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Experiment Description and Results for Arrival Operations Using Interval Management with Spacing to Parallel Dependent Runways (IMSPiDR)

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June 2013

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Abbreviations and Acronyms

4D	4 dimensional (longitudinal, lateral, vertical, and temporal)
ADS-B	Automatic Dependent Surveillance – Broadcast
AGL	Above Ground Level
ANOVA	Analysis Of Variance
ANSP	Air Navigation Service Provider (synonymous with ATC)
ARTCC	Air Route Traffic Control Center
ASTAR	Airborne Spacing for Terminal Arrival Routes
ASTOR	Aircraft Simulation for Traffic Operations Research
ATC	Air Traffic Control (synonymous with ANSP)
ATOL	Air Traffic Operations Laboratory
ATOS	Airspace and Traffic Operations Simulation
CDTI	Cockpit Display of Traffic Information
ConOps	Concept of Operations
CPDLC	Controller-Pilot Datalink Communications
Data Comm	Data Communications
DTS	Development and Test Simulator
EFB	Electronic Flight Bag
EICAS	Engine Indicating and Crew Alerting System
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FAS	Final Approach Speed
FIM	Flight deck Interval Management
FMC	Flight Management Computer
FMS	Flight Management System
FNL	Final
ft	Feet
GIM-S	Ground-based Interval Management – Spacing
HITL	Human-in-the-Loop
IFD	Integration Flight Deck
ILS	Instrument Landing System
IM	Interval Management
IMSPiDR	Interval Management with Spacing to Parallel Dependent Runways
JPDO	Joint Planning and Development Office
KDAL	Dallas Love airport
KDFW	Dallas-Fort Worth airport
LaRC	Langley Research Center
LNAV	Lateral Navigation (mode of the FMS)
M	Mean

MACS	Multi Aircraft Control System
MCDU	Multi-function Control and Display Unit
MCH	Modified Cooper-Harper
MCP	Mode Control Panel
MSL	Mean Sea Level
N	Sample Size
ND	Navigation Display
NextGen	Next Generation Air Transportation System
NASA	National Aeronautics and Space Administration
nmi	Nautical Miles ('NM' used in Data Comm messages)
OPD	Optimized Profile Descent
PF	Pilot Flying
PFD	Primary Flight Display
PM	Pilot Monitoring
PTH	Path
RCP	Required Communication Performance
RMS	Root Mean Square
RTA	Required Time of Arrival
RUC	Rapid Update Cycle
SBS	Surveillance Broadcast Services (FAA Office)
SD	Standard Deviation
SPD	Speed
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival Route
TGT	Target
TOD	Top Of Descent
TRACON	Terminal Radar Approach Control
TTF	Traffic To Follow
TTG	Time-To-Go
VNAV	Vertical Navigation (guidance mode of FMS)

1 Introduction

1.1 Background

The Joint Planning and Development Office (JPDO) document “Concept of Operations for the Next Generation (NextGen) Air Transportation System” describes a 2025 air traffic system that will experience significant growth [1]. To achieve this increase in capacity while maintaining safety, new technologies and procedures will have to be developed and tested. The National Aeronautics and Space Administration (NASA) Airspace Systems Project has conducted research in collaboration with the Federal Aviation Administration (FAA), the aviation industry, and academia to address many of the issues identified in that document. The research described in this technical paper was conducted at NASA Langley Research Center (LaRC) in 2011 to test procedures for the JPDO’s “super-density operations”; that is, arrival and departure operations at busy major airports. The goal of this area of research is to explore and develop technologies and procedures designed to increase runway throughput, reduce flight delay and fuel burn, and improve predictability of flight operations [2].

NASA LaRC’s research of precision control for arrival operations began in the 1970’s with an exploration of “constant distance” and “constant time” spacing techniques along a common trajectory [3], with onboard information and software used to enable the aircraft to independently achieve Air Traffic Control’s (ATC) operational goal. These original concepts and algorithms matured into a trajectory-based algorithm that accommodates complex route structures arriving to the airport from all directions.

In 2006, the NASA LaRC research team joined the Interval Management (IM) working group, led by the FAA Surveillance Broadcast Services (SBS) Office, to develop the Flight deck Interval Management (FIM) concept. (Note: “FIM” is now used to define the subset of the IM concept, technology, and procedures that pertain only to the flight deck or flight crew, “GIM” the subset pertaining to the ground. Any use of “IM-S”, or “Interval Management – Spacing” is the earlier nomenclature, and was replaced with FIM at the end of the experiment. In certain places in this document, such as questionnaires, the IM-S nomenclature is retained to maintain a historically accurate record.)

The FIM concept goal is to improve the precision of the spacing interval between aircraft through accurate scheduling of traffic, controller automation and support tools, flight deck automation, and new procedures. A key contributor to this goal is the flight crew’s management of the aircraft’s speed to achieve the ATC-specified spacing interval behind the lead, or Target aircraft. Throughout this operation, the controller remains responsible for maintaining separation between the spacing aircraft and all other aircraft, including the Target aircraft.

This work has been published by the FAA as the FIM Concept of Operations (ConOps) document [4], and subsequently as a joint FAA and EUROCONTROL document that also defined requirements, assessed safety and performance, and conducted analysis of expected flight crew tasks [5].

1.2 Arrival Operations to Dependent Parallel Runway Problem Statement

Commercial aviation operations are forecast to grow 3.7% annually for the next 20 years, and annual revenue passenger miles to double by 2023 [6]. To offset this anticipated growth, aviation tools and concepts are being explored with the goal of increasing throughput and flight efficiency, and reducing fuel consumption. One promising area of development is arrival operations at major airports during high demand periods. Currently, arrivals typically have intermediate level-off altitudes to deconflict routes and increase the aircraft's ability to decelerate for improved time control. These "step-down" type of arrival operations do assist maintaining high airport throughput, but imparts an additional operating cost to aircraft.

To improve the efficiency of arrival operations, Optimized Profile Descents (OPD) have been developed to reduce fuel consumption and perceived ground noise by using near-idle descents to the runway. However, the range of optimum descent angles and speeds causes large variability in the flight time of these aircraft. As a consequence, in current day arrival operations, this variability and unpredictability makes it difficult for the Air Navigation Service Provider (ANSP) to maintain aircraft separation (particularly at merge points), and therefore OPDs are frequently not given or terminated early during periods of high demand.

OPD procedures are further reduced when the additional separation requirements necessary for dependent parallel runway operations are incorporated. Arrivals to parallel dependent runways are particularly challenging due to different separation criteria for aircraft proceeding to each runway (more details in Appendix B). The FAA's separation criteria requires 1000 feet (ft) vertical and 1 nautical mile (nmi) separation between aircraft proceeding to parallel runways during dependent operations prior to being established on final approach; additional requirements include the distance between runway centerlines as well as the ground facilities at that airport [7].

Figure 1 is an excerpt from this FAA Air Traffic Control regulation, and illustrates the separation and spacing requirements used in this experiment that are modeled after the Dallas Fort-Worth airport (KDFW) operations. Aircraft lateral separation (landing on different runways) requirements are determined by the distance between runway centerlines (KDFW ground equipment assumed to be not available, and the aircraft wake category has no bearing on the requirement). In this illustration, at least 2 nmi separation is required for aircraft #1 and aircraft #2 since the distance between runway centerlines is between 4300 ft and 9000 ft. Separation requirements for aircraft in-trail (landing on the same runway) are 1000 ft and 3 nmi prior to being established on final, then criteria based on wake vortex category is applied. In the example shown, 6 nmi is required between the heavy aircraft #1 and the small aircraft #3 based on their wake vortex categories.

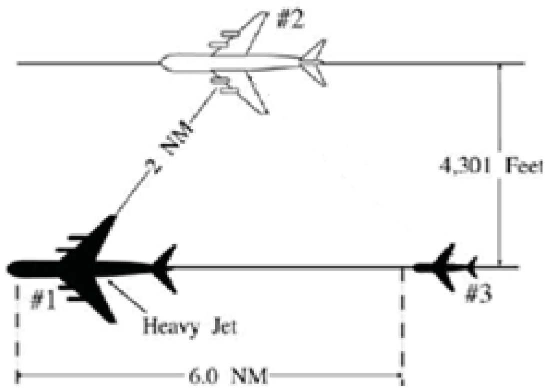

Figure 1. Aircraft separation criteria during parallel dependent operations.

1.3 Interval Management with Spacing to Parallel Dependent Runways

Previous research has been conducted at LaRC to develop and publish a FIM concept for precise arrivals to single runways [8]. A 2006 study at NASA LaRC used this concept to investigate single runway FIM operations and reported that precise runway delivery can reduce ATC's spacing buffer by 10 to 15 seconds, thereby supporting a 5% to 10% increase in runway throughput [9]. The same human-in-the-loop (HITL) experiment indicated that pilots found the FIM spacing procedures, commanded speeds, and required workload level to be acceptable [10].

The FIM concept to single runways document [8], as well as the FAA and RTCA documents cited previously [4][5], were used by LaRC researchers in 2010 to develop the FIM ConOps for precise spacing of aircraft during arrival operations to parallel dependent runways [11]. In 2011, a human-in-the-loop experiment at LaRC based on this concept called Interval Management with Spacing to Parallel Dependent Runways (IMSPiDR) used 24 air transport pilots to study FIM operations. The focus of the experiment was to understand the spacing algorithm performance, flight crew performance, and flight crew acceptability of FIM procedures during parallel dependent runway operations. Since there were no a priori hypotheses, objectives were defined to structure the experiment design and data analysis. The overall IMSPiDR experiment objectives were:

- Measure the performance and behavior of the FIM software;
- Measure the performance and behavior of flight crew during FIM operations;
- Have the flight crew assess the FIM concept, procedures, and displays; and
- Identify potential operational issues of the FIM concept.

The Dallas Fort-Worth airport was selected for this experiment due to the research team's familiarity with the airport and surrounding airspace, and because the distance between the centerlines of the landing runways is less than 9000 ft. When arriving aircraft are landing on runways with less than 9000 ft between centerlines, parallel dependent runway operations (discussed in the next sub-paragraph) may be required based on the available ground equipment at that airport. KDFW has the appropriate ground equipment currently installed to not require dependent parallel operations; nevertheless, for this research experiment, that equipment was assumed to be unavailable and the additional requirements for these operations had to be met. Nevertheless, a visit to the KDFW Terminal Radar Approach Control (TRACON) and discussions with the Training Manager and Procedures Manager were instrumental in designing realistic operations for this experiment. Pertinent subsets of procedures discussed in that meeting, and from documents provided to the LaRC IMSPiDR research team, are detailed in Appendix B.

Several conference papers have been previously published on the expanded concept of FIM operations to parallel dependent runways used as the basis for the IMSPiDR experiment. Those papers include: a description of the experiment methodology, and the findings to evaluate the concept, procedures, speed guidance, and pilot interface [12]; a description of the data communication (Data Comm) procedures and messages, pilot response time to these messages, and the acceptability rating given by pilots to the concept and procedures [13]; the impact variances in pilot actions and compliance to procedures has on FIM operations [14]; and the performance of the spacing algorithm performance during parallel dependent runway operations [15].

This NASA Technical Paper incorporates all the previously published conference papers, plus additional data analysis to complete the examination of the five objectives listed above. The Results in Section 5 are structured to align with the four experiment objectives described in Section 4.1, with the exception of there is no Results sub-section for the fourth objective (identify operational issues), and there is a Results sub-section discussing data from the one off-nominal event scenario that each crew experienced. The Conclusions in Section 6 are presented in a format that directly addresses the four objectives.

2 Concept of Operations

2.1 Overview of FIM Operations to Parallel Dependent Runways

The operational goal of FIM is to enable high runway throughput by precisely achieving the ATC derived spacing interval behind the Target aircraft when crossing the runway threshold. Deviation from the assigned spacing interval is termed a “spacing error” in the FIM concept, since it may result in loss of separation (less than the interval) or reduced throughput (greater than interval).

The FIM concept relies on a ground based tool to calculate an achievable arrival schedule based on appropriate routes and the assigned runway. Once the runway has been assigned and a Scheduled Time of Arrival (STA) established, this information is made available to controllers as a FIM clearance for pilots of FIM equipped aircraft. The controller issues the FIM clearance to the flight crew, and the crew enters the clearance into the onboard spacing software, Airborne Spacing for Terminal Arrival Routes (ASTAR). [Note: once the STA has been entered into the spacing software and the flight crew is flying the required airspeed to meet that time, the STA is referred to as the Required Time of Arrival (RTA).] Operations for aircraft without FIM equipment remain unchanged for normal arrival procedures conducted as of the publication date of this technical paper. Figure 2 provides a high level overview of normal (non-FIM) and FIM operations to parallel dependent runways.

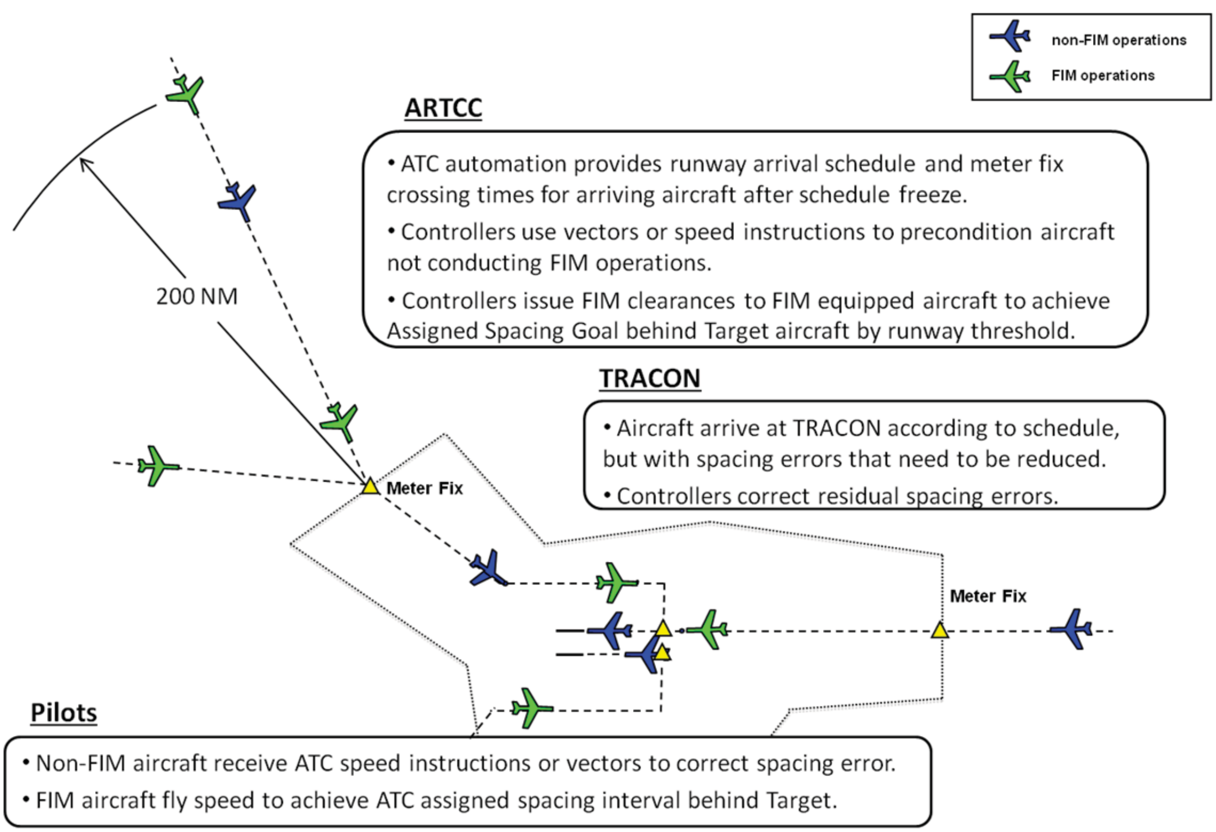

Figure 2. Aircraft conducting in-trail and parallel dependent FIM operations.

2.2 Schedule Automation

The FIM operation begins with a schedule of arrival times to a particular runway, for all arriving aircraft, arriving from any direction. The STAs at the runway thresholds are calculated by the ground automation to create a logical and time-deconflicted arrival sequence that allows aircraft to fly a feasible and efficient airspeed, and the difference between subsequent STAs must meet or exceed safe separation and wake vortex spacing criteria. The difference in STAs is also the spacing interval behind the Target aircraft used by ATC in the FIM clearance.

Aircraft conducting FIM operations into high-density airports follow procedures similar to those in use today. From cruise altitude, the aircraft will either fly an OPD or step-down descent along a Standard Terminal Arrival Route (STAR), and enter terminal airspace at a metering fix (or corner-post). Then Air Route Traffic Control Center (ARTCC) hands off the aircraft to the TRACON. The difference between FIM and today's procedure is that the schedule must establish a continuous four-dimensional (4D) trajectory from en route altitude to the runway threshold for the aircraft. This route is passed by the controller to the flight crew, who must enter it into the aircraft spacing software to calculate the FIM speed. If the published STAR does not connect to the instrument approach for that runway, either the scheduling software or the controller must assign waypoints to connect them, and the pilots enter those points into the spacing software.

Finally, the schedule must identify FIM capable aircraft and provide information required to issue a FIM clearance with the appropriate information (described in the next section). For the IMSPiDR experiment, the spacing goal was given as a time interval behind aircraft landing on the same runway and as a distance for aircraft landing on the parallel runway.

2.3 FIM Clearance

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 as much as possible with existing FIM guidance [5], proposed message formats by the FAA [16], and international standards [17][18]. Due to the complexity and length of an RTA+FIM clearance for parallel dependent runway operations, only Controller-Pilot Data Link Communications (CPDLC) was used in this experiment.

Four additional information elements were added to the list of standard FIM data elements for the IMSPiDR experiment, and two data elements were not used. First, an RTA to the runway threshold was included to enable the flight crew to begin controlling the aircraft to the location desired by ATC even when outside of Automatic Dependent Surveillance – Broadcast (ADS-B) range. The RTA function normally associated with current commercially available Flight Management Systems (FMS) was not used in this experiment. Instead, the RTA algorithm used in the IMSPiDR HITL experiment was identical to the FIM algorithm, with the dependency of the lead aircraft removed and replaced by an arrival time. The ASTAR10 algorithm uses the RTA to provide speed guidance until valid ADS-B data is available. Secondly, the CPDLC message included the text WHEN ABLE to make the FIM clearance conditional; that is, the aircraft speed commanded is based on the assigned time at the runway threshold until the aircraft is within ADS-B range of a lead aircraft, at which time the commanded ASTAR speed will be based on the lead aircraft's position. Third, the lead aircraft's Final Approach Speed (FAS) was included based on previous research that showed significant improvement in delivery precision when the ASTAR spacing tool compensates for differences in those speeds. Finally, a November 2010 IM workshop attended by the FAA, NASA, MITRE, pilots, and controllers generated feedback that the experiment include the flight crew notifying ATC when the spacing tool transitions from a speed based on the RTA, to a speed based on the spacing interval behind the target aircraft. The concern was that the commanded speed from the spacing tool, and therefore the aircraft's position, may be different enough between absolute (RTA) and relative spacing (FIM) to create operational issues for the air traffic controllers.

The left column of Table 1 lists the FIM clearance data elements defined by the ASPA-FIM standard (reference [5]), and the right column data used in the IMSPiDR experiment. An asterisk (*) indicates those elements that are unique to one aircraft (consequently need two of them for a FIM clearance for dependent runway operations behind two aircraft). The "FIM tolerance" and "Intercept point" data specified in the ASPA FIM standard were not included in the IMSPiDR experiment since neither had not been implemented in the software at that time.

Table 1. Data Elements in a FIM Clearance

ASPA FIM [standard]	IMSPiDR [this experiment]
(CPDLC uplink)	
-	RTA time
-	RTA location
-	Conditional phrase
Target aircraft ID	Target aircraft ID (*)
Spacing goal	Spacing goal (*)
FIM clearance type	FIM clearance type (*)
Achieve-by-point	Achieve-by-point
Termination point	Termination point
Target aircraft route	Target aircraft route (*)
-	Target aircraft FAS (*)
FIM tolerance	-
Intercept point	-
(CPDLC downlink)	
ACCEPT or REJECT	ACCEPT or REJECT
-	IM SPACING NASA2 (*)

(*) *indicates data elements that must be included for each Target aircraft*

Shown below is an example of a CPDLC message containing all the data elements for a RTA+FIM clearance. The first target aircraft, NASA1, is on the CEDAR CREEK SIX arrival to the Instrument Landing System (ILS) on runway 17C, and the second target aircraft is on the

GLEN ROSE NINE arrival to the ILS on runway 18R. Figure 5 through Figure 8 in section 2.5 use this example to illustrate various cockpit displays.

```
CROSS R-17C AT 0028:26Z. WHEN ABLE CLEARED IM-SPACING 95 SEC
WITH NASA1 AND 2.2 NM WITH NASA2. ACHIEVE BY R-17C. TERMINATE
AT R-17C. NASA1 ROUTE GGG CQY6 PENNY ILS17C, FAS 130 KT.
NASA2 ROUTE INK JEN9 YOHAN ILS18R, FAS 130 KT. REPORT
COMMENCING IM-SPACING.
```

RTA operations are not part of the core FIM concept; however, they were included in this experiment to allow flight crew to conduct operations when outside of ADS-B range of the Target aircraft, and to understand the difference in performance of absolute time and relative spacing. The corresponding RTA only clearance is:

```
CROSS R-17C AT 0028:26Z.
```

2.4 Aircraft FIM System Overview

2.4.1 Spacing Software Overview

NASA LaRC has developed the trajectory-based ASTAR algorithm for more than a decade [19]. This spacing algorithm uses enhanced arrival and approach route information to generate the spacing speed command, and is also a relative spacing concept. That is, the algorithm spaces to the relative difference between the Target (lead) aircraft's estimated time of arrival and the ownship's estimated time of arrival. This relative spacing technique, versus an absolute time of arrival, allows for the potential to reduce the buffer needed between aircraft since only the FIM aircraft's relative spacing error needs to be considered. Additionally, because the ASTAR algorithm is trajectory-based, it also has the inherent ability to support RTA operations. Fundamental operations and capabilities of the ASTAR algorithm are:

- The ability to achieve an RTA to the runway threshold (RTA only mode).
- The ability to achieve an ATC-directed time interval or spacing distance behind a Target aircraft (FIM only mode).
- The ability to begin the operation with an RTA and then transition to FIM once valid ADS-B information becomes available from a traffic aircraft (RTA+FIM mode).
- The use of forecast wind and real-time wind data in the 4D trajectory calculation.
- The maximum speed variation is limited to 10% of the published speed for the segment currently being flown to provide operational predictability and arrival string stability.
- The filtering of the spacing error to reduce the number of commanded speed changes.
- The transition to FAS from FIM when the FIM aircraft crosses the FAF.
- The use of the Target FAS (if issued by ATC in the FIM clearance) and FAS of the FIM aircraft to establish an offset at the Final Approach Fix (FAF) to compensate for the compression or expansion that occurs after the FAF due to differences in FAS.

For parallel dependent runway operations, an ASTAR10 version was created with additional functionality to meet new requirements [20]. They include:

- The ability to calculate a trajectory and spacing errors for a second traffic aircraft, with this aircraft landing on a parallel runway.
- The ability to compensate for offset runway thresholds.
- The ability to meet unique lateral spacing requirements for parallel dependent approaches (occurs after both aircraft were on their respective final approach course).

ASTAR10 can generate three spacing error calculations at any given time: the error for RTA, the error for the first traffic aircraft, and the error for the second traffic aircraft. The RTA error is used to calculate the ASTAR10 speed command prior to any FIM operation. That is, ASTAR10 will operate in its RTA mode until ADS-B and valid trajectory data become available for a traffic aircraft. Once ADS-B and valid trajectory data become available for a traffic aircraft, ASTAR10 enters FIM mode and will not revert to an RTA. If both traffic aircraft data are valid, ASTAR10 calculates its speed command based on the "controlling" aircraft data. This controlling aircraft is the one that requires the FIM aircraft to be the farthest back, thereby ensuring that both spacing intervals are either met or exceeded.

The ASTAR10 algorithm generates two speeds: instantaneous FIM End Commanded Speed, and the FIM Commanded Speed. The FIM Commanded End Speed is the airspeed at the completion of a speed change, is the speed set in the Mode Control Panel (MCP) by the crew, and is displayed in the upper left of the Primary Flight Display (PFD) in Figure 3. The FIM Commanded Speed is the instantaneous speed estimated by ASTAR10 to account for deceleration, and is shown as a green speed bug just to the right of the speed tape in Figure 3.

2.4.2 Aircraft FIM Displays

Three different simulators (details in Section 3) were used to explore different levels of aircraft equipage, which in turn drove the use of different FIM displays and flight crew procedures. Additional details of the differences between the simulators are given in Appendix C.

Once the flight crew activated the FIM clearance, RTA speed guidance is shown on the PFD. During the RTA-only scenarios, pilots flew the RTA speeds to the runway. During the RTA+FIM scenarios, aircraft transitioned from RTA (absolute time) to FIM (precise interval) once valid ADS-B data from the Target aircraft was received. When this transition occurred, the flight crew was required to notify ATC. Since the aircraft in this experiment were arriving to dependent parallel runways, pilots were cleared to space behind two Target aircraft. The spacing algorithm uses the aircraft that was furthest back as the controlling aircraft to determine the commanded speeds. The flight crew is not required to know which Target aircraft the displayed FIM speeds are based on; however, the crew may ascertain which Target aircraft the FIM speeds are based on by selecting the FIM page on the Multi-function Control and Display Unit (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 3).

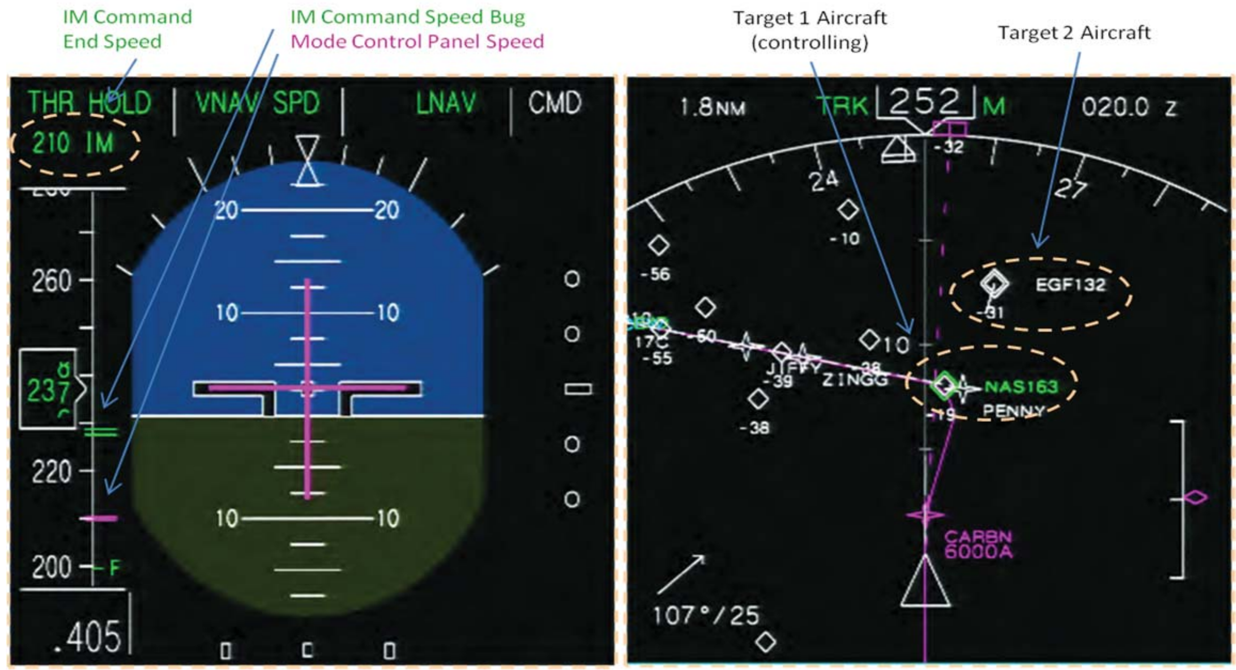

Figure 3. Cockpit displays of FIM speeds and target aircraft.

2.5 CPDLC Procedures for FIM Operations

A description of general flight crew procedures for FIM operations is provided in Appendix G. This section pertains to the subset of flight crew procedures for CPDLC. For the IMSPiDR experiment, no machine-to-machine transmission delays between ATC and the flight crew were modeled.

A high-level flow chart of the procedures used by the flight crew to receive, interact, and respond to FIM clearances using CPDLC and spacing tool equipment is shown in Figure 4 below. After receiving the FIM clearance via a CPDLC message, the flight crew auto-loaded the message into the ASTAR10 spacing tool. Next the crew activated the tool, reviewed the speed calculated by the tool, then determined whether that speed was operationally acceptable or not.

The next step in the crew procedure was to notify ATC of that decision using CPDLC by sending either an ACCEPT or REJECT downlink message. If the speed was acceptable, the crew was instructed to send an ACCEPT downlink message and then depress the EXECUTE button on the MCDU, causing FIM information to appear on the PFD and ND. If the clearance was not acceptable, the crew was to send a REJECT downlink message and continue to follow the previous clearance.

The blue and red brackets in Figure 4 indicate the CPDLC 'Read' and 'Respond' times correspond to the two paragraphs above, and are discussed later in Section 5.2.3 and shown by the same blue and red lines in Figure 34.

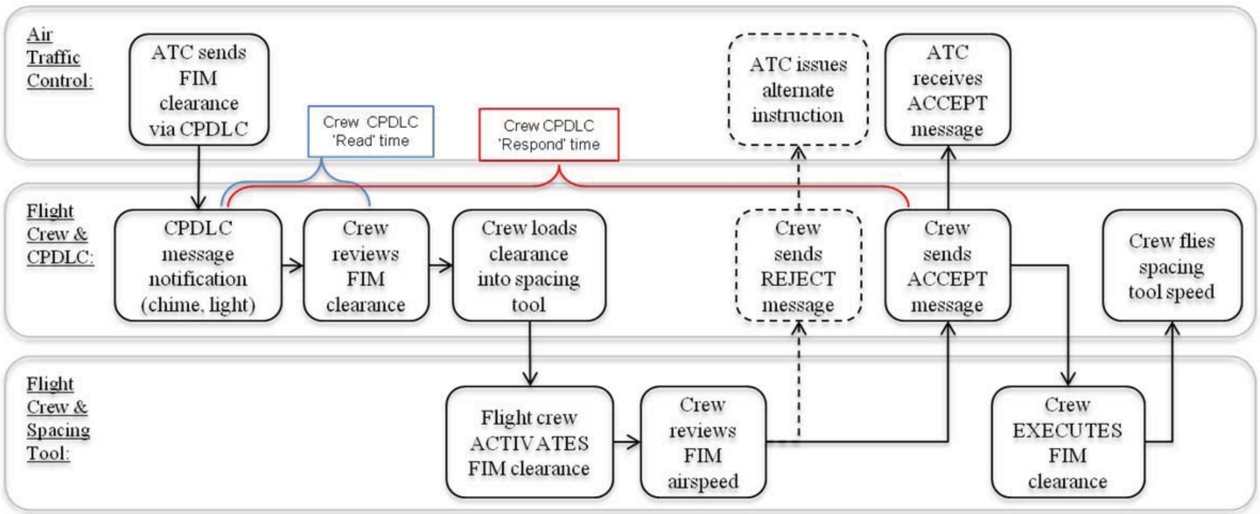

Figure 4. Procedural flow chart for FIM operations.

A more detailed description of flight crew FIM procedures in Figure 4 is given below for the single pilot simulators, with minor differences to procedures used in the two pilot simulators (differences and details discussed in Section 3).

FLIGHT CREW NOTIFICATION:

The flight crew received notification of a CPDLC uplink message from ATC as a single chime, and a message on the Engine Indicating and Crew Alerting System (EICAS) as either a "Large ATC Uplink" or "ATC Message".

REVIEW FIM CPDLC MESSAGE:

The pilot monitoring (PM) pressed the appropriate button to read the uplink message, reviewed the message, and then briefed the pilot flying (PF). The CPDLC message containing the FIM clearance from the previous section of this paper is shown in Figure 5 (single-pilot simulator) and Figure 6 (two-pilot simulator).

LOAD FIM:

To auto-load the CPDLC message into ASTAR10, the flight crew pressed the LOAD IM-S button on the EICAS (single-pilot simulator) or LOAD on left side of MCDU (two-pilot simulator). Once the FIM clearance had been loaded into ASTAR10, the LOAD IM-S or LOAD functionality was removed from the EICAS or MCDU.

Figure 5. CPDLC FIM clearance on an EICAS page (single-pilot simulator).

Figure 6. CPDLC FIM clearance on MCDU pages (two-pilot simulator).

ACTIVATE:

The third step was to press the ACTIVATE button on the MCDU to have ASTAR10 initiate calculation of the speed required to achieve either the RTA or RTA+FIM clearance (all simulators). The ACTIVATE display was removed from the MCDU after the button press, and the EXECUTE light was illuminated. The spacing tool required 15 to 20 seconds to determine the speed required to achieve the ATC assigned RTA or RTA+FIM clearance. This speed was displayed only on the first of the three MCDU pages of the spacing tool, in the second from the top in the left column (circled in Figure 7).

Figure 7. FIM Commanded End Speed shown on MCDU.

SEND CPDLC RESPONSE:

The crew then determined whether the ASTAR10 commanded speed was operationally acceptable, and then sent an ACCEPT or REJECT CPDLC downlink message from either the EICAS (single-pilot simulator) or MCDU (two-pilot simulator) (Figure 8).

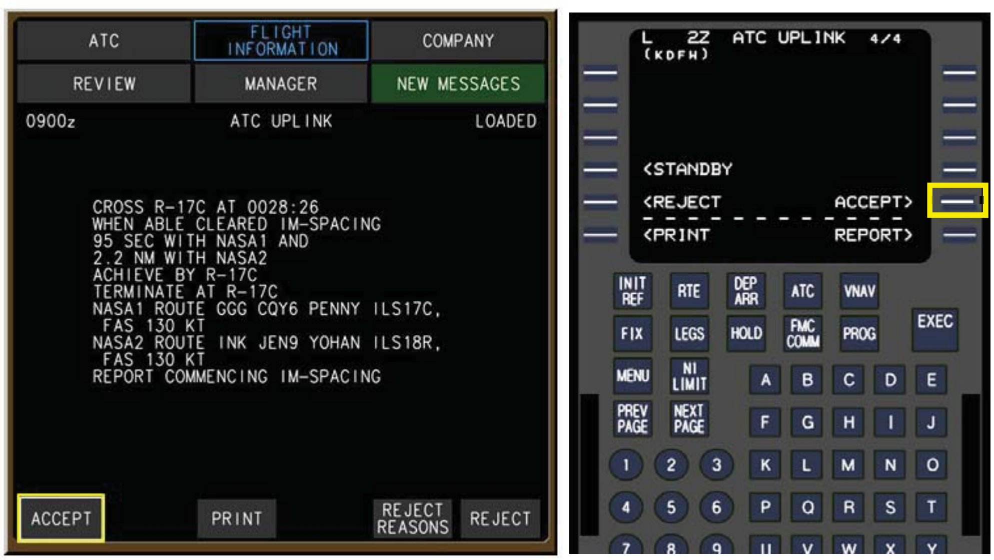

Figure 8. CPDLC ACCEPT downlink message on EICAS (left) and MCDU (right).

