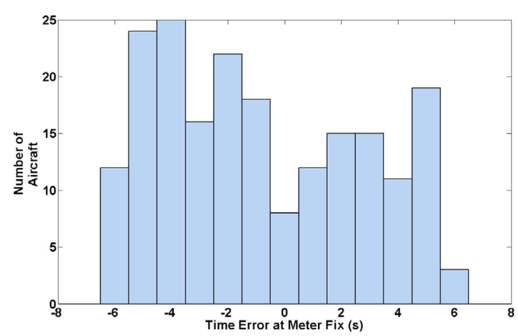

Figure 6. Predicted Arrival Time Error

Wind Error

Figure 7 shows the arrival-time error histogram for the 90-second inter-arrival spacing constraint at the meter fix. As expected, wind error had a larger impact on arrival-time accuracy but had little effect on precision. The mean error was 8 seconds, caused by the wind field drifting all aircraft from both streams more or less uniformly on their descent to the meter fix. Due to the narrow distribution of arrival-time errors, there was little disturbance to the inter-arrival spacing at the meter fix, despite the larger mean error. Similar results were observed from the 70-sec and 80-sec time spacings.

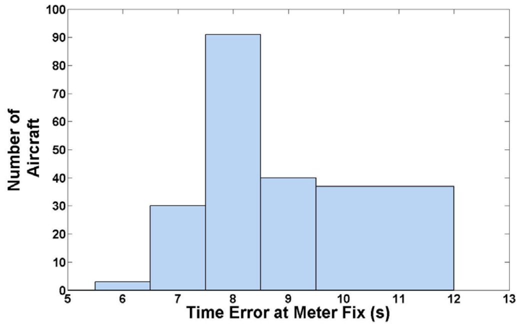

Figure 7. Predicted Arrival Time Error

Inter-Arrival Spacing

Although the desired inter-arrival spacing was set to a fixed value (70 sec, 80 sec or 90 sec) for each test case, the realized inter-arrival spacing was different for two reasons. First, the desired inter-arrival spacing interval may have had to be compromised (made larger) to accommodate a traffic merge or conflict resolution maneuver for the trailing aircraft. Second, trajectory uncertainty in the form of descent CAS error or wind prediction error induced arrival-time errors that caused the actual inter-arrival spacing to be more or less than the amended inter-arrival spacing target. In this section, the magnitude of these two effects is presented.

Descent CAS Error

Figure 8 depicts the first effect described above, showing the frequency with which the planned inter-arrival spacing interval—70 seconds in this case, as denoted by the blue dotted line—had to be compromised by the algorithm, and by how much. The data plotted in red indicates that the planned 70-second interval had to be sacrificed in most cases, typically in order to accommodate a conflict-resolution maneuver inserted by the Arrival Manager for the trailing aircraft. The resulting "expected" inter-arrival spacing interval was most frequently 72 seconds (the mode), and the largest expected interval was 79 seconds.

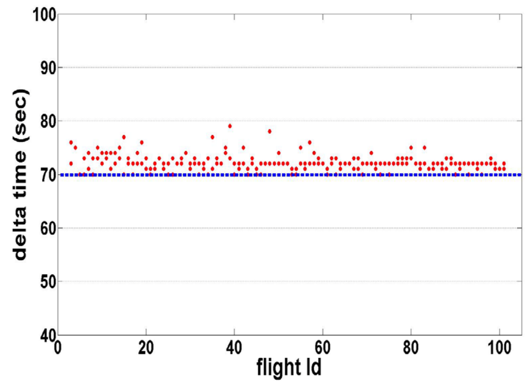

Figure 8. Time Interval Between Successive STA's

Figure 9, then, depicts the second effect described above, showing the actual inter-arrival spacing interval realized as the aircraft crossed the meter fix. The modeled descent CAS error of (15, -10) kts produced significant differences (positive and negative) from the expected spacing intervals depicted in red in Figure 8. Similar results were observed in the 80-sec and 90-sec interval test cases.

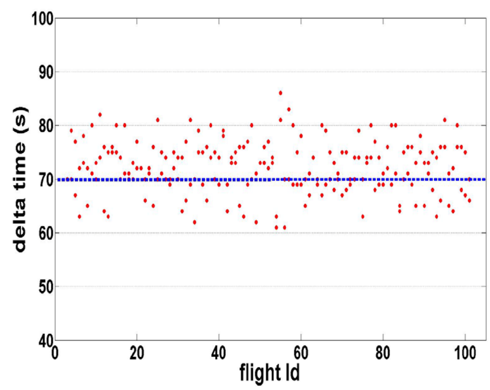

Figure 9. Time Interval Between Successive ATA's

Two observations can be made from these results. The complexity of the airspace structure in terms of merging or intersecting routes and the complexity of the traffic flow in terms of predicted conflicts introduce significant delay and stochasticity into the system (ref. Figure 8). Subsequently, descent CAS error further disrupts the arrival process, introducing additional stochasticity that would likely require the incorporation of considerable safety buffers in the form of spacing margins to accommodate unexpectedly early arrivals such as those points near the bottom of the data range in

Figure 8. Such margins would presumably come at the expense of throughput and runway utilization.

Wind Error

As expected, the modeled wind errors were less disruptive to the system than the modeled descent CAS errors. Figures 10 and 11 depict the scheduled and actual inter-arrival spacing intervals, respectively. A reason for the reduced variance observed in these data is that while CAS error was applied to each individual aircraft's flight trajectory, the wind error was applied to the wind field as a whole, thereby affecting the aircraft in a correlated way. Results for the 80-sec and 90-sec interval test cases were similar to those presented in Figures 10 and 11.

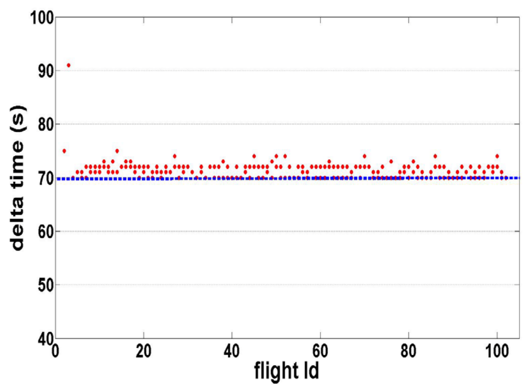

Figure 10. Time Interval Between Successive STA's

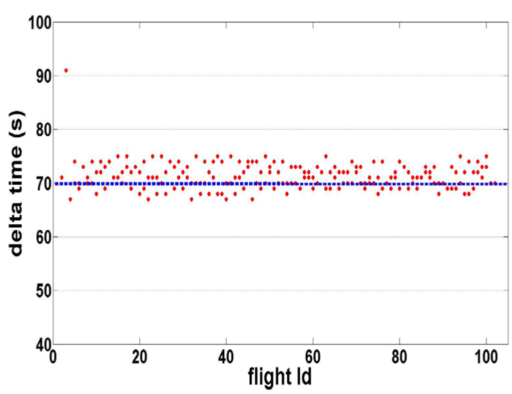

Figure 11. Time Interval Between Successive ATA's

Scheduled Delay

Scheduled delay is the difference between the original expected time of arrival (OETA) for a flight at the meter fix and its STA. The OETA for each aircraft is recorded as it crosses the freeze horizon and is independent of any Arrival Manager maneuverings or scheduling. However, when the Arrival Manager applies flight maneuvers to avoid any future conflicts due to a constant descent CAS error, a new scheduled time of arrival for each flight is assigned. Scheduled delay, then, is the difference between the final STA assigned to an aircraft and its OETA.

Descent CAS Error

Figure 12 shows an overlay of the scheduled delay for each aircraft; color is used to differentiate between the 70-, 80- and 90-sec planned inter-arrival spacing intervals at the meter fix. All four different random seeds (A, B, C, & D) are depicted. The flight data was separated into two sets of 100 flights because of the algorithm's time delay limitation of 5 minutes. Without this separation, time delay would have accumulated very fast hence reaching the 5 minute limitation. Also Figure 12 shows a positive slope with slightly less variance between flights 1 and 30 than for flights 40-100. This means while all random seeds had an effect and larger meter time spacing had a minimum effect, the constant descent CAS error had an impact in producing airborne delay.

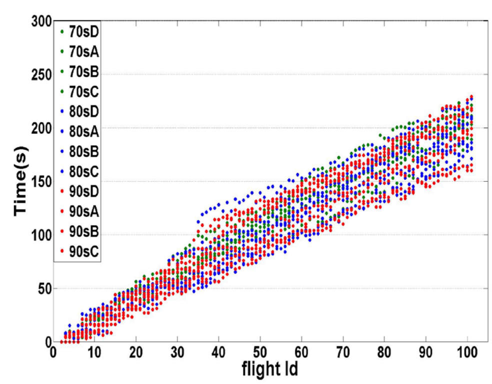

Figure 12. Scheduled Delay for All Spacing Intervals an All Seeds

Wind Error

It was anticipated that a wind error airborne scheduled delay would be much less significant than that of the descent CAS error scheduled delay. The slow time delay progression of the wind error is due to the small wind field directional changes as each aircraft from both streams experiences a head wind with no drift between aircraft while on descent to the meter fix. In comparing each error's trend, the CAS error has a much steeper slope than that of the wind error, implying that the effect of the wind error was less than the effect of the descent CAS error. As compared to Figure 12, Figure 13 shows a slower progression of airborne scheduled delay over the course of the arrival process.

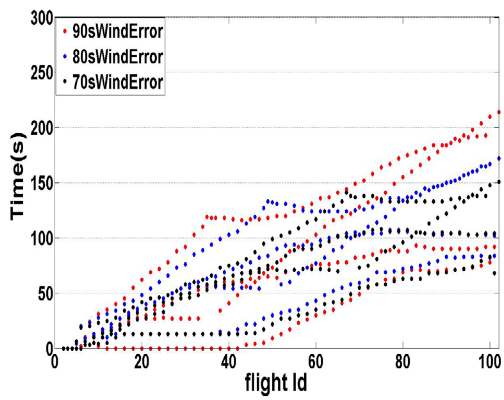

Figure 13. Scheduled Delay for All Spacing Intervals and All Seeds

Discussion

To study the performance of the Arrival Manager certain errors were chosen to model two non realistic scenarios. As a baseline, preliminary data showed no LOS's and no scheduled delays when CAS and wind speed errors were not applied. All merging arrival flights arrived at the meter fix with their corresponded intended separation times. It was then extended to use CAS and wind speed errors to the simulations. A uniform distribution of data was selected to the study for the descent CAS uncertainty experiment. Using a uniform distribution, it gives a basic understanding of how the integrated automation system performed under descent CAS error effects. This can then be further extended to different types of data distributions which can be optimized and aggregated to represent a more comprehensive and realistic study. The results for both error study cases would be expected to change. Also, a flight data run for a 2.5-hr high traffic flow is an extreme case of study since most high traffic flows have short time limit durations throughout the day. A descent CAS and wind error value was chosen instead of a percentage. The reason for doing this was to obtain more direct control over the error range. Also, a less constrained inter-arrival spacing interval for the Arrival Manager scheduling would provide a more realistic representation.

An increase of a horizontal distance separation buffer between aircraft was added to decrease the number of LOS near the meter fix for a 70s time seperation. However, the horizontal distance separation buffer had no effect on the results. An increased vertical separation buffer could have been considered but was out of scope for this study.

Conclusions and Future Work

The Arrival Manager is part of an integrated ground-based approach to separation assurance in the presence of meter fix crossing constraints. The work presented explored the effects of descent trajectory prediction errors on the performance of the AAC Arrival Manager in a simplified time-based metering environment. The goal of this study was to characterize the impact of certain errors in predicted descent calibrated airspeed (CAS) and wind speed on the performance of the Arrival Manager algorithm in terms of metering conformance, airborne delay and the number of LOS.

Under wind speed error the imposed descent CAS error had a significant and greater effect. Wind speed error resulted in no LOS and only a slower accumulation of airborne scheduled delay than CAS error. Crossing time errors at the meter fix were between -6 sec and 6 sec in the presence of descent CAS errors and +6 to +10 sec in the presence of wind errors. Losses of separation were fewer for the larger inter-arrival spacing requirements at the meter fix, with no significant disparity in induced delay. These results suggest that the AAC Arrival Manager performed well.

Future studies should examine more uncertainty types, for example weight, Top of Descent (TOD), cruise speed, and maneuver initiation time. Comparing these errors to real aircraft trajectory data will help to obtain a best estimate for aircraft trajectory prediction errors. The inclusion of more meter fixes, the combined error effects, buffer estimation, maximum throughput estimate, and the variations of high and low traffic flows would result in a more complete modeling of uncertainty errors.

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