

# INTERVAL MANAGEMENT WITH SPACING TO PARALLEL DEPENDENT RUNWAYS (IMSPiDR) EXPERIMENT AND RESULTS

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## Abstract

*An area in aviation operations that may offer an increase in efficiency is the use of continuous descent arrivals (CDA), especially during dependent parallel runway operations. However, variations in aircraft descent angle and speed can cause inaccuracies in estimated time of arrival calculations, requiring an increase in the size of the buffer between aircraft. This in turn reduces airport throughput and limits the use of CDAs during high-density operations, particularly to dependent parallel runways. The Interval Management with Spacing to Parallel Dependent Runways (IMSPiDR) concept uses a trajectory-based spacing tool onboard the aircraft to achieve by the runway an air traffic control assigned spacing interval behind the previous aircraft. This paper describes the first ever experiment and results of this concept at NASA Langley. Pilots flew CDAs to the Dallas Fort-Worth airport using airspeed calculations from the spacing tool to achieve either a Required Time of Arrival (RTA) or Interval Management (IM) spacing interval at the runway threshold. Results indicate flight crews were able to land aircraft on the runway with a mean of 2 seconds and less than 4 seconds standard deviation of the air traffic control assigned time, even in the presence of forecast wind error and large time delay. Statistically significant differences in delivery precision and number of speed changes as a function of stream position were observed, however, there was no trend to the difference and the error did not increase during the operation. Two areas*

*the flight crew indicated as not acceptable included the additional number of speed changes required during the wind shear event, and issuing an IM clearance via data link while at low altitude. A number of refinements and future spacing algorithm capabilities were also identified.*

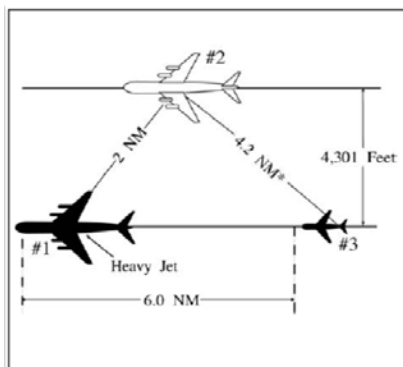
## 1 Introduction

Commercial aviation operations are forecast to grow 3.7% annually for the next 20 years, and annual revenue passenger miles to double by 2023 [1]. To offset this anticipated growth, many aspects of aviation are being explored to increase operational efficiency and reduce fuel consumption. One promising area is arrival procedures at major airports during high-density operations. Current arrivals typically have intermediate level-off altitudes to deconflict routes and improve time control. This maintains high airport throughput, but imparts an additional operating cost to aircraft. To address this, Continuous Descent Arrivals (CDAs) have been developed to reduce fuel consumption and noise by using near-idle trajectories to the runway. However, the range of optimum descent angles and speeds cause a larger error distribution of the estimated time of arrival for these aircraft. One approach has been to increase the size of the spacing buffer between aircraft to ensure safe separation is always maintained; however, this reduces airport throughput.

A different approach to enable the use of CDAs to achieve improvements in aircraft

efficiency without impacting airport throughput is the flight deck based concept called Interval Management with Spacing (IM-S). NASA Langley Research Center has conducted work in this type of terminal area arrival operations for many years [3-6], and recently worked directly with the FAA to develop the IM Concept of Operations [7], as well as safety and performance analyses [8]. (Note: the name recently changed to Interval Management, and will be referred to as IM in this paper.)

Arrivals to parallel dependent runways are particularly challenging due to different separation criteria for aircraft proceeding to each runway. The separation criteria are based on either wake vortex category or distance between runway centerlines, and changes once the trail aircraft is established on final (Figure 1) [2]. During high-density parallel dependent arrivals, CDAs are not used due to the variability of each aircraft's flight time. It is postulated that IM may enable the use of CDAs during this operation.



**Fig. 1. Aircraft Separation Criteria**

This paper describes the Interval Management with Spacing to Parallel Dependent Runways (IMSPiDR) experiment conducted at NASA Langley in 2011. Commercial pilots flew CDAs during high-density operations into the Dallas Fort-Worth (KDFW) airport, using airspeeds generated onboard the aircraft. Results in this paper focus on algorithm performance and behavior. Other papers contain results for flight crew acceptance and usefulness of cockpit displays [9], and data link procedures [10].

## 2 IM to Dependent Parallel Runways

### 2.1 Concept Overview

The operational goal of IM is to achieve a precise interval between aircraft at an *achieve by point*. The *achieve by point* can be the runway threshold, a meter fix, or any other waypoint ATC specifies (the runway threshold was used in this experiment). The spacing algorithm is capable of controlling to a time or distance spacing interval, and can use either a 'step-down' or CDA procedure. However, the benefits of IM are expected to be more pronounced when CDAs are used; particularly during parallel dependent runway operations.

The IM operation begins when scheduling software calculates deconflicted Required Time of Arrivals (RTAs) to the runways. This information is presented to controllers as a list of aircraft callsigns and RTAs (current day operation), and as a list of Target aircraft and spacing intervals (IM operation). These are different versions of the same schedule, and produce identical results if both procedures are conducted correctly. The controller issues the IM clearance to crews of suitably equipped aircraft, who enter the information into the spacing tool and then fly the IM speed it generates [11].

RTA operations are not required in the IM concept; however, they were included in this experiment to allow flight crew to conduct operations when outside of Automatic Dependent Surveillance – Broadcast (ADS-B) range from the Target aircraft. Furthermore, the spacing algorithm's RTA functionality was used to provide comparison data to the IM behavior, and is significantly more precise than current day RTA operations derived from Flight Management Computers (FMC).

#### 2.1.1 The Schedule

The IM operation begins with a schedule of arrival times to a particular runway, for all arriving aircraft, arriving from any direction. The RTAs at the runway thresholds are set to create a logical arrival sequence that allows aircraft to fly a feasible and efficient airspeed, and must meet or exceed safe separation and

wake vortex spacing criteria. The FMC calculated planned Final Approach Speeds (FAS) of the Target and IM aircraft, and used these speeds to establish the required offset at the Final Approach Fix (FAF) to compensate for the change in spacing that occurs after the FAF due to differences in FAS.

The schedule must identify IM capable aircraft and provide information required to issue an IM clearance to the controller that contains the Target (lead) aircraft, the Target's route of flight, and the assigned spacing goal. The spacing goal is given as a time interval behind aircraft landing on the same runway, and in distance for aircraft landing on a parallel runway.

### 2.1.2 The Controller

Prior to the aircraft reaching Top Of Descent (TOD), the controller issues the spacing clearance to flight crews of appropriately equipped aircraft. Clearances used during the IMSPiDR experiment were aligned with existing guidance [7,8]. Due to the complexity and length of an RTA+IM clearance for dependent parallel runway operations, only Controller Pilot Data Link Communications (CPDLC) was used in this experiment. Below is an example of a message containing the RTA+IM clearance issued to NAS557. (Figures 2, 4, and 6 are from a run using this clearance.)

```
CROSS R-17C AT 0026:30Z. WHEN
ABLE CLEARED IM-SPACING 120
SEC WITH NAS163 AND 2.2 NM
WITH EGF132. ACHIEVE BY R-
17C. TERMINATE AT R-17C.
NAS163 ROUTE HYDES MASTY3
BOSSI ILS17C, FAS 126 KT.
EGF132 ROUTE INK JEN9 YOHAN
ILS18R, FAS 133 KT. REPORT
COMMENCING IM-SPACING.
```

The corresponding RTA only clearance is:

```
CROSS R-17C AT 0026:30Z.
```

### 2.1.3 The Flight Crew

Flight crews followed established procedures, in operational use today, to evaluate and accept

clearances delivered via CPDLC. After receiving the IM clearance via CPDLC, the flight crew 'auto-loads' the clearance into the onboard spacing tool (i.e., no manual typing required) via the Multi-function Control and Display Unit (MCDU). The crew then activated the tool, reviewed the IM speed calculated by the tool, then sent an 'ACCEPT' or 'REJECT' downlink message based on their determination of operational feasibility. The crew then attempted to remain within 5 knots of the IM Command Speed (the green speed bug in Figure 2) by setting the speed in the Mode Control Panel (MCP) and modulating the throttles and speed brake.

## 2.2 Airborne Spacing Algorithm

NASA Langley Research Center has developed the trajectory-based Airborne Spacing for Terminal Arrival Routes (ASTAR) algorithm. Capabilities from previous versions of ASTAR used in the IMSPiDR experiment included:

- achieve a time at a point (RTA),
- achieve a time interval or spacing distance behind an aircraft (IM)
- meet a time at a point, then transition to relative spacing once valid ADS-B information becomes available (RTA+IM)
- incorporation of forecast wind data
- maximum speed within 10% variation of published speed for that segment
- compensation for different FAS flown by the Target and IM aircraft
- error notch, gain schedule, and 'look-ahead' to reduce the number of speed changes
- transition to FAS when the IM aircraft crosses the Final Approach Fix

For dependent parallel runway operations, the ASTAR10 version included the following enhancements [12]:

- trajectory and spacing calculations for two aircraft (one landing on a parallel runway)
- compensation for offset runway thresholds
- accommodation of changes to aircraft separation criteria after aircraft are established on final

- a command lead-time compensation for flight crew and auto-throttle reaction time

ASTAR10 calculates the ‘raw’ time errors to achieve the RTA and to achieve the spacing interval behind each Target aircraft. A ‘filtered’ time error is used to calculate the IM speed commands, which employs notch filtering and gain scheduling to reduce the number of speed changes. The ASTAR10 spacing algorithm generates two speed commands: the IM Commanded End Speed, and an instantaneous IM Commanded Speed. The IM Commanded End Speed is an estimate of the commanded speed at the completion of a speed change and is the speed set in the Mode Control Panel by the crew, and is displayed in the upper left of the Primary Flight Display (PFD) in Figure 2. The IM Commanded Speed is the instantaneous speed estimated by ASTAR10 to account for deceleration, and is shown as a green speed bug on the speed tape of Figure 2.

Once valid position and route data to either Target aircraft are available, the IM speeds displayed to the crew are to achieve the spacing interval behind the Target aircraft (in seconds

for in trail aircraft, and nautical miles for an aircraft on the parallel approach) by the runway threshold. If position and route data for both aircraft are available, the time error to achieve both spacing intervals is calculated, but the IM Speeds displayed to the crew are based on the ‘controlling’ aircrafts’ data. This is the aircraft that requires the FIM aircraft to be the farthest aft, thereby ensuring that both spacing intervals are met or exceeded.

The flight crew is not required to know which Target aircraft the displayed IM speeds are based on, however they were required to notify ATC when the algorithm had switched from RTA to RTA+IM mode. However, the crew may ascertain which Target aircraft the IM speeds are based on by selecting the IM page on the MCDU, or from the Navigation Display (ND) symbology. The ND displays both Target aircraft with a matching outer icon (in this case a diamond) and the aircraft’s callsign, with the controlling Target outer icon and callsign in green (NAS163 in Figure 2).

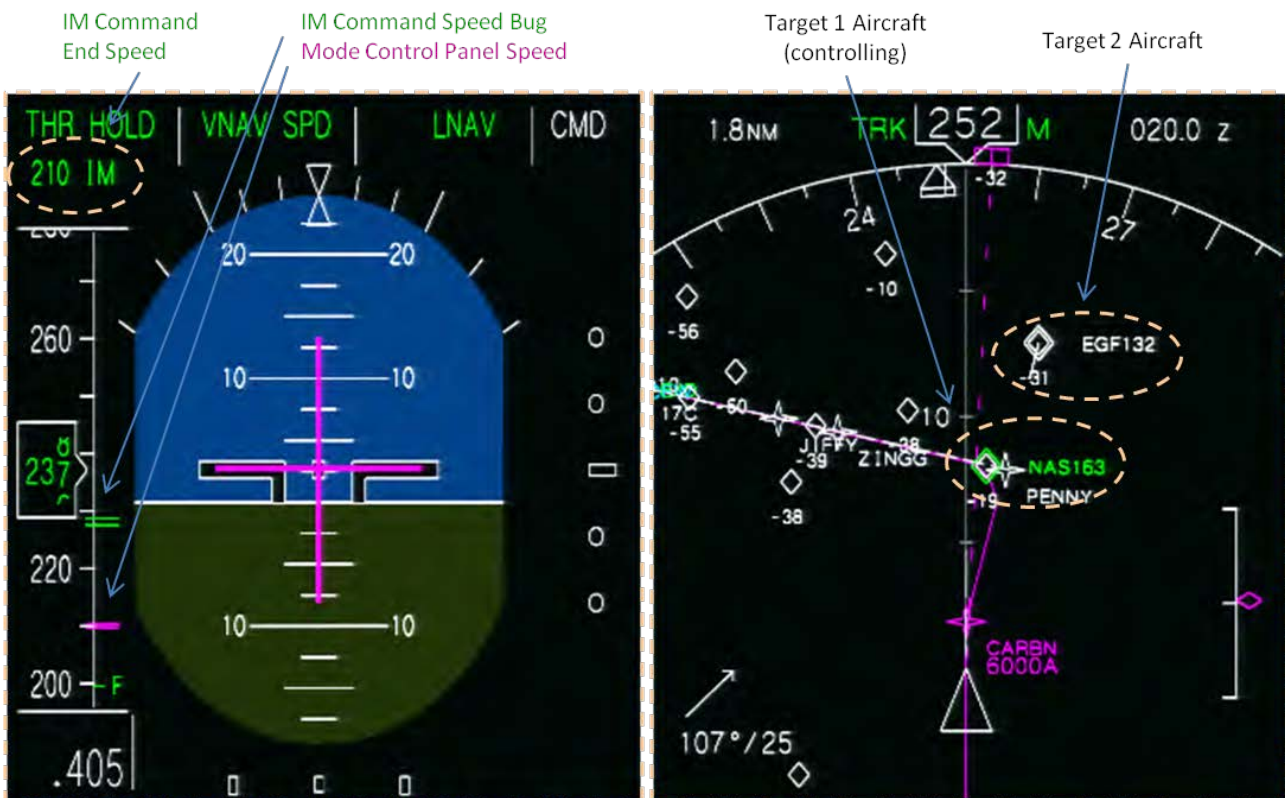


Fig. 2. Displays of IM Speeds and Target Aircraft

### 3 Simulation Description

#### 3.1 Experiment Objectives

Objectives of the IMSPiDR experiment included delivery precision of aircraft to the runway threshold, the stability of the aircraft arrival streams, flight crew acceptance of workload and IM-S procedures, and identifying potential operational issues of the IM-S concept. Scenarios and parameters were selected to test the spacing algorithm and flight crew procedures under stressful conditions (steep CDAs, lengthy CPDLC messages, cumbersome flight crew interfaces, high traffic volume, etc), and not designed to represent the most likely implementation of IM operations.

#### 3.2 Test Facilities and Equipment

Three different simulators were used to explore a range of current and future aircraft equipage. The first simulator was the medium-fidelity Air Traffic Operations Laboratory (ATOL), employing the Airspace and Traffic Operations Simulation (ATOS) platform and the Multi Aircraft Control System (MACS) [13]. ATOS is a network of Aircraft Simulation for Traffic Operations Research (ASTOR) computer stations. Each station contains two video monitors, is equipped with experimental cockpit displays and pilot interfaces, and is operated by either a single pilot or 'Pilot Model' software logic. Components include: six degrees of freedom equations of motion aircraft model, PFD, ND, autopilot and auto-throttle systems, FMC, MCDU, MCP, CPDLC, ADS-B, and ASTAR10.

The Integration Flight Deck (IFD) is a full-scale high-fidelity simulator of a large commercial transport aircraft with standard operational instruments (Figure 3). The cockpit's visual system is a panorama system that provides 200° horizontal by 40° vertical field-of-view. The visual scene was identical to the DTS.



**Fig. 3 Integration Flight Deck (IFD)**

The Development and Test Simulator (DTS) is a full-scale simulator representative of a large commercial transport category aircraft. The DTS has a 210° horizontal by 45° vertical out the window field of view, is equipped with eight D-Sized LCD displays, sidestick controls, rudder pedals, two color Control Display Units (CDU), and additional interface devices derived from a variety of other transport aircraft. The visual display was the KDFW terminal environment and all aircraft traffic in a daytime setting.

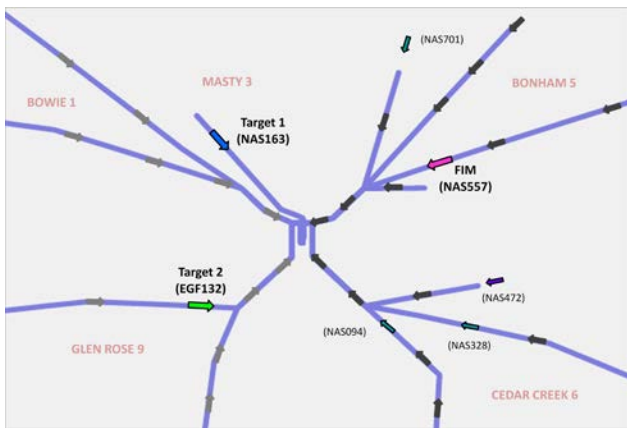
#### 3.3 Scenarios

##### 3.3.1 Nominal Scenario

Simulated CDAs into KDFW were created by laterally overlaying existing arrival routes and removing most altitude constraints (approach constraints were retained) and creating the steepest angle considered acceptable by the FAA's Terminal Area Route Generation, Evaluation, and Traffic Simulation (TARGETS) software. Each scenario contained 35 aircraft on one of 14 CDAs into KDFW, 25 aircraft departing KDFW, and 4 aircraft arriving to Dallas Love (KDAL). Arriving aircraft not flown by subject pilots were generated using 'Pilot Model' ASTOR stations, and departing aircraft generated by MACS. The aircrafts' initial conditions (callsign, route, altitude, arrival sequence) were identical during the ten data collection runs, while the particular aircraft flown by the subject pilot varied by run.

The six aircraft flown by subject pilots were in the middle of the arrival stream and in

level flight. Four of the six aircraft were ASTOR stations, one the DTS, and one the IFD (the pilots did not change their location during the experiment). Figure 4 shows the approximate starting position of aircraft arriving to KDFW, with the 6 aircraft flown by subject pilots identified by their NASA callsign. Prior to top of descent, a CPDLC message was issued containing either the RTA or RTA+IM clearance. The aircraft receiving the RTA+IM clearance in Section 2 is shown as a magenta arrow, and the Target aircraft as blue and green arrows. (Some results in Section 4 are also based on this scenario.)



**Fig. 4. Arrival Routes and Aircraft Position**

Four confederate controllers issued traffic callouts, frequency changes, and landing clearances to the six aircraft flown by subject pilots. Voice communications between controllers and ‘Pilot Model’ ASTORs were pre-recorded and played back at the appropriate time to enhance operational realism.

### 3.3.2 Exploratory Off-Nominal Scenario

One exploratory scenario (only questionnaire data analyzed) examined a range of operational events, to include the Target aircraft slowing down unexpectedly, inserting aircraft into the arrival stream, spacing behind aircraft landing on a converging runway, issuing a new RTA+IM clearance below 10,000’ MSL, and changing the assigned spacing goal. The scenario utilized the same aircraft callsigns and routes; however, the arrival sequence was different. Smaller spacing intervals appropriate for visual conditions were used, and the

RTA+IM clearance was for one Target aircraft (independent runway operations).

### 3.4 Experiment Design

The IMSPiDR experiment used a 2x3 test matrix with two replicates. Time constraints precluded flying the second replicate of ‘no error’ conditions, therefore each pilot flew ten nominal scenarios followed by the one off-nominal scenario.

The spacing algorithm ‘Control Method’ was the first independent variable, and the options were: RTA or RTA+IM. Although RTA only operations are not part of the IM Concept, they were included to allow operations outside of ADS-B reception range, and for comparison of control to an absolute time (RTA) or relative time behind another aircraft (IM). Additionally, the RTA functionality provided by ASTAR10 is significantly more capable than typical RTA performance available in current day aircraft.

The ‘Error Condition’ was the second independent variable, and the options were: No Error, Wind Error, and Offset Error. The ‘Wind Error’ scenarios replicated an operational environment with a constant and cumulative error. This was accomplished by using actual winds different from the forecast winds, and a significant wind shear just prior to turning on final at 5000 feet (a tailwind for aircraft arriving from the east and headwind for those from the west). The ‘Offset Error’ scenarios replicated an operational environment with a single, pulsed error (a 30 second delay applied to the schedule). The ‘Offset’ RTA scenarios contained a second CPDLC clearance approximately nine minutes into the scenario that delayed each aircraft’s landing time by 30 seconds. The ‘Offset’ RTA+IM scenarios had a second CPDLC message sent to only one aircraft (immediately preceding the first subject pilot aircraft). The error propagated through the stream as each aircraft that received the CPDLC message modified its speed to adhere to the new clearance.

### 3.5 Pilots and Experiment Procedure

Twenty four current, commercial airline pilots employed by major U.S. air carriers were used in 3 groups of 8 participants, each group completing the experiment in 2 ½ days. To minimize potential effects associated with different airline operating procedures, all two-person crews were paired from the same airline. The pilots received approximately a half day of training, including several hours of hands-on training in the simulators, supplemented by pre-mailed reading material. Following each run, pilots completed a post-scenario questionnaire, and after the final scenario, a post-experiment questionnaire and group debriefing session.

## 4 Results and Discussion

Since the focus of the research was the ASTAR10 spacing algorithm’s performance, worst-case conditions and some compromises to current air traffic procedures were made to challenge the algorithm. Arrival procedures had level segments removed to reduce the controllability of the algorithm, and events were timed to coincide to provide distraction to the flight crew (CPDLC messages occurred just after ATC gave a traffic point-out, etc.).

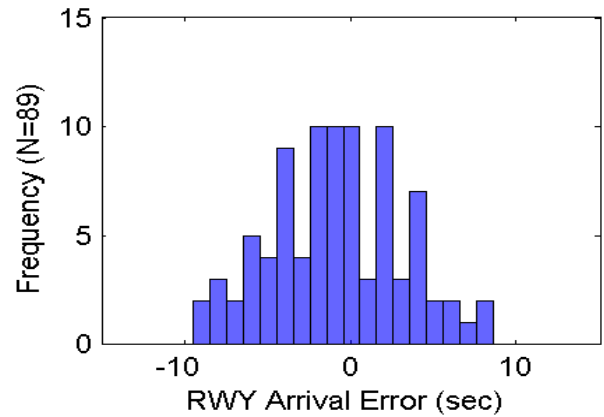
### 4.1 Spacing Algorithm Delivery Precision

The primary goal of the ASTAR10 spacing algorithm is precise delivery of aircraft to the runway threshold at the assigned interval behind the two Target aircraft. Results from IMSPiDR indicate all aircraft using relative spacing (RTA+IM) were able to arrive at the threshold within a mean of 2 seconds (4 seconds standard deviation) of the assigned spacing goals regardless of the error source or the runway they landed on (Table 1).

**Table 1. Runway Arrival Error**

Error Source	RTA only		RTA+IM	
	Mean (s)	SD (s)	Mean (s)	SD (s)
None	-3.30	4.87	-1.81	3.87
Wind	3.53	3.28	0.90	3.91
Offset	-2.30	3.25	-2.16	3.29

Despite the lengthy IM clearance, the cumbersome CPDLC crew procedures, and significant forecast wind error and wind shear, the results align with or improve upon results from previous research. [3,4,5,6] A histogram of the spacing error for the piloted aircraft during RTA+IM scenarios is shown in Figure 5.



**Fig. 5. Histogram of RTA+IM Time Error at Runway Threshold for Piloted Aircraft**

ASTAR10 and the IM flight crew procedures are able to precisely deliver aircraft to the runway threshold during dependent parallel runway operations, in the presence of fairly significant wind error and time offset.

### 4.2 Spacing Algorithm Performance

Figure 6 contains typical algorithm performance observed during the IMSPiDR experiment, and is used to explain in detail how the ASTAR algorithm works, and the impact of flight crew performance on the IM operation. This particular data is from the IFD during a RTA+IM with forecast wind error and wind shear scenario, with both Target aircraft beginning outside of ADS-B range. The FIM aircraft is NAS557 arriving from the east, and issued spacing intervals of 120 seconds behind NAS163 and 2.2 nautical miles behind EGF132 (see CPDLC message in Section 2 and Figure 4 in Section 3). The horizontal axis for all plots is “Distance to go in NM”.

The top panels describe the ASTAR10 calculated time error. The raw time error for Target 1 (dashed blue line), raw time error for Target 2 (dashed green line), and ‘filtered’ time error (solid magenta line). The three colors

align with the colors in Figure 4. Also shown are when the algorithm switched from RTA to IM control method and between Target aircraft (vertical magenta lines), and when the algorithm ceased correcting for spacing errors and transitioned to FAS (black triangle).

In this scenario, the ‘filtered’ time error began at 120 nm (approximately 2 minutes into the scenario), when the RTA+IM clearance was entered by the flight crew into the onboard spacing tool. The ‘filtered’ time error (used to compute the IM Commanded End Speed and IM Commanded Speed) was calculated to achieve the RTA at the runway until 101 nautical miles (nm) when it transitioned to achieving the spacing goal for Target 1. After that point, the algorithm’s selection of controlling aircraft was based on whichever Target aircraft required the latest arrival time for the FIM aircraft. The switch at 20 nm from Target 1 to Target 2, and back to Target 1 at 12 nm, was due to the significant wind shear at 5000’. At 5.5 nm from the runway, the IM Commanded Speed no longer used the ‘filtered’ time to correct spacing error, instead it switched to the Final Approach Speed (black triangle).

The second row of panels illustrates the spacing algorithm correcting for the time error in the top row. Shown are the speed of the published approach (solid black line), IM Commanded End Speed (dashed magenta line, corresponds to speed in upper left of Figure 2), when the basis of the ‘filtered’ time error changed (vertical dashed magenta lines), and the transition from Mach to airspeed (red ‘X’). The horizontal segment left of the ‘X’ indicates level cruise flight (130 to 115 nm distance to go), with the sloped segment left of the ‘X’ a constant Mach descent (115 to 95 nm distance to go). At approximately 101 nm from the runway, the ADS-B signal from Target 1 was received, and the ‘filtered’ time error calculation based on Target 1 resulted in a five knot increase of the IM Commanded End Speed. Positive time error (aircraft arrives late) results in IM speeds higher than the published speed (e.g., from 95 to 65 nm), and negative time error (aircraft arrives early) results in IM speeds less than the published speed (e.g., 14 to 6 nm). The multiple speed changes and the large speed

differential between IM and published speeds after 15 nm is a result of the FIM aircraft descending below the unexpected wind shear, and the resulting change in estimated time of arrival at the runway for that aircraft.

The third row of panels illustrates the flight crews’ performance to achieve the IM Speed. The IM Command Speed (solid magenta line corresponds to green speed bug in Figure 2) is the estimated instantaneous speed based on the IM Commanded End Speed and the aircraft’s deceleration rate. Also shown is the aircraft’s airspeed (dashed black line), and flap and gear deployment (blue and green dots).

The bottom row of panels describes crew actions in response to an IM ‘Drag Required’ message that appeared when the airspeed was more than 6 knots above the IM Command Speed (red line), percent speed brake deployment (black line), and throttle lever angle (blue line).

Overall, the flight crew on this particular run exhibited precise speed control, with the wind shear during the turn to final creating several interesting effects. One interesting event occurs at 21 nm (brown bar in Figure 6, and corresponds to Figure 2). The FIM aircraft had been on speed with no time error at 23 nm; therefore, the ASTAR10 algorithm commanded the next published speed (210 knots). The extra thrust generated by not having the throttles at idle kept the aircraft from decelerating as rapidly as the algorithm had expected. This would be expected to cause the ‘filtered’ time error to decrease (aircraft arrive early), however in this scenario, the wind shear overwhelms the error generated by the deviation in airspeed from IM Command Speed. Furthermore, Target 1 and Target 2 errors are affected differently due to the arrival route geometry. The time error for Target 1 arriving from the north increases (FIM aircraft late), despite the FIM crew flying slightly faster than the IM Commanded Speed. This occurs because Target 1 has descended below the wind shear, and the faster ground speed creates an earlier ETA at the runway for Target 1. This in turn generates a 5 knot increase in IM Commanded Speed at 21 nm for the FIM aircraft. Meanwhile, due to arrival geometry, the time error for Target 2 from the



west has been decreasing (FIM aircraft early) due to the slower than anticipated progress (caused by the unexpected headwind). This causes Target 2 to become the ‘controlling’ aircraft at 19.5 nm.

A second characteristic of this run is the flight crew correctly perceived by 16 nm that maximum deceleration was needed. They fully deployed the speed brakes, deployed the flaps as early as possible, and lowered the gear considerably earlier than normal. This enabled the aircraft to achieve the IM Commanded

Speed, which was significantly less than the published speed, thereby reducing the spacing error caused by the wind shear. Had they not foreseen the need for drag, there would have been considerable time error at the runway.

Finally, during the final four miles the time error increases (top right panel, the FIM aircraft arrives early) despite the aircraft’s actual speed being equal to the IM Commanded Speed. This is due to the error between the forecast wind and actual wind during this scenario.

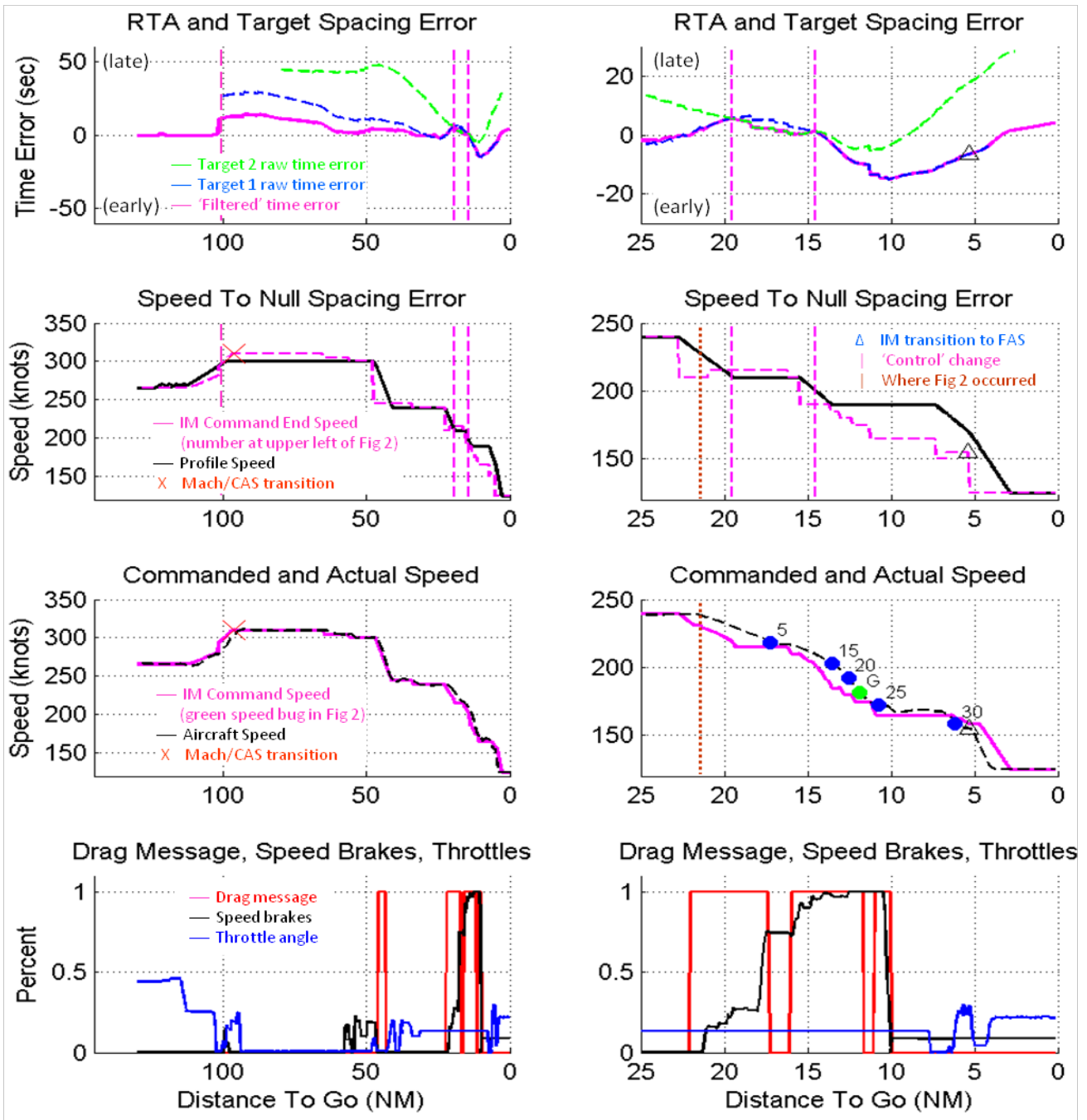


Fig. 6. Algorithm Characteristics for Single Aircraft

### 4.3 Aircraft Arrival Stream Stability

Another key goal of the ASTAR10 spacing algorithm is a stable arrival stream, that is the time error and necessary control inputs (speed changes) do not increase as the string of aircraft lengthens. Figure 7 shows the average absolute value of time error at both runways for the six conditions, with subject pilot aircraft indicated by dots. Operationally significant differences in precision (greater than 5 seconds) were not observed as a function of arrival position. (Data from aircraft prior to the sixth arrival was not used in this particular analysis since they were initialized below 15,000', and data after the last aircraft flown by subject pilots (#24) was not available since the scenarios terminated when the last subject pilot landed.) The aircraft #24 time error during the 'RTA No Error' condition was primarily caused by one ASTOR pilot's confusion on how to operate the ASTOR simulator to configure the gear and flaps with a computer mouse interface. This caused the aircraft to go from -2 seconds (early) at 8 nm to the runway, to -17 seconds when crossing the runway threshold. This condition was flown only once per group, which affected the time error more significantly than the conditions flown twice.

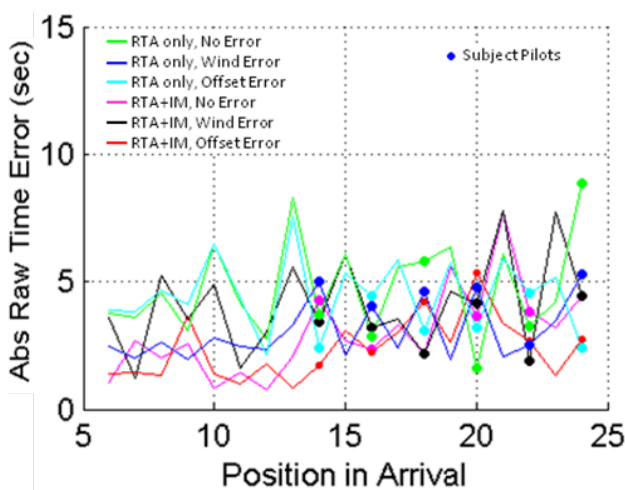


Fig. 7. Absolute Value of Time Error by String Position

A one way Analysis Of Variance (ANOVA) was conducted on each factor shown in Figure 7 to determine if there were any statistically significant differences in the absolute value of the time error at the runway threshold, between arrival positions. If significant differences were found, Tukey's range test was used to determine which arrival positions were significantly different from each other. The results of the ANOVA determined that there were statistically significant differences within every factor ( $P < 0.019$ ); however, Tukey's test showed that the statistical differences did not form a trend of increasing error. Instead, statistical differences between time error at the runway were interspersed throughout the stream, suggesting the differences may have been caused by natural variability (such as differences in configuration and/or pilots). The RTA+IM offset error condition has been included in this paper as an example of this analysis. Figure 8 demonstrates that the variance of the time error increased substantially at the 16th aircraft (the second human piloted aircraft). Figure 9 shows the Tukey 95% confidence intervals. The 20th aircraft in the string (a human piloted aircraft) was the only string position that was statistically different from the remainder of the string positions. The other conditions showed similar trends, indicating that the ASTAR10 spacing algorithm was able to maintain a stable arrival flow for the conditions in this experiment.

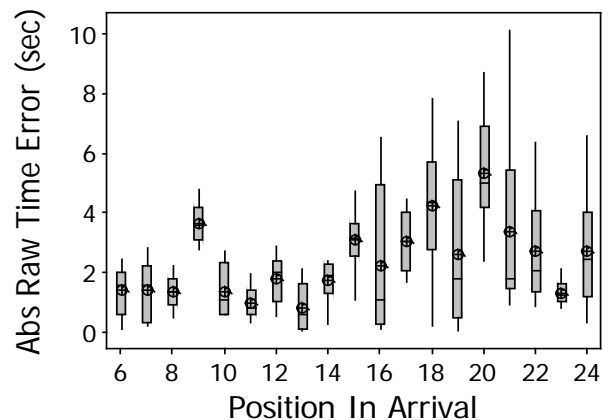
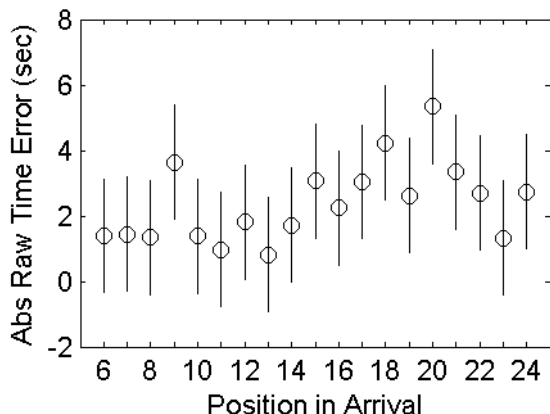


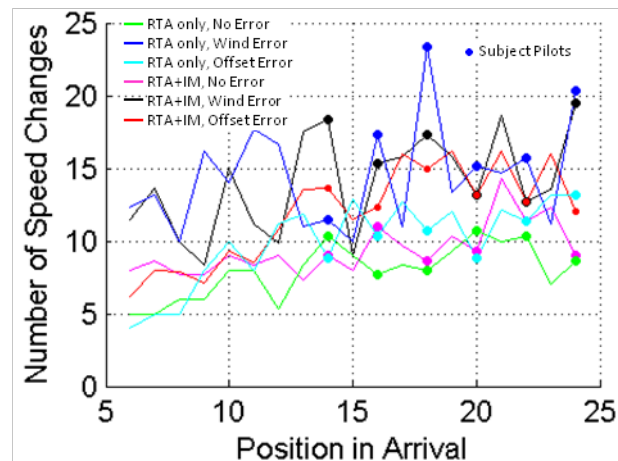
Fig. 8. Time Error by Arrival Position during RTA+IM Offset Error Condition



**Fig. 9. Tukey Test Results by Arrival Position for RTA+IM Offset Error Condition**

Figure 10 shows the number of speed changes, for all aircraft and conditions, as a function of position in the arrival stream. The number of changes increases slightly until aircraft #14, then remains approximately constant until the last aircraft. The initial increase is due to fewer speed changes required for those aircraft (already in a descent or decelerated below 250 knots based on where it was initialized). The constant number of speed changes for aircraft in level cruise flight indicates algorithm performance in the presence of error does not significantly change as a function of arrival stream position. Significant differences were found in the number of speed changes required between the error type ( $p < 0.001$ ), control method ( $p = 0.003$ ), as well as significant interactions between the error type and control method ( $p < 0.001$ ). The RTA only and RTA+IM control approaches yield the lowest number of speed changes during ‘No Error’ conditions. The ‘Offset Error’ condition created more speed changes than the ‘No Error’ condition, with the RTA+IM control having more changes than RTA only. The ‘Wind Error’ condition yielded the greatest number of speed changes.

This analysis indicates, but not conclusively, that the ASTAR10 spacing algorithm is capable of creating a stable arrival stream of aircraft using IM flight crew procedures over a range of operating conditions, uncertainty, and error.



**Fig. 10. Speed Changes Number by Position**

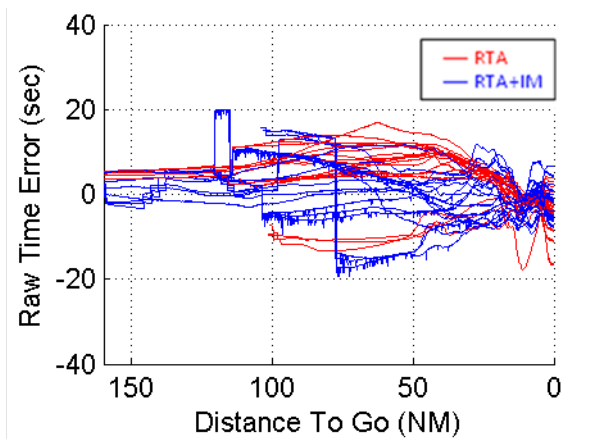
#### 4.4 Arrival Stream Algorithm Performance

The highest number of ASTAR10 speed changes occurred during the ‘Wind Error’ condition for both Control Methods ( $p < 0.001$ ) (Table 2, subject pilot aircraft only), which coincided with the lowest IM procedure acceptability rating by flight crew during post-scenario questionnaires. The majority of the additional speed changes happened during the wind shear, which occurred when the crew were configuring the aircraft and intercepting final.

**Table 2. Speed Changes per Condition**

Error Source	RTA	RTA+IM
No Error	9.28	9.72
Wind Error	17.22	16.11
Offset Error	10.44	13.14

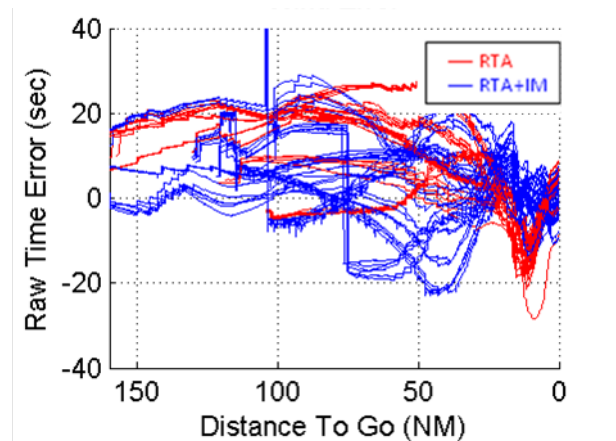
The raw time error at the runway threshold of the 6 piloted aircraft is plotted by control method (RTA in red, RTA+IM in blue) for ‘No Error’ conditions in Figure 11. The high frequency noise during RTA+IM runs are generated by the ASTAR10 algorithm’s updates to ownship and Target position estimation, and are removed as part of the calculations to generate ‘filtered’ time error (used to generate the IM Commanded Speed). The large, singular jumps in RTA+IM data are due to differences between the actual Top Of Descent point of either the FIM aircraft or the Target aircraft, and those estimated by ASTAR10. None of the discontinuities or singular jumps affected the speed that the pilots were provided.



**Fig. 11. Time During No Error Conditions**

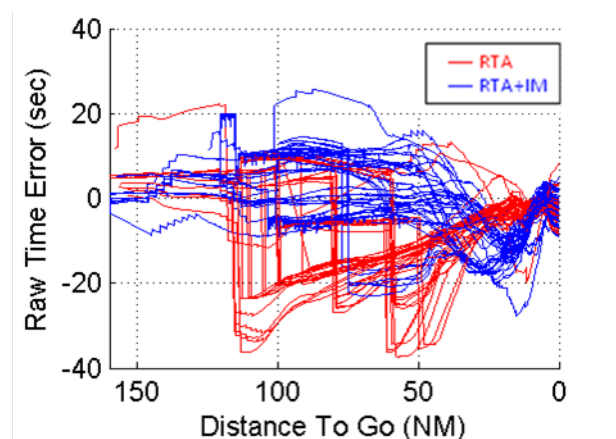
There does not appear to be an operationally significant difference (30 seconds in Center airspace, and 15 seconds in TRACON airspace) between how the RTA and RTA+IM control method corrected the time error. Both control methods exhibited high precision to the FAF with a slight increase in variance by the runway threshold. This increase was primarily due to the flight crew not matching the deceleration schedule from the final IM Commanded Speed to the FAS. Causes for this include: 1) aircraft not within five knots of the final IM Commanded Speed when ASTAR10 switched to FAS, 2) gear and at least flaps 200 not deployed when ASTAR10 switched to FAS, 3) crew response to set FAS not timely, and 4) airspeed allowed to decelerate quicker than IM Commanded Speed or momentarily go below FAS. A potential mitigation strategy is to fix the location where the ASTAR10 algorithm switches to the FAS, thereby allowing crews to anticipate changes to the desired aircraft configuration.

During the ‘Wind Error’ condition, the RTA+IM control method had a greater variation of time error to correct at 40 nm from the runway than the RTA control method did (Figure 12), however both methods delivered the aircraft to the threshold with high precision and little variance (Table 1). Both control methods exhibited an increase in error variance after the FAF (as previously described); however, they also had a 3-second late bias due to the stronger than expected headwind.



**Fig. 12. Time During Wind Error Conditions**

The large, singular jumps in RTA time error during ‘Offset Error’ conditions is due to the second CPDLC message nine minutes into the scenario that delayed the aircraft’s runway arrival time by 30 seconds. The RTA control method appears to resolve time error sooner than the RTA+IM method, however most of the apparent difference is due to how the time error is calculated (that is, the difference of aircraft position using the two control methods was much less than the time shown). There is no statistically significant difference in time error at the runway threshold ( $p=0.27$ ) (Figure 13).



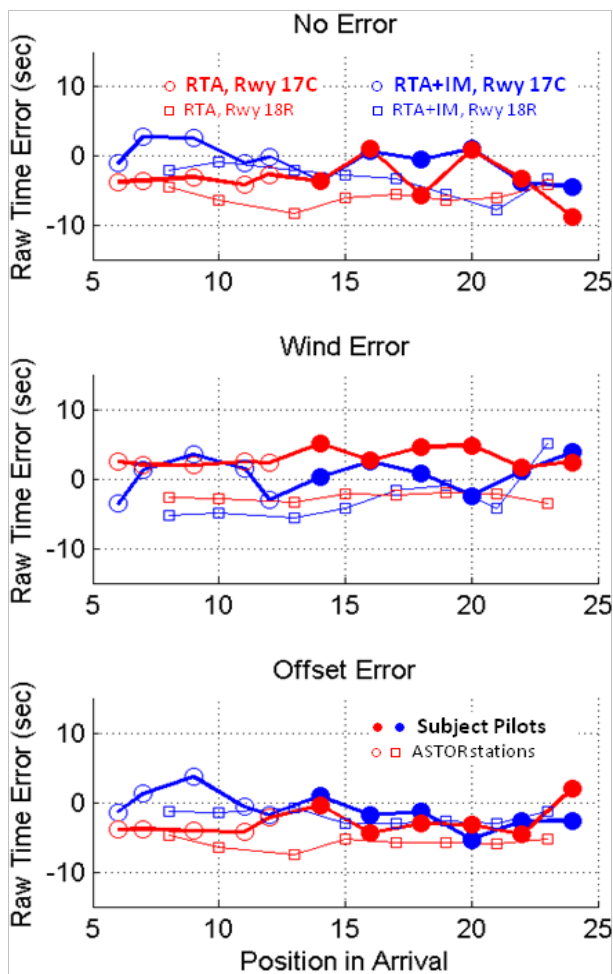
**Fig. 13. Time During Offset Error Conditions**

In summary, although the total amount of time error to be resolved within each error condition was the same, the way that the ASTAR10 spacing algorithm resolved the error was different based on ‘Control Method’ (RTA only, or RTA+IM). Furthermore, the two

specific error types ('Wind' and 'Offset') created different ASTAR10 behavior within that condition based on 'Control Method.'

#### 4.5 Algorithm Performance by Runway

Analysis of time error by landing runway and by position in the arrival stream showed no statistically significant difference between the two control methods during the 'No Error' and 'Offset Error' conditions, and no statistical difference between the two conditions themselves (Figure 14).



**Fig. 14. Time Error by Position by Runway**

The 'Wind Error' condition also indicated no statistical difference for both control methods to a particular runway, and no statistical difference between control methods. However, both control methods showed a bias for aircraft landing on Runway 17C (the eastern runway, with arrival routes having an unforecast tailwind from 24 to 16 miles) approximately 2

seconds late, while aircraft landing on Runway 18R (western runway with unforecast headwind) approximately 4 seconds early. However, the mean spacing error at the runway threshold for all RTA+IM operations for all conditions was less than 2.2 seconds (Table 1). This indicates ASTAR10's ability to respond to unknown and continuous error (forecast wind error and wind shear), and a known pulse error (offset to create time delay).

#### 4.6 Off-Nominal Scenario Results

The exploratory off-nominal scenario examined go-around due to pending loss of separation, inserting an aircraft into the arrival stream, issuing an IM clearance at low altitude, and spacing on an aircraft to a converging runway. ATC issued the IFD flight crews a 'go-around for insufficient spacing' approximately 2 miles from the runway (caused by the Target aircraft slowing to 150 knots 9 miles from the runway). All three crews were aware of the situation developing through voice communication and cockpit displays of traffic location, and felt the closure generated by following the IM Commanded Speed was too great (range, speed, and closure information was intentionally not displayed on the ND).

After the go-around, the IFD crews were also issued a new IM clearance while climbing to 5000'. Even though the aircraft was in the weather (out-the-window display was clouds at this point) and ATC responsible for aircraft separation, crews reported head down time and workload was too great for CPDLC messages and initiating IM clearances in that environment (below 10,000', conducting approach checklists, proximity to other aircraft, etc.).

Approximately 9 minutes into the scenario, flight crews flying the DTS had their IM clearance amended to increase the spacing interval from 100 to 145 seconds (ATC creating a gap in the arrival stream for the 'go-around' aircraft). Approximately 12 minutes into the scenario that IM clearance was canceled and a new IM clearance with a different Target aircraft issued (70 seconds behind the IFD). Several crews commented the workload was manageable but a significant challenge.

The crews spacing behind a Target aircraft proceeding to a converging runway reported no additional workload to conduct that operation.

#### 4.7 Flight Crew Qualitative Results

Overall, flight crews were able to maintain their speed within approximately 6 knots of the IM Commanded Speed; however, they reported a need for more salient notification of changes to that speed (flashing box, chime, etc.).

Crews reported that an indication of the ‘control aircraft’ (green outer icon and data tag on ND) was not necessary for conducting IM operations. However, a strong preference was given for more salient displays to indicate when a speed change had occurred, and a display to monitor the progress of the operation.

The published arrival and approach procedure required 5 speed changes from cruise altitude to runway threshold. The mean number of all speed changes during RTA+IM operations was 9.7 (no error), 16.1 (wind error), and 13.1 (offset error). Analysis indicates the CDAs need to be shallower or slower (or both) to provide the algorithm greater control authority to react to environmental perturbations or flight crew variability. Further tuning of the ASTAR10 algorithm should also reduce the number of speed changes; however, the impact on delivery precision will need to be researched.

The crews also reported that the desired deceleration rate (shown by the IM Commanded Speed) appeared too great, particularly during the wind error scenario. Modification of the route, as described above, should reduce both the number of speed changes and how frequently the speed brake is required.

Two ASTAR10 characteristics reported as undesirable were: 1) several speed changes over a short time period, especially if they were in opposite direction, and 2) an increase in speed that exceeded the flap limit. The vast majority of these events occurred during the wind error scenario, and were caused by the unexpected wind shear at 5000’.

The off-nominal scenario required one of the flight crew to accept a new IM clearance while being vectored at 5000’ back to the runway after a go-around. The head down time

required to accept and implement the IM clearance using CPDLC was rated as not appropriate for this high task load and low altitude environment.

## 5 Conclusion

Experiment results of CDA operations to parallel dependent runways at Dallas Fort-Worth show the ASTAR10 spacing algorithm and IM flight crew procedures are able to deliver aircraft to the runways within a 2-second mean and 4-second standard deviation from the assigned spacing interval. Analysis of the time error and number of IM speed changes as a function of position in the arrival stream suggest the spacing algorithm generates stable behavior in the stream while in the presence of continuous (wind) or impulse (offset) error.

The ASTAR10 algorithm behavior for an individual aircraft was generally predictable and expected, and transitions from current arrival operations to arrival operations with time constraints or spacing interval constraints were acceptable. The algorithm compensated for deviations in flight crew performance (speed control) and two different types of error conditions. The behavior of the arrival stream varied both by Control Method and type of Error; however, all achieved the desired precision by the runway.

Two areas rated not acceptable were the spacing algorithm’s behavior in the presence of unknown wind shear, and initiation of IM procedures during low altitude operations. The scenarios with wind forecast error plus wind shear required approximately 7 additional IM speed changes over a 25 minute arrival, with many of them occurring as the aircraft passed through the wind shear.

Areas identified for improvement and further research include: CDAs designed with shallower descent angles and slower speeds if speed control is to be used, more salient crew alerting when IM speed change occurs, fixed location for airspeed change to FAS and final aircraft configuration, cockpit display to allow monitoring of IM operation progress, and fewer speed changes (wind shear).

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