EXECUTE:

The fifth and final step was for the flight crew to depress the execute button on the MCDU (green bar at lower right of Figure 7). Prior to this button push, the ASTAR10 spacing software only displayed information on the MCDU. After depressing the EXECUTE button, the spacing software commanded speed was shown in green text in the top-left of the PFD, with the green speed bug available as a second indicator. The spacing mode (RTA, IM) was also shown, just to the right of this speed. The ND displayed all ADS-B equipped aircraft as a chevron (single-pilot simulator) or diamond (two-pilot simulators). If the Target aircraft was within ADS-B reception range (i.e., ASTAR10 in FIM mode), that aircraft icon had a second chevron or diamond drawn around it. Figure 9 shows the spacing algorithm has calculated a speed of 300 knots to achieve the assigned spacing behind BTA291 (left side of ND) and DAL421 (right side of ND).

Figure 9. PFD and ND with FIM information (single-pilot simulator).

FIM MODE TRANSITION:

Not shown in Figure 4 is the flight crew procedure to notify ATC when the spacing tool transitions from fixed-time spacing (RTA) to relative spacing (FIM). If neither aircraft was within ADS-B range of the FIM aircraft when the ASTAR10 algorithm was initiated, the speed calculated by ASTAR10 was to achieve the assigned RTA. Once within ADS-B range of either Target aircraft, the algorithm switched automatically to FIM based calculations and updated both the PFD and EICAS displays.

Regardless of whether the spacing algorithm initiated in FIM mode or switched to it later in the flight, the crews were instructed to notify ATC when the transition occurred (via CPDLC in the single-pilot simulator, voice in the two-pilot simulators). An example would be:

- `NASA4 SPACING WITH NASA2`

The FIM clearance could be terminated at any time by the flight crew or ATC (some of the scenarios did have ATC amend the spacing interval). Within the ASTAR10 spacing tool was logic that terminated the algorithm and gave warnings on the PFD and EICAS, such as when an aircraft was more than 6000 ft off the vertical path of the trajectory, greater than 2.5 nmi from trajectory centerline, or greater than 90 degrees from trajectory heading. If the FIM operation was terminated by the onboard spacing tool or by the crew for operational reasons, the flight crew was instructed to contact ATC and continue flying the previous commanded speed until receiving further instruction.

3 Facilities and Software

Three different simulators were used to explore a range of aircraft equipage and flight crew procedures appropriate for each: the Air Traffic Operations Laboratory (ATOL), the Development and Test Simulator (DTS), and the Integration Flight Deck (IFD). The ATOL was configured to emulate an integrated, fully NextGen capable aircraft; the DTS a near-term, partially capable NextGen aircraft; and the IFD as a current day, retrofit equipped aircraft.

3.1 Air Traffic Operations Laboratory

The ATOL was a medium-fidelity simulator, comprised of the Airspace and Traffic Operations Simulation (ATOS) platform, ATC controller stations operating Multi Aircraft Control System (MACS) software developed and provided by NASA Ames, and a network of hundreds of real-time, medium-fidelity aircraft simulators that can be used for batch Monte Carlo studies as well as real-time HITL experiments [21]. The ASTOR simulators were equipped with cockpit displays similar to current commercial aircraft, and employed pilot interfaces to be operated by a single pilot (Figure 10). These ASTOR stations also had a "Pilot Model" function that, when selected, controlled the simulator using software logic. ASTOR components include: six degrees of freedom dynamics model, PFD, Multi-Function Display (MFD), autopilot and auto-throttle systems, Flight Management Computer (FMC), Multi-function Control Display Unit (MCDU), MCP, voice communication, CPDLC, ADS-B, and ASTAR10.

ASTOR stations were flown by the pilots using the auto-pilot fully coupled, the auto-throttles engaged, the MCP speed window closed, and the aircraft in Vertical Navigation (VNAV) Path mode. The ASTAR10 algorithm was integrated into the FMS, and the FIM speed overrode the FMS speed.

Figure 10. Aircraft Simulation for Traffic Operations Research (ASTOR) station.

3.2 Development and Test Simulator

The Development and Test Simulator (DTS) was a full-scale simulator representative of a current, large generic commercial transport category aircraft and was driven by a high fidelity aircraft dynamics model. The DTS has a 210° horizontal by 45° vertical out the window field of view and 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 (shown in Figure 11 without flight crew to allow unobstructed view of the flight instruments). The visual scene used for this experiment was the KDFW terminal environment in a daytime setting.

The DTS was flown by the flight crew using fully coupled auto-pilot and auto-throttle, with the MCP speed window closed, and the aircraft in VNAV Path mode. The ASTAR10 algorithm was integrated into the FMS, and the FIM speed overrode the FMS speed.

Figure 11. Development and Test Simulator (DTS).

3.3 Integration Flight Deck

The Integration Flight Deck (IFD) was a full-scale simulator of a current generation commercial transport category aircraft and was driven by a high fidelity dynamics model (Figure 12). The cockpit includes standard ship's instruments representative of an operational aircraft, and the cockpit's visual system is a panorama system that provides 200° horizontal by 40° vertical field-of-view (shown in Figure 12 without flight crew to allow unobstructed view of the flight instruments). The visual scene used for this experiment was the KDFW terminal environment in a daytime setting.

The IFD was flown by the flight crew using fully coupled auto-pilot and auto-throttle, the MCP speed window was open, and the aircraft in VNAV Speed mode. The ASTAR10 algorithm was not integrated into the FMS.

Figure 12. Integration Flight Deck (IFD) simulator.

3.4 ASTAR10 Spacing Algorithm

3.4.1 Overview

This section provides a simple overview of the basic, trajectory-based concept for ASTAR10, with special emphasis on the additions and modifications made to ASTAR10 to support operations to parallel dependent runways [20]. If the 4D trajectory of an aircraft and its current position is known, then the aircraft's position on that trajectory can be determined. By knowing the aircraft's position on a trajectory, the aircraft's estimated time-to-go (TTG) to a point can be calculated (the runway threshold was used during IMSPiDR). To apply this to a self-spacing concept, a TTG is calculated for the Target aircraft (TA) and for the ownship, noting that the trajectories do not need to be the same. The nominal spacing time, $t_{nominal}$, and the spacing time error, t_{error}, can then be calculated as:

$$t_{nominal} = TTG_{TA} + \textit{planned spacing interval}$$

$$t_{error} = TTG_{ownship} - t_{nominal}$$

In the FIM concept, ATC retains responsibility for safe separation of aircraft; therefore ATC determines the Target aircraft and the spacing interval behind it.

The capability described in Section 2 of this document can also be implemented in a manner similar to the traffic spacing technique, and can be calculated as:

$$t_{nominal} = RTA - \textit{current time}$$

From this time, a speed error value can be calculated. A conceptual example for the determination of error for traffic spacing is shown in Figure 13.

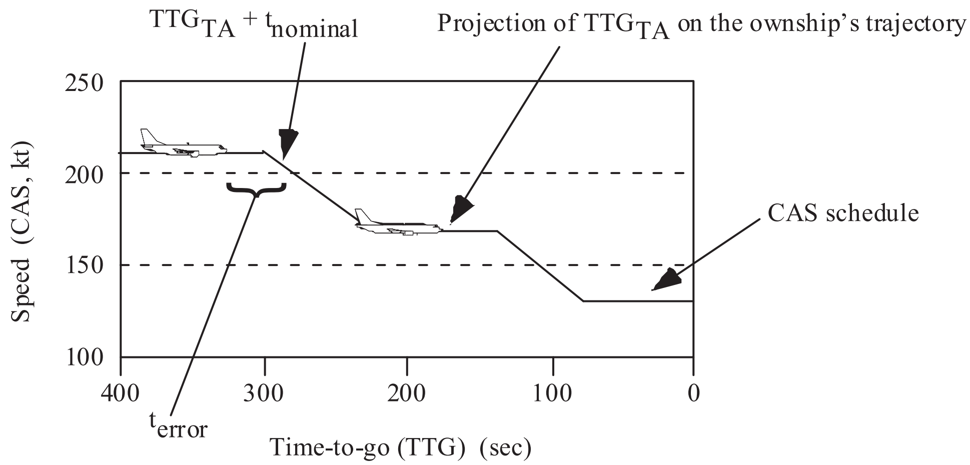

Figure 13. ASTAR10 time error example.

3.4.2 Trajectory Generation

In ASTAR10, the ownship trajectory definition begins with a path definition, for example, a STAR with a continuous connection to an instrument approach procedure, along with relevant speed and altitude constraints. The same data is required to calculate the Traffic aircraft's trajectory, and this information is obtained via CPDLC as part of the FIM clearance. An internal trajectory generator within ASTAR10 then computes a full 4D trajectory defined by a series of Trajectory Change Points [19].

In conjunction with the basic calculations, ASTAR10 preprocessed the trajectory input data depending on the situation, and three parameters of the generic trajectory were modified by ASTAR10. They were:

- FAS: For the FIM aircraft, this information was obtained from the FMS. For the Target aircraft, this information is part of the CPDLC FIM clearance.
- Initial cruise altitude and Mach. For the FIM aircraft, this information is obtained from the FMS. For the Target aircraft, this information was conveyed through a scenario artifact. The real-world implementation has not yet been determined.
- TOD point: ASTAR10 monitored aircraft state data to establish the TOD point. If either FIM or Target aircraft began its descent from cruise before the point that ASTAR10 predicted, ASTAR10 recalculated a new 4D trajectory based on the actual TOD. A similar technique was used for a late descent except that ASTAR10 continues to recalculate the 4D trajectory until the actual TOD occurs.

It was assumed in the design of ASTAR10 that a highly developed wind forecast model would be used to provide vertical profile wind data at the waypoint locations. Of special importance to ASTAR10 is the wind estimation at the altitude that the trajectory crosses the waypoint's position. It was also assumed that the externally provided waypoint wind data is reasonably accurate and bounds the expected waypoint trajectory crossing altitude. ASTAR10 then provides local modifications to the forecast wind data provided to its trajectory generator.

3.4.3 Calculation of the Spacing Interval

Several relative spacing interval calculations are performed by ASTAR10, depending on the situation. The two primary intervals used in this experiment are the basic interval and the diagonal distance interval, with the latter being used for the parallel dependent operations.

3.4.3.1 Common Runway Traffic

The basic time spacing interval is the interval that ATC would assign the spacing aircraft to obtain a precise interval behind the assigned Target aircraft at the runway threshold. The basic spacing interval for ASTAR10 is a time-reference interval against a traffic aircraft that is landing on the same runway as the ownship. The operational goal in this situation is for the ownship to cross the runway threshold at the assigned interval after the traffic aircraft crossed the same threshold. For this basic time interval case, there is no additional calculation required for the spacing interval; it is simply the time assigned by ATC.

3.4.3.2 Parallel Runway Traffic

In many airport environments, calculation of the diagonal distance interval requires some compensation for offset runway thresholds between the parallel runways. To accommodate parallel dependent approach spacing where the runway thresholds are not aligned, ASTAR10 internally calculates the approach time difference due to this offset and adjusts the spacing interval to account for this difference. In Figure 14, the runway threshold for the traffic aircraft is beyond the threshold of the ownship. Since the inbound approach course is known, the distance d can then be calculated using right-triangle geometry. From d, which is the distance-to-go value for the traffic aircraft (TA) when it is abeam with the ownship's runway threshold, the time-to-go at that point for the traffic aircraft can be determined. Defining this time as $threshold_{offset}$, the adjusted spacing time interval is then calculated as:

$$adjusted\ spacing\ time\ interval = planned\ spacing\ interval - threshold_{offset}.$$

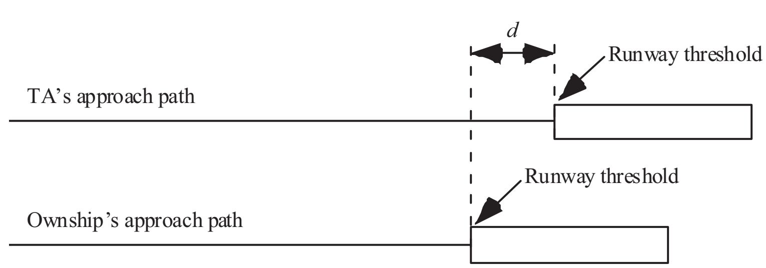

Figure 14. Example of non-aligned runway thresholds.

A similar calculation can be made for the case where the runway threshold for the ownship is beyond the threshold of the traffic aircraft. In this case, the adjusted spacing time interval is calculated as:

adjusted spacing time interval = planned spacing interval + threshold$_{offset}$.

To support parallel dependent approaches, ATC uses a spacing interval based on the diagonal distance between successive aircraft on adjacent approaches (Figure 15). Given that the diagonal distance interval and the distance between the runway centerlines are known, the effective in-trail distance that provides the diagonal distance interval can be calculated using right-triangle geometry. From this effective in-trail distance, the adjusted time spacing interval can be calculated by determining the ownship's trajectory state at the effective in-trail distance from the threshold. The spacing time goal is then the time-to-go to the threshold at this distance. That is, the relevant spacing time is the time-to-go on the ownship's trajectory at a distance-to-go equal to the effective in-trail distance calculated.

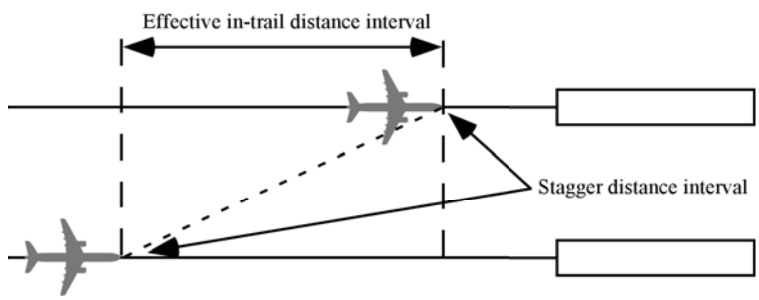

Figure 15. Diagonal distance interval during parallel dependent operations.

3.4.4 Selection of the Spacing Target

ASTAR10 can simultaneously calculate the time error relative to all of the operational targets, i.e., an RTA, spacing against a traffic aircraft going to a common runway, and spacing against a traffic aircraft going to a parallel runway. In a typical arrival operation, both of the traffic aircraft may be initially outside of ADS-B range. In this situation, ASTAR10 calculates the speed command against the RTA time error. Once ADS-B data from either of the traffic aircraft is received and a trajectory is calculated for that aircraft, spacing against the RTA is inhibited and pair-wise spacing, i.e., spacing against a traffic aircraft, is initiated. The algorithm does not revert into an RTA mode if the traffic aircraft data are subsequently lost or become invalid.

If the algorithm has valid data for both traffic aircraft, then data from the Target aircraft that has the largest nominal spacing time is used to compute the speed command, where for each Target aircraft:

$t_{nominal} = TTG_{TA} +$ *adjusted spacing time interval.*

Using this technique, there are no step changes in the nominal TTG value being used by the speed control law when the selection switches between the traffic aircraft.

3.4.5 Maximum Spacing Interval

While the Interval Management concept allows for any spacing interval, the maximum speed deviation ASTAR10 can command is ±10% of the profile speed. Limiting the deviation from the profile speed prevents the algorithm from commanding speeds that are unacceptably low or high for the FIM pilot, produces more predictable behavior for the pilots of the ownship and air traffic controllers who are monitoring the spacing operation, and results in increased string stability when a numbers of aircraft spacing are behind each other. An estimate of the amount of time delay or gain the spacing algorithm can achieve for a generic arrival is shown in Figure 16. The time an aircraft can delay (red line) is greater than the time it can gain (blue line) due to the procedural requirements (250 knots or less below 10,000 ft Mean Sea Level (MSL)), and the impact of groundspeed (slowing 10 knots over a certain distance causes a larger change in time than accelerating 10 knots over the same distance).

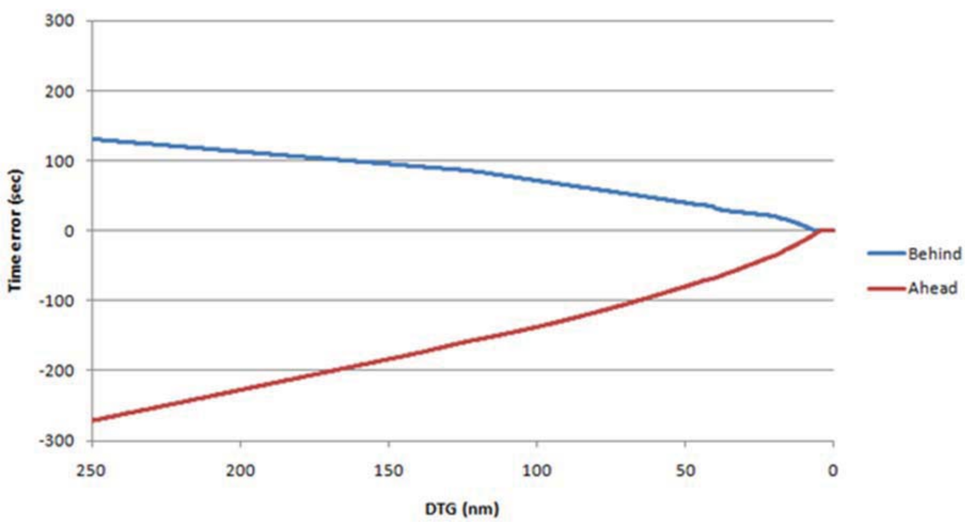

Figure 16. Time error correctable by ASTAR10 versus Distance To Go.

3.4.6 Speed Change Minimization and Lag Compensation

One design goal for ASTAR10 was to minimize pilot workload by minimizing the number of speed command changes presented to the pilot. Several capabilities are provided within the algorithm that attempt to balance the number of speed changes against the spacing performance.

3.4.6.1 Spacing Error Filtering

One method used to reduce the number of speed changes is the application of a filter on the spacing error value in the speed control law. By applying a filter, small variations due to system noise or small spacing error perturbations would not be propagated into a change into the speed command. In implementing this filter, when the aircraft is far from the runway threshold, fairly large spacing errors are allowed without inducing a speed correction. One performance issue with using this technique is that by not correcting large spacing errors when far from the runway, the algorithm may not be able to recover from what may have been a recoverable error. In the current IM concept, this must be mitigated by air traffic control, and flight crew procedures have been developed to temporarily suspend the FIM operation and resume once within the range of correctable error (see section 3.4.5).

3.4.6.2 End Speed Estimation

In this implementation of ASTAR10, the pilot is expected to implement the algorithm's speed command by matching the aircraft's autothrust command to the ASTAR10 speed command. During a programmed deceleration segment (for example, the change from 210 to 170 knots shown in Figure 17), the ASTAR10 speed command changes smoothly from 210 to 170 knots and is shown as a solid line. To reduce workload so that the pilot does not need to continuously monitor the speed command and continuously change the input to the autothrust system, a secondary speed command is output by ASTAR10 for display to the pilot. This secondary speed command, termed the FIM Commanded End Speed, is an estimate of the speed command at the end of the speed change. In this example, the FIM Commanded End Speed would change from 210 to 170 knots as soon as the aircraft reaches the start of the deceleration segment, and is shown as the dashed line.

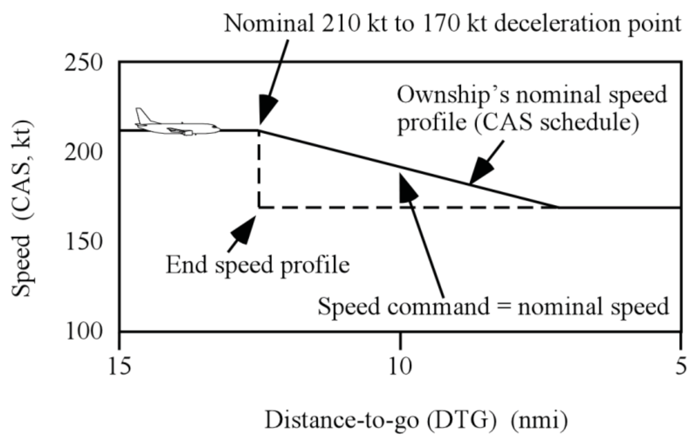

Figure 17. Speed change with no spacing correction.

3.4.6.3 Speed Command Quantization

Another method for reducing the number of ASTAR10 speed changes was quantization of the FIM Command End Speed. By applying a quantization to the speed command prior to its output, the end speed command changes would only occur in discrete intervals, thus reducing the number of commanded speed changes. Hysteresis was included in the quantization logic to reduce dithering of the end speed command when the command speed is near the breakpoint for the quantization value.

For example, if the speed command was to change from 210 to 172 knots and using a 5 knot quantization value, then the following would occur:

- Immediately prior to the speed change, the output values for both the FIM Commanded Speed command and the FIM Commanded End Speed would be 210 knots.

- At the start of the speed change, the output value for the FIM Commanded Speed would slowly begin to decrease (209, 208, 207, etc.), while the output for the FIM Commanded End Speed jumps to 170 knots (due to the 5 knot quantization, or "chunking").
- At the end of the speed change, the output values for both the speeds would be 170 knots.

3.4.6.4 Nominal Deceleration Roll-In Logic

During development of ASTAR10, it was determined that the lag in response to a speed command change by the simulated aircraft was problematic and contributed to undesirable spacing performance. To reduce this problem at the start of a planned deceleration segment in the nominal profile (where this lag was most apparent), a predictive, nominal speed roll-in logic was added to the speed command. Examples of a deceleration in the nominal profile without and with this roll-in logic are shown in Figure 18 and Figure 19.

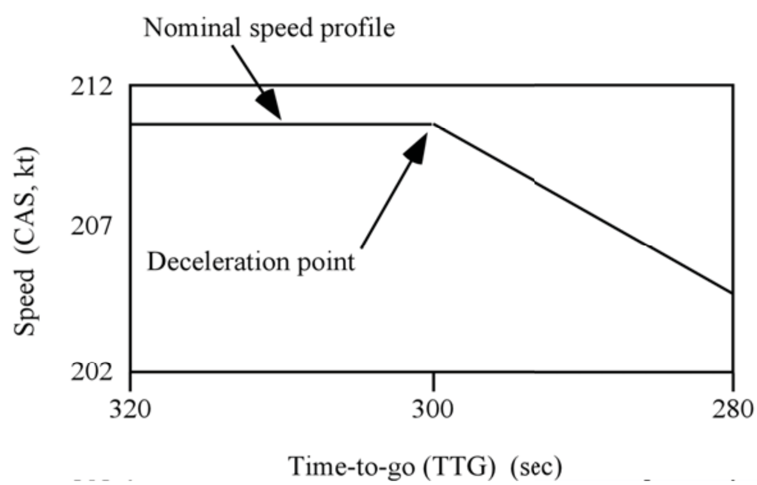

Figure 18. Speed change without roll-in logic.

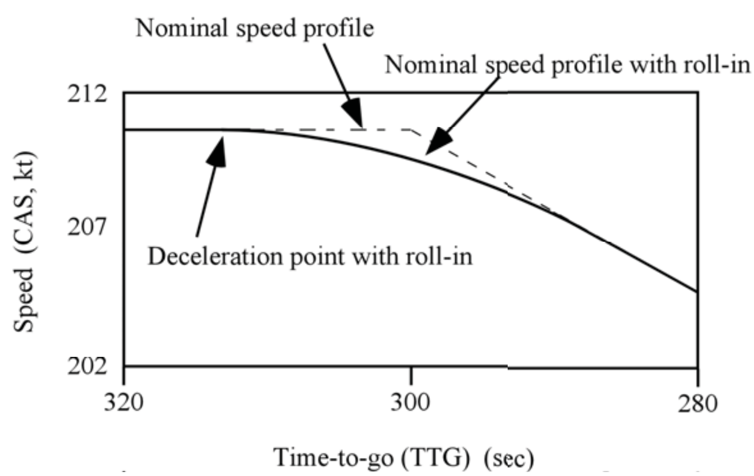

Figure 19. Speed change with roll-in logic.

3.5 Traffic Generators

The ASTOR platform with Pilot Model was used to model traffic arriving to KDFW and Dallas Love (KDAL) airports, except for the six aircraft flown by the subject pilots. MACS was used to generate aircraft departing the KDFW airport. All aircraft were visible in the out-the-window view of the IFD and DTS, and visible on any other aircraft's ND as an ADS-B target. All voice communication by controllers or pilots was heard by anyone on that frequency, regardless of simulator type.

All aircraft transmitted ADS-B data in compliance with DO-260B standards [23]. No position inaccuracies were modeled, and the maximum reception range of ADS-B data was limited to within 120 nmi.

3.6 Connectivity of Simulators

A gateway between the ATOL, DTS, and IFD allowed for the transmission of aircraft state data, Data Comm messages, and audio transmissions. In addition to the ASTOR machines in the ATOL, there were also four confederate ATC controller stations, voice servers and recorders (one for each frequency of that scenario), and a server for the electronic questionnaires. ATOL pilots completed the questionnaire on their ASTOR station computer, and the IFD and DTS pilots utilized a small table outside the simulator that contained tablet computers connected to the server in the ATOL.

4 Experiment Methodology and Design

4.1 Objectives

The four objectives of the IMSPiDR experiment were:

- Measure the performance and behavior of the FIM software;
- Measure the performance and behavior of flight crew during FIM operations;
- Have the flight crew assess the FIM concept, procedures, and displays; and
- Identify potential operational issues of the FIM concept.

Scenarios and parameters were selected to expose the FIM spacing algorithm to significant operational error, and explore the limit of flight crew procedure acceptability when using less than optimum equipment and displays. For example, arrival routes were modified to remove all level segments to emulate OPDs, CPDLC messages were intentionally long and complex, sub-optimized CPDLC crew interfaces were used, the forecast wind error was 150% of that model's expected error value, a strong wind shear existed where the routes converged onto final approach, and CPDLC messages and ATC traffic call-outs were timed to occur simultaneously with other crew tasks. This experiment was not intended to explore possible increases in operational efficiencies unique to a particular airfield; however, that work is planned for future research work.

4.2 Assumptions

The following assumptions were made during the IMSPiDR experiment:

- FIM did not constrain or exceed the maximum arrival rate for a runway; rather it supported whatever arrival rate ATC set in the ground scheduling tool.
- Routes were defined from the enroute structure to the runway threshold (a continuous path from the arrival to the approach), with a speed assigned for each segment.
- Routes for ownship and the traffic to follow were accessible to the ground tool and aircraft, for both ownship and the Target aircraft.
- The ground scheduling tool generated a logical and achievable arrival sequence, with spacing between aircraft pairs that met all constraints (runway occupancy, wake vortex limits, separation criteria, etc.). Periodic updates were provided during cruise flight, but not after the freeze horizon (typically just prior to TOD).
- The RTA from the ground schedule to the flight crew was to the runway threshold. This RTA was superseded by ADS-B In data from the Target aircraft once it was received, and the ASTAR10 algorithm was able to calculate the speed to achieve the assigned spacing interval behind that aircraft.
- The corrected FAS of both Target aircraft was available, and sent to the FIM aircraft as part of the FIM clearance sent via CPDLC.
- All aircraft were equipped with ADS-B Out, and were compliant with DO-260B.
- Communication between flight crew and controllers occurred primarily via CPDLC datalink; however, voice was used for time critical, safety of flight, and complex or off-nominal types of communication.

- Flight crews were expected to respond within 60 seconds to a CPDLC message.
- The same forecast wind fields were used for both the ground scheduler and aircraft avionics. The aircraft dynamics model used the truth wind field.

4.3 Test Matrix

The IMSPiDR experiment utilized a *split-plot design* as shown in Table 2. Each ASTOR pilot, DTS crew, and IFD crew was designated as a *whole plot*, and Simulator Type served as the *whole-plot factor*, since each pilot or crew was assigned to fly one of the three types of simulators previously described. To meet time constraints, the two scenarios with No Error were flown only once, and the remaining four scenarios twice. Therefore, each pilot or crew flew 10 nominal scenarios, with each whole plot "split" into 10 *sub-plots*, or treatment conditions. As described below in the Scenario Design section, each flight scenario (i.e., treatment condition) was designed according to a combination of two independent variables (e.g., Control Method and Error Source). Therefore, Control Method and Error Source served as the experiment's *sub-plot factors*.

Table 2. Experiment Test Matrix for Nominal Scenarios

ERROR SOURCE \ CONTROL METHOD	RTA	RTA+FIM
None	Scenario A (1 replicate)	Scenario B (1 replicate)
Wind	Scenario C & G (2 replicates)	Scenario D & H (2 replicates)
Offset	Scenario J & L (2 replicates)	Scenario K & M (2 replicates)

An exploratory eleventh scenario (Scenario I) was flown after the 10-scenario test matrix was complete; however, only subjective data (post-run questionnaire) were analyzed.

4.4 Independent Variables

4.4.1 Control Method

The first independent variable was the ASTAR10 algorithm's "Control Method", and the options were RTA (absolute time to the runway threshold) or RTA+FIM (start with absolute time to the runway, then transition to relative spacing behind the Target aircraft). Although RTA-only operations are not part of the FIM 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 (FIM). Additionally, the RTA functionality provided by ASTAR10 is significantly more precise than typical RTA performance available in current day aircraft.

4.4.2 Error Source

The second independent variable was “Error Source,” with values of No Error, Wind Error, and Offset Error. Two wind fields were defined that were uniform and did not vary over time, but did vary direction and speed as a function of altitude. The forecast (or predicted) wind field was used for every scenario for creating the schedule, data link to the flight crew, and calculations by ASTAR10. It was also the wind field that the aircraft model experienced during the No Error and Offset Error conditions. The actual wind field was used during the Wind Error condition, but only by the aircraft model. The logic used to create the truth wind file is outlined in the next paragraph.

4.4.2.1 Forecast Wind Error

The Wind Error condition was intended to emulate the difference between the forecast and actual wind. This error was created in two steps. First, 150% of the error expected of a Rapid Update Cycle (RUC-13) three hour forecast (Figure 20, the difference between the solid blue and dotted orange lines) was added to an observed wind during KDFW south flow operations. Second, an observed wind shear, strategically set at the merge altitude of 5000 ft MSL, was also added. (Note: 1 m/s = 1.94 kt.)

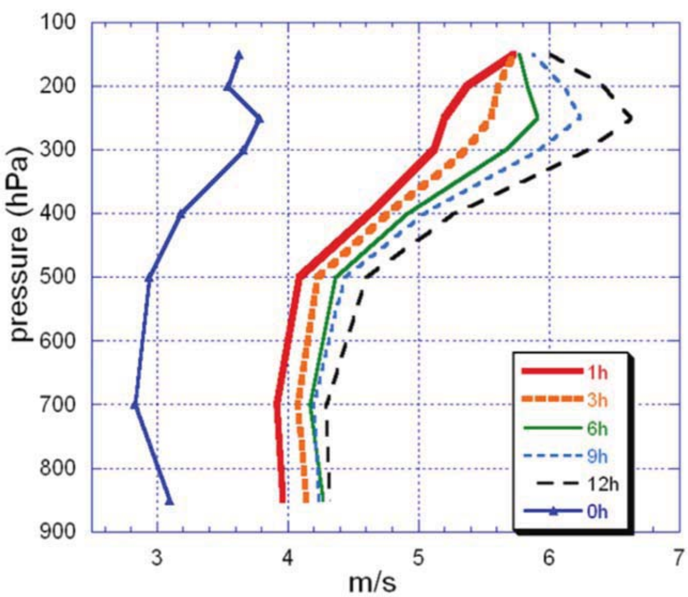

Figure 20. Expected errors of various RUC wind forecasts.

The summation of these two errors, added to the base wind, resulted in the wind field shown in Figure 21. This figure has lines connecting the circles to represent the forecast wind direction and speed, and the lines connecting the squares represent the actual wind direction and speed.

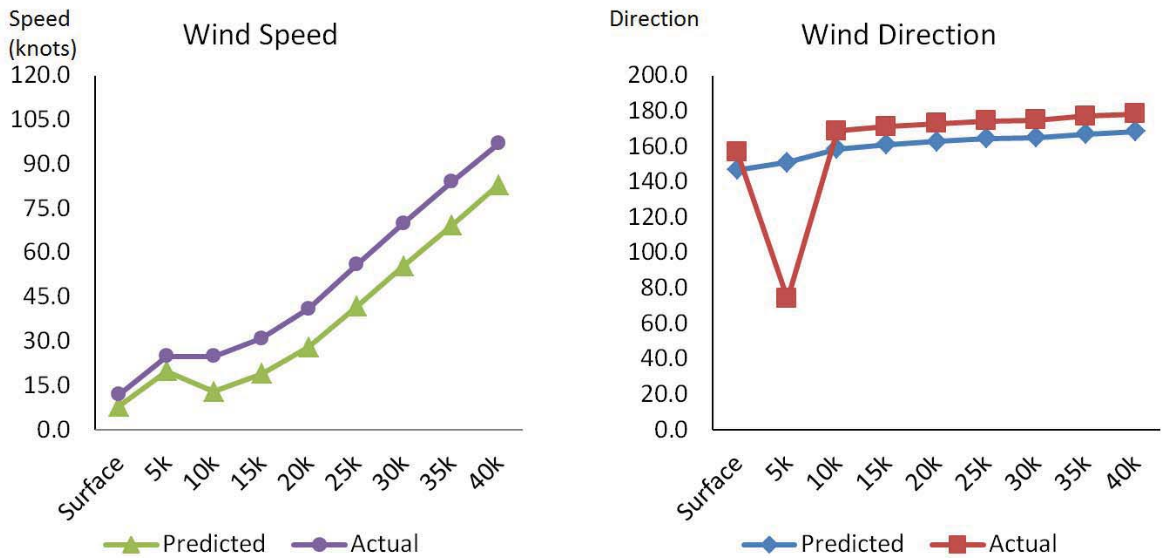

Figure 21. Predicted, actual, and FMS winds used in IMSPiDR.

Table 3. Predicted, Actual, and FMS Wind Values

	Predicted		Actual		FMS	
Altitude	**Direction (degrees)**	**Speed (knots)**	**Direction (degrees)**	**Speed (knots)**	**Direction (degrees)**	**Speed (knots)**
Surface	147.0	8.0	157.0	12.0	147.0	8.0
5k	151.0	20.0	74.0	25.0	151.0	20.0
10k	158.8	13.0	168.8	25.0	158.8	13.0
15k	161.2	19.0	171.2	31.0		
20k	163.0	28.0	173.0	41.0		
25k	164.6	41.8	174.6	56.0		
30k	165.1	55.5	175.1	70.0		
35k	167.1	69.3	177.1	84.0		
40k	168.5	83.0	178.5	97.0	168.5	83.0

NOTE 1: The Predicted wind values were used during all scenarios to calculate the schedule, and was the wind used by the ASTAR10 spacing algorithm to calculate time.

NOTE 2: The Actual wind values were used during the Wind Error condition, and were what the aircraft model and simulation platform experienced.

NOTE 3: The FMS wind values were entered into the FMS prior to every scenario, regardless of control method or error condition.

4.4.2.2 Offset Error

The Offset Error scenarios replicated an operational environment with a single 30 second perturbation (a 30 second delay applied to the schedule). All aircraft in all the Offset Error conditions begin with no schedule error, and experienced no error between the forecast and actual wind fields. To emulate the pulsed error, in the Offset Error RTA scenarios, a second CPDLC message was issued approximately 9 minutes into the scenario that delayed each aircraft's landing time by 30 seconds. For the Offset Error RTA+FIM scenarios, a second CPDLC message containing a new FIM clearance was sent to only one aircraft (the one immediately preceding the first subject piloted aircraft).

4.5 Dependent Measures

Dependent measures included a range of data collected to characterize system and human performance, and sequentially link directly to the first 3 objectives in Section 4.1.

4.5.1 Quantitative Algorithm Performance Measures

Quantitative data was collected to characterize ASTAR10 algorithm performance during FIM operations for parallel dependent runways into KDFW. These measures included the deviation from the RTA or the assigned spacing interval (also called arrival error) at the runway and throughout the arrival, the number and location of speed changes, and the timing of speed changes. This information was also used in additional analyses to describe ASTAR10 behavior and assess algorithm performance by runway and by position in the arrival stream.

4.5.2 Quantitative Pilot Performance Measures

The quantitative measures of flight crew performance of primary interest were pilot reaction time to the FIM speed change and pilot conformance to the FIM speed. Of secondary interest was the time required to "Read" and "Respond" to CPDLC messages. Of tertiary importance was gear and flap deployment by the pilot, which was used to analyze examples of not achieving the FIM speed or improperly conducting FIM operations.

4.5.3 Qualitative Pilot Assessments

Pilot ratings regarding the acceptability and workload of the FIM concept and procedures, as well as the spacing algorithm's speed guidance and pilot interface, were collected through a post-run questionnaire (Appendix D), a post-experiment questionnaire (Appendix E), and during post-experiment group debrief sessions. Workload ratings were obtained using the Modified Cooper-Harper (MCH) Rating Scale [22]. Use of the MCH scale yields an overall workload rating ranging from "1" (indicating that the instructed task was very easy/highly desirable; operator mental effort was minimal; and desired performance was easily attainable) to "10" (indicating that the instructed task was impossible and could not be accomplished reliably).

4.6 Scenario Description

4.6.1 Nominal Scenario

Scenarios were designed to simulate a near term NextGen environment. Each scenario had the six piloted aircraft flying different approaches to runway 17C at DFW airport in visual weather conditions and using instrument flight rules. Additional traffic was added to the scenarios with pilot model flown ASTOR machines. The routes were created by modifying existing STARs into KDFW, with the piloted aircraft on the MASTY 3, BONHAM 5, and CEDAR CREEK 6 arrivals (Figure 22). Altitude restrictions on the routes were modified to approximate OPDs, simulating near idle continuous descents designed to be fuel efficient and reduce noise. The airport diagram, arrival procedures, and instrument procedure diagrams, are available in the Appendix F.

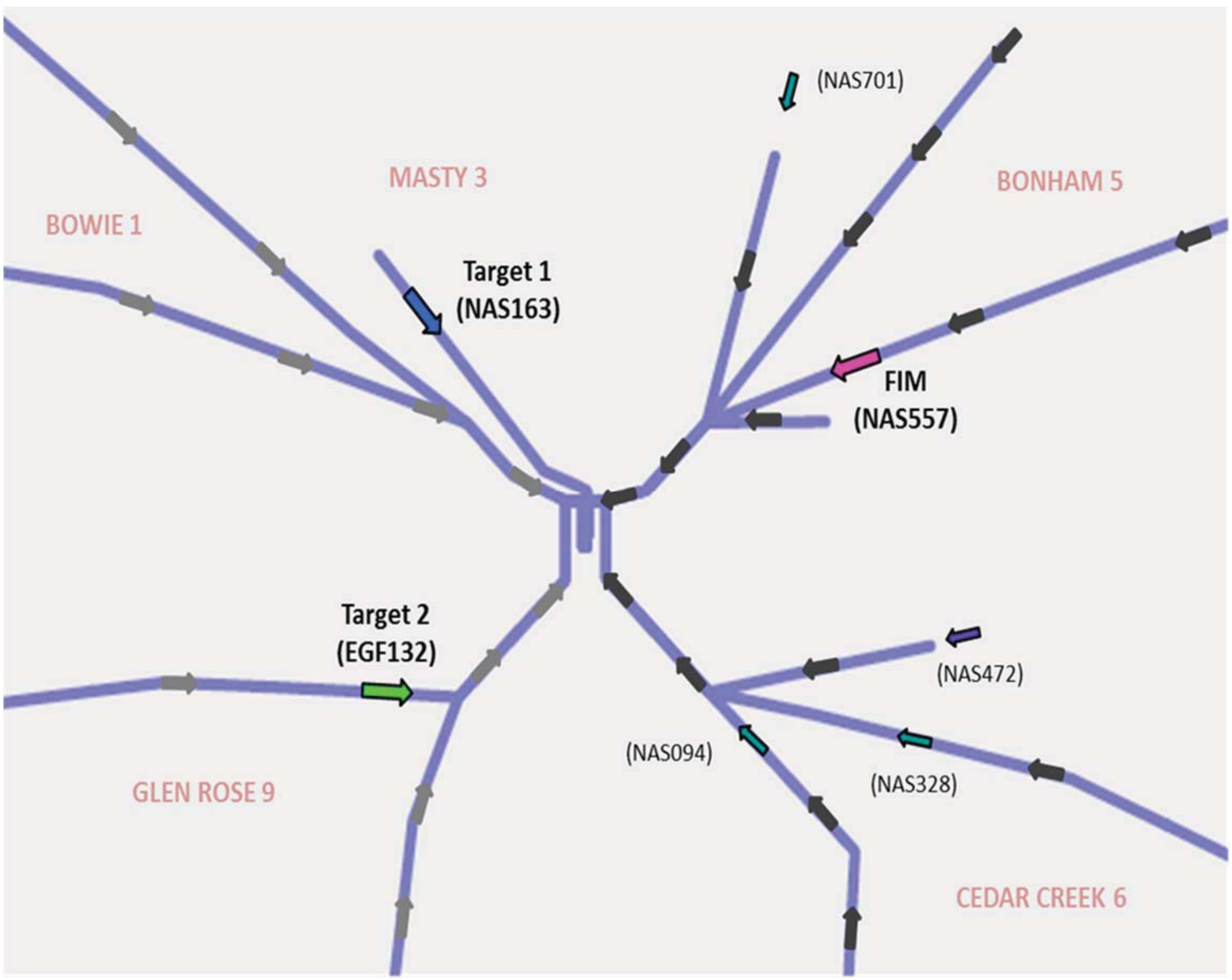

Figure 22. Arrival routes and initial aircraft positions.

NOTE: Figure 22 has been created to show the relative starting position of all aircraft arriving to KDFW, with the six aircraft piloted by the subject pilots indicated by the NASA callsigns. The relative position and color coding of NAS557, NAS163, and EGF132 pertains to the results described in Figure 30 and Figure 31.

Each scenario contained 35 aircraft on one of 14 arrivals into KDFW, 25 aircraft departing KDFW, and 4 aircraft arriving to KDAL. Arriving aircraft not flown by subject pilots were generated using ASTOR stations using the Pilot Model function, and departing aircraft generated by MACS. The aircraft's initial conditions (callsign, route, altitude, arrival sequence) were identical during the ten data collection runs, while the particular aircraft flown by the subject pilots 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 simulators, one was the DTS, and one was the IFD. The pilots maintained the same position (ASTOR pilot, First Officer in the DTS, etc.) throughout the experiment.

In order of arrival, Table 4 gives the piloted aircraft's callsign, route of flight, approximate time of flight, RTA clearance, and FIM clearance for the ten data collection scenarios.

Table 4. Callsign, Routes, and Clearances, by Arrival Sequence

Callsign	Route / Transition	RTA Clearance	RTA+FIM Clearance
NAS094	Cedar Creek 6 / Humble	CROSS R-17C AT 0022:30	CROSS R-17C AT 0022:30. WHEN ABLE CLEARED IM-SPACING 120 SEC WITH DAL421 AND 2.2 NM WITH BTA291. ACHIEVE BY R-17C. TERMINATE AT R-17C. DAL421 ROUTE FSM BYP5 PENNY ILS17C, FAS 133 KT. BTA291 ROUTE INK JEN9 YOHAN ILS18R, FAS 126 KT. REPORT COMMENCING IM-SPACING.
NAS163	Masty 3 / Hydes	CROSS R-17C AT 0024:30	CROSS R-17C AT 0024:30. WHEN ABLE CLEARED IM-SPACING 120 SEC WITH NAS094 AND 2.2 NM WITH AAL351. ACHIEVE BY R-17C. TERMINATE AT R-17C. NAS094 ROUTE IAH CQY6 PENNY ILS17C, FAS 126 KT. AAL351 ROUTE TXO UKW1 YOHAN ILS18R, FAS 133 KT. REPORT COMMENCING IM-SPACING.
NAS557	Bonham 5 / Little Rock	CROSS R-17C AT 0026:30	CROSS R-17C AT 0026:30. 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.
NAS328	Cedar Creek 6 / Alexandria	CROSS R-17C AT 0028:30	CROSS R-17C AT 0028:30. WHEN ABLE CLEARED IM-SPACING 120 SEC WITH NAS557 AND 2.2 NM WITH AAL15. ACHIEVE BY R-17C. TERMINATE AT R-17C. NAS557 ROUTE LIT BYP5 PENNY ILS17C, FAS 126 KT. AAL15 ROUTE SAT JEN9 YOHAN ILS18R, FAS 133 KT. REPORT COMMENCING IM-SPACING.
NAS472	Cedar Creek 6 / Gregg County	CROSS R-17C AT 0030:30	CROSS R-17C AT 0030:30. WHEN ABLE CLEARED IM-SPACING 120 SEC WITH NAS328 AND 2.2 NM WITH UPS391. ACHIEVE BY R-17C. TERMINATE AT R-17C. NAS328 ROUTE AEX CQY6 PENNY ILS17C, FAS 126 KT. UPS391 ROUTE SAT JEN9 YOHAN ILS18R, FAS 133 KT. REPORT COMMENCING IM-SPACING.
NAS701	Bonham 5 / Mc Alester	CROSS R-17C AT 0032:30	CROSS R-17C AT 0032:30. WHEN ABLE CLEARED IM-SPACING 120 SEC WITH NAS472 AND 2.2 NM WITH JBU853. ACHIEVE BY R-17C. TERMINATE AT R-17C. NAS472 ROUTE GGG CQY6 PENNY ILS17C, FAS 126 KT. JBU853 ROUTE TXO UKW1 YOHAN ILS18R, FAS 133 KT. REPORT COMMENCING IM-SPACING.

During these scenarios, the pilots used FMS guidance to fly the aircraft from its initial position to the runway. Pilots were cleared for the descent prior to the beginning of the scenario and had a route preloaded into the FMS. Before reaching the TOD, pilots were issued a CPDLC clearance containing their spacing instructions. Since all messages provided within this experiment were correct, pilots were expected to load the clearance and accept it. Once the clearance was accepted and the spacing operation was executed, pilots were instructed to follow ASTAR10's speed commands to achieve a precise spacing or RTA at the runway threshold. In each of the nominal scenarios, the initial CPDLC clearance was given prior to the TOD; however, Offset Error scenarios involving the use of RTA procedures included an additional message that was sent when the aircraft reached 9,000ft MSL to create a spacing error.

While CPDLC messages were used for the FIM clearance, voice was used for all other communication. Three ATC stations were staffed by confederate controllers who gave landing clearances, provided frequency changes, and handled any unexpected events. In addition to the communications between subject pilots and the confederate air traffic controllers, communication between pilot model ASTORs and ATC were recorded and played to provide background chatter.

4.6.2 Exploratory Scenario

One exploratory scenario was designed to examine various off-nominal events. During the exploratory scenario, the ATC assigned spacing interval was decreased to 75 seconds to simulate operations in visual flight rules conditions. Additionally, a new display element, the conformance box, was added to the PFD during this scenario. This exploratory run contained multiple events; however, of primary interest was the acceptability of FIM procedures at a relatively low altitude after a go-around. This operation was flown by the crew in the IFD, with the crew in the DTS provided several changes to their FIM clearance to create adequate space for the IFD to merge back into the traffic flow. Other events in this scenario included a clearance to space off an aircraft landing on runway 13R, and spacing behind a Target aircraft on the same route but landing on the parallel runway. Only questionnaire data was collected and analyzed for this run.

4.7 Subject Pilots

Twenty-four current commercial airline pilots, employed by major U.S. air carriers, participated in three groups of eight participants, each group completing the experiment in 2.5 days. All pilots were male and ranged in age from 37-61 years, with a mean age of 51.5 years and 6.3 years standard deviation (SD), and an average of twenty years flying experience and over 11,000 hours of flight time. Seventeen of the subjects were qualified as Boeing 777 pilots, four as Boeing 757/767 pilots, two as Boeing 747 pilots, and one as a Boeing 737 pilot. Twelve participants flew as single pilots in the ATOL while the remaining twelve flew as members of six two-person crews in either the IFD or DTS. To minimize potential effects associated with different airline operating procedures, all two-person crews were paired from the same airline, with pilots in the same Captain or First Officer position they fly operationally.

Each pilot was required to meet specific qualifications, which differed by simulation platform, and are outlined below.

a) Category I (2 pilots in the IFD):
   i) current B-757 pilots (preferred) or have flown B-757 within the past 6 months
   ii) one pilot will be qualified as a Captain, the other as First Officer (or have been qualified in that position within the past 6 months)
   iii) the Captain and First Officer will be from the same airline
   iv) experience with CPDLC Data Comm is desired

b) Category II (2 pilots in the DTS):
   i) current in a Boeing glass cockpit aircraft (preferred), such as B-747-400, B-777, B-737NG, or B-767-400, or have flown them within the past 6 months
   ii) one pilot will be qualified as a Captain, the other as First Officer (or have been qualified in that position within the past 6 months)
   iii) the Captain and First Officer will be from the same airline
   iv) experience with CPDLC Data Comm is desired

c) Category III (4 pilots in the ATOL):
   i) currently flying an aircraft with glass cockpit displays and a Flight Management System (required)
   ii) experience with CPDLC Data Comm is desired

4.8 Protocol

Three sessions were scheduled over consecutive weeks, each with a different group of pilots, for a total of 24 pilots. Within each group of participants, four flew as single pilots using the ASTOR stations, two flew as a two-person crew in the DTS, and two flew as a two-person crew in the IFD. For the ten nominal scenarios, the aircraft's initial position and arrival sequence was identical, with the six aircraft flown by subject pilots identified by a NASA callsign. The subjects remained at the same physical location throughout the experiment (ATOL, IFD, DTS), but rotated among these six aircraft with NASA callsigns.

All pilots received training material tailored to their simulator prior to arriving at NASA LaRC (see Appendix G for the IFD version), plus five hours of hands-on training after arriving. Emphasis was on conducting FIM procedures in accordance with their company's standard operating procedures while flying in a busy terminal environment and complete cockpit tasks appropriately as workload permitted. It was further emphasized they should accomplish FIM related tasks within the context of other priority tasks, and that the experiment goal was not to determine how quickly the tasks could be accomplished. Several training runs were held on the first day, and a refresher on the second day (Appendix H). During data collection runs, each group of pilots simultaneously flew their aircraft in shared scenarios, i.e., they piloted six of the 39 aircraft arriving to the Dallas Forth-Worth airport. The remaining aircraft were controlled and flown by software designed to replicate normal pilot behavior.

5 Results

This Section presents results in four sub-sections: quantitative algorithm performance, quantitative pilot performance, qualitative pilot responses, and off-nominal scenario. The first three sub-sections align directly to the first three objectives in Section 1.3, and also align directly to the three dependent measures in Section 4.5. The fourth sub-section in Results, off-nominal scenario, is listed separately since only qualitative pilot data was collected and analyzed.

5.1 Quantitative Algorithm Performance Results

5.1.1 Spacing Interval Precision at the Runway

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 the mean spacing error of aircraft using relative spacing (RTA+FIM) at the threshold was under five seconds regardless of the error source (Table 5). The inter-arrival time recorded in this experiment revealed an interaction effect between Control Method and Error Source (p = 0.002), and results of post hoc comparisons revealed that Wind Error scenarios conducted using RTA procedures resulted in a greater arrival error when compared with each of the other five Control Method by Error Source combinations ($p < 0.05$). Furthermore, Wind Error scenarios conducted using RTA+FIM procedures resulted in a significantly smaller arrival error when compared with Offset Error with RTA+FIM scenarios, and RTA scenarios involving either an Offset Error or No Error ($p < 0.05$). ASTAR10's control design was estimated to have a ±4 second error using a five-knot granularity in the commanded speed. All of the mean arrival errors in this experiment were below 3.5 seconds, demonstrating the effectiveness of the ASTAR10 algorithm when large wind and offset errors are present. (Complete table of data and additional analysis is in Appendix I.)

Table 5. Runway Arrival Error

	RTA only		RTA+FIM	
Error Source	**Mean (s)**	**SD (s)**	**Mean (s)**	**SD (s)**
None	-3.3	4.0	-1.8	3.9
Wind	3.5	3.3	0.9	3.9
Offset	-2.3	3.3	-2.2	3.3

Despite the lengthy FIM 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 [8][9][10]. A histogram of the spacing error for the piloted aircraft during RTA+FIM scenarios is shown in Figure 23.

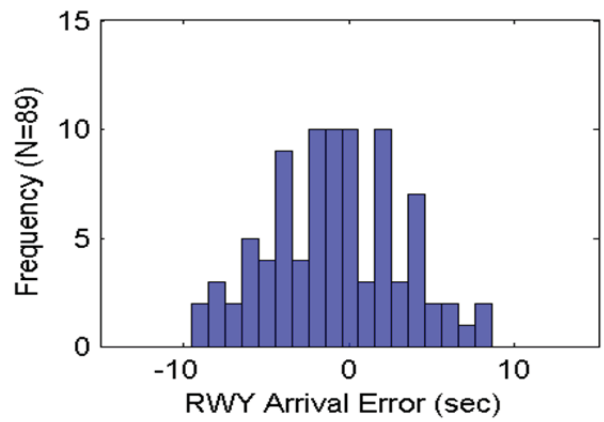

Figure 23. Histogram of RTA+FIM time error at the runway, piloted aircraft only.

5.1.2 Spacing Interval Error Throughout the Arrival

The raw time error at the runway threshold of the six piloted aircraft is plotted by control method (RTA in red, RTA+FIM in blue) for No Error conditions (Figure 24). The high frequency noise during RTA+FIM 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 FIM 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.

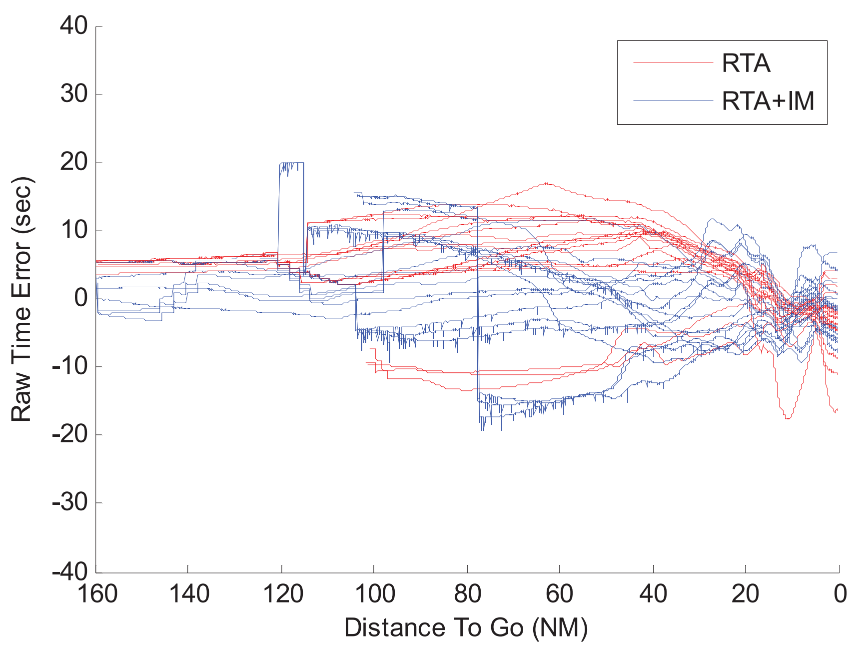

Figure 24. Time error during No Error conditions, piloted aircraft only.

For the No Error scenarios, there does not appear to be an operationally significant difference (defined as 30 seconds in Center airspace and 15 seconds in TRACON airspace) between how the RTA and RTA+FIM 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 spacing error increase was primarily due to the flight crew not matching the deceleration schedule from the final FIM Commanded Speed to the FAS. Causes include: 1) aircraft not within five knots of the final FIM Commanded Speed when ASTAR10 switched to FAS, 2) gear down and at flaps set to at least 20 degrees not achieved when ASTAR10 switched to FAS, 3) crew response to set FAS not timely, and 4) airspeed allowed to decelerate too quickly or momentarily go below FAS. Currently, the location where the ASTAR algorithm switches to the FAS depends on the difference between the nominal profile speed and the FIM commanded speed. It is hypothesized that the variance in the location where ASTAR switches to the FAS contributed to the increase in spacing error between the FAF and the runway threshold. A potential mitigation strategy would be 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+FIM control method had a greater variation of time error to correct at 40 nmi from the runway than the RTA control method did (Figure 25). However, the RTA control method's spacing error consistently had a large increase in the time error at 20 nmi from the runway, which corresponded to the location of the wind shear. This wind shear resulted in the RTA control method needing a larger control input than the RTA+FIM control method to correct for the wind shear during the final 20 nmi of flight. In the end, both methods delivered the aircraft to the threshold with high precision and little variance (Table 5). Both control methods also exhibited an increase in error variance after the FAF; however, they also had a 3-second late bias due to the stronger than expected headwind.

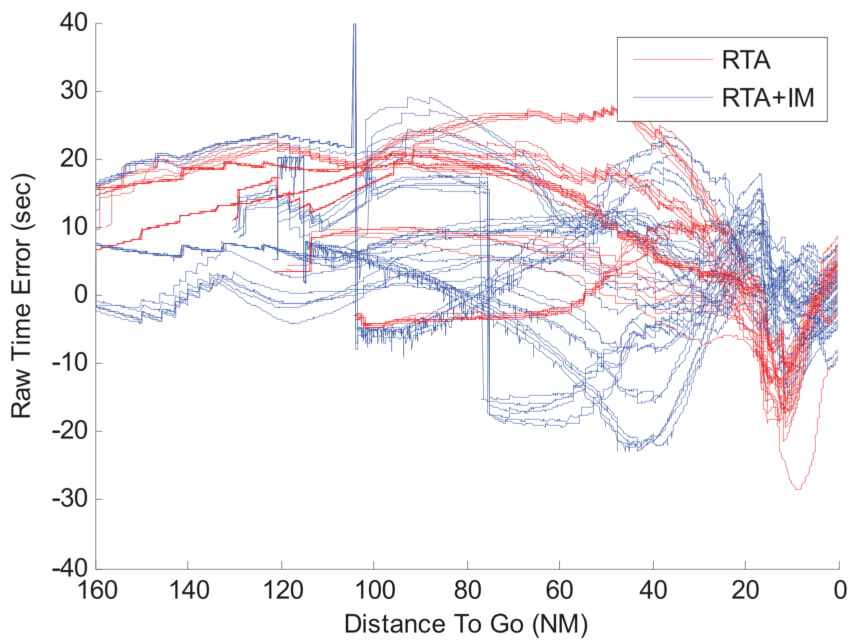

Figure 25. Time error during Wind Error conditions, piloted aircraft only.

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+FIM method; however, most of the apparent difference is due to how the time error is calculated (i.e., the difference of aircraft position using the two control methods was much less than the time shown). As seen in Figure 26, there is no statistically significant difference in time error at the runway threshold (p=0.27).

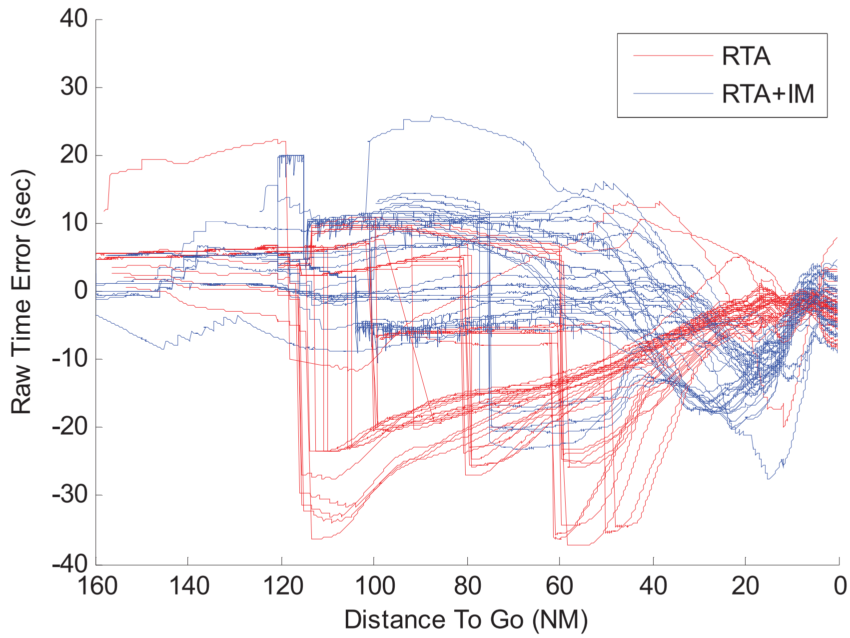

Figure 26. Time error during Offset Error conditions, piloted aircraft only.

The previous plots graphically illustrated the differences between the RTA and RTA+FIM control methods. These differences can also be examined numerically. One measure of the magnitude of control inputs provided by the spacing algorithm is the Root-Mean-Squared (RMS) difference between the FIM-commanded speeds and the nominal profile speeds (Figure 27). The RMS difference between the commanded speeds and the profile speeds was examined for differences between control methods and error sources. The results demonstrated that there were significant differences between error sources (p<0.001) and significant interactions between the control methods and error sources (p<0.001). A Tukey pairwise comparison test was used to examine which factors were significantly different from each other. This analysis revealed that the aircraft in the scenarios without error had the smallest deviation from the nominal profile, followed by the Wind Error and Offset Error scenarios. Furthermore, there were a number of significant interactions between the errors sources and control methods.

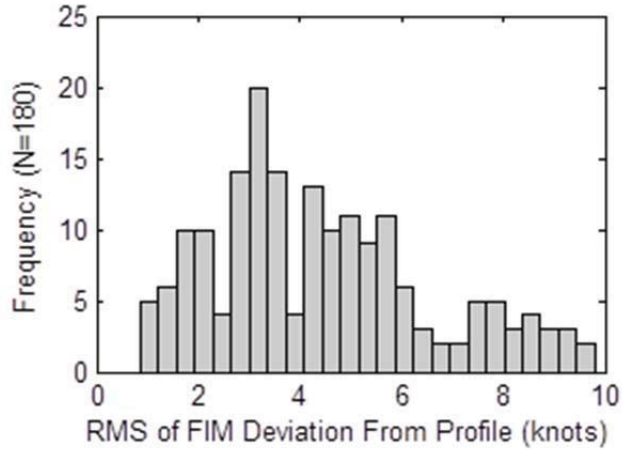

Figure 27. RMS difference between nominal profile speed and commanded speed.

An interesting result was the effect of Wind Error on both Control Methods. As seen in Table 6, the aircraft in the Wind Error scenarios remained significantly closer to their nominal profile when using the RTA+FIM control method versus the RTA control method. This observation is consistent with the results shown in Figure 25, where it was shown that the wind shear (at 20 nmi) created a larger time error for aircraft using only the RTA control method than it did for aircraft using the RTA+FIM control method. It is hypothesized that this occurred because the RTA aircraft had to compensate for the wind error to achieve the scheduled time. In contrast, aircraft using the RTA+FIM control method were responsible for achieving an interval. Thus, both the spacing aircraft and lead aircraft flew through the same wind error, enabling the interval to be maintained without the need for large corrections. However, this result is unique to the particular scenarios used in this experiment and is not representative of other results obtained for relative spacing in the presence of Wind Error.

Table 6. Difference Between Profile Speed and Aircraft Speed by Control Method

	RTA		RTA+FIM	
Error Source	**Mean (knots)**	**SD (knots)**	**Mean (knots)**	**SD (knots)**
No Error	2.8	1.7	2.2	1.3
Wind Error	6.0	2.0	3.6	1.2
Offset Error	5.0	1.8	4.9	2.2

In summary, although the initial 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+FIM). Furthermore, the two specific error types (Wind and Offset) created different ASTAR10 behavior within that condition based on Control Method. The most notable difference was that the RTA control method needed almost twice the control input than the RTA+FIM control method during the Wind Error scenarios.

5.1.3 Number and Frequency of FIM Speed Changes

It was expected that the majority of the workload and disruptions associated with the spacing operation would result from monitoring and implementing FIM speed changes. And as described in a later section, many of the pilots made comments related to undesirable responses driven by large wind and offset errors. Therefore, it is useful to understand the effect of the wind and offset errors on both the number and distribution of speed changes.

The highest number of ASTAR10 speed changes occurred during the Wind Error condition for both Control Methods (p<0.001) (Table 7, subject pilot aircraft only), which coincided with the lowest FIM procedure acceptability rating by flight crew during post-scenario questionnaires. The majority of the additional speed changes happened during the wind shear, which was intentionally designed to occur when the crew was configuring the aircraft and intercepting final. (Complete raw data and further analysis is available in Appendix J.)

The total number of speed changes strongly depended on the error source, with the No Error condition being associated with the lowest number of speed changes and the Wind Error condition being associated with the highest number of speed changes. Of the FIM speed changes during the 25 to 30 minute arrival, five correspond to scheduled profile speed changes. Note that these five speed changes do not take into account the additional number of speed changes that would normally be issued by ATC in a traditional spacing operation. To better understand the commanded speeds, the total number of speed changes was examined in conjunction with distributions of speed change frequency and speed changes as a function of distance to go.

Table 7. Total Number of Speed Changes, by Control Method and Error Source

	Control Law			
	RTA		RTA+FIM	
Error Source	**Mean (sec)**	**Std Dev (sec)**	**Mean (sec)**	**Std Dev (sec)**
No Error	9.3	2.0	9.7	1.9
Wind Error	17.2	4.0	16.1	3.3
Offset Error	10.4	2.3	13.1	1.8

One comment flight crew made throughout the post-scenario and post-experiment questionnaires was related to the algorithm providing flight crew with multiple speed commands within a short period of time, thereby generating higher workload and causing some pilots to question the rationale of the algorithm. To better understand the distribution of the time between consecutive speeds changes, a histogram was created (Figure 28). When all scenarios were examined together, it was found that 71% of speed changes occurred less than one minute after the previous speed change, 41% of speed changes occurred fewer than 30 seconds after the previous speed change, and 12% of speed changes occurred fewer than 10 seconds after the previous speed change. Scenarios involving the No Error condition contained the best distribution, with 68% of speed changes occurring less than one minute after the previous speed change, 33% of speed changes occurring fewer than 30 seconds after the previous speed change, and 9% of speed changes occurring fewer than 10 seconds after the previous speed change. These percentages must be read in the context of the total number of speed changes shown in

Table 7. While the distribution of the scenario involving the No Error condition has a similar distribution to the scenarios involving Wind Error and Offset Error, the smaller number of speed changes makes it less likely for speed commands to be closely spaced together in time.

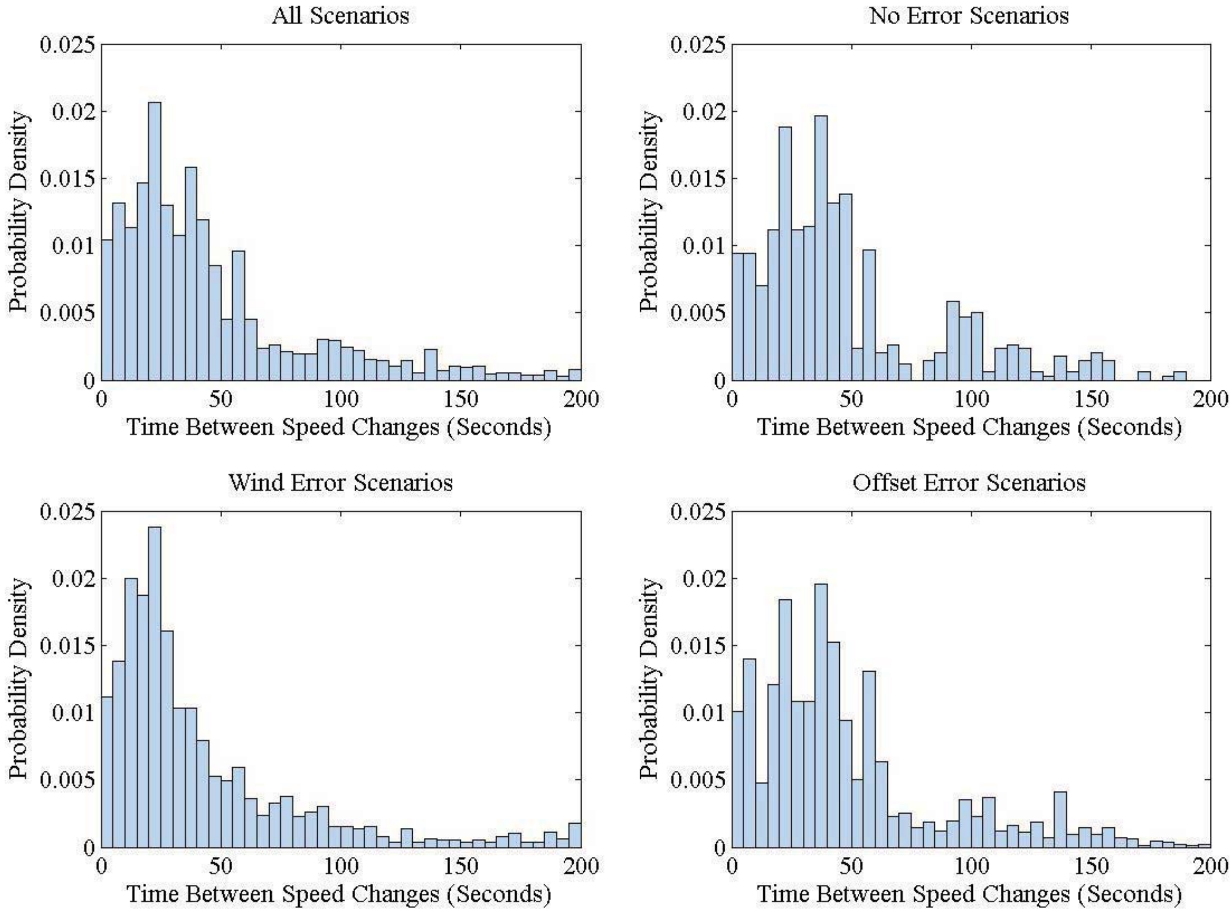

Figure 28. Histogram of time between consecutive speed changes.

Since several flight crews reported that the number of speed changes on final approach seemed excessive, the number of speed changes that occurred when the aircraft was on final approach was also analyzed, and a histogram of the location along the arrival was plotted (Figure 29). The shape of the distribution of speed changes as a function of distance-to-go was dictated by the filtering in ASTAR10 that ignored some time error when the aircraft was far from the runway, resulting in fewer total speed changes, but resulted in a higher percentage of speed changes as the aircraft approached the runway. When examining all scenarios (i.e., those using the RTA control method and the FIM control method), the speed changes that occurred on final approach during the Wind Error scenarios were found to be significantly greater than the speed changes on final for the scenarios involving No Error and the scenarios involving the Offset Error ($p<0.0005$). The No Error scenarios had an average of 2.44 (SD=0.80, N=36) speed changes on final; the Offset Error scenarios had an average of 2.68 (SD=0.93, N=72) speed changes on final; and the Wind Error scenarios had an average 3.38 (SD=1.10, N=71) speed changes on final.

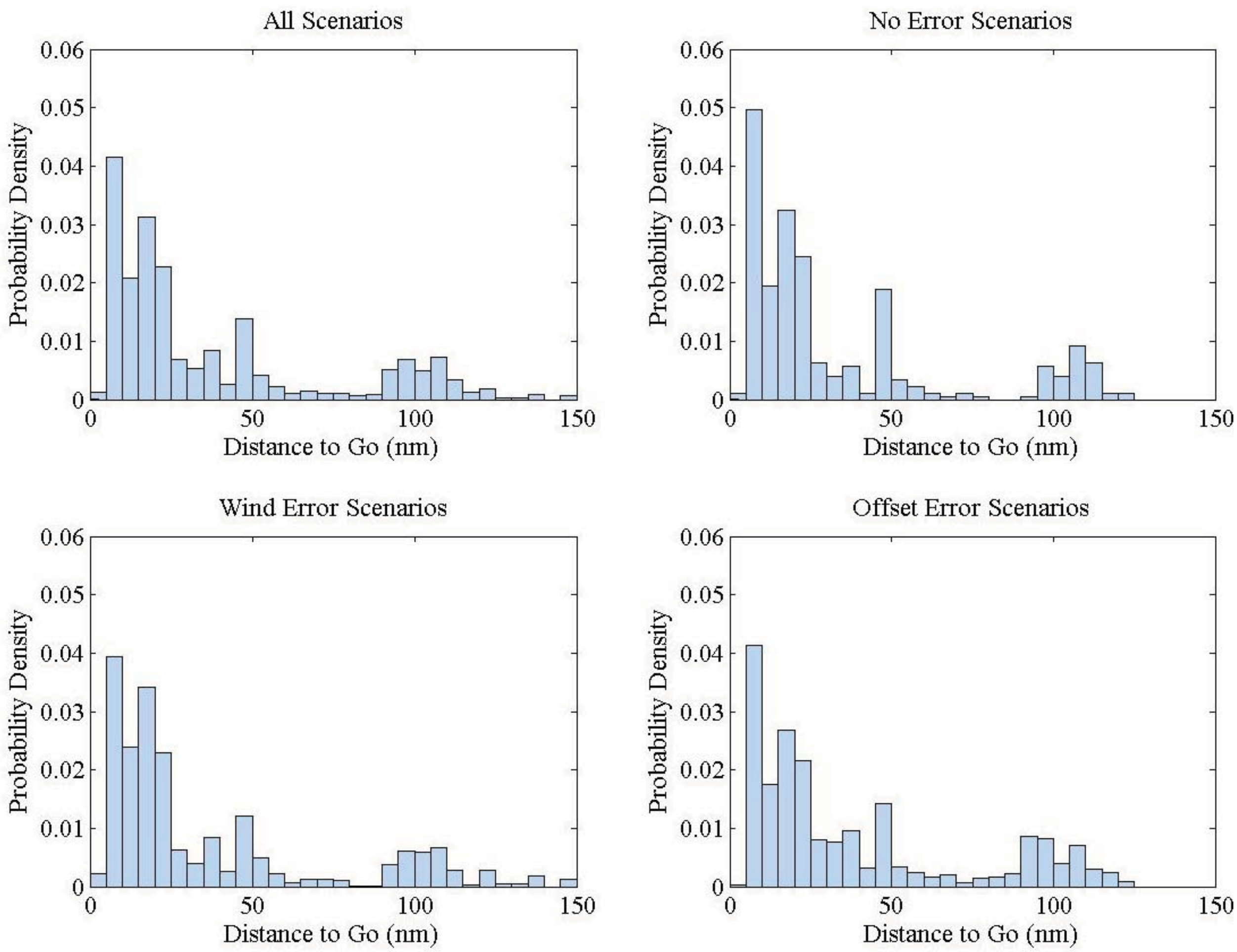

Figure 29. Histogram of speed changes as a function of distance remaining.

When speed changes were examined as a function of distance to go, 89% of speed changes occurred during the last 100 nmi, 69% occurred during the last 40 nmi, and 21% of speed changes occurred during the last 10 nmi of flight. These results are consistent with those indicating that a majority of the pilots' peak workload occurred while below 5,000 ft MSL. When asked if the spacing tool required an extraneous expenditure of mental resources that should be used for landing preparation, 67% of flight crew rated the expenditure of resources as acceptable, 13% said that the spacing tool freed up mental resources, and 21% stated that the spacing procedure demanded mental resources needed to prepare for landing. Those who stated that spacing procedure's requirement of mental resources was too great, cited inadequate cues to notify the flight crew of a speed change and undesirable speed changes.

A third issue reported by the flight crew was related to undesirable speed increases. To attempt to limit the number of speed increases shortly followed by speed decreases, the ASTAR10 algorithm inhibited speed increases 10 seconds prior to a scheduled profile speed decrease. However, some flight crew still commented that speed increases were shortly followed by a speed decrease, leading to the perception that the speed increase was unnecessary. Additionally, flight crew commented that speed increases were undesirable once they had begun to configure their aircraft (approximately 20 nmi from the runway threshold). To better understand the impact of undesirable speed increases, two metrics were examined: the time between a speed increase and a subsequent speed decrease, and the number of speed increases given when the distance-to-go was less than 20 nmi. The average number of speed increases for all scenarios was 3.58 (*SD*=2.21, *N*=180). Overall, aircraft were issued an average of 1.56 (*SD*=1.40, *N*=180) commanded speed increases when they were within 20 nmi of the runway threshold, with aircraft in the No Error scenarios involving receiving a mean number of 0.53 commanded speed increases (*SD*=0.84, *N*=180), aircraft in the Wind Error scenarios receiving a mean of 1.89 commanded speed increases (*SD*=1.30, *N*=180), and aircraft in the Offset Error scenarios receiving a mean number of 1.74 commanded speed increases (*SD*=1.49, *N*=180) within 20 nmi of the runway threshold. Additionally, the time between a speed increase and subsequent speed decrease was examined, and the results are shown in Table 8. These results indicate that a short time between speed increases and a subsequent speed decrease was a greater problem for the Wind Error scenarios than it was for Offset and No Error scenarios.

Table 8. Distribution of Time Between Speed Increase Then Decrease

Time Between Speed Increase and Subsequent Speed Decrease	No Error	Wind Error	Offset Error	All Scenarios
<10 seconds	0.08	0.31	0.08	0.17
<20 seconds	0.19	1.24	0.27	0.65
<30 seconds	0.28	1.82	0.51	1.01
<60 seconds	0.64	2.68	1.09	1.67

5.1.4 Example of ASTAR10 Performance

Figure 30 contains typical algorithm performance observed during the IMSPiDR experiment, and Figure 31 is an expanded view illustrating the final 25 nmi of flight. Data shown in these figures are from the IFD during a RTA+FIM with Wind Error 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 nmi behind EGF132. [NOTE: to assist in understanding the events that occurred to this particular crew during this example, Figure 22 illustrates the aircraft's initial condition and arrival procedures, Table 4 contains the FIM clearance for NAS557, and the colors in Figure 30 and Figure 31 align with the colors used in Figure 22.]

The top plot describes the ASTAR10 calculated time error, with positive (+) seconds indicating the FIM aircraft arrived late to the runway, and negative (-) seconds indicating the aircraft arrived early. The horizontal axis for all plots is "distance to go in nmi". Shown are 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 filtered time error began when the RTA+FIM clearance was entered by the flight crew into the onboard spacing tool, approximately 120 nmi or 2 minutes into the scenario, and is initially based on the RTA to the runway since both Target aircraft are outside of ADS-B range. At approximately 101 nmi from the runway, the FIM aircraft received ADS-B information on Target 1, and ASTAR10 transitioned to achieving the assigned spacing interval (FIM). During the final portion of the flight, the ASTAR10 spacing tool momentarily transitioned to Target 2, then back to Target 1 (discussed next and shown in greater detail in Figure 31).

The second plot illustrates how the spacing algorithm corrected for the time error in the top row. Shown are the published approach speed (solid black line), FIM Commanded End Speed (dashed magenta line, corresponds to speed in upper left of Figure 3), and the transition from Mach to airspeed (red X). The horizontal segment left of the X indicates level cruise flight (130 to 115 nmi distance to go), with the sloped segment left of the X a constant Mach descent (115 to 95 nmi distance to go). At approximately 101 nmi 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 FIM Commanded End Speed. Positive time error (aircraft arrives late) results in FIM speeds higher than the published speed (e.g., from 95 to 65 nmi).

The third plot illustrates the flight crews' performance to achieve the FIM Speed. The FIM Command Speed (solid magenta line, corresponding to green speed bug in Figure 3) is the estimated instantaneous speed, and the dashed black line is the actual aircraft speed. This crew exhibited very good speed control during this scenario.

The bottom row of panels illustrates the crew action (or inaction) in response to the "IM Drag Required" message that appeared whenever the aircraft's airspeed was more than six knots above the FIM Command Speed (red line). Also shown is the percent speed brake deployment (black line) and throttle lever angle (blue line). Just after 50 nmi, the FIM Drag Required message was displayed for a very short duration, and the crew elected to not deploy the speed brake. Failure to respond to the Drag Required message had such a small impact on the spacing interval error that no new FIM speed was generated, because a considerable distance remained to the Achieve By Point. At 23 nmi remaining to the runway, the crew was attentive to EICAS message and deployed speed brakes as required; however, the wind shear overwhelmed the correction, and multiple new FIM speeds were generated to slow the aircraft down.

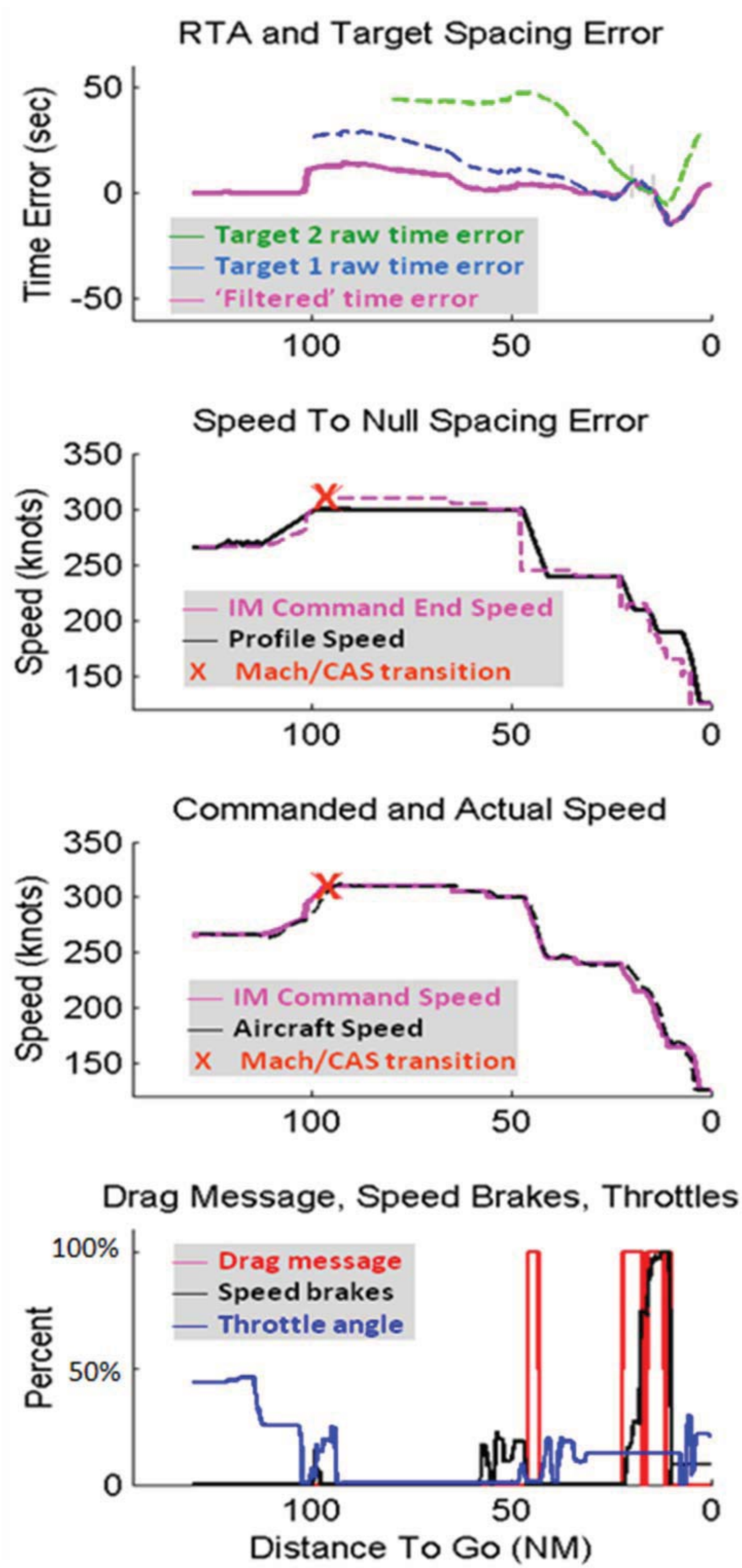

Figure 30. Example of ASTAR10 spacing algorithm performance.

Figure 31 is an expanded view of the final 25 nmi of flight for this scenario to better illustrate several interesting effects that occurred during the wind shear, which was intentionally designed to occur as the aircraft turned onto final approach. Additional information shown in the top two panels of Figure 31 is when ASTAR10 ceased correcting for spacing errors and displayed the FMS computed Final Approach Speed (blue triangle), and the third plot shows the aircraft's airspeed (dashed black line), flap deployment (blue dots), and gear deployment (green dots).

The first effect was that ASTAR10 switched from Target 1 to Target 2 at the beginning of the wind shear, then back to Target 1 as the FIM aircraft descended below the wind shear (top plot). The impact that the wind shear had on the ASTAR10 algorithm is highlighted by the two gray lines, indicating where the green dashed raw time error for Target 2 became the controlling parameter to calculate the filtered time error. The transition between Target aircraft did not generate a change to the FIM Commanded End Speed and did not require any notification to the crew or action by the flight crew. Complicating the FIM calculations, the Target 1 and Target 2 spacing errors were 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 FIM Commanded Speed. The transition occurred because Target 1 descended below the wind shear, and the faster ground speed created an earlier ETA at the runway for Target 1. In turn, this generated a 5 knot increase in FIM Commanded Speed at 21 nmi for the FIM aircraft. Meanwhile, due to arrival geometry, the time error for Target 2 from the west decreased (FIM aircraft early) due to the slower than anticipated progress (caused by the unexpected headwind). As a result, Target 2 became the controlling aircraft at 19.5 nmi.

A second effect was caused by the flight crew not bringing the throttles completely to idle (fourth plot), and the extra thrust kept the aircraft from decelerating as rapidly as the algorithm had expected (second plot). Coupled with the wind error, not bringing the throttles to idle initially caused the aircraft to increase the time error, that is, arrive early (first plot); however, the crew recognized this issue and deployed the flaps and gear considerably earlier than normal. Deploying the flaps and gear early enabled the aircraft to achieve the FIM Commanded Speed, which was now significantly less than the published speed at this point. Had they not foreseen the need for drag, there would have been considerable time error at the runway.

Finally, the combined effect of not spacing after the algorithm switched to the FAS with an incorrect wind forecast, and flying slower than the FIM speed, caused almost 15 seconds of change in the spacing error after the FAF (top plot).

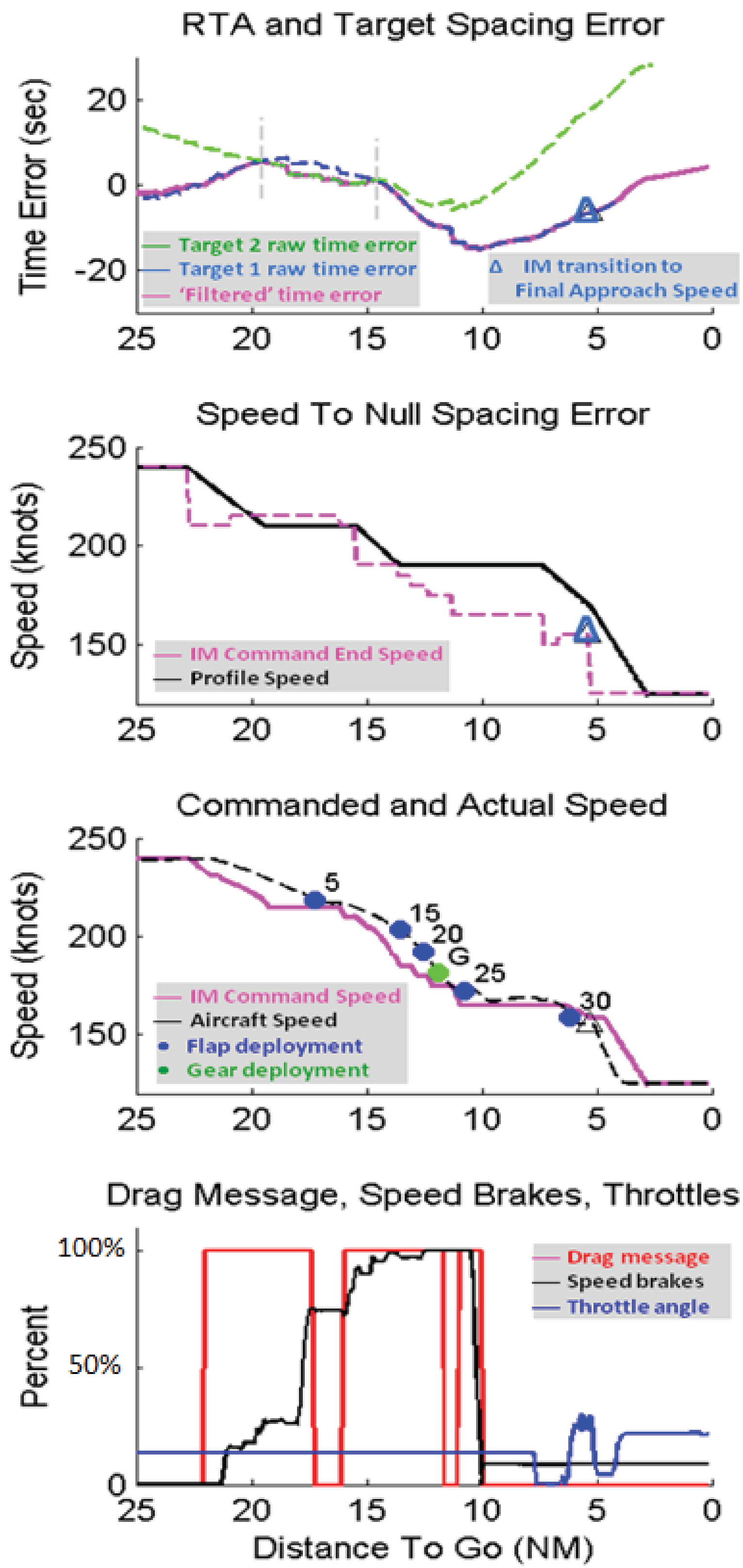

Figure 31. Expanded view of ASTAR10 performance during final 25 nmi.

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. In summary, the ASTAR10 algorithm behaved predictably and as designed, and reacts to and compensates for variations in pilot performance (if sufficient distance remains to the runway). ASTAR10 produced the desired spacing precision when the pilots flew the FIM speed, and used less control authority than controllers do in current day operations and also smaller speed changes than the aircraft is capable of.

5.1.5 Algorithm Performance by Runway

Analysis of time error by runway and 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 statistically significant difference between the two conditions themselves (Figure 32). Data shown are results averaged from both repetitions, and all three groups.

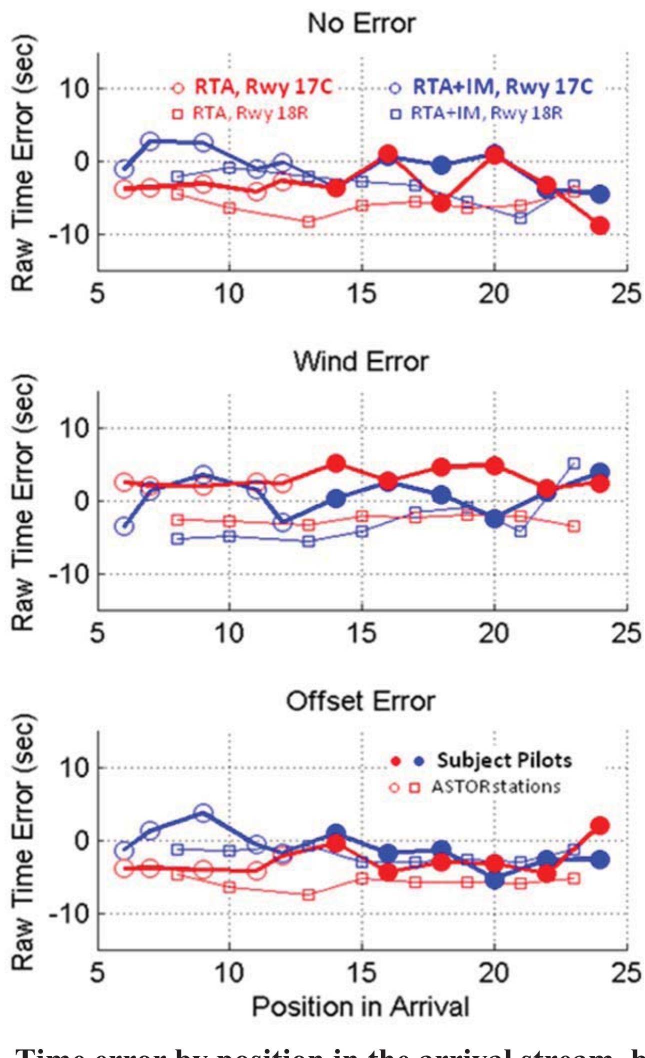

Figure 32. Time error by position in the arrival stream, by runway.

The Wind Error condition also produced no statistically significant difference for both control methods (RTA and FIM) to a particular runway and no statistically significant difference between the control methods. However, both control methods showed a bias for aircraft landing on Runway 17C (the eastern runway) approximately 2 seconds late. The aircraft landing on Runway 18R showed a bias for landing approximately 4 seconds early. However, the mean spacing error at the runway threshold for all RTA+FIM operations for all conditions was less than 2.2 seconds (Table 5). These results indicate ASTAR10's capability to respond to unknown and continuous error (forecast wind error and wind shear), and a pulse error (offset to create time delay).

5.2 Quantitative Pilot Performance Results

5.2.1 Pilot Reaction Time to FIM Speed Change

While conducting FIM, it is important for pilots to respond to speed changes within an appropriate timeframe to ensure that the aircraft achieves its required spacing interval, and prevent ASTAR10 from commanding further deviations from the nominal profile. During this experiment, pilots in the IFD were expected to notice speed changes and dial them into the MCP speed window in a timely manner. Pilots in the ATOL and DTS had their auto-throttles coupled to the ASTAR10 commanded speed for a majority of the flight; however, the MCP speed window opened when they captured the ILS and the pilots were expected to manually dial the commanded speeds into the MCP speed window. The pilot's reaction time to these speed changes was defined as the time it took for pilots to dial the speeds into the MCP speed window after a new commanded speed is given.

The time it took pilots to notice and respond to commanded speeds (during both RTA and RTA+FIM operations) was examined and compared with assumptions made by the automation during the periods when the MCP speed window was open. To complete the analysis, the response time data were averaged for each run. If a new speed change occurred before the pilot reacted to the old speed change, the reaction time for that particular speed change was considered to be the time between the two speed changes. The square root of the response data were taken to transform it into a normal distribution to enable the use of non-parametric statistical analysis. The square root transformation provided a better, though not perfect, approximation of a normal distribution (Figure 33). When the square root of the reaction time was analyzed, significant differences were found between the error (p=0.035) source and the simulator type (p<0.001).

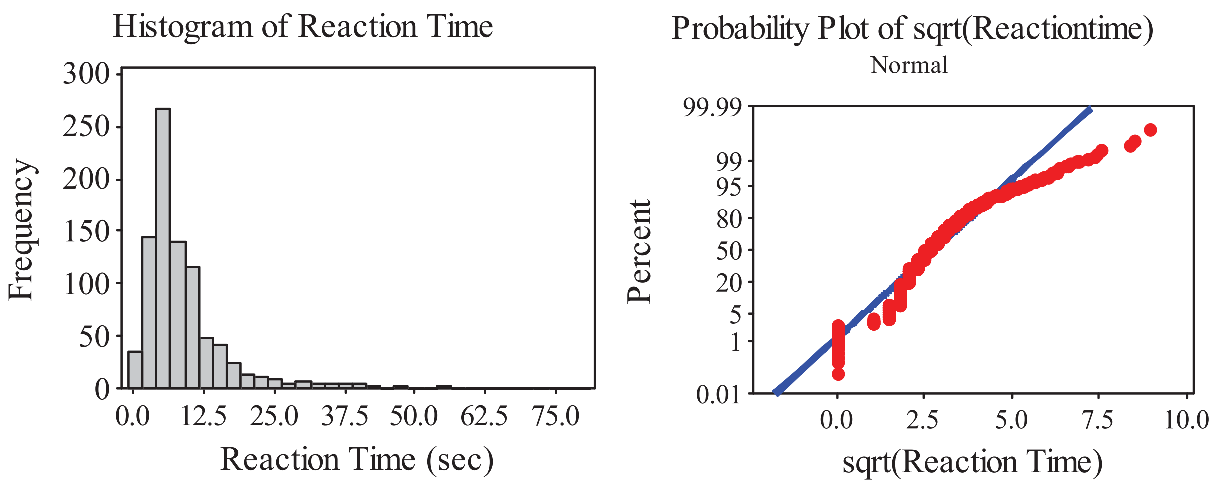

Figure 33. Pilot reaction time to change (left) and distribution of reaction time (right).

A Tukey pairwise comparison test revealed that the reaction times of the pilots in the scenarios without error were larger than the reaction times of the Wind Error scenarios (Table 9). It is hypothesized that the scenarios without error had a larger reaction time because they had fewer speed changes, and the pilots may not have been looking for them as actively. There was also a statistically significant difference in the pilots' reaction time between the different simulator types, with the ATOL having the highest reaction time (*M*=10.5, *SD*=9.2) and the IFD having the lowest reaction time (*M*=6.6, *SD*=7.4). Part of the difference in reaction times between simulators may be that the IFD flew a majority of its arrival with the MCP speed window open, whereas the ATOL and DTS pilots had the commanded speed coupled directly to the auto-throttle, with the MCP speed window opening automatically when they captured the ILS. Pilots who flew in the ATOL and DTS commented that this transition often took them by surprise, since the FMS had managed their speed throughout most of the arrival.

Table 9. Pilot Reaction Time to FIM Speed Change, by Condition

	RTA		RTA+FIM	
Error Source	**Mean (sec)**	**SD (sec)**	**Mean (sec)**	**SD (sec)**
No Error	11.6	10.7	10.4	10.7
Wind Error	8.0	7.3	8.5	7.2
Offset Error	9.1	9.8	8.8	8.9

The reaction time data shows that pilots were able to dial new commanded speeds into the MCP speed window within a reasonable period of time during all experimental conditions. However, it was determined that the reaction time was shorter for the scenarios with error conditions and for the simulator that required pilots to manually dial new commanded speeds into the MCP speed window throughout the entire arrival. Additionally, the reaction times observed in the experiment closely matched with reactions times pilots stated were reasonable in their post-experiment questionnaires.

5.2.2 Pilot FIM Speed Conformance

During the training program, pilots were instructed to keep their speed within ±5 knots of the commanded speed if feasible within normal operating procedures. A significant Control Method x Error Source interaction effect was found ($p<0.0005$), indicating that the effect of error source on pilot speed conformance was dependent upon the control method used (Table 10). Pilot conformance to the commanded FIM speed was best during scenarios conducted under conditions of No Error and was worse when RTA procedures were used during the presence of Wind Error. The No Error scenarios were the only scenarios during which the average speed deviance was within the ±5 knot bound. Researcher observations indicated that many of the segments of non-conformance occurred when commanded speed changes required a large acceleration or deceleration. Excursions of greater than 5 knots from the appropriate speed were partially due to the fact that the auto-throttles used in this experiment had a sensitivity of ±10 knots, forcing the pilots to manually adjust the throttles to maintain a ±5 knot interval. Additionally, pilot comments along with researcher observations revealed that there were pilots who preferred allowing the aircraft to slow without using the speed brake to fly a smoother flight for passengers, causing larger speed conformance errors.

Table 10. Flight Crew Deviation From FIM Speed

Error Source	Mean Error (knots)	Std Dev (knots)
None	3.6	1.2
Wind	6.2	2.0
Offset	5.8	1.6

5.2.3 Pilot CPDLC Interaction Times

This section provides data collected and analyzed pertaining to the human flight crew CPDLC interactions during the normal scenarios. These secondary metrics were of particular interest to the FAA Data Comm Program office, in particular the time from CPDLC uplink message receipt to intra-cockpit crew action to read the message, and time between message receipt to crew sending a CPDLC downlink response (shown earlier in Figure 4). Therefore, the time from the chime simultaneously sounding with the ATC Message light illuminating on the EICAS, until the flight crew sent a CPDLC downlink message of ACCEPT or REJECT, is the Required Communication Performance (RCP) time labeled “Responder” and outlined by the red box in Figure 34 (excerpt from Appendix B of reference [18]). None of the simulators used during the experiment modeled any of the other systems or categories shown in the diagram below.

The time expected for the entire CPDLC process to occur within 95% probability is either 210 or 350 seconds (based on equipment type), and are the top and bottom horizontal lines labeled “RCP type” in Figure 34. This time includes the message composition, message sent by air traffic control, transmission delays, message received and responded to by the flight crew, and response read by the controller. The time allocated for the Responder is 60 seconds, regardless of equipment type.

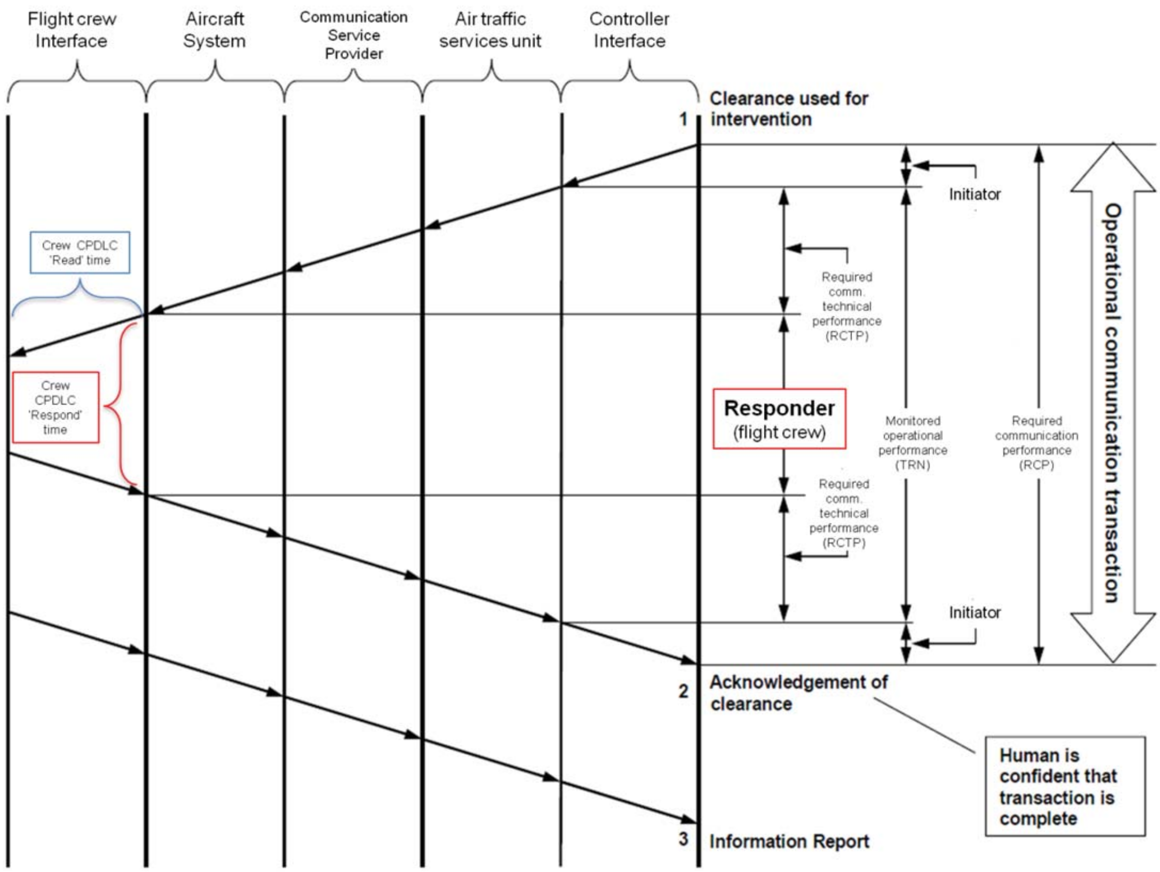

Figure 34. Required Communication Performance (RCP) diagram.

Three data runs (two in the ATOL and one in the DTS) were discarded for the Read and Respond data analysis in this section due to extremely lengthy response times. A review of the recorded video for two of these runs indicated the crews understood and were attempting to follow the FIM spacing procedures; however, they were having difficulty finding the correct button to push to send the ACCEPT CPDLC downlink message. The third run discarded was due to the failure of one of the two MCDUs in the DTS. (The complete list of raw data is available in Appendix K.)

Time used by the flight crew to Read and to Respond to CPDLC uplink messages containing the FIM clearance are shown in Figure 35, with the left group of columns containing data for condition by simulator type (by condition), the middle group of columns data for control method by simulator type (by control), and the right group of columns the data by simulator type. The data are also shown as histograms in Figure 36, using 0.5 second bins and blocked by simulator category.

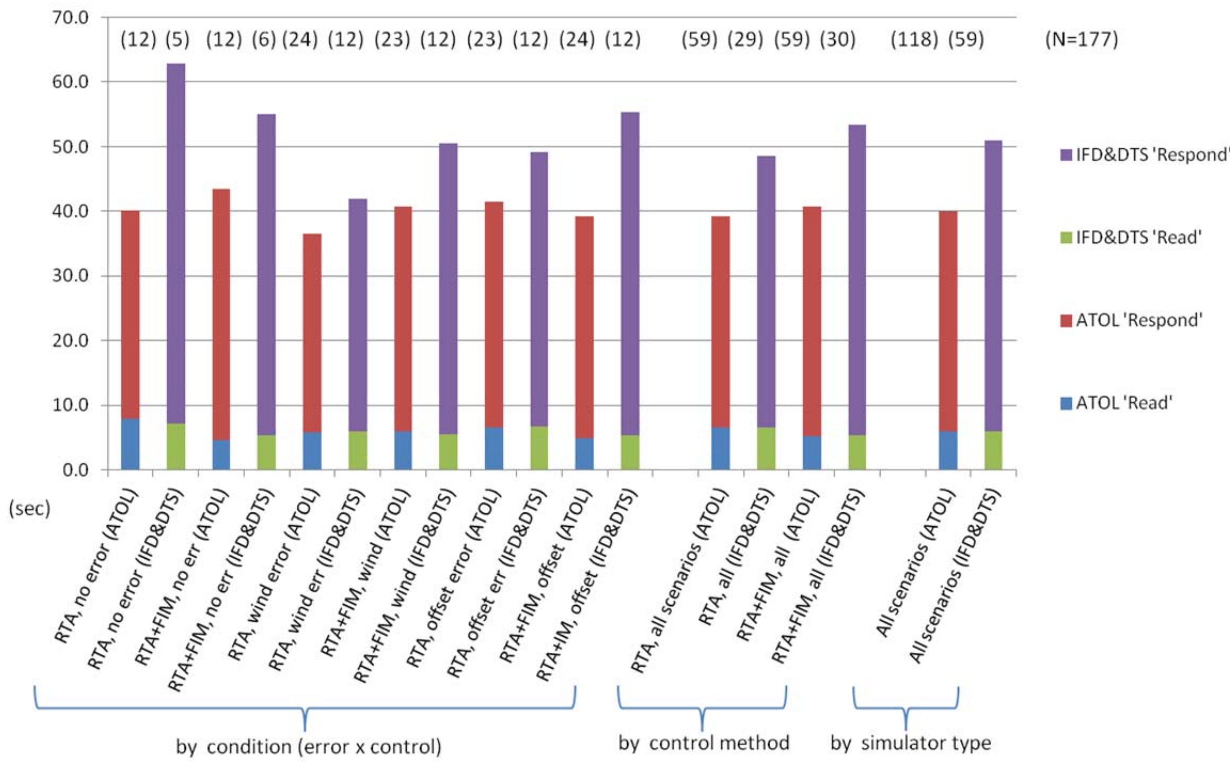

Figure 35. Mean CPDLC times by condition, by control method, and by simulator.

Large variation in flight crew Respond time to the FIM clearance sent via CPDLC appears to be primarily influenced by simulator type (one-person versus two-person crew) and sequence order of the run (learning continued throughout the experiment). 23 of the 177 (13%) data points analyzed for flight crew Respond time were greater than 60 seconds, of which 18 of the 23 were in the IFD and DTS category of simulator type. Review of recorded audio and video files reveals in almost all cases, these particular data points were from scenarios early in the run sequence (see Figure 37), and the conversation was geared to resolving questions about the CPDLC equipment or locating the correct button to press. Furthermore, the FIM procedures used in the experiment represented the most complex possible as defined in the data link standards. There were no observed runs where the crew did not have time to respond, or was not willing to respond, within 60 seconds.

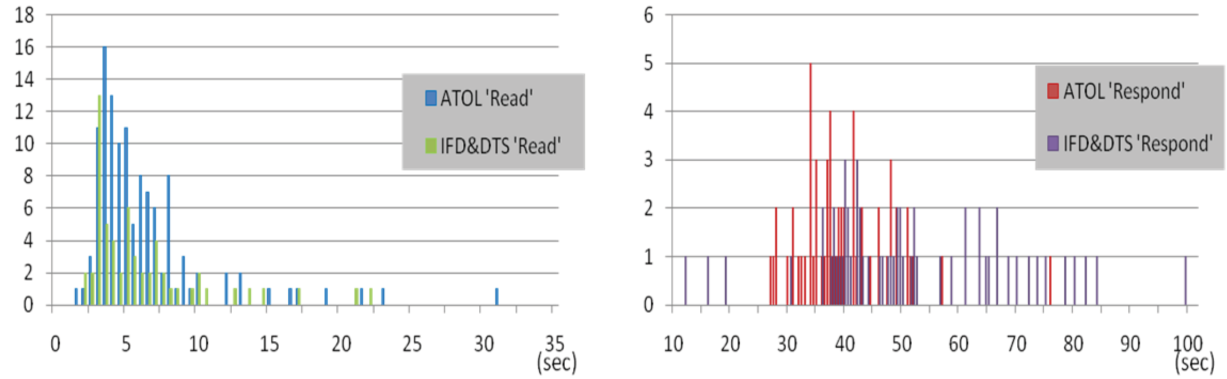

Figure 36. Histogram of Read (left) and Respond (right) CPDLC times, by simulator.

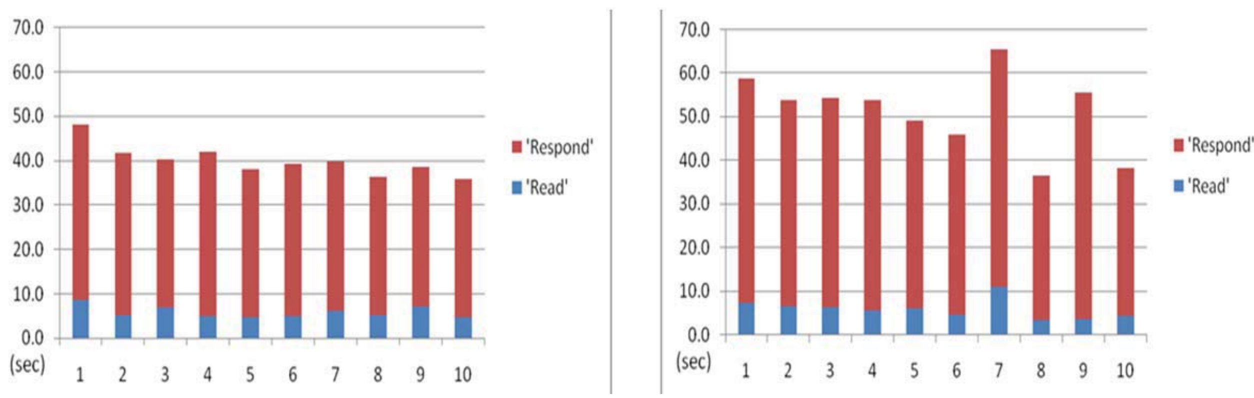

Figure 37. Mean CPDLC times by simulator (left, ATOL; right, IFD & DTS), by run.

The mean flight crew Read time of 5.9 seconds was similar across single-pilot simulator (ATOL) and two-person crew simulators (IFD&DTS), and no statistically significant difference by error or by error × control was found. A statistically significant difference in Read response time was found by control condition (RTA: M=6.57, SD=4.43; RTA+FIM: M=5.26, SD=3.31; p=0.009); however, the time difference is considered operationally insignificant. Therefore, a detailed table is not shown for Read time results.

Table 11 shows flight crew Respond time (in seconds), analyzed across error condition (No Error, Wind Error, and Offset Error), control type (RTA, RTA+FIM), and error × control. No statistically significant difference was found for control or error × control, which is an unexpected result considering the length and complexity of the RTA+FIM clearance compared to the RTA only clearance. A statistically significant difference was found by error condition, with an unexpected result that the No Error condition had the highest mean Respond time. However, this is considered a statistical anomaly since error has no effect on the flight crew's interaction with CPDLC.

Table 11. CPDLC Respond Time, by Condition

	Mean	SD	N			Mean	SD	N
Error (p=0.001)					**Condition** (p=0.131)			
None	49.03	19.39	35		None / RTA	50.72	21.99	17
Wind	41.19	10.52	71		None / RTA+FIM	47.34	16.87	18
Offset	44.40	15.21	71		Wind / RTA	38.32	9.89	36
Control (p=0.538)					Wind / RTA+FIM	44.15	10.45	35
RTA	43.13	15.70	88		Offset / RTA	44.17	15.48	35
RTA+FIM	44.99	13.79	89		Offset / RTA+FIM	44.63	15.16	36

Table 12 shows flight crew Respond time by simulator type (ATOL, IFD and DTS), and was statistically and operationally significantly different between simulator types. Based on crew debrief comments and research observations, it is postulated that the difference is caused by two factors: (1) the time required for the two-person crew to verbally brief the CPDLC message to each other, and (2) the use of a mouse to operate the personal computers in the ATOL compared to actual aircraft hardware in the IFD and DTS. Considered much less of a contributing factor were the effect of using the EICAS system for CPDLC (ATOL) versus the MCDU for CPDLC (IFD and DTS), and operating the aircraft in VNAV Path Mode (VNAV PTH) versus VNAV Speed Mode (VNAV SPD).

Table 12. Flight Crew Respond Time to FIM CPDLC Message, by Simulator

	Mean	SD	N
Simulator (p=0.002)			
ATOL	39.9	10.0	118
IFD and DTS	52.1	18.8	60

5.2.4 Pilot Deployment of Flap and Gear

In this experiment, the pilots' primary responsibility was to operate the aircraft safely and to use their normal procedures to ensure the aircraft's FIM commanded speeds were safe to fly. To reduce the amount of drag on the aircraft, pilots were instructed to use the minimum flap setting needed to achieve the FIM speeds calculated by ASTAR10. Pilots were also instructed to lower the landing gear, extend the flaps to 20 degrees, and set the aircraft's target speed in the MCP window when ASTAR10 commanded their FAS. After this point, pilots were required to configure the aircraft as necessary to be stable by 1000 ft AGL.

The data from this experiment showed all aircraft maintained appropriate flap settings for the aircraft's speed and met all regulatory requirements. Examples include at or below 250 knots when below 10,000 ft MSL and configuration and speed requirements for a stabilized approach. Some pilots used more than the minimum flap setting for their assigned speed, and some pilots lowered their landing gear well before they were required to. Data were analyzed to determine if there was a correlation between arrival time and distance from the runway when the pilot lowered the landing gear.

The ASTAR10 spacing algorithm uses a nominal deceleration rate to predict the deceleration from the current arrival speed to the FAS. If the landing gear is lowered early, aircraft power can be increased to fly the FIM speeds, and the aircraft will slow to the FAS by reducing power. If the landing gear is lowered late (i.e., well after ASTAR10 commands the FAS), the interval error can increase since there is less drag on the aircraft than is predicted by the spacing algorithm.

The data illustrated in Figure 38 are a scatter plot of the gear deployment versus arrival time error. Blue circles with positive time error show when the gear was lowered prior to ASTAR10 estimating it needed to be lowered, and whether the aircraft arrived at the runway after the assigned spacing interval. Blue circles with negative time error show gear lowered early and a spacing interval at the runway less than assigned by ATC. Red circles with negative time error indicate gear lowered later than estimated and the spacing interval less than assigned by ATC, and red circles with positive time error indicate gear lowered late and the spacing interval larger than assigned by ATC. Figure 38 and Table 13 contain data for all runs, with the exception of one run in the first group that encountered an unexpected runway assignment error.

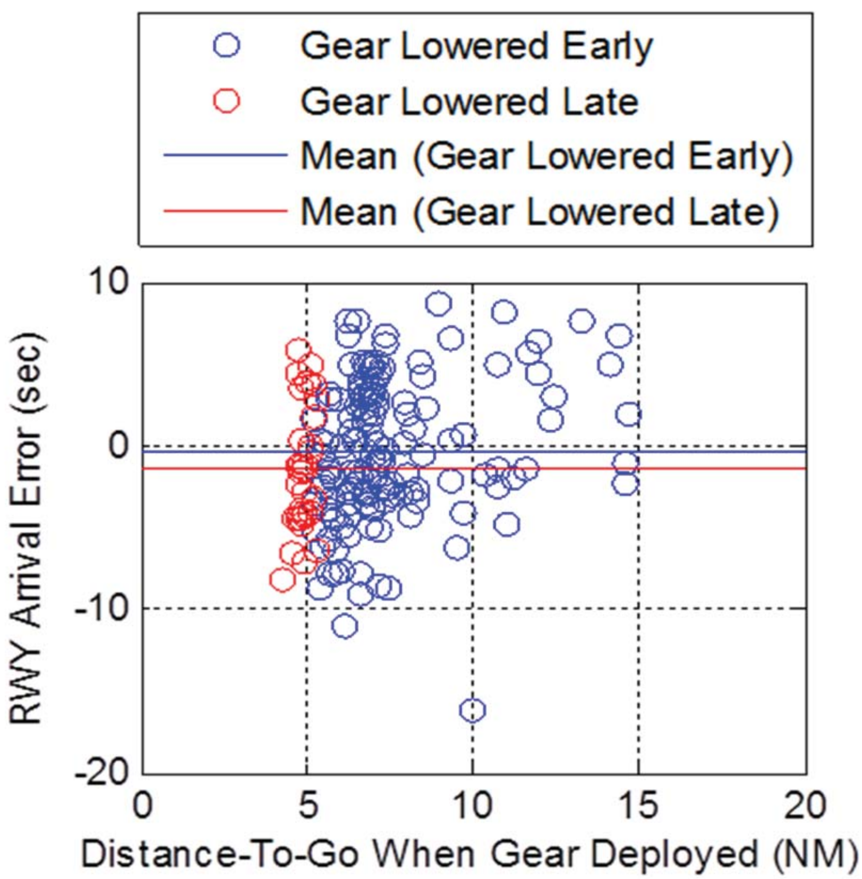

Figure 38. ASTAR10 time error, by when the gear was deployed.

Table 13 provides data for the mean and SD from the assigned spacing interval for when the gear was deployed early and when deployed late. It is noted that the relationship between the pilots lowering the gear and the FIM spacing interval error is a multi-faceted issue. Some pilots commented that they lowered the landing gear early to achieve the arrival speed ASTAR10 was commanding without using other forms of drag. Other pilots stated lowering the landing gear early allowed the use of higher power settings, which enabled more precise speed control, but at cost of additional fuel consumption.

Table 13. Spacing Interval Error, by Early or Late Gear Extension

Gear Extension	Mean (seconds)	SD (seconds)
Early	-0.3	4.4
Late	-1.5	3.8

This cursory analysis does not appear to indicate an operationally significant difference between when the gear was deployed and the precision of the FIM operation. However, more detailed analysis is required before concluding that the ASTAR10 algorithm is robust to variance in pilots' execution of FIM procedures and the differences between the standard operating procedures of various airlines. Metrics required for this level of detail were not included in the IMSPiDR experiment, but will be in future research.

5.2.5 Examples of Flight Crew Non-Conformance

5.2.5.1 Flight Crew Not Timely Achieving FIM Speed

Figure 39 illustrates a data run where the pilots in the IFD did not properly follow the pilot procedures for following FIM commanded speed changes. The aircraft's airspeed stayed well above the Profile speed ("Cmd Speed"). The IM DRAG REQUIRED message was displayed on the EICAS between 20 nmi and 5.5 nmi, indicating to the pilots that their aircraft needed more drag to properly follow FIM guidance. Between 20 and 7.5 nmi, the pilots failed to add sufficient drag to allow the aircraft to decelerate quickly enough to catch multiple speed reductions commanded by the ASTAR10 algorithm ("Cmd End Speed") between 20 and 16 nmi. Sufficient drag was added when the landing gear was lowered at 7.5 nmi from the threshold. Therefore, this lack of timely response and drag management caused a negative, or early, time error to build to approximately 28 seconds.

Another event occurred on this run caused an interesting outcome. At approximately 7.5 nmi remaining to the runway threshold, the ASTAR10 algorithm commanded a speed of 150 knots. The pilots lowered the landing gear, but instead of setting the FIM commanded speed of 150 knots in the MCP window, they set the FAS of 130 knots. The unexpected setting of the FAS caused the aircraft to decelerate well below the FIM speed guidance at that point on the approach, and as a result, substantially reduced the time error. The cumulative result of these multiple failures to follow FIM guidance was a spacing error of approximately 8 seconds.

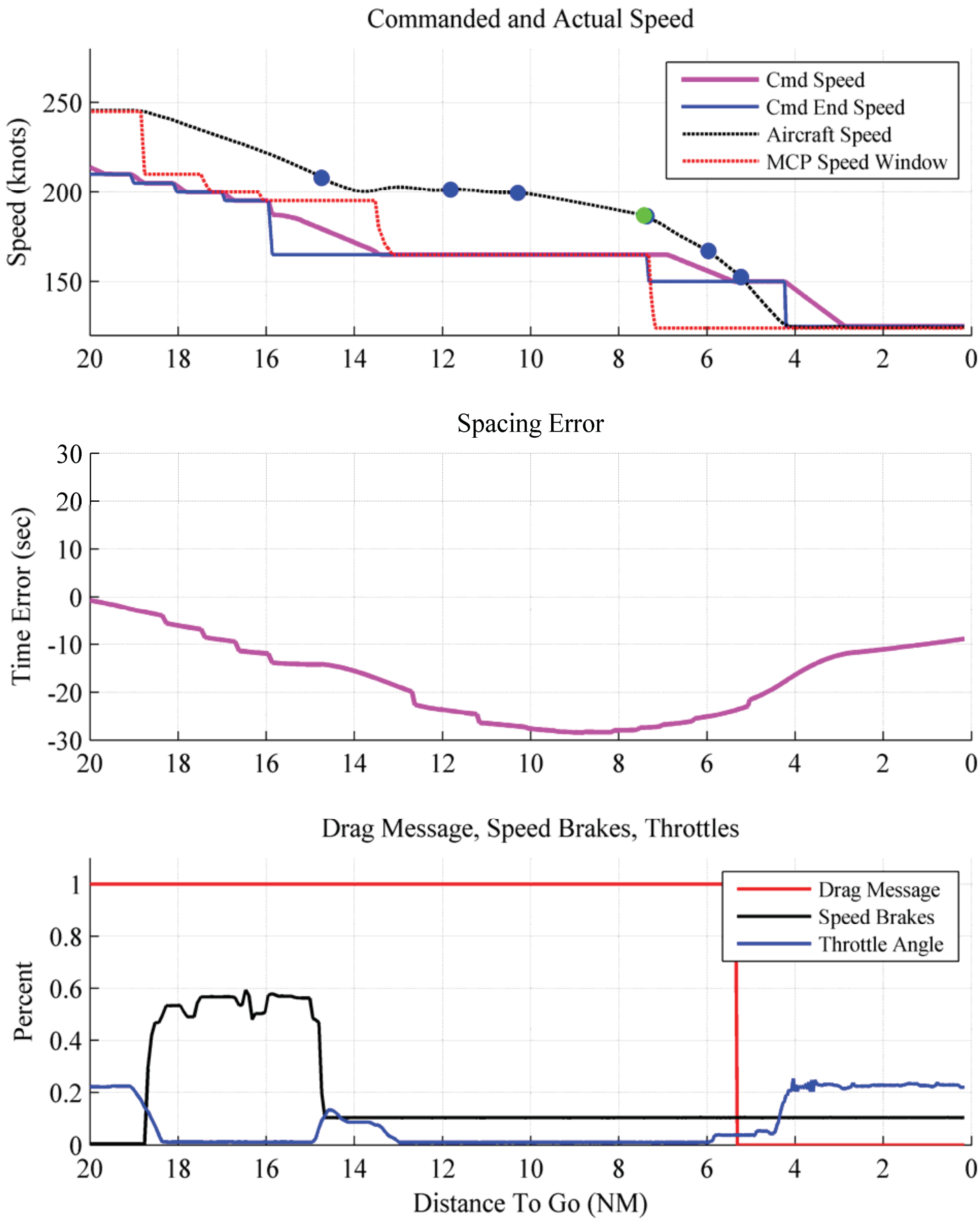

Figure 39. Example of failure to follow FIM guidance (IFD).

5.2.5.2 Flight Crew Using Incorrect FIM Speed

Each of the ASTOR simulators was operated by a single pilot; consequently, those pilots did not benefit from having another pilot present to ensure FIM procedures were followed properly. Figure 40 is ASTAR10 data from an ASTOR during the final 10 nmi of the approach, when the MCP speed window was open (after ILS capture) and the pilot was required to set the FIM commanded end speed manually in the MCP window. In the left plot, the pilot correctly followed the FIM guidance as instructed. The ASTAR10 commanded end is shown in black, and corresponds to green speed at the top left of the PFD in Figure 41. The aircraft's commanded speed set manually by the ASTOR pilot in the MCP window is shown as a dashed magenta line in Figure 40. During this run, the pilot set the aircraft's commanded speed in the MCP window to match the FIM commanded end speed every time that speed changed.

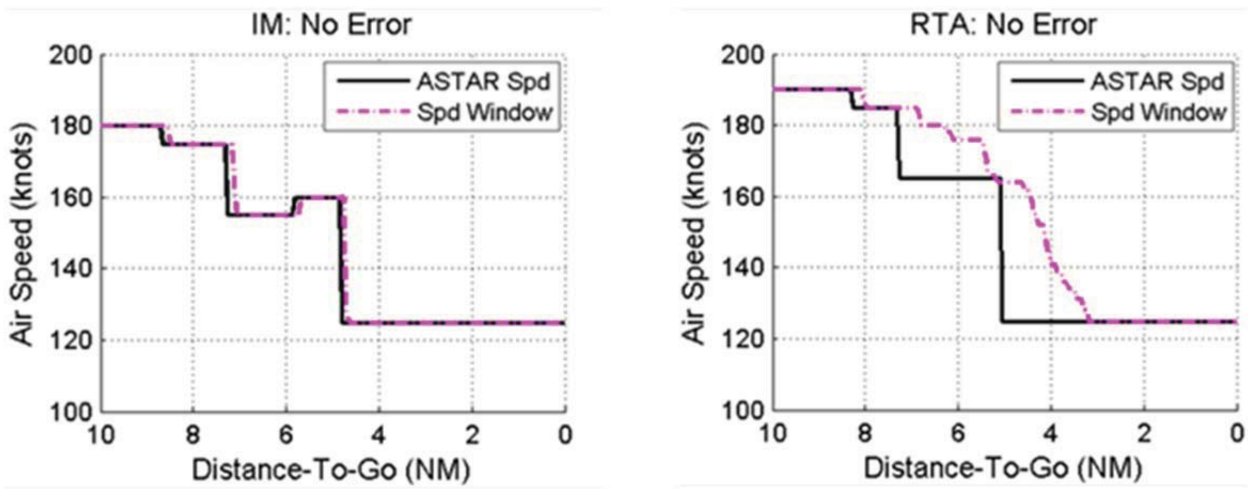

Figure 40. Correct (left) and incorrect (right) setting of FIM speed in MCP.

Figure 41. FIM speed guidance on ND.

The right plot of Figure 40 illustrates data from a single RTA run that had no induced error. It also covers the last 10 nmi of flight when the aircraft was following ILS guidance, and manual speed entry of the FIM commanded speed generated speed was required. In this example, instead of correctly entering the FIM commanded end speed (green number in upper left of PFD, Figure 41) into the MCP window, the pilot continuously adjusted the MCP speed to match the FIM commanded speed (green speed bug to right of the speed tape). The FIM commanded end speed was intended to be available to the crew to provide an estimate of the deceleration rate, and is not appropriate to act as a guide for the speed to set in the MCP.

This unexpected use of the FIM commanded end speed to set the value in the MCP window by the pilot did not substantially affect the precision performance of the experiment shown in Table 5. The small effect on arrival precision was partially due to the robustness of the algorithm, which continuously calculated a corrected speed for the pilots to fly. In setting the MCP speed to the speed indicated by the FIM speed bug at the edge of the speed tape, the pilot was required to spend a substantial amount of time tracking the speed bug and setting the aircraft's commanded speed in the MCP speed window to match the FIM commanded speed. The pilot did not identify his method of complying with the ATC FIM clearances in his post flight questionnaires.

Analysis in this section indicates ASTAR10 will continue to update speed guidance to address the cumulative error of pilot deviation. Analysis also indicates that pilot training may need to be more extensive for some pilots, and FIM guidance and alerting may require adjustments to enable better adherence to FIM procedures.

5.3 Qualitative Pilot Responses

The sub-section addresses the third experiment objective, "Have the flight crew assess the FIM concept, procedures, and displays." Information to address this objective comes from data and comments provided by the flight crew in response to the post-run and post-experiment questionnaires, and during the post-experiment verbal debrief. (Complete data from the post-run questionnaires are found in Appendix L, and from the post-experiment questionnaires in Appendix M.) Within this sub-section, the results are presented in order of importance: acceptability, workload, spacing algorithm, use of Data Comm, and cockpit displays.

5.3.1 Flight Crew Acceptability of FIM ConOps and Procedures

Post-experiment responses were examined to evaluate the acceptability of the spacing concept in terms of additional responsibility, perceived safety, and change in workload as compared with current day operations. When asked whether the added responsibility of meeting a spacing interval was acceptable, 75% of the flight crew responded positively. Those who did not find the responsibility acceptable cited concerns regarding the speed behavior and the interface, rather than unacceptability of the airborne spacing concept. Using a scale of 1 (Not Safe At All) to 7 (Much More Safe), all flight crew rated the safety of the spacing operation as being "as safe as" or "slight more safe than" current day operations (M=4.88, SD=1.12, N=24).

When asked if the FIM procedures used during this experiment were complete, accurate, and logical, 92% of the flight crew answered positively. However, when asked to use a scale of 1 (Very Difficult) to 7 (Very Easy) to rate the ease with which the spacing procedures could be integrated with current day procedures, the flight crews' mean response was 4.58 (*SD*=1.56, *N*=24), indicating that they were somewhat undecided. Many comments also indicated that flight crews thought the spacing operation would be associated with a significant learning curve, and that simulator training would be required to adequately learn the airborne spacing procedures. One specific issue that was consistently noted in questionnaires, debrief sessions, and researcher observation logs was that pilots found it counterintuitive to terminate the existing spacing operation before loading a new spacing clearance. Comments suggested that, upon acceptance of the spacing clearance, the old operation should automatically be overwritten.

Flight crews in both the IFD and DTS were asked to characterize how the spacing operation affected the distribution of tasks between the pilot flying (PF) and pilot monitoring (PM), and to indicate whether it changed their crew coordination. Three-quarters of the flight crews reported that the distribution of tasks required to complete the spacing operation was desirable and complemented their current distribution of tasks, and 83% of the pilots indicated that the spacing operation did not change their crew coordination. However, the pilots found it somewhat difficult to coordinate the acceptance of CPDLC messages. In this experiment, the PM was expected to load and accept the CPDLC clearance, while the PF was expected to simultaneously review the information on the FIM MCDU page and ensure that ASTAR10's commanded speed was acceptable. Half of the flight crew commented that the system should allow the PM to both accept the clearance and execute the spacing operation, and at least one crew ignored the distribution of tasks outlined in the procedures they were asked to follow and completed the operations by having the PM operate both flight crews' MCDUs.

Flight crews were asked to provide the amount of time they thought would be reasonable to notice and implement a speed change. Pilot responses in the post-experiment questionnaire indicated that they would consider noticing the speed change within nine seconds (*M*=9, *SD*=5, *N*=24) of a commanded speed change, and dialing the speed commands into the MCP speed window within seven seconds (*M*=7, *SD*=4, *N*=24) of noticing the speed command as acceptable.

5.3.2 Pilot Workload Ratings

Using a scale of 1 (Much More) to 7 (Much Less), pilots responded that they would expect the workload of the FIM spacing operation to be the same or slightly greater than current day operations (*M*=3.88, *SD*=1.39, *N*=24). While concerns were raised regarding the specific implementation of FIM in this experiment (described below), pilots found the overall FIM concept acceptable.

Flight crews used the MCH rating scale, ranging from "1" (indicating that the instructed task was very easy/highly desirable; operator mental effort was minimal; and desired performance was easily attainable) to "10" (indicating that the instructed task was impossible and could not be accomplished reliably), to provide assessments of both average and peak levels of workload experienced during each flight scenario. No significant differences were found to exist between workload levels reported for a given control method or among workload levels reported for a given error source ($p < 0.05$). The flight crews rated their mean "average" workload as 1.97 (*SD*=0.86, *N*=240), and their mean "peak" workload as 2.32 (*SD*=1.01, *N*=240), which is comparable to the average workload of 1.87 (*SD*=0.78, *N*=207) found in a previous airborne spacing experiment conducted at NASA LaRC [10]. These results indicate that the average workload associated with the task the flight crew were asked to perform was easy/desirable, their mental effort was low, and the desired performance was attainable. The pilots' peak workload ratings indicated that the task they were asked to perform was mildly difficult; however, the mental effort was acceptable, and an adequate level of performance was attainable. The average workload was not expected to be rated higher than a "3," indicating that the pilots' instructed task had a mild difficulty level and required an acceptable level of mental effort to attain adequate system performance. However, the data indicated that eight flight crews rated their average workload between a "4" and "6." Half of these relatively high workload ratings occurred during the first data collection scenario of a particular group, while the remaining high workload ratings were associated with pilot errors in operating the simulators and undesirable speed change behavior (discussed below).

In addition to workload ratings, pilots were given the option of selecting the segment of flight during which their peak workload occurred. Of the 191 flights associated with responses, pilots indicated that their peak workload occurred below 5,000 ft, 70% of the time, and peak workload occurred when their aircraft was between the altitudes of 5,000 ft and 11,000 ft, 17% of the time (Table 14). The greatest variation from the average result occurred during the RTA only control scenarios with an Offset Error. During 38 of these scenarios, flight crews reported that their peak workload occurred between 11,000 ft and 5,000 ft, 32% of the time, and peak workload occurred below 5,000 ft, only 50% of the time. It is suggested that the discrepancy between the aggregate results and results for Offset Error scenarios and use of the RTA control method is directly related to the issuance of a CPDLC message sent when the aircraft reached 9,000-ft, instructing flight crew to amend the original spacing clearance.

Table 14. Flight Segment Associated With Peak Workload

Segment of Flight	Responses (N=191)
>18,000ft (cruise, initial descent, CPDLC)	10%
18,000ft – 11,000ft (descent, approach check)	3%
11,000ft - 5,000ft (TRACON, low altitude merge)	17%
<5,000ft (final approach, configure aircraft)	70%

The off-nominal scenario required the IFD crew to accept a new FIM clearance while being vectored at 5000 ft back to the runway after a go-around. These crews rated the head down time required to accept and implement the FIM clearance using CPDLC as not appropriate for this high workload environment.

5.3.3 Flight Crew Comments about the ASTAR10 Spacing Algorithm

After each scenario, flight crews were asked to rate the acceptability, safety, and correctness of ASTAR10's commanded speeds and to describe any unexpected behavior exhibited by the algorithm. They found the commanded speeds acceptable; however, large errors, such as the Wind Error and Offset Error used in this experiment, can lead to some instances of less than desirable speed behavior. The ASTAR10 algorithm was designed with mechanisms to provide flight crews with desirable speed behavior. However, based on pilots' comments, it is suggested that the time between consecutive speed changes, the distribution of speed changes as a function of time-to-go, and analysis of speed increases can be used in conjunction with the total number of speed changes as quantitative metrics to help predict pilots' acceptance of speed changes.

The crews reported that the desired deceleration rate (shown by the FIM Commanded Speed) appeared too great, particularly during the scenarios with the Wind Error condition. Modification of the route (shallower descent angle and slower speeds) 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 scenarios and was caused by the unexpected wind shear at 5000 ft.

Overall, pilots found the IM concept acceptable; however, pilots found some behaviors of the automation less than desirable (Table 15). Pilots were asked to rate a series of questions about their perceptions of the IM speeds using a scale that ranged from "1" (completely disagree) to "7" (completely agree), with "1" being the most favorable response and "7" being the most unfavorable response. The data were averaged across replicates, and a Friedman test was conducted to examine the data for statistical differences using a 95% confidence interval. The Friedman test was blocked by crewmember, and examined whether the answers to the questions changed when different error sources were present.

Table 15. Pilot Ratings for FIM Speed Commands

Question	Mean	SD	Median	P Value
10 a) Unsafe	1.35	0.84	1	0.223
10 b) Incorrect	1.47	0.99	1	0.282
10 c) Interruption	2.48	1.55	2	0.068
10 d) Unexpected	2.12	1.57	1	0.247
10 e) Conflicted With Other Information	1.68	1.18	1	0.793
10 f) Uncomfortable	1.56	1.24	1	0.341
10 g) Frustrated	2.08	1.49	1	0.053

No statistically significant differences were found between any of the experimental factors (p>0.05). However, both the question asking if IM was an interruption (p=0.068), and the question asking if the IM speed frustrated the crew (p=0.053) were close to being significant. For the IM scenarios, the Wind Error scenarios received the worst ratings for both the frustration question (M=2.5, SD=1.7) and the question asking about interruptions (M=2.7, SD=1.4). The non-error conditions received the most favorable ratings for both the frustration question (*M*=1.7, *SD*=1.1), and the question asking if pilots were interrupted (*M*=2.2, *SD*=1.1). While the difference in the mean values may be small, they appear to be indicative of a greater number of outliers with unfavorable responses during the scenarios containing Wind Error. The results are also consistent with many comments pilots provided that stated that the speed guidance was too twitchy, or that the gains should be turned down. In general, the data suggest that the IM operation was acceptable during all of the error condition circumstances; nevertheless, the Wind Error and Offset Error scenarios had a greater chance of creating outlier ratings that were unacceptable. It is suspected that the pilot ratings indicating high frustration with the IM procedures occurred because of the large number of speed changes that were present in these conditions. It may be possible to decrease the frustration and interruptions by providing pilots with display and procedures that show them why the algorithm is commanding specific speed changes, and increase their ability to predict the spacing algorithm's behavior in the near future. Despite the frustration, there were only a few instances where pilots thought IM was unsafe.

It is useful to understand some of the outliers in the ratings provided by pilots. Of particular interest are the three instances where the flight crew slightly agreed that the IM operation was unsafe and the two instances when they provided a neutral rating. Some of these ratings were caused by a simulator anomaly, which commanded the pilots to fly at Mach 0.85 prior to their TOD. Other comments indicated that the ASTAR10 waited until a point after the FAF to command the aircraft's final approach speed (this will occur if the aircraft is below the profile speed), and because pilots were not given adequate time to slow their aircraft to meet the 250 knot speed limit at 10,000 ft. The two neutral comments were provided because pilots had to reconfigure the aircraft to achieve the commanded speed, and because they spent too much time monitoring the PFD for commanded speed changes. The ratings that indicated that the commanded speeds were incorrect were provided because of commanded speed increases that were shortly followed by speed decreases, ASTAR10 commanding the final approach speed after the FAF, and because speed changes occurred too frequently. The ratings that stated that speed changes occurred too frequently occurred during Wind Error scenarios and to a lesser extent during the Offset Error scenarios.

There were questionnaire responses that indicated that the spacing algorithm could interrupt pilots thought processes, primarily due to the pilots' inability to predict FIM speed changes. Other responses indicated some of the FIM speed changes were unexpected, appeared to conflict with other information, or too many occurred within a short period of time. Ratings indicating that pilots were frustrated included speed changes that were very frequent, speed changes that did not make sense to the flight crew, speed changes that forced pilots to reconfigure their aircraft, and the need to use an excessive amount of speed brakes. These examples as discussed demonstrate the rationale behind the worst ratings provided by pilots. It should be remembered that the poor ratings represented a small number of runs, and that many of them were instigated by large error sources that pilots are not expected to encounter very often. Nevertheless, these ratings can provide insight into what behavior pilots typically find unacceptable. A majority of the critiques that flight crews provided throughout the experiment can be broken down into three categories: too many speed changes on final, too many speed changes within a short period of time, and undesirable speed increases.

5.3.4 Pilot Comments about Use of Data Comm

Following each scenario, the flight crew completed an electronic questionnaire with questions about workload, situation awareness, procedure acceptability, and display elements. Two specific questions were: 1) was the time required to respond to CPDLC a distraction from other tasks, and 2) if the head down time required to respond to CPDLC messages was acceptable. There are 120 responses from ATOL flight crew (3 groups of 4 pilots, each group completed 10 scenarios) and 60 responses from IFD and DTS flight crew (only the Pilot Monitoring results used in this analysis, therefore 3 groups of 2 pilots, for 10 scenarios each). Figure 42 shows the median response given by flight crew (red line) was Moderately Agree to Completely Agree when asked if the CPDLC messages used for the FIM clearance in the IMSPiDR experiment did not detract from other cockpit tasks. Figure 43 shows the mean response of Moderately Agree to Completely Agree when asked if the amount of head down time required to respond to CPDLC messages was acceptable. The edges of the blue box indicate the 25th and 75th percentile, the black whisker bar extends to the most extreme data point not considered an outlier, and outliers are shown as blue circles.

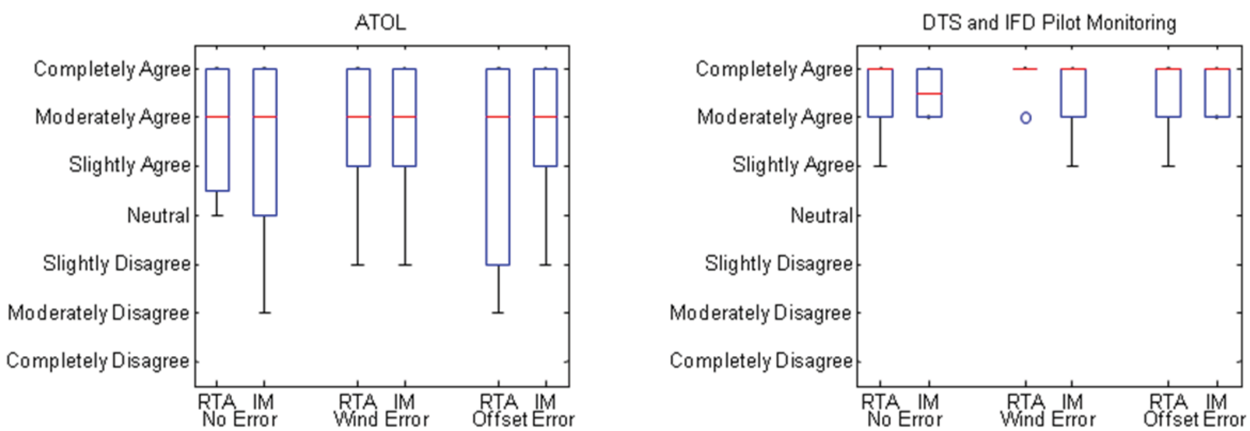

Figure 42. Pilot rating for CPDLC not detracting from other tasks.

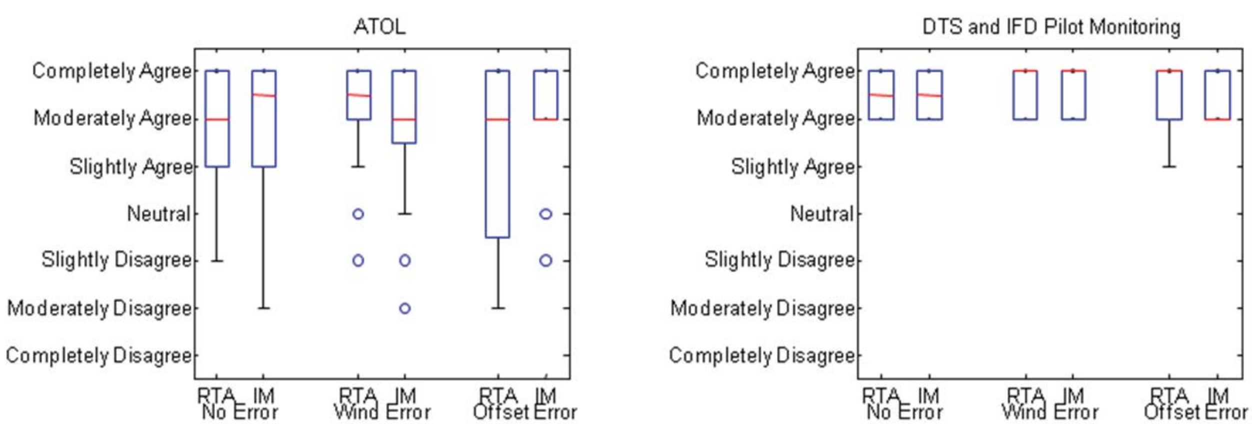

Figure 43. Pilot acceptability rating of head down time required for CPDLC.

Prior to the Post-Experiment questionnaire, the crews were reminded that the instructions they received during training were to consider these Interval Management spacing procedures in the context of a busy operational terminal area environment, to include poor weather, at an unfamiliar airport, and with an inexperienced crewmember.

The flight crews were asked to rate if "The use of CPDLC messages were operationally acceptable as simulated in this experiment" on a scale of "1" (Completely Disagree) to "7" (Completely Agree), with "6" defined as Moderately Agree. The mean acceptability rating of the FIM procedures for the 24 flight crews was 6.25, with a SD of 1.07.

The flight crews were asked "How long should a pilot have in a busy terminal (as simulated by this experiment) to respond to a CPDLC uplink message? Consider other cockpit tasks, environmental conditions, complexity of flight operation, importance of the message, crew coordination and briefing, etc." The mean rating for all 24 crews was 42.7 seconds, with a SD of 35.6 seconds.

23 of the 24 flight crew answered YES to "Within the context of an approach into a busy terminal area, are there times when it is not acceptable to receive an FIM CPDLC message?" A breakdown of how the flight crew responded to when it would not be acceptable to send FIM clearances via CPDLC is shown in Table 16.

Table 16. Acceptable Use of CPDLC by Altitude

Altitude	**Number**	**Percent**
Acceptable at all times	2	8%
Acceptable with caveat for altitude	20	--
(1) No messages below 18,000ft	(1)	4%
(2) No messages below 10,000ft	(13)	54%
(3) No messages below 5,000ft (includes within 10 minutes of landing, on downwind, and when on final)	(20)	83%
When given with ATC verbal communication (no altitude associated)	1	4%
In weather, turbulence, off-nominal conditions (no altitude associated)	1	4%
TOTAL	**24**	--

Following the post-experiment questionnaire, a debrief session with the research team and the subject pilots was held, generally lasting 45 to 60 minutes. A synopsis of comments pertaining to use of CPDLC in a busy terminal area for FIM spacing operations includes:

- Appropriate use of CPDLC reduces voice communication, which reduces stress and miscommunication.
- Use of CPDLC tends to be more acceptable in airspace with all aircraft operating under ATC control (above 18,000 ft MSL in the U.S.) and when weather conditions preclude aircraft operating under visual flight rules (poor weather), since flight crew have reduced visual scan responsibilities.

- As experience is gained with CPDLC, the workload would decrease further and acceptability should increase.
- The procedure should allow for reloading a CPDLC message into the spacing tool if required.
- If the CPDLC equipment is certified to accurately transmit messages from the ground to the aircraft, and the aircraft avionics are certified to accurately transfer the information from the CPDLC message into the spacing tool, the crews should conduct only a cursory review of the data in the MCDU FIM spacing pages. Certified CPDLC equipment was estimated to reduce flight crew Respond time by 10 seconds.
- The CPDLC interaction required too many button pushes to accomplish the FIM procedure. The multiple button pushes, especially when occurring in different locations (for example, the CPDLC pages on one MCDU and FIM pages on the other), were confusing, time consuming, and the root cause for the three runs excluded from data analysis. The crews made two suggestions to reduce the number of steps in the FIM procedure:
    (1) 5-step as implemented: Review, Load, Activate, Accept, Execute (Figure 4)
    (2) 4-step recommendation: combine the ACTIVATE and EXECUTE functionality for the spacing tool into one button push.
    (3) 3-step recommendation: if transmission and transfer accuracy can be certified (see comment above), the LOAD button push should auto-load the message into the spacing tool and the spacing tool should automatically calculate the speed (Review, Load, Accept). A CPDLC process utilizing only 3 steps would require the ground scheduling software to send a very high rate of operationally acceptable clearances to the crew, and allow for the crew to request a change or terminate the clearance at a later time (currently in the concept of operations document). It was estimated this procedure would probably reduce flight crew Respond time by 15 to 30 seconds.

5.3.5 Pilot Comments about FIM Displays

5.3.5.1 Saliency of FIM Display Elements

Overall, flight crews were able to maintain their speed within approximately six knots of the FIM Commanded Speed; however, they reported a need for more salient notification of changes to that speed (e.g., flashing box, chime). Crews reported that an indication of the controlling aircraft (green outer icon and data tag on ND) was useful, but not needed for conducting FIM operations. However, a strong preference was given for more salient displays to indicate when a speed change had occurred. Additionally, a strong preference was given for a display to monitor the progress of the operation.

On the PFD, the commanded end speed was displayed directly above the FMS commanded speed, and the commanded speed bug was designed to mate with the FMS speed bug. Displaying FIM speeds on the PFD allows flight crew to easily determine if the FMS speed matches the commanded speed, and what the commanded speed is in relation to other parameters displayed on the PFD. Similarly, the modifications to the ND were designed to allow flight crews to quickly identify the lead aircraft and maintain situation awareness regarding their progress.

Additionally, redundancy was built into the pilot interface. If the flight crew failed to implement a speed decrease and was flying too fast, they could see the discrepancy on the PFD, and the IM DRAG REQUIRED message would appear on the EICAS display. As a result of this human-centered design, flight crews found most of the display elements intended to support spacing operations to be useful and intuitive. For example, 63% of the flight crews reported that the display elements used in this experiment were easy to understand and positioned in logical locations. However, 29% of the flight crews stated that the information conveyed by the displays was adequate and that improvements were needed regarding how and/or where the information was displayed. Most of the flight crews recommending that improvements be made focused on the need for a more salient alert associated with changes to the commanded speed.

5.3.5.2 Usefulness of FIM Display Elements

While various display elements did not serve as independent variables within this experiment, qualitative data collected from the pilot participants were used to examine their interaction with the spacing tool in terms of how useful they found each display element and how they monitored the displays. Using a scale of "1" (Detrimental) to "6" (Required), flight crew rated all of the display elements on the PFD as "very useful" or "required," with the exception of the box located around the commanded speed (to alert flight crew of a speed change) that was rated as moderately useful (M=4.67, SD=1.46, N=24) (Figure 44). A majority of the other display elements on the ND, MCDU, and EICAS were rated as moderately useful, with the lowest rated display element, an IM SPEED LIMITED message on the EICAS, receiving a rating of slightly to moderately useful (M=3.38, SD=1.31, N=24).

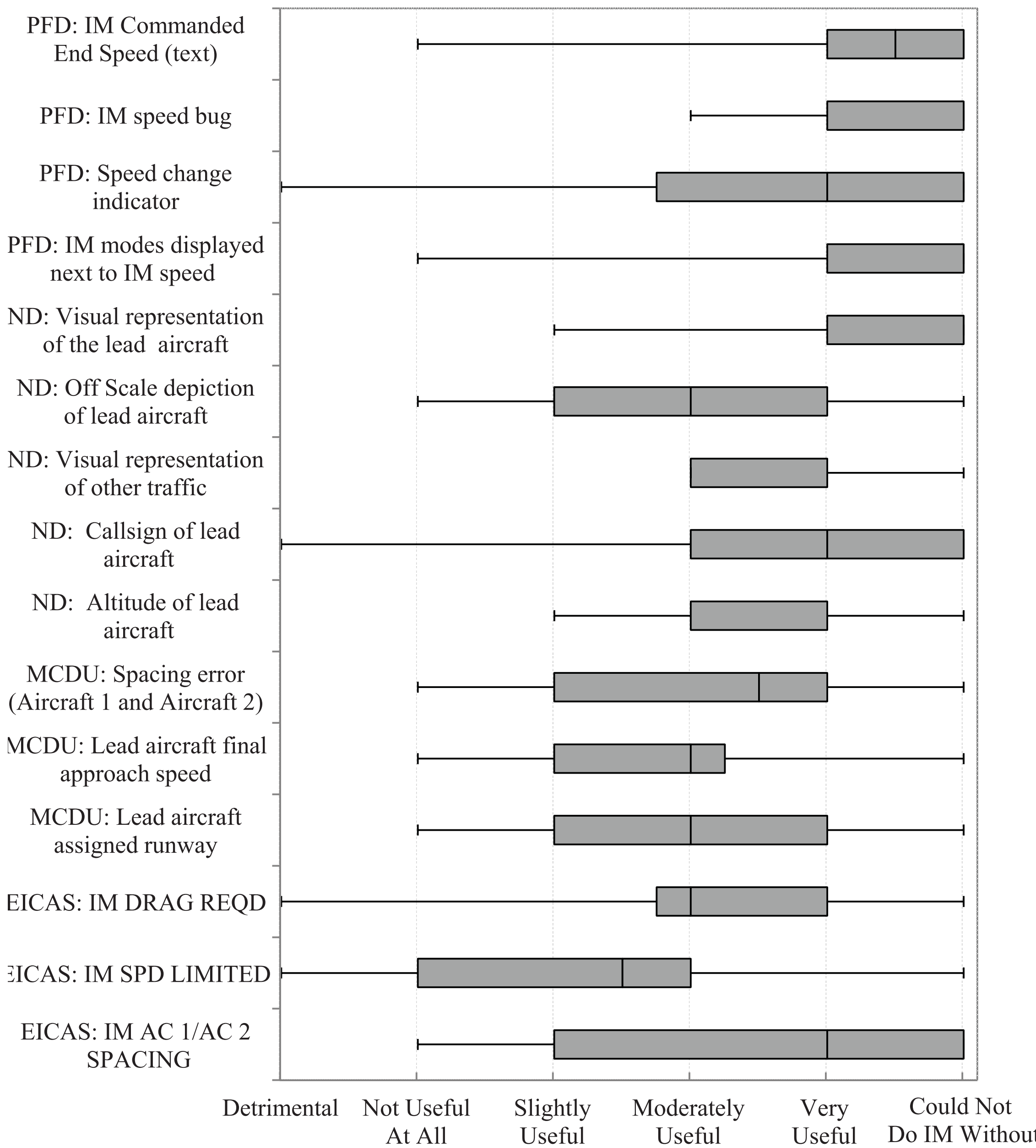

Figure 44. Pilot rating of FIM display elements.

In addition to asking flight crews about the usefulness of each display element, they were asked to rate how frequently they used each display to monitor the spacing operation. Using a scale of 1 (Never) to 5 (All the Time), flight crews reported that they monitored the PFD very often (*M*=4.26, *SD*=0.75, *N*=24), monitored the ND moderately to very often (*M*=3.86, *SD*=1.11, *N*=24), and monitored the MCDU slightly to moderately often (*M*=2.70, *SD*=0.97, *N*=24) (Figure 45). These data demonstrate that the flight crews used the displays as anticipated and found the displays used in this experiment to be useful.

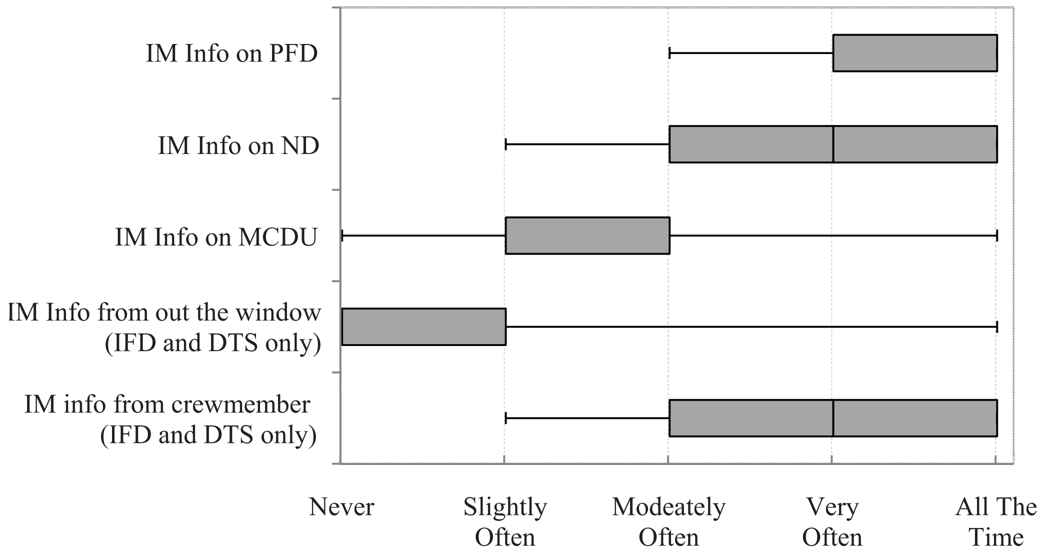

Figure 45. Pilot ratings regarding how often FIM displays were monitored.

Since the spacing error was displayed only on the first FIM MCDU page, there was concern that flight crews would spend more time than desired monitoring that page rather than utilizing the MCDU for normal flight tasks as intended. The metrics collected included the total number of visits to the first FIM page and the time spent on the first FIM page as a percentage of total flight time. The full crew simulators collected the metric of total visits to either of the MCDUs, and the total time either of the MCDUs showed the first FIM page as a percentage of flight time. Results indicate that the flight crew visited the first MCDU page an average of 4.44 (*SD*=3.13, *N*=180) times throughout a flight and spent an average of 26% (*SD*=30, *N*=180) of the flight on the MCDU. However, median time spent on the first FIM page was 11%. Since the IFD and DTS each have two MCDUs, the FIM page could be kept on one and not the other. When only the IFD and DTS data were reviewed, the median percentage of time spent monitoring the first FIM MCDU page was 17% (*M*=22, *SD*=21, *N*=60) of the simulation time, and the median number of times the page was visited was 4% (*M*=4.58, *SD*=2.7, *N*=60). Since the pilots were more likely to monitor the FIM MCDU pages within the context of this experiment, the data suggest that pilots will use the spacing error but will not spend excessive amounts of time viewing the first FIM MCDU page.

5.3.5.3 Speed Changes Alerts and Non-Conformance

One of the flight crews' major responsibilities with respect to airborne spacing was to monitor the PFD for changes to the commanded speed. Within this experiment, the alert that was provided to the flight crew was the illumination of a green box around the commanded end speed for ten seconds. Pilot responses reveal that the green box was inadequate to attract the pilots' attention, and it caused the pilots to spend too much time monitoring the PFD for speed changes. Of the 24 pilot participants, 23 thought that a more salient alert, either in place of or in addition to the green box, was needed. Additional comments throughout the questionnaires as well as researcher observations of flight crews confirm this result. Within the post-experiment questionnaire, the flight crews were asked to select whether they desired the currently implemented green box, a flashing box, a chime, or any combination. 67% of flight crews indicated that they would like an aural alert to be included as part of a system to notify them of speed changes; 54% stated that they would like the box around the commanded end speed to flash for ten seconds; and 25% desired both a flashing box around the commanded end speed as well as an aural alert.

While it is useful to gather pilot opinions regarding the type of alert they desire, it is also important to discuss the potential impact from a human factors standpoint. The type of alert used should depend on the importance of the alert. A distinct aural alert will immediately direct a pilot's attention to a new commanded speed. However, it will cause increased disruption if the flight crews are in the process of completing other critical tasks. Based on distribution of speed changes as a function of time-to-go and the dependence of the number of speed changes on error source, the disruption will worsen as the aircraft approaches the runway and as conditions worsen. In contrast, a flashing green box would provide a more salient alert than the non-flashing box implemented in this experiment; however, the chance of the flight crew missing the speed changes is greater with this implementation than for an aural alert.

In addition to the alert given for a new commanded speed, an EICAS alert, presenting the text IM DRAG REQUIRED, was given when the aircraft was greater than 6 knots above the commanded speed and was turned off when the aircraft returned to within 4 knots of the commanded speed. A few pilots stated that the EICAS message, IM DRAG REQUIRED, did not necessarily indicate when they had to apply drag. Data were evaluated to determine how often flight crews used the speed brake when the EICAS message appeared. The IM DRAG REQUIRED message was activated an average of 3.53 (*SD*=1.44, *N*=180) times per flight, and the flight crews used the speed brake during 84% (*SD*=25, *N*=180) of these instances, demonstrating that the message resulted in the desired response a majority of the time. The high SD of compliance coupled with researcher observations suggests that there were some flight crews who judicially used the speed brake to meet the commanded speed, while there were others who did not desire to use the speed brake to maintain the five knot tolerance. It is hypothesized that those who are willing to judicially use the speed brakes will find the IM DRAG REQUIRED message helpful, while those who do not will find it a nuisance.

5.3.5.4 Predictability of Speed Changes

Having the flight crews be able to predict when the next ASTAR10 speed change occurs was not a design goal. Using a scale of 1 (Completely Disagree) to 7 (Completely Agree), the flight crews moderately agreed that it is important to be able to predict changes to the commanded speed (*M*=5.46, *SD*=1.28, *N*=24). Additionally, flight crews moderately agreed that the spacing tool behaved in a predictable manner (*M*=6.04, *SD*=0.55, *N*=24) and slightly agreed that they were able to predict commanded speeds before they occurred (*M*=5.36, *SD*=1.37, *N*=180). Thus, the pilots' qualitative ratings indicate both the importance of predictability and that the spacing tool was somewhat predictable. To help drive future design decisions, it is important to discern what information pilots use for their predictions. Flight crews were asked to describe the displays and/or trends that helped them predict changes to the commanded speed, and their comments showed that 46% of them used the first FIM page on the MCDU to drive their predictions while

46% used the published speed profile, scheduled speed decreases, or general flight rules to enable their predictions. Finally, 29% of the flight crews stated that they used visual representations of the lead aircraft to predict when speed changes would occur.

A number of the comments that pilots provided suggested that they were attempting to understand the relationship between the time error that was displayed on the MCDU and the speed commands generated by ASTAR10. The following comments demonstrate that pilots often had an incorrect or incomplete mental model of the relationship between the time error displayed on the MCDU and the commanded speed changes.

- *"Maybe with more experience I'd have a better feel for what speed comes next, but even when we seem to be ahead of our goal (time) we still get commands to speed up."*
- *"The conformance box was the easiest method to predict performance and trends. Without it I had to refer to the IM page in the CDU. Even then it was difficult to predict the next commanded speed. On several occasions when I checked the IM page it showed me as much as 23 sec ahead of schedule and yet it subsequently commanded a speed increase."*
- *"I was looking at the IM page and noting error in the progress. For example, if I noticed it was late and trending later, it was easy to expect that there was a change coming for an increase."*

Based on the comments, it appears as if some pilots thought that speed changes would only increase if the time error was positive (arriving late), and only decrease if the time error was negative (arriving early). In reality, the commanded speed will move toward the nominal profile speed as the time error moves toward zero. This means that if the time error is increasing, the commanded speed will increase, and if the time error is decreasing, the commanded speed will decrease (regardless of the value of the time error). The pilot that provided the final comment was close to figuring this relationship out; however, the commanded speed will increase even if he was early and the time error was increasing. Overall, most of the confusion appears to be centered on the relationship between the FIM speed and the time error. Future indicators of the time error between the spacing aircraft and lead aircraft should concentrate on providing clear indication of the relationship between the time error and commanded speed changes.

5.3.5.5 FIM Conformance Box

Flight crews in this experiment were presented with a "conformance box" during the experiment's final, exploratory run. This display was a green box that appeared around the depiction of the ownship aircraft on the ND, indicating how much control authority ASTAR10 has. If the ownship moved outside the conformance box, the algorithm is predicting that it is no longer possible for the aircraft to meet the spacing goal by a given "achieve by point." The goal of the conformance box was to provide flight crew with better predictability regarding the spacing operation. Using a scale of 1 (Completely Disagree) to 7 (Completely Agree), pilots slightly to moderately agreed that the conformance box helped them monitor the FIM operation (M=5.29, SD=1.78, N=24) and that the conformance box should be part of any display designed to support FIM operations (M=5.36, SD=1.62, N=24). However, the flight crews were only neutral to slightly in agreement with the statements that the conformance box helped them predict speed changes (*M*=4.75, *SD*=1.80, *N*=24), that it increased the level of safety of FIM (*M*=4.75, *SD*=1.78, *N*=24), or that it increased their comfort with FIM (*M*=4.88, *SD*=1.98, *N*=24). Additionally, one pilot misinterpreted the conformance box as a separation box, and one pilot would have disobeyed the commanded speed to center his aircraft in the box if his crewmember had not intervened.

In the end, the conformance box provided pilots a snapshot of their time error relative to the "excessive error" bounds. However, it did not help pilots understand why they were receiving particular speed commands, or help the pilots obtain an accurate mental model of ASTAR10. An example is demonstrated by the following quote:

- *"The conformance box was the easiest method to predict performance and trends. Without it I had to refer to the IM page in the CDU. Even then it was difficult to predict the next commanded speed. On several occasions when I checked the IM page it showed me as much as 23 sec ahead of schedule and yet it subsequently commanded a speed increase."*

The comment suggests that while the conformance box provided pilots with an easy way to determine how well the spacing operation was proceeding, it did not help them understand the rationale behind the commanded speeds or provide them with a more accurate mental model of IM. The pilot made the same mistake that was present in previous comments; that a negative (early) time error meant that the commanded speeds would always decrease. Pilot comments demonstrate that they are attempting to connect the time error shown on their displays to the speed commands they are receiving. Future trend indicators should concentrate on making this relationship more apparent.

5.4 Off-Nominal Scenario

Each flight crew experienced one exploratory off-nominal scenario, and only questionnaire data were collected and analyzed. This off-nominal scenario occurred after all the other scenarios were complete, and examined:

- Issuing a FIM clearance at low altitude;
- Terminating the FIM operation and issuing a new FIM clearance;
- Inserting an aircraft into the arrival stream;
- Spacing behind an aircraft to a converging runway; and
- Spacing behind an aircraft on the same arrival but landing on a parallel runway.

Traffic arrived from all directions; however, normal KDFW operations (independent parallel runways) were used and the spacing behind aircraft reduced to simulate a typical arrival rate during visual weather conditions (approximately 70 to 100 seconds between aircraft). A cloud deck between 2000 ft and 6000 ft MSL was added to invoke instrument flight rule scan patterns and tasks for the flight crew (in particular, to allow for head-down time below 10,000 ft).

To explore issuing a FIM clearance at low altitude, the final controller instructed one of the aircraft conducting a FIM operation to “go-around for insufficient spacing” when approximately two miles from the runway threshold. To create realistic closure behind the Target aircraft on controller scopes and cockpit displays, the appropriate Target aircraft (an ASTOR station) was intentionally slowed to 150 knots well prior to when it should have slowed. The three crews that experienced this event were aware of the closure to Target through voice communication and cockpit displays, and commented that the closure allowed by the FIM Commanded Speed appeared to be 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 FIM clearance while climbing to 5000 ft MSL. Even though the aircraft was in the weather and ATC responsible for aircraft separation, crews reported head down time and workload as too great for CPDLC messages containing FIM clearances in that environment (below 10,000 ft, proximity to other aircraft, etc.).

To create a gap in the arrival stream, a different crew had their FIM clearance amended to increase their spacing interval from 100 to 145 seconds. This was timed to occur just after the aircraft in the paragraph above initiated the go-around procedure, which the research team felt would be representative of a robust FIM operation. Three minutes later, the original FIM clearance was terminated, and the crew was issued a new FIM clearance with a different Target aircraft and spacing interval. The flight crew were generally passing through 12,000 ft MSL and changing frequencies to the TRACON controller when the second FIM clearance was issued. All three crews commented the workload was manageable but a significant challenge, and were somewhat aware that the change and new clearance had been issued to accommodate the insertion of an aircraft into the arrival stream.

Both crews (the one being inserted into the arrival stream, and the one creating a gap and changing to a new Target) were asked to comment about the feasibility and acceptability of inserting an aircraft into the arrival stream. All the crews involved felt comfortable with the physical location of the aircraft (range and closure to other traffic); however, the response to whether the FIM operation was acceptable was driven by the altitude the crew was at when the event occurred. The crew of the go-around aircraft stated conducting any operation that required significant head-down time was not acceptable at low altitude, and the crew of the aircraft creating the gap in the arrival stream reported that the FIM operation was acceptable.

The crews spacing behind a Target aircraft proceeding to a converging runway, and those spacing behind a Target aircraft on the same arrival but landing on a parallel runway, reported no additional workload to conduct that operation, and that the procedure was operationally acceptable.

6 Conclusions

This section provides a high-level general summary conclusion of the IMSPiDR experiment, then more detail for each of the four experiment objectives. The final sub-section addresses issues that require further research.

6.1 General Summary Conclusion

Pilot participants flew arrivals into KDFW using one of three different simulators located at NASA LaRC to explore a range of aircraft equipage levels and the resulting crew procedures for FIM operations. Scenarios were flown using either RTA or RTA+FIM control methods during various types of error. Results indicate that pilots delivered their aircraft to the runway threshold within 3.5 seconds (*SD*=4 seconds) of the RTA, and within 2.2 seconds (*SD*=3.9 seconds) of the spacing interval for the respective control methods. 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 mean time for the flight crew to load the FIM clearance into the spacing tool, review the calculated speed, and respond to ATC was under 43 seconds.

An overall mean rating of Moderately Agree was given when the crews were asked if the use of CPDLC was operationally acceptable as simulated in this experiment. Flight crews reported the FIM concept, procedures, and interfaces acceptable, and associated workload levels to be low. Concerns cited included the occurrence of multiple speed changes within a short time period, speed changes required within twenty miles of the runway, and an increase in airspeed followed shortly by a decrease in airspeed.

6.2 Performance and Behavior of the FIM Software

Experiment results indicate that aircraft, with the flight crew using FIM procedures to fly a speed generated by the ASTAR10 spacing algorithm, were able to arrive at the runway threshold within a 2.2 second mean (*SD*=0.9 seconds) from the assigned spacing interval. The type of error (wind or offset) did cause different algorithm behavior to resolve the spacing time error; however, the difference of the final error at the runway threshold was within 1.3 seconds, which is considered operationally insignificant.

To achieve this precision at the runway, the number of additional speed changes over that required for the published approach, ranged from “5” (No Error scenarios) to “11” (wind shear plus forecast wind error scenarios). In general, these speed changes happened predictably and used smaller magnitude speed changes than currently used by controllers. The number of speed changes was also dependent on, and compensated for, the variance in pilot performance.

One of the major differences between aircraft controlled to an absolute time (RTA scenarios) and those controlled to an interval behind a lead aircraft (RTA+IM scenarios) occurred during the Wind Error scenarios. Plots of the time error throughout the arrival demonstrated that the aircraft in the RTA scenarios had a large increase in time error when flying through the wind shear, whereas the aircraft in the RTA+IM scenarios were less affected by the wind shear when on the same trajectory as the controlling Target aircraft. The difference is most likely due to the fact that the wind shear occurs during a segment of flight where the spacing aircraft and lead aircraft were on the same path, thus they flew through the same wind shear and were able to maintain the spacing between themselves and their lead aircraft. The analysis of the difference between an aircraft's nominal profile speed and the FIM commanded speeds did not reveal large differences between the RTA control method and the RTA+IM control method for No Error and Offset Error scenarios.

Analysis of time error by runway showed no statistically significant difference. Analysis of the time error and number of FIM speed changes as a function of position in the arrival stream suggest the spacing algorithm generates predictable and desirable behavior in the stream while in the presence of continuous (wind) or impulse (offset) error.

6.3 Performance and Behavior of Flight Crew During FIM Operations

Pilot reaction time to changes in the FIM speed varied by error condition, and it is hypothesized that No Error scenarios had a longer reaction time because the flight crew were less vigilant in monitoring the FIM speed than during the Wind Error scenarios. However, the 1.6 second difference in mean reaction time is considered operationally insignificant. The pilots' ability to remain within 5 knots of the FIM speed varied by error condition, with the Wind Error again being the most challenging. In-depth analysis indicates the majority of the deviation (in all scenarios) occurred during the initial deceleration to the next FIM speed.

In general, it took approximately 6 seconds for the flight crew to read the CPDLC message containing the FIM clearance, and this did not vary by simulator type or run order. In 87% of the runs, the flight crew were able to respond via CPDLC within 60 seconds (send an accept message). Review of all 23 of 177 data points where a CPDLC response was not sent within 60 seconds indicates the flight crew had sufficient time to respond; however, they either forgot or thought they had sent the FIM clearance accept message via CPDLC. The mean response time for the two-crew simulators was approximately 12 seconds more than the single-pilot simulator, reflecting the time required for the crew to coordinate with each other about the message.

6.4 Flight Crew Assessment of the FIM Concept, Procedures, and Displays

Flight crews generally found the airborne spacing concept and procedures acceptable, and reported the speeds commanded by ASTAR10 as correct, safe, and comfortable. However, the large wind and offset errors injected into the system resulted in specific algorithm behaviors that flight crews found undesirable. These behaviors included too many speed changes within a short period of time, too many speed changes while on final approach, speed reversals, and speed increases that required the flaps to be raised.

Flight crews rated the workload of FIM operations as 1.97 (1 very easy, 10 impossible), and the pilot interface used in support of the spacing operation was found to be useful and utilized in the way anticipated. The subject pilots reported that the alert designed to notify them of speed command changes was not sufficiently salient, causing them to spend excessive time monitoring the speed command symbology on the PFD.

Flight crews provided post-run and post-experiment ratings regarding the use of CPDLC as the means of communication for FIM operations. On a scale of 1 (completely disagree) to 7 (completely agree), they moderately agreed that the use of CPDLC did not detract from other tasks, and moderately agreed that the amount of head down time required for CPDLC was acceptable. However, they also reported that the particular procedure used for the FIM operation required too many button pushes, and the procedure should be simplified.

Although the flight crews were able to remain within approximately 6 knots of the FIM speed, the need for more salient notification of changes to the FIM speed was reported. On the same scale of 1 to 7, flight crews moderately agreed that it was important to be able to predict the next FIM speed change, and moderately agreed that the spacing software itself was predictable. In addition to that result, a few pilots misinterpreted the relationship between the time error value on the MCDU and the speed commands that the spacing algorithm provided. Future displays depicting the time error should concentrate on making this relationship more apparent to the flight crew.

The desire most often expressed by the flight crews was to have a selectable (not always visible) representation of the current status and trend of the FIM operation (similar to the conformance box used during the off-nominal scenario). The crews also expressed a desire for more predictable FIM speed changes, and fewer of them (primarily during Wind Error scenarios). Finally, crews expressed a desire for more salient alerting for FIM speed changes.

6.5 Potential Operational Issues of the FIM Concept

This section discusses issues that were outside the scope of the experiment or beyond the capability of the simulation platforms at the time of the IMSPiDR experiment.

6.5.1 Aircraft Avionics

An accurate understanding is needed of the likelihood of various aircraft equipment failures, and future FIM experiments should explore the procedures to be used when those events occur. Examples include failure of the Target aircraft's ADS-B, failure of the FIM aircraft's ADS-B, and failure of the FIM aircraft's CPDLC.

FIM arrival operations that begin when within the jet stream may exhibit behavior not yet simulated. A real-world operational example is en route controllers must begin the descent of east-bound aircraft into KDFW early to compensate for the jet stream from the west.

The behavior of an aircraft conducting FIM and a second aircraft not conducting FIM as they approach a common merge point from different directions must be thoroughly studied and understood.

The FIM procedures and controller-pilot phraseology would be considerably simplified, resulting in lower workload and less error, if the FIM software was able to determine the FIM and Target aircraft's route without requiring the flight crew to enter that information.

6.5.2 Flight Crew Procedures

A study should be conducted to determine if flight crews can be more precise if the ASTAR10 spacing software uses a static location for when the FIM mode changes to the FAS (currently it varies based on the time error left to be corrected).

The FIM procedures should be retested using CPDLC with the acknowledgement timers turned on. These were intentionally turned off at the request of the FAA (to measure all crew response times); however, this twice created a situation where the crew thought they had sent an ACCEPT message to ATC and were conducting the FIM operation, but ATC had in fact not been notified.

6.5.3 Air Traffic Control Software

The current version of software available to en route and terminal airspace controllers does not have a mechanism to indicate which aircraft are FIM capable, which aircraft are conducting FIM operations, which aircraft are being used as a Target, nor is there method to display the FIM clearance. Furthermore, there are no controller decision support tools or displays to indicate the position and trend of the FIM aircraft to the desired location.

The current flight plan format does not enable the flight crew or the airline to specify which aircraft or what flight is FIM capable.

6.5.4 Air Traffic Control Procedures

To enable arrival operations that rely on speed control alone, the published arrival procedures (for example, a STAR) should be designed with slightly shallower descent angles and slower speeds to enable the use of speed control only during arrival operations.

References

The References section credits both published and unpublished works that are used throughout the document to either support or refute statements or offer alternatives. Unpublished references are limited to those that are complete, but in the peer review process prior to publication, and are annotated as such. The references section includes higher level and adjacent concepts on which this document depends.

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Appendix A: Glossary

This Appendix is the Glossary of terms and their definitions frequently used and important to this experiment. Well known acronyms (e.g., FAA, NASA) are not included.

Table 17. Acronyms and Definitions

Acronym	Term	Definition
4D trajectory	Four-dimensional trajectory	The centerline of a path formed by segments that link consecutive trajectory change points; each point defined by a longitude, latitude, altitude. NOTE: some waypoints may have time, altitude, and/or speed constraints. These restrictions can be equality (e.g., specific altitutude) or inequality (e.g., at or above) constraints.
--	Achieve-By Point	Waypoint on the FIM aircraft's route where the Assigned Spacing Goal behind the Target aircraft is expected to be achieved.
ADS-B	Automatic Dependent Surveillance – Broadcast	ADS-B is a technology where aircraft avionics (or ground equipment) autonomously broadcasts the aircraft's (or ground vehicle's) position, altitude, velocity, and other parameters. "ADS-B Out" refers to the broadcast of ADS-B transmissions from an aircraft or vehicle, and "ADS-B In" refers to reception of the ADS-B transmissions from other aircraft or vehicles.
ASTAR	Airborne Spacing for Terminal Arrival Routes	Advanced flight deck-based automation that constantly calculates the airspeed required to position an aircraft at the Achieve By Point at the Assigned Spacing Goal behind the Target aircraft.
ASTAR10	Airborne Spacing for Terminal Arrival Routes	Version of ASTAR specifically designed for dependent parallel runway operations (two Target aircraft).
ETA	Estimated Time-of-Arrival	The current estimate of the aircraft's time-of-arrival at a point along its flight path based on forecast winds, aircraft performance and defined arrival procedures, but not adjusted to compensate for traffic separation or metering delays. The ETA is re-calculated whenever an event occurs, such as route-of-flight change, etc.
FAS	Final Approach Speed	The airspeed flown from the FAF to the runway. There are flight crew and airline variances for when this speed is achieved.
FIM	Flight deck Interval Management	Flight crew makes use of specialized avionics that provides speed commands for interval management. Exclusively the airborne component of entire IM system.
--	FIM aircraft	The aircraft receiving speed commands from the onboard FIM equipment to achieve the assigned spacing behind the Target aircraft. This aircraft must have ADS-B transmit and receive equipment, and be equipped for FIM operations.
--	FIM clearance	The FIM clearance contains the Target aircraft's identification (callsign) and the Assigned Spacing Goal (ASG), the RTA to the Achieve By Point (the runway threshold in IMSPiDR), and the Target's route of flight.
--	FIM Commanded End Speed	The speed calculated and provided by the aircraft FIM equipment during a FIM operation to achieve the Assigned Spacing Goal behind the Target by the Achieve-By Point. Airspeed at the end of the change; occurs as a discrete jump; shown in digits on displays.
--	FIM Commanded Speed	The FIM Commanded End Speed adjusted for aircraft's deceleration, estimated for that moment, shown by the speed bug.

Table 17. Acronyms and Definitions (concluded)

Acronym	Term	Definition
--	FIM operations	Refers to one or more FIM aircraft actively spacing to achieve the ASG behind their Target aircraft. Responsibility for spacing (accomplished by flying the FIM speed) resides with the flight crew, aircraft separation responsibility remains with ATC.
--	FIM speed mode: - RTA - FIM - FNL	Various ASTAR10 modes once FIM clearance has been entered. - Airpeed to meet time at runway (no Tartget ADS-B data) - Airpseed to achieve Spacing Interval behind Target - FMS calculated final approach speed; after FAF
FMS	Flight Management System	Computerized avionics component found on most commercial and business aircraft for navigation, flight planning, and aircraft control functions. It is composed of: Flight Management Computer, Auto Flight System, Navigation System (including Inertial Reference System and Global Positioning System), and an Electronic Flight Instrument System.
GIM-S	Ground-based Interval Management - Spacing	Ground-based functions to support aircraft crossing the TRACON boundary along the route of flight at specific times or STAs.
IM	Interval Management	Systems to achieve and maintain spacing between aircraft. Includes flight deck (FIM) and ground-based (GIM-S) elements.
OPD	Optimized Profile Descent	Designed to reduce fuel consumption, emissions, and noise during descent by allowing aircraft to fly an optimized descent during arrival with engines near idle from en route altitude to the runway threshold (however, it may not include the instrument approach portion). OPD procedures specify the lateral path, vertical boundaries, and a speed for every segment of the procedure. The vertical boundaries of the OPD are established to accommodate a wide range of descent profiles.
--	Ownship	Refers to the FIM aircraft.
RTA	Required Time of Arrival	Entered by the flight crew into the ASTAR10 software; is the same as the Scheduled Time of Arrival.
SI	Spacing Interval	The true horizontal along-path spacing (expressed in time) between the FIM and Target Aircraft. The SI should equal the ASG by the Achieve-By Point (final approach fix).
STA	Scheduled Time of Arrival	Calculated by the ground scheduling software to meet all of the scheduling and sequence constraints; set at “Freeze Horizon” and normally not changed thereafter.
STAR	Standard Terminal Arrival Route	A pre-planned instrument arrival procedure published for pilot use in graphic and/or textual form. Provides transition from the en route structure to an instrument approach fix in the terminal area.
TGT or TTF	Target aircraft, or Traffic To Follow	The aircraft lead specified by ATC for the FIM aircraft. Must be equipped with ADS-B Out (transmit), but is not required to be ADS-B In (receive) equipped or capable of FIM operations. TGT used in CPDLC messages, TTF used by ASTAR10.
TOD	Top-Of-Descent	The computed transition from the cruise phase of flight to the descent phase, the point at which the descent to final approach altitude is initiated.

Appendix B: Dependent Runways and KDFW Operations

B.1 Dependent Parallel Runway Criteria

Below are excerpts from the FAA guidance for when dependent parallel runway operations must occur [7]. The ground equipment installed at the Dallas-Fort Worth airport (KDFW) allows normal operations to occur as independent parallel runway operations despite the runway centerlines being less than 9000 ft apart [7]. This experiment assumed that ground equipment was not available to explore Flight deck Interval Management (FIM) during dependent parallel runway operations.

- 1000 feet (ft) vertical and 3 nautical miles (nmi) radar separation between aircraft during turn on.
- At least 1.5 nmi radar separation diagonally between aircraft when runway centerlines are at least 2500 ft but no more than 4300 ft.
- At least 2.0 nmi radar separation diagonally between aircraft when runway centerlines are more than 4300 ft but no more than 9000 ft apart.
- Provide minimum applicable radar separation between aircraft on the same final.

B.2 KDFW Operations

A site visit and briefing was held at KDFW Terminal Radar Approach Control (TRACON) on 9/13/2010 to discuss the Interval Management with Spacing to Parallel Dependent Runways (IMSPiDR) experiment. Present were Bruce Thorson (TRACON Training Manager), Greg Juro (Air Traffic Manager and acting Procedures Manager), James Karanian (FAA Air Traffic Operations Office and retired KDFW Center Line Supervisor), and Brian Baxley. Mr. Thorson provided to NASA the following documents to describe KDFW TRACON operations:

- D10 TRACON Air Traffic Control, D10 7110.65 (June 8, 2010)
- D10 TRACON Arrival / Final Monitor Study Guide
- D10 TRACON Departure Control Study Guide

From these documents and briefing, the following is a description of operations that typically occur at KDFW, and were used to the maximum extent possible in the IMSPiDR experiment:

- Maximum arrival rate is approximately 30 aircraft per hour per arrival runway.
- Arrival runways are typically (east to west) runways 17L, 17C, and 18R.
- Most of the traffic arrives from the northeast (~65%), followed by southeast (~35%).
- If traffic is too light to require three runways, runway 17L is not used.
- If runway 17C is too busy, aircraft will be crossed from the east to the west, and landed on runway 18R, or from west to east and landed on runway 17C (~5%).
- Traffic landing at Dallas Love airfield and arriving from the northwest will be vectored north of the field at low altitude (not desired), or brought in over DFW and then rapid descent while in a left turn for approach to runway 13L or 13R at Love Field.
- Turbo-prop aircraft generally arrive from the south and land on runway 13R.

- For south flow, the NE and NW corner posts are “low-side”, SE and SW “high-side”.
- Parallel flows from the “low-side” corner posts (northern points during south flow) will offset towards the center line of the airfield (e.g., MASTY Arrival). These flows are used to for aircraft flying a different speed, to a different runway, or to a different airfield.
- Converging ILS approaches are only used when Tower cannot provide visual separation, usually when weather is worse than 1000 ft ceiling or 3 nmi visibility.
- Altitude to intercept runway centerline (Figure 46 for a two runway example is from KDFW TRACON training material that is referenced above):
    - Aircraft arriving to runway 17C will always be the highest
    - 2 runway: runway 17C 5000 ft, runway 18R 4000 ft
    - 3 runway: runway 17C 6000 ft, runway 18R 5000 ft, runway 17L 4000

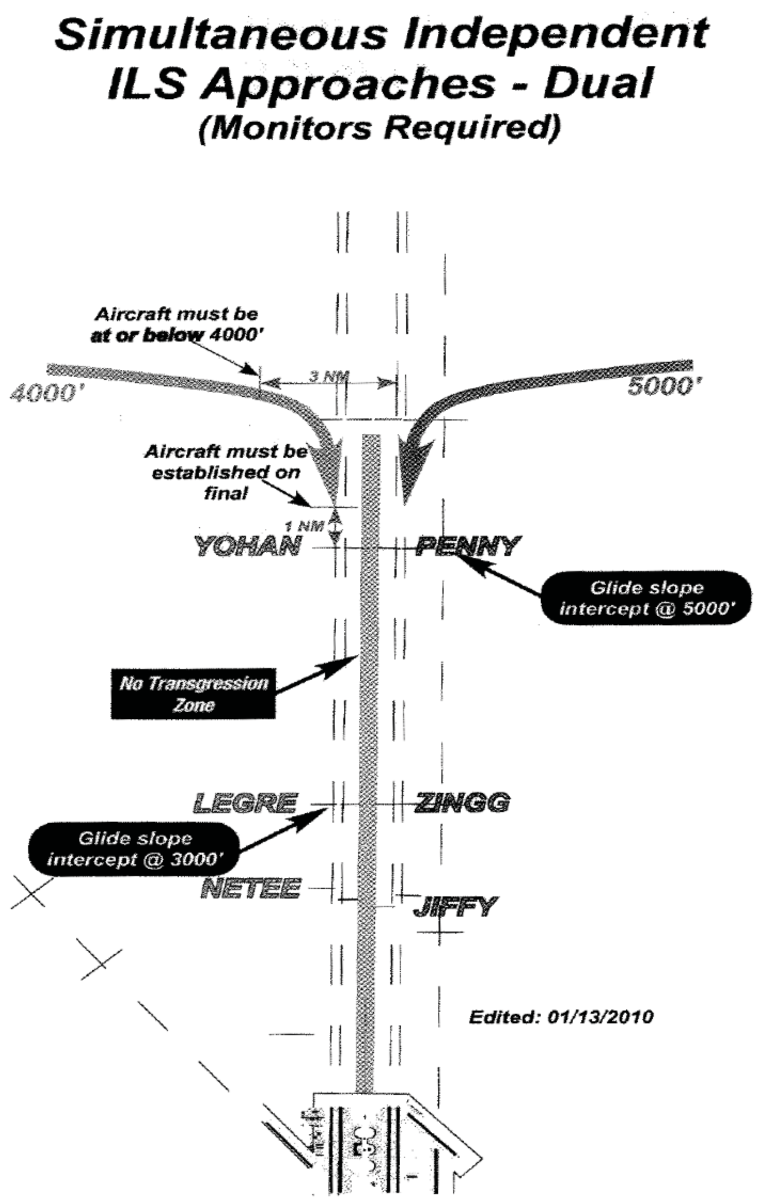


Figure 46. Separation Requirement for Parallel Approaches

Table 18 lists those callsigns and associated airlines that were observed to operate to and from KDFW during the site visit hosted by the TRACON in 2010. These callsigns were used in the IMSPiDR experiment, and in questions asked after the experiment about using data tags that did not align with voice callsign.

Table 18. Aircraft Callsigns and Associated Airline

Display	**Spoken**	**Airline**
UPS	UPS	UPS
FDX	FedEx	FedEx
AAL	American	American Airlines
DAL	Delta	Delta Airlines
COA	Continental	Continental Airlines
BTA	JetBlue	JetBlue Airlines
EGF	Eagle Flight	American Eagle
RPA	Brickyard	Republic Airlines
SWA	Southwest	Southwest Airlines
AWE	America West	America West
DLH	Lufthansa	Lufthansa Airlines
TRS	Citrus	Airtran Airways
USA	US Air	US Airways
FFT	Frontier	Frontier Airlines
GA/Business aviation		
N305LM	N305LM	n/a

Appendix C: Differences of FIM Displays by Simulator

Features and differences in the Primary Flight Displays (PFD) of the Aircraft Simulation for Traffic Operations Research (ASTOR) stations, Development and Test Simulator (DTS), and Integration Flight Deck (IFD) are shown in Figure 47), and described below.

- Flight Mode Annunciator bar (upper middle of PFD):
  - ASTOR and DTS: SPD (Speed), LNAV (Lateral Navigation), VNAV PTH (Path)
  - IFD: SPD, VNAV PTH, LNAV

- Auto-pilot (A/P or AP) engaged:
  - ASTOR: A/P in upper center
  - DTS: AP ON in upper right
  - IFD: CMD at top right

- Aircraft's FMS commanded speed:
  - ASTOR, DTS: magenta number in upper left
  - IFD: no number displayed

- Aircraft's FMS commanded speed on the vertical speed tape:
  - ASTOR: triangle-rectangle (automatic and discrete jump to next value)
  - DTS: butterfly (automatic and discrete jump to next value)
  - IFD: single line in the IFD and moved in conjunction with value in Mode Control Panel (MCP) window
    - NOTE: In the ASTOR and DTS, as the aircraft intercepted the final approach course, the final approach mode of the Flight Management System (FMS) is triggered, which caused the MCP Speed Window to open, and the speed bug to behave as in the IFD.

- FIM commanded end speed (speed to flown, discrete value):
  - ASTOR, DTS, IFD: green number, above FMS speed (if shown)

- FIM mode (immediate right of FIM speed):
  - Required Time of Arrival (RTA): time at achieve-by point (runway threshold)
  - FIM: paired with Target aircraft transmitting valid ADS-B data
  - Final (FNL): speed shown is the FMS calculated final approach speed

- Change to FIM commanded speed number or mode:
  - ASTOR, DTS, IFD: green box around speed or mode for 10 seconds; removed after 10 seconds regardless of crew action or inaction (see left plot of Figure 47)

- FIM commanded speed (accounts for aircraft deceleration, continuous value):
  - ASTOR: green butterfly to left of magenta FMS speed bug
  - DTS: green triangle to left of magenta FMS speed bug
  - IFD: green double line

- Aircraft magnetic heading (bottom middle of PFD):
    - ASTOR, DTS: shown
    - IFD: not shown

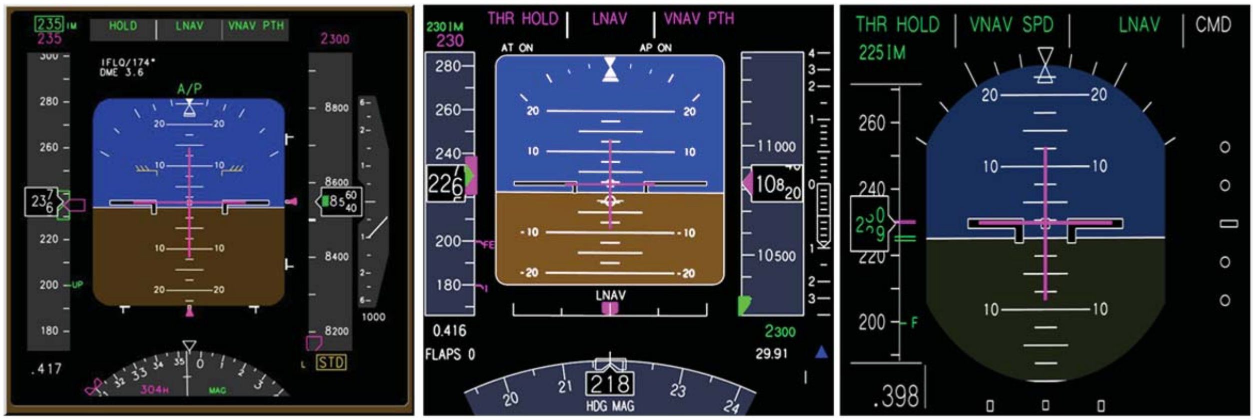


Figure 47. PFD for ASTOR (left), DTS (center), and IFD (right).

Features and differences in the Navigation Displays (ND) of the three simulators is shown in Figure 48 and described below.

- Magnetic heading:
    - ASTOR: white triangle outside of the heading arc
    - DTS: green triangle inside the heading arc
    - IFD: white triangle inside the heading arc

- Aircraft transmitting ADS-B data shown as:
    - ASTORL: chevrons
    - DTS, IFD: diamonds

- FIM Target aircraft shown as:
    - ASTOR: double chevron
    - DTS, IFD: double diamond

- Target aircraft that determined the FIM speed:
    - ASTOR: second (outer) chevron green
    - DTS, IFD: second (outer) diamond green

- Target aircraft not visible on the ND:
    - ASTOR: TRAFFIC OFF SCALE text
    - DTS, IFD: half-symbol at the edge of the display

Figure 48. ND for ASTOR (left), DTS (center), and IFD (right).

Other simulator differences included:

- Controller-Pilot Datalink Communications (CPDLC) interfaces to receive and respond to FIM clearance:
  - ASTOR: used the Engine Indicating and Crew Alerting System (EICAS)
  - DTS, IFD: used the Multi-function Control and Display Unit (MCDU)

- MCDU:
  - ASTOR, DTS, IFD: IM button in the top row, fourth from the left
  - IFD: FMC COMM button on the second row, fourth from the left

- Aircraft control interfaces (flight controls, throttle, speed brake, flaps, gear):
  - ASTOR: computer mouse for all interactions
  - DTS: side-stick controller and standard throttle/flap/speed brake quadrant
  - IFD: yoke and standard throttle/flap/speed brake quadrant

- Aircraft terminated when:
  - ASTOR: 35 ft above the runway threshold
  - DTS, IFD: once below 5 knots during rollout

Appendix D: Post-Run Questionnaire

You will be asked to complete a more extensive questionnaire at the end of the experiment, so please try and keep written comments as concise as possible. Some questions intended for pilots flying a specific simulator are labeled with *DTS*, *IFD*, and *ATOL*. Please only answer these questions if the label for the simulator you are flying is present. Questions without a label are intended for all participants.

Administrative Questions

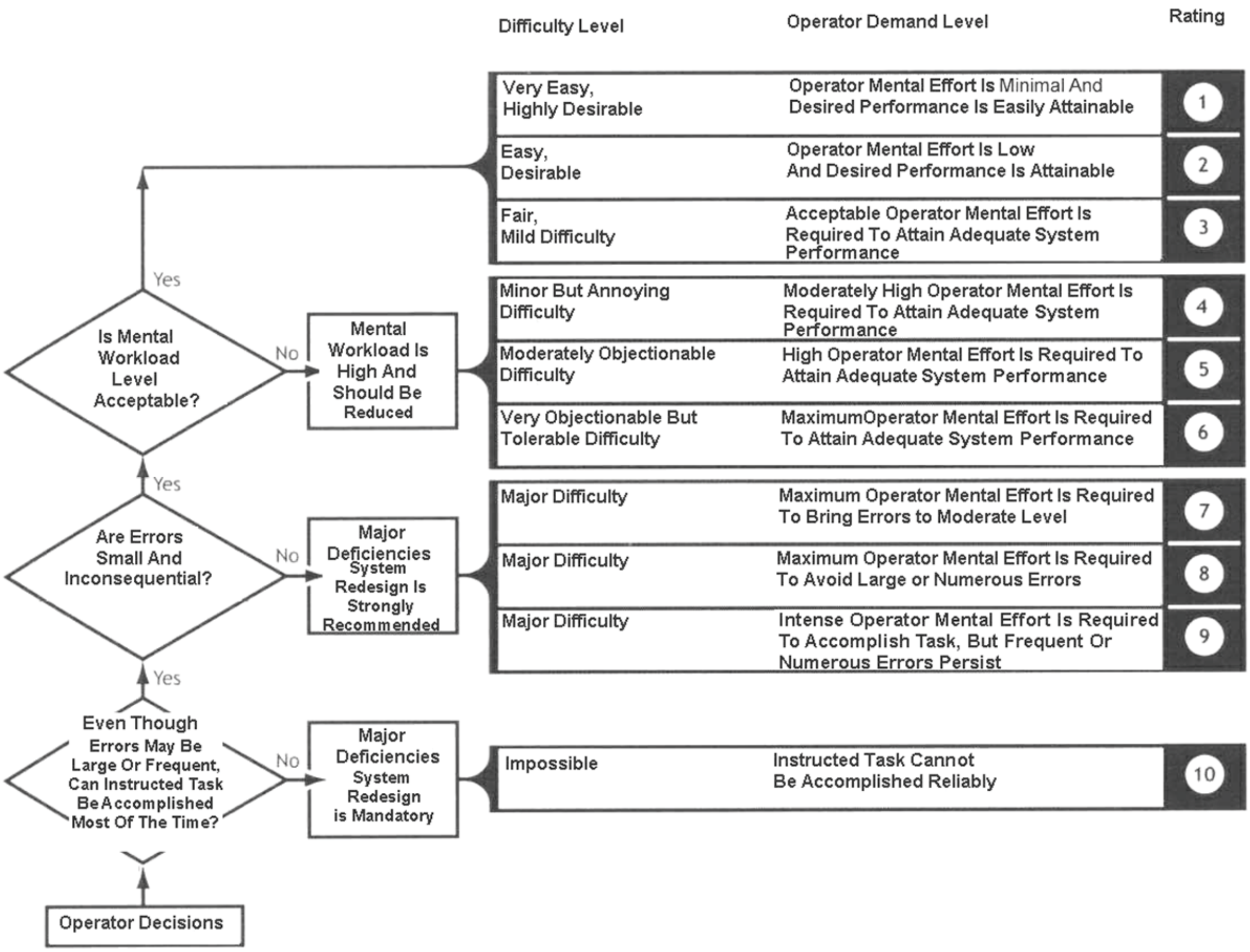
1. Please circle the scenario you just completed from the list below:

- Scenario 1
- Scenario 2
- Scenario 3
- Scenario 4
- Scenario 5
- Scenario 6
- Scenario 7
- Scenario 8
- Scenario 9
- Scenario 10
- Scenario 11
- Scenario 12 (Extra Scenario, time permitting)
- Scenario 13 (Extra Scenario, time permitting)

2. Please circle the simulator you are flying from the list below:

- ASTOR 4
- ASTOR 5
- ASTOR 9
- ASTOR 10
- DTS Right Seat
- DTS Left Seat
- IFD Right Seat
- IFD Left Seat

Average and Peak Workload Ratings (Modified Cooper-Harper)



3. **Follow the flow chart above to select the <u>average</u> workload <u>you</u> experienced during the scenario you just completed.**
   - ➢ Rating of your average workload level: _________

4. **(DTS, IFD only) Follow the flow chart above to select the <u>average</u> workload you believe <u>your crew member</u> experienced during the scenario you just completed.**
   - ➢ Rating of your crew member's average workload level: _________

(Optional) Use the space provided below to record any clarifying comments or interesting observations related to the workload level you experienced during the last run:

5. **Follow the flow chart above to select the <u>peak</u> workload <u>you</u> experienced during the scenario you just completed.**
   - Rating of your peak workload level: __________
   - Please select the segment of flight during which your peak workload level occurred:
     - >18,000ft (cruise, initial descent, CPDLC)
     - 18,000ft – 11,000ft (descent, approach check)
     - 11,000ft - 5,000ft (TRACON, low altitude merge)
     - <5,000ft (final approach, configure aircraft)

6. **(DTS, IFD only) Follow the flow chart above to select the <u>peak</u> workload you believe <u>your crew member</u> experienced during the scenario you just completed.**

   - Rating of your crew member's peak workload level: __________
   - Please select the segment of flight during which you believe your crew member's peak workload level occurred (same as above).

(Optional) Use the space provided below to record any clarifying comments or interesting observations related to the workload level you experienced during the last run:

Situation Awareness and Crew Coordination Ratings

7. **Respond to each of the statements shown below using a scale ranging from "1" (Low) to "7" (High). Circle one number in conjunction with each statement.**

Demand on Attentional Resources: Rate your overall impression of the scenario in terms of how much attention and effort was required to successfully perform the tasks. Items to consider include: the likelihood of the situation changing suddenly, the degree of complexity associated with the scenario, and the number of variables changing in the scenario.	1 2 3 4 5 6 7
Supply of Attentional Resources: Rate the degree of spare attention that you had available to perform tasks other than your primary task of flying the aircraft. Items to consider include: the amount of focus and concentration needed to complete the tasks and how divided you attention was between flying the aircraft and other tasks.	1 2 3 4 5 6 7
Understanding: Rate your overall understanding of the events in the previous scenario. Items to consider include: the quantity and quality of information, and the familiarity you had with events in the scenario.	1 2 3 4 5 6 7

8. **Respond to each of the statements shown below using a scale ranging from "1" (Completely Disagree) to "7" (Completely Agree). Circle one number in conjunction with each statement.**

Relevant information, including operational plans, decisions, and changes in aircraft state were effectively communicated between yourself and your crewmember.	1 2 3 4 5 6 7
Task priorities were clearly communicated between yourself and your crewmember.	1 2 3 4 5 6 7
The time available for tasks was well managed.	1 2 3 4 5 6 7
Potential distractions caused by automated systems were anticipated, and either appropriate action was taken or appropriate plans were made to decrease the impact of the distraction.	1 2 3 4 5 6 7

Awareness and Acceptability Ratings

9. **Respond to each of the statements shown below using a scale ranging from "1" (Completely Disagree) to "7" (Completely Agree). Circle one number in conjunction with each statement.**

I was aware of commanded speed changes within an appropriate timeframe. (You will be asked to define "timely awareness" in the post experiment questionnaire)	1 2 3 4 5 6 7
I was able to implement the speed changes within an appropriate timeframe when the speed window was open. (You will be asked to define "timely implementation" in the post experiment-questionnaire)	1 2 3 4 5 6 7
The commanded speed was operationally acceptable and appropriate.	1 2 3 4 5 6 7
The frequency of IM speed commands was acceptable at all times throughout the scenario.	1 2 3 4 5 6 7
I was able to predict when IM speed changes would occur before they were given.	1 2 3 4 5 6 7
I maintained adequate awareness of my lead aircraft throughout the scenario	1 2 3 4 5 6 7
The events I experienced in this scenario are operationally realistic.	1 2 3 4 5 6 7
The flight crew procedures for the events in this scenario are operationally feasible.	1 2 3 4 5 6 7
The amount of head down time required to respond to CPDLC messages was acceptable.	1 2 3 4 5 6 7
The time take to review and respond to CPDLC clearances did **not** detract from your ability to complete other critical tasks.	1 2 3 4 5 6 7

10. **Answer the following questions based on your experience with the IM spacing tool and procedure during the previous run.**

There was a time in the scenario where you thought it was unsafe to fly the commanded speed.	1 2 3 4 5 6 7
There was a time in the scenario where you thought the commanded speed would **not** get you to the runway threshold at the correct time.	1 2 3 4 5 6 7
The IM commanded speed interrupted you while you were in the process of completing other critical tasks.	1 2 3 4 5 6 7
There was a time in the scenario where the spacing tool behaved in an unexpected manner.	1 2 3 4 5 6 7
There was a time in the scenario where you felt that the commanded speed or other information available from the spacing tool conflicted with other information available through ATC, your CDTI display, voice comm., etc.	1 2 3 4 5 6 7
There was a time in the scenario where you felt uncomfortable flying the commanded speed.	1 2 3 4 5 6 7
There was a time in the scenario where you felt frustrated by the spacing tool (The spacing tool refers to CPDLC messages, displays, and automation that has been added to the aircraft to aid in spacing).	1 2 3 4 5 6 7

11. **If desired, please explain any undesirable ratings from the statements above.**

12. **Did you receive an EICAS message other than "IM DRAG REQD", "IM SPD LIMITED", or "IM AC 1/AC 2 SPACING" during the arrival or approach? Yes/No**

    If "yes," please describe the message(s) that appeared (exact text not needed).

13. **If you received an EICAS Caution message during the arrival or approach, please respond to each of the following statements using a scale from "Completely Disagree" to "Completely Agree", or N/A if appropriate**.

It was clear why the EICAS Caution message was given.	NA	1	2	3	4	5	6	7
As the arrival progressed, I expected this EICAS Caution to occur.	NA	1	2	3	4	5	6	7
The EICAS Caution message was warranted for this event.	NA	1	2	3	4	5	6	7
The flight crew procedures for this EICAS caution message were clear.	NA	1	2	3	4	5	6	7

14. **Describe any unusual or unexpected event(s) and your reaction(s), if applicable.**

15. **(Optional) This space is reserved for any additional comments related to awareness and acceptability issues. If you have any clarifying comments or interesting observations related to awareness and acceptability issues, please provide them below.**

Appendix E: Post-Experiment Questionnaire

Administrative Questions

1. **Please circle the simulator you flew from the list below:**
   - ASTOR 4
   - ASTOR 5
   - ASTOR 9
   - ASTOR 10
   - DTS Captain
   - DTS First Officer
   - IFD Captain
   - IFD First Officer

Simulator and Flight Scenarios

2. **Were there any anomalies or inconsistencies in the simulator that affected your ability to perform the requested tasks? Yes/No**

   If "yes," describe the anomalies and/or inconsistencies in the simulator that you encountered and how they affected your ability to perform the requested tasks:

3. **Was the workload required to operate the simulator much less than, the same as, or greater than the workload required to fly an actual aircraft?**

Much More	Moderately More	Slightly More	The Same	Slightly Less	Moderately Less	Much Less
1	2	3	4	5	6	7

   Please provide any additional comments regarding the simulator:

4. **Please share your impressions of the flight scenarios (e.g., comment on their level of realism, appropriateness, and/or diversity) and comment on how the design of the scenarios impacted your ability to perform the spacing task.**

Training

5. **Did you receive adequate training with respect to flying the simulator? Yes/No**

   If not, briefly describe how simulator training can be improved.

6. **Did you receive adequate training with respect to the IM spacing procedure and the spacing tool? Yes/No**

   If not, briefly describe how IM procedure or spacing tool training can be improved:

Interval Management Procedures

7. **In a real world environment, how much additional workload do you think would be required to carry out the spacing procedures while flying the Optimized Profile Descent (OPD) compared to current step-down procedures?**

Much More	Moderately More	Slightly More	The Same	Slightly Less	Moderately Less	Much Less
1	2	3	4	5	6	7

8. **Did you find the responsibility and workload associated with complying with speeds generated by onboard automation to be acceptable?**

   YES ___
   NO ___
   If not, why not, and what could be done to make the responsibility or workload acceptable?

9. **How difficult do you think it would be for a typical flight crew to learn and integrate the IM spacing procedures into their current daily operational flight procedures? Consider how similar the procedure is to current practices, the information and tasks required to conduct the procedure, etc.**

Very Difficult	Moderately Difficult	Slightly Difficult	Neutral	Slightly Easy	Moderately Easy	Very Easy
1	2	3	4	5	6	7

   Briefly describe any challenges to integrate the IM procedures with existing procedures:

10. **Given the experience with IM that you gained during this simulation, what is your overall assessment of the safety of the spacing procedure compared with current day operations? ("Safety" in this question refers to your holistic opinion to include workload, awareness, position relative to other aircraft, etc.)**

Not Safe At All	Moderately Less Safe	Slightly Less Safe	As Safe	Slightly More Safe	Moderately More Safe	Much More Safe
1	2	3	4	5	6	7

   Briefly describe any characteristic or event that determined your rating (if appropriate):

11. Were the IM procedures used during this experiment complete, accurate, and logical? Yes/No

Please provide any suggestions regarding the way(s) in which the procedures may be improved.

12. ATC controllers are accustomed to aircraft callsign data tags on their radar scope not matching the respective voice callsign or airline name (examples: Airtran Airways is "TRS" but pronounced "Citrus," and Express Jet Airlinesis "BTA" but pronounced "JetLink"). Was it an issue to correlate verbal ATC instructions with the CPDLC instructions?

Insurmountable Issue	Significant Issue	Somewhat of an Issue	Insignificant Issue	Not an Issue at All
1	2	3	4	5

Please identify any method(s) that might make this a less challenging issue:

13. In this experiment the FMS automatically managed the commanded speed in the ASTOR and DTS aircraft, while the IFD pilots were required to manually input the IM commanded speed into the MCP. Are there specific times during an approach into a terminal area when one of these methods would be preferable over the other? Yes/No

If "yes," please describe when a particular method of speed control would be preferable and why it would be preferable, or conversely why a particular method would not be acceptable.

CPDLC, MCDU, and Spacing Tool

14. How long should a pilot have in a busy terminal (as simulated by this experiment) to respond to a CPDLC uplink message? Consider other cockpit tasks, environmental conditions, complexity of flight operation, importance of the message, crew coordination and briefing, etc.

Flight crews should typically respond to a CPDLC message within _________ seconds.

15. During the Post Run Questionnaire, you were asked whether you noticed the speed changes within an appropriate timeframe. What did you consider to be "timely awareness" of a change in the commanded speed in a busy terminal area?

Timely awareness = noticing speed changes within _________ seconds of the change being displayed on the PFD.

16. In each Post Run Questionnaire, you ware asked whether you were able to implement the speed changes within an appropriate timeframe when the speed window was open. What did you consider to be "timely implementation" of the commanded speed?

Timely implementation = Dialing the new commanded speed into the MCP within _________ seconds of noticing that a speed change was required.

17. Did following the IM commanded speed and procedure ever cause unexpected or undesirable behavior? Yes/No

If "yes," please explain what the unexpected or undesirable behavior was:

18. What steps did you take to determine if the RTA or IM clearance was or was not acceptable? Describe information you accessed and considered during your decision making process, and any coordination that occurred with your crewmember (if applicable).

19. Describe any displays or trends that helped you predict changes to the commanded speed before they occurred. Please include any specific displays that helped you with the prediction.

20. Describe in general terms the desirable behavior the spacing tool should use to determine speed commands. Examples include: frequency of speed changes, magnitude of speed change, when the change occurs, the rate at which the aircraft achieves the assigned spacing interval, etc.

21. Does the automated spacing tool support pilot performance without introducing unnecessary or undesirable features? In this case pilot performance refers maintaining acceptable levels of workload and awareness:

Please circle the most accurate statement below:

- o The automated spacing tool supports pilot performance without introducing unnecessary and/or undesirable features.
- o The automated spacing tool supports pilot performance, but the tool has unnecessary and/or undesirable features that need to be changed.
- o The automated spacing tool does not support pilot performance, either as a result of unnecessary/undesirable features, or for some other reason described below.

If applicable, briefly outline any unnecessary or undesirable features of the spacing tool as well as any other undesirable aspects of the tool:

22. Do interruptions caused by the spacing tool or distracting features of the spacing tool undermine a pilot's ability to engage in high-level planning, problem solving, and/or other time critical tasks?

YES ___
NO ___

If "yes," describe which aspect(s) of the automated spacing tool distracted and/or interrupted you, the task(s) and/or planning you were completing at the time of the interruption, and how the use of the automated spacing tool negatively affected high-level planning, problem solving, and/or time critical tasks:

23. Does use of the spacing tool require the extraneous expenditure of mental resources that should instead be devoted to the main task of flying the aircraft and activities associated with preparing to land?

Please circle the most accurate statement below:

- o Yes
- o No, use of the spacing tool requires an acceptable expenditure of mental resources.
- o No, use of the spacing tool "frees up" mental resources that may be devoted to the main task of flying the aircraft and activities associated with preparing to land.

If "yes," briefly describe how use of the spacing tool consumes an excessive amount of mental resources:

24. Within the context of an approach into a busy terminal area, are there times when it is not acceptable to receive a CPDLC message? Yes/No

If "yes," briefly when it is not be acceptable to receive a CPDLC clearance:

25. Please rate each of the following statements using a scale ranging from "Completely Disagree" to "Completely Agree:"

a) Based on my experience during this simulation, the spacing tool behaves in a predictable manner.

Completely Disagree	Moderately Disagree	Slightly Disagree	Neutral	Slightly Agree	Moderately Agree	Completely Agree
1	2	3	4	5	6	7

b) It is important to be able to predict changes to the commanded speed before they occur.

Completely Disagree	Moderately Disagree	Slightly Disagree	Neutral	Slightly Agree	Moderately Agree	Completely Agree
1	2	3	4	5	6	7

c) The use of CPDLC messages were operationally acceptable as simulated in this experiment.

Completely Disagree	Moderately Disagree	Slightly Disagree	Neutral	Slightly Agree	Moderately Agree	Completely Agree
1	2	3	4	5	6	7

Display Elements

26. Using a scale ranging from "Detrimental (Hurts Performance)" to "Could Not Do IM Without", rate how useful you think each display element would be in order to gather information regarding how the IM process was proceeding (after all clearances and information had been entered).

	Detrimental (Hurts Performance)	Not Useful At All	Slightly Useful	Moderately Useful	Very Useful	Required for IM
PFD: IM Commanded End Speed (text)	1	2	3	4	5	6
PFD: IM speed bug	1	2	3	4	5	6
PFD: Speed change indicator (green box around speed)	1	2	3	4	5	6
PFD: IM modes displayed next to IM speed (RTA, IM, RVT, FNL)	1	2	3	4	5	6
ND: Visual representation of the target (lead) aircraft	1	2	3	4	5	6
ND: Off Scale depiction of target (lead) aircraft	1	2	3	4	5	6
ND: Visual representation of other traffic	1	2	3	4	5	6
ND: Callsign of target (lead) aircraft	1	2	3	4	5	6
ND: Altitude of target aircraft	1	2	3	4	5	6
MCDU: Spacing error (for aircraft 1 and aircraft 2)	1	2	3	4	5	6
MCDU: Lead aircraft final approach speed	1	2	3	4	5	6
MCDU: Lead aircraft assigned runway	1	2	3	4	5	6
EICAS message: IM DRAG REQD	1	2	3	4	5	6
EICAS message: IM SPD LIMITED	1	2	3	4	5	6
EICAS message: IM AC 1/AC 2 SPACING	1	2	3	4	5	6

27. Is there any information not listed above that you believe would be needed (or desirable) during IM operations into a busy terminal area, or was there any information that seemed to conflict with other displays or ATC instructions? If so, please explain:

28. Did the displays associated with the spacing tool provide you with adequate feedback about its operation (please consider awareness of the IM speed, the IM mode indicator, and whether you were able to crosscheck that the spacing tool was operating correctly). Was the feedback presented in an easy to understand manner and in a logical location?

Please circle the best answer:

- o The spacing tool presented too much feedback
- o The spacing tool presented adequate feedback in an easy to understand manner and in a logical location
- o The spacing tool provided adequate feedback, but either the location and/or the manner in which the feedback was presented, was undesirable
- o The spacing tool did not provide adequate feedback

If there are any display elements that are not in a desirable location or do not have a desirable format, please explain. Additionally, please include any suggestions you have for improving the IM displays.

29. Please select all of the following display elements that you desire to help direct your attention to the commanded speed when it changes. For example, if you want a flashing box and a chime, select both flashing box and chime; if you do not want any awareness displays that are listed, select none of the above:

Please check all that apply:

- ☐ A green box that appears around the commanded speed for 10 seconds after a speed change (like you had in the experiment you just completed)
- ☐ A flashing green box that appears around the commanded speed for 10 seconds after a speed change
- ☐ A chime that sounds when a new commanded speed is displayed to the crew
- ☐ Speed command on PFD without box or aural chime
- ☐ Other (please explain below)

Please use the space below to provide any alternative display elements you desire to assist you in detecting IM speed changes.

30. The conformance box is the green box that should have appeared on the ND during the last scenario. Respond to each of the statements shown below using a scale ranging from "1" (Completely Disagree) to "7" (Completely Agree). Circle one number in conjunction with each statement.

	Completely Disagree			Neutr al			Completely Disagree
The conformance box helped me monitor the interval management operation.	1	2	3	4	5	6	7
The conformance box helped me predict speed changes before they were given.	1	2	3	4	5	6	7
My level of comfort with the IM operation was increased as a result of the conformance box being present.	1	2	3	4	5	6	7
The level of safety associated with the IM operation is increased as a result of the conformance box being present.	1	2	3	4	5	6	7
I disobeyed the posted commanded speed on the PFD to try and center my aircraft in the conformance box.	1	2	3	4	5	6	7
The conformance box should be a part of a display for any aircraft conducting interval management operations.	1	2	3	4	5	6	7

31. Please describe in detail how you used the information provided by the conformance box and any decisions the conformance box helped you make.

Crew Coordination and Awareness

32. (DTS, IFD only) Do you think the division of tasks between the Pilot Flying (PF) and Pilot Monitoring (PM) was both desirable and fits within the current distribution of tasks between PF and PM?

YES ____

NO ____

If "no," what was wrong with the division, and how would you reallocate the tasks?

33. (DTS, IFD only) Did the use of CPDLC or the IM spacing tool change the way you and your crewmember communicated or coordinated activities?

YES ___

NO ___

If "yes," please elaborate:

34. The goal of this question is to better understand how you monitor the IM process. Please rate the frequency at which you observed the following areas in order to gather information regarding how the IM process was proceeding (after all clearances and information had been entered). Please rate the following areas using a scale from "Never" to "All The Time."

	Never	Slightly Often	Moderately Often	Very Often	All The Time
IM Information on the PFD	1	2	3	4	5
IM Information on the ND	1	2	3	4	5
IM Information on the MCDU	1	2	3	4	5
Information from ATC	1	2	3	4	5
Visual information available out the window (DTS, IFD only)	1	2	3	4	5
Verbal communication from your crew member (DTS, IFD only)	1	2	3	4	5

Functional Allocation

35. Please indicate where you believe a particular function is best performed, assuming the collaborative NextGen air traffic management system, aircraft equipage used in this experiment, and the Interval Management with Spacing (IM-S) procedure.

a) Optimization of aircraft route and altitude	AOC	ATC	Pilot	Aircraft automation
b) Establishing arrival sequence of aircraft	AOC	ATC	Pilot	Aircraft automation
c) Setting the spacing interval between aircraft	AOC	ATC	Pilot	Aircraft automation
d) Determining the speed to fly during an arrival to meet the sequence and spacing	AOC	ATC	Pilot	Aircraft automation
e) Setting the airspeed to fly during the arrival	AOC	ATC	Pilot	Aircraft automation
f) Responsibility for achieving spacing interval	AOC	ATC	Pilot	Aircraft automation
g) Responsibility for separation from the lead aircraft	AOC	ATC	Pilot	Aircraft automation

If desired, describe the reasoning behind your answers.

Additional Comments

36. Do you have any additional comments about the experiment?

Appendix F: Airspace, Arrivals, and Airport Charts

This Appendix contains the Dallas-Fort Worth (KDFW) airport diagram, Standard Terminal Arrival Procedures (STARs), and Standard Instrument Approach Procedures (SIAPs) used by the subject pilots during the Interval Management with Spacing to Parallel Dependent Runways (IMSPiDR) experiment. Not shown in this Appendix are the departures from KDFW and the STAR into the Dallas Love (KDAL) airport.

Figure 49 provides a general overview of all the arrival routes into the KDFW airport used during the IMSPiDR experiment. Every scenario had 41 arriving aircraft (33 to KDFW, 8 to KDAL), and of those, the 6 aircraft flown by subject pilots were always on the MASTY THREE, BONHAM FIVE, or CEDAR CREEK SIX Arrival. All aircraft on those three arrivals intercepted the ILS Runway 17C, and landed on runway 17 Center. The aircraft flown as Aircraft Simulation for Traffic Operations Research (ASTOR) stations used a software Pilot Model, and flew the BOWIE ONE Arrival and GLEN ROSE NINE Arrival to intercept the ILS to runway 18R and land on runway 18R.

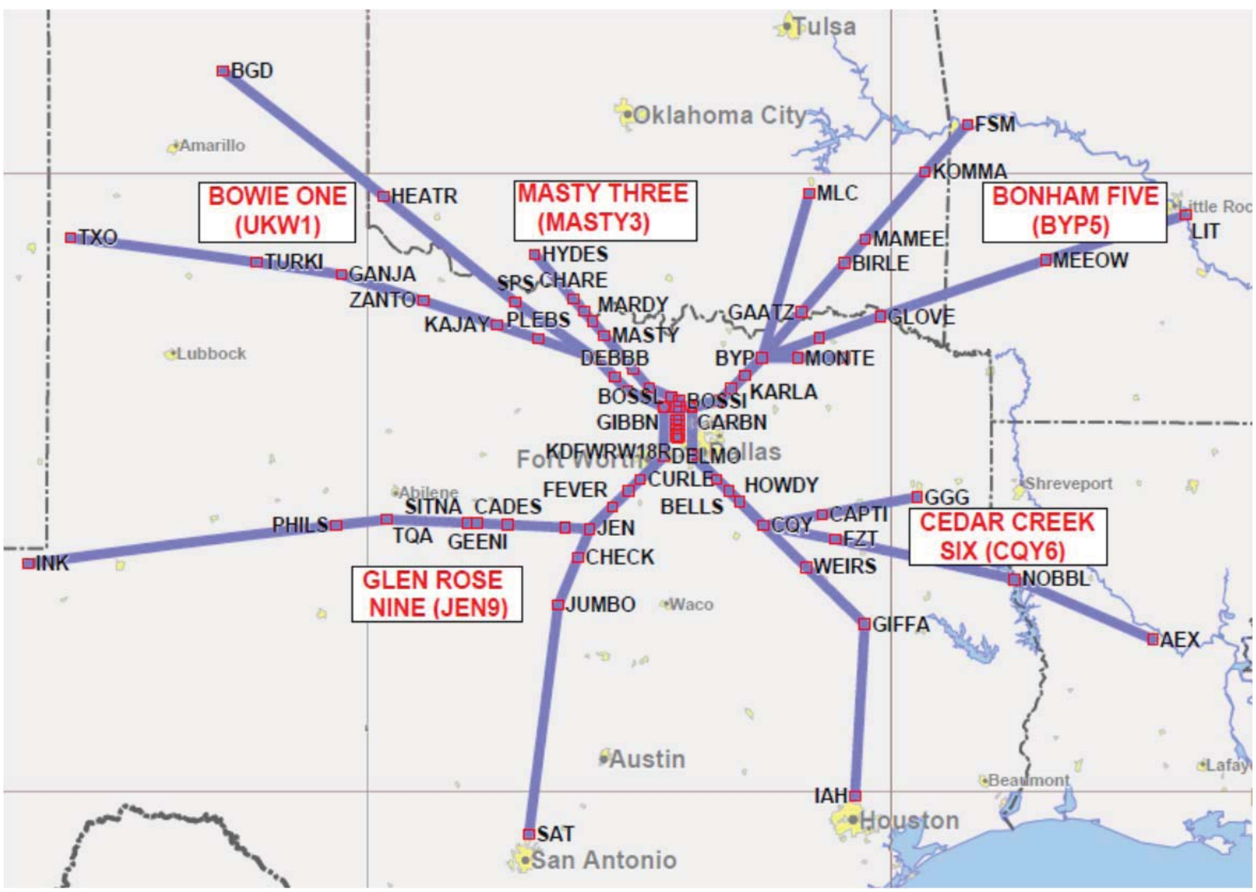


Figure 49. Arrival Routes into KDFW Airport

The next three figures show in clockwise sequence from the north the three Arrival procedures to runway 17C.

The MASTY THREE Arrival (Figure 50) is based on the current MASTY TWO Arrival to KDFW, which is normally only assigned by ATC when aircraft arriving from the northwest will land on the eastern runway (based on conversations with DFW TRACON controllers during the site visit). Modifications made for the IMSPiDR experiment include changing the crossing altitude and speed restriction at GREGS, removing waypoint GIBBI, adding waypoint BOSSL, and including waypoint BOSSI (an IF for the ILS 17C). Altitude and speed restrictions were also added for BOSSI, and BOSSL.

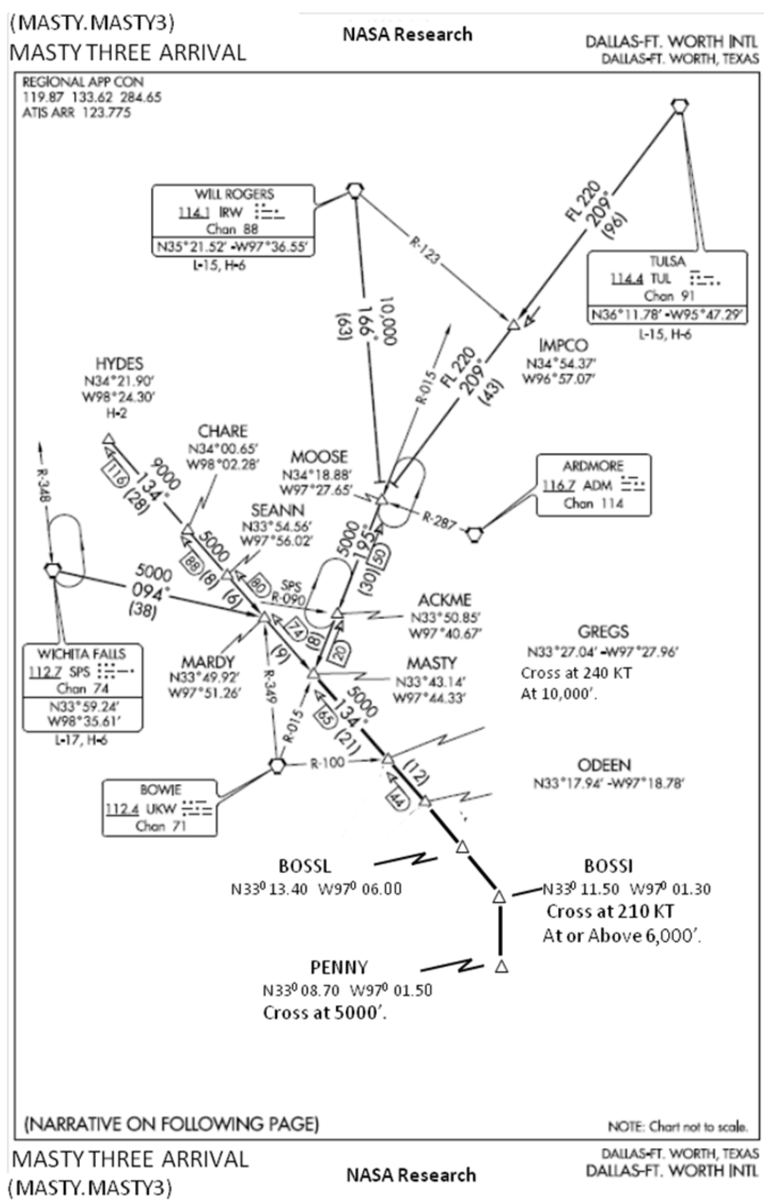


Figure 50. MASTY THREE Arrival (North)

The BONHAM FIVE Arrival (Figure 51) is based on the current arrival of the same name into KDFW. Modifications for the IMSPiDR experiment include changes to altitude and speed restrictions at COVIE and LEMYN, the removal of waypoints STONZ and DIRKK, the addition of waypoint CARBN (with altitude and speed constraints), and the inclusion of PENNY, an IF for the ILS 17C. Text was also added for aircraft landing south to "Expect ILS Runway 17C".

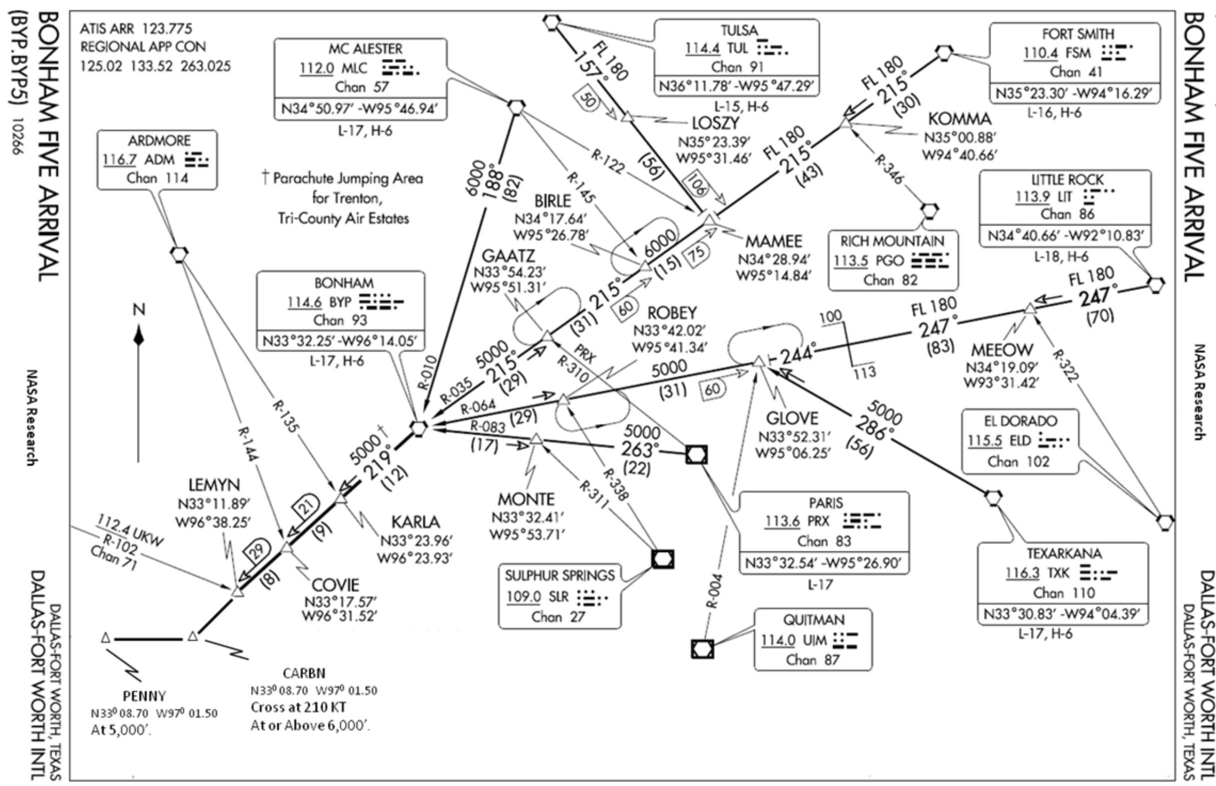


Figure 51. BONHAM FIVE Arrival (Northeast)

The CEDAR CREEK SIX Arrival (Figure 52) is based on the current arrival of the same name into KDFW. Modifications for the IMSPiDR experiment include moving the 11,000 ft altitude restriction from HOWDY to DIETZ, a 240 knot speed restriction at DIETZ, adding waypoint CARBN (and an altitude and speed constraint), and including PENNY (an IF for ILS 17C). Text was also added for aircraft landing south to "Expect ILS Runway 17C."

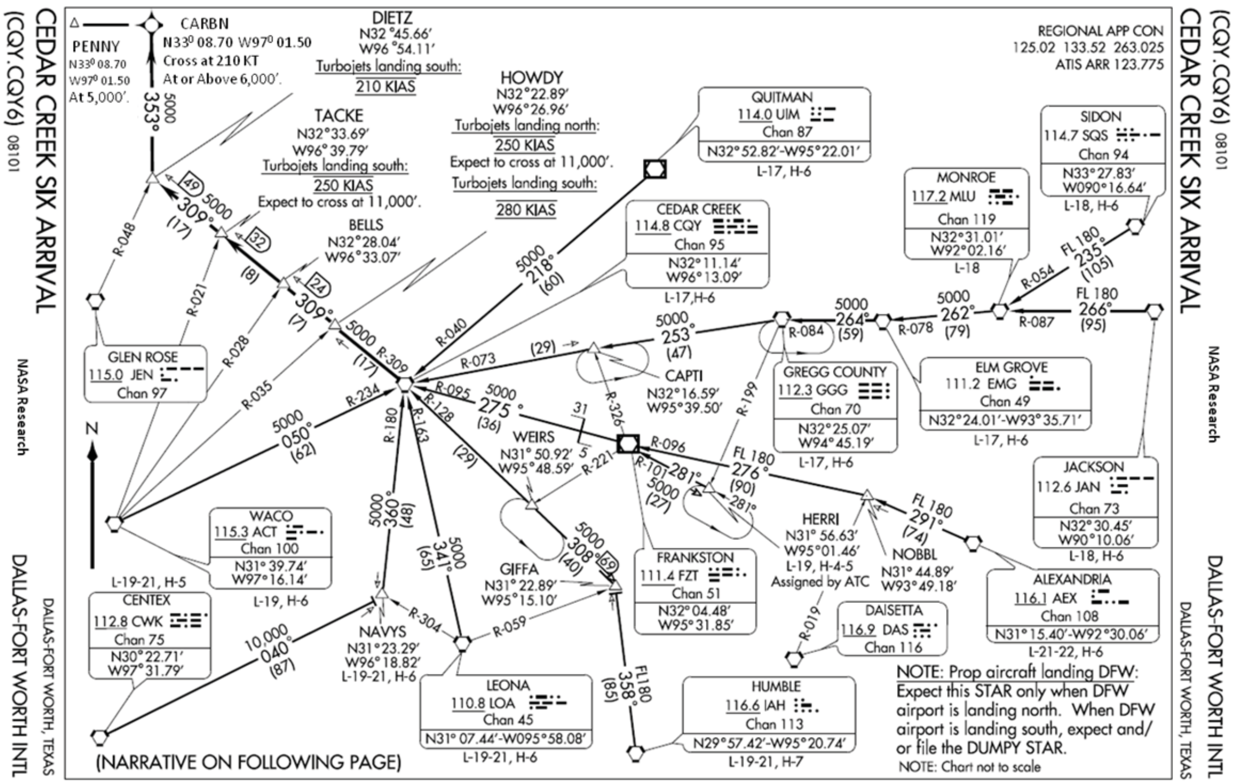


Figure 52. CEDAR CREEK Arrival (Southeast)

A version of the ILS Runway 17C from early 2011 was used during the IMSPiDR experiment (Figure 53). Just prior to the experiment, the final approach course and missed approach course were updated to 176^0, however there was not sufficient time to update all the simulator databases, therefore the previous early 2011 version was used (final heading of 174^0).

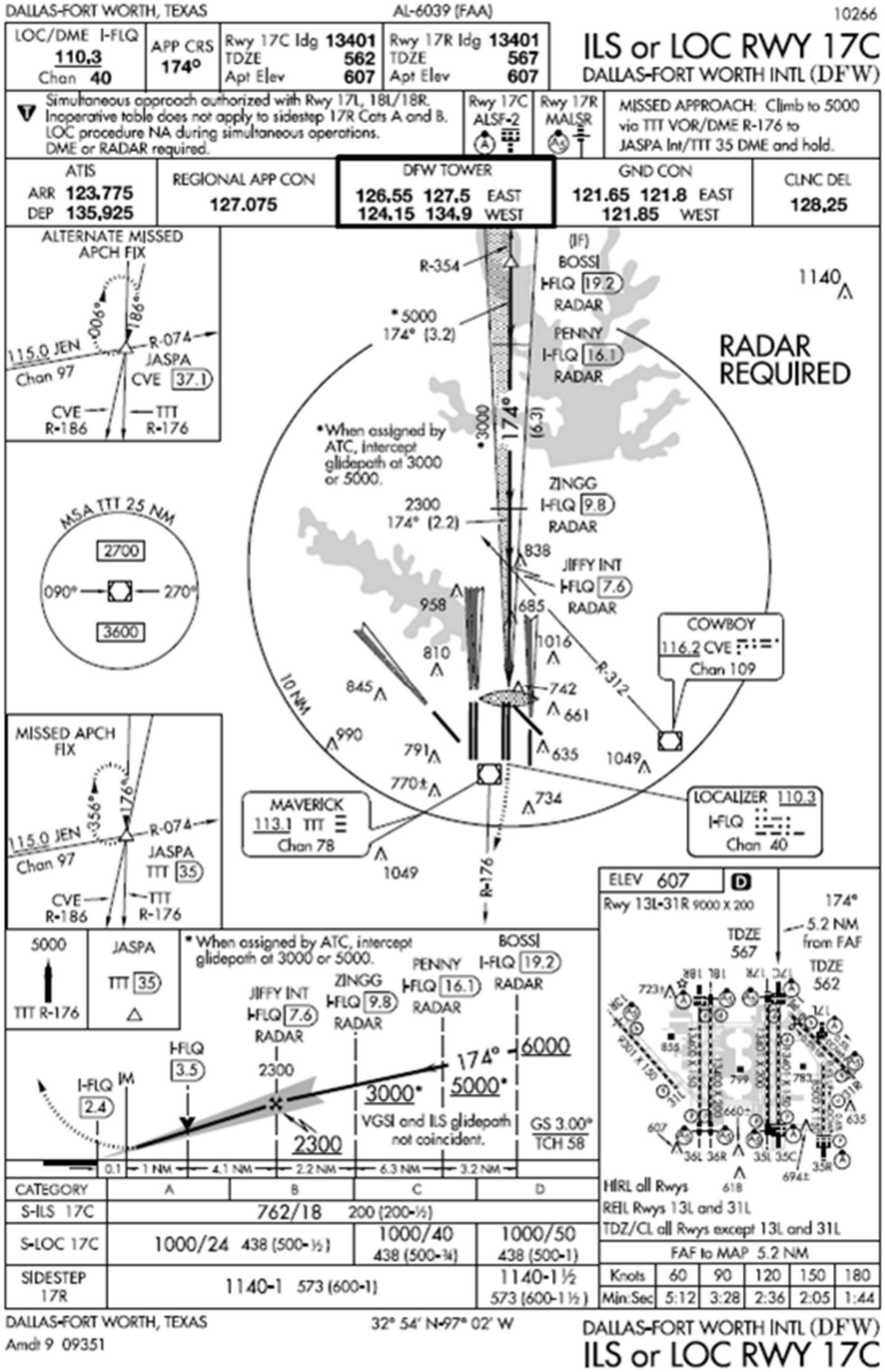


Figure 53. ILS Runway 17C

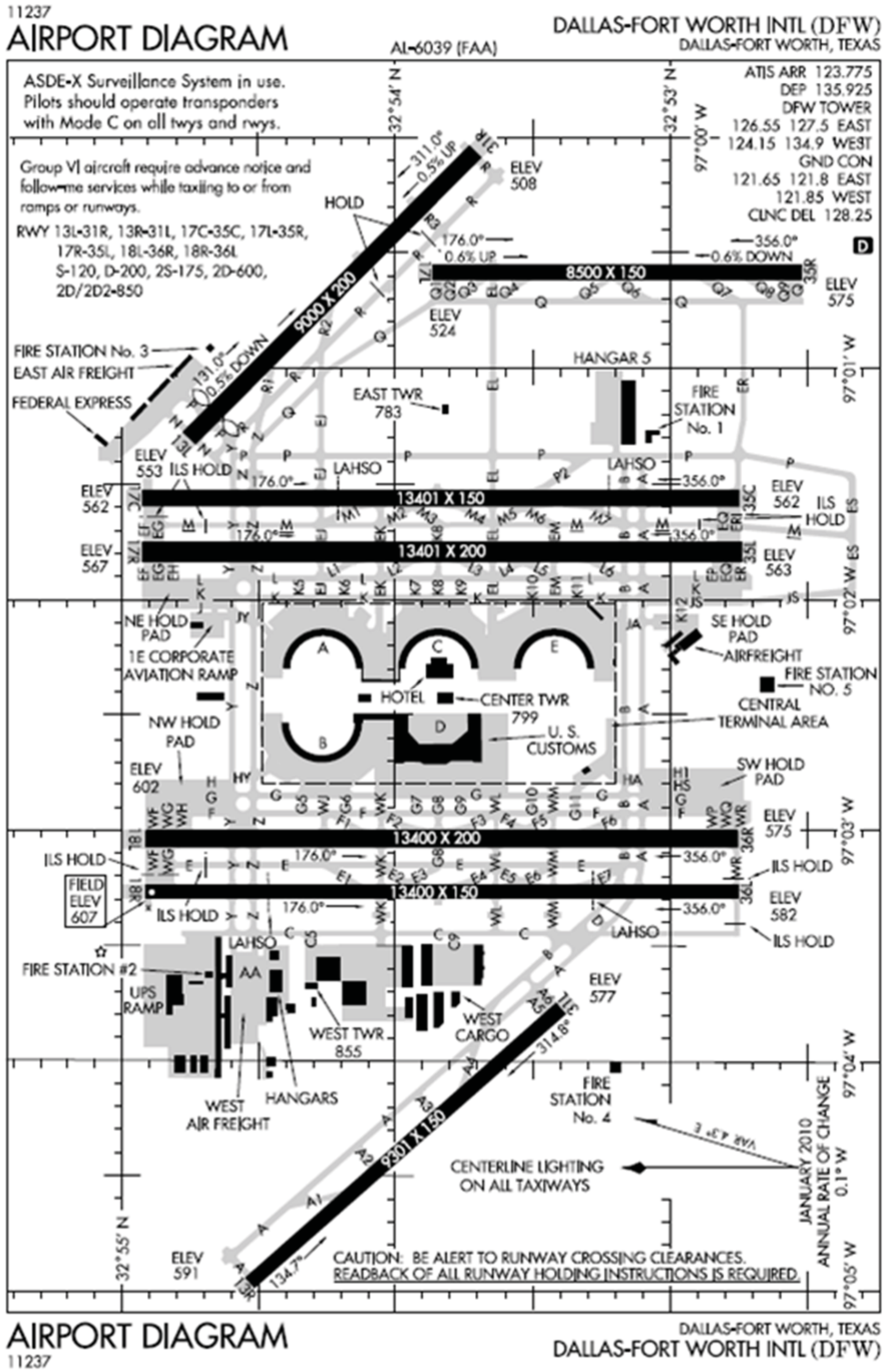


Figure 54. KDFW Airport Diagram

Appendix G: Pilot IM User Guide

This Pilot's IM User Guide is tailored for the IFD, with similar guides for the DTS and ASTOR (not included in this Appendix). Each subject pilot received the appropriate User Guide prior to arriving at LaRC based on their assigned simulator.

IM Users Guide (IFD)	2011 - 05

Revision 004, May 9, 2011

INTERVAL MANAGEMENT (IM)

BACKGROUND

Merging aircraft into a manageable sequence and controlling their spacing on final approach are essential to improving the productivity of the National Airspace System (NAS). Airport arrival capacities are governed by runway configurations, runway occupancy times, and wake turbulence separation requirements. ATC often adds buffers to in-trail arrival spacing due to the limitations of ground-based surveillance, the procedures used to communicate and confirm speed commands, as well as uncertainties about how instructions will be followed,. This leads to large variances in the actual arrival separation values. By increasing aircraft separation accuracy and precisely spacing aircraft over the runway threshold, the need for such buffers may be reduced. In turn, this would reduce the spacing variance, effectively increasing airport arrival capacity without lowering separation minima.

The arrival sequence into an airport can be set by the Airline Operations Center (AOC) and/or Air Traffic Control (ATC). Once the arrival sequence is determined, the time interval between landing aircraft can be adjusted to meet operational needs.

Interval management (IM) concepts were derived from development activities occurring within the FAA and the global aviation community. IM is designed to facilitate the needs of aircraft operators while at the same time provide Air Traffic Controllers with an easier way to manage the sequence and spacing of aircraft into any airport. This is done by providing the flight crew with automated speed guidance for their "Ownship" during IM operations. By following IM speed guidance, precise time intervals can be achieved between successive aircraft on approach.

IM employs a new onboard avionics system that provides speed guidance to the flight crew. This speed guidance is generated by the NASA LaRC Airborne Spacing for Terminal Arrival Routes (ASTAR) algorithm.

ASTAR uses relatively small speed changes to achieve the desired spacing interval by the runway threshold. This is done in a predictable and safe operation that allows the merging of multiple arrival streams and the delivery of aircraft to the runways within a 5 second window. For situations where multiple arrival routes are being flown to common or parallel runways, the IM speed guidance also ensures safe and accurate merging at the points where arrival routes converge.

Interval management operations and Optimized Profile Descent (OPD) are part of the FAA's Next Generation Air Transportation System (NextGen). Many of the NextGen applications will rely on the predictability of the aircraft's speed and vertical path for separation assurance. To ensure the predictability of vertical paths during IM operations, flight crews will be required to modulate thrust and drag to stay on both the IM speed profile and the OPD vertical path.

In this experiment, flight crews will fly a charted Optimized Profile Descent (OPD) to an ILS approach into Dallas Fort Worth (KDFW) airport while following IM speed guidance. In addition, IM avionics and the ASTAR algorithm will be accessed through the Multi-function Control Display Unit (MCDU).

Prior to performing the OPD and ILS approach flight crews will be assigned either one or two target aircraft to perform interval management with to include the required spacing in either time or distance. An optional RTA to the runway threshold may also be assigned. The IM system will command speed to meet the RTA at the runway until there is valid data on the target aircraft. At this time the IM commanded speed will achieve the required spacing from that aircraft at the runway threshold. The assigned spacing interval will meet wake vortex and instrument flight rules separation criteria. Information about the target aircraft and the precise time (or distance) interval to be achieved at the runway threshold are used by the ASTAR algorithm to generate IM speed guidance and is entered into the IM avionics via the MCDU either by loading from CPDLC or manual entry.

The merge to the same lateral path behind the target aircraft landing on the same runway may occur at altitude, during descent, or in the terminal area. The other target aircraft would be landing on a parallel runway. IM speed guidance is only given until Ownship reaches the Final Approach Fix (FAF). At this point the system will provide commanded speeds so that the aircraft is stabilized at final flap setting and approach speed at 1000 feet AGL. During IM operations, the separation between aircraft should never be less than the standard separation criteria used today. Air Traffic Control (ATC) is responsible for separation assurance.

UNDER LAYING TECHNOLOGIES

- **Automatic Dependent Surveillance – Broadcast (ADS-B)**

In commercial aviation the basic ADS-B signal is sent out from the aircraft using the same 1090MHZ frequency as the transponder. When a commercial aircraft is equipped with ADS-B the transponder is expected to send, among other things, the aircraft's registration number, altitude, squawk code and the aircraft's position. In most cases the aircraft's position data is likely to be based on the Global Positioning System (GPS). This basic data is referred to as the aircraft's "State Data". It is possible for the transponder to send more data and other ADS-B concepts are being developed to take advantage of an expanded ADS-B data set.

- **Automatic Dependent Surveillance – Rebroadcast (ADS-R)**

Non-commercial aircraft are expected to use a Universal Access Transceiver (UAT) data link to transmit their state data and ground stations will be used to receive data over the UAT data link and rebroadcast that information over the over 1090MHz data link used by commercial aircraft. This will enable aircraft equipped with a 1090MHz ADS-B receiver to receive data from aircraft transmitting using the UAT data link.

- **Traffic Information Services – Broadcast (TIS-B)**

Data concerning aircraft that are not equipped with either the UAT or 1090MHz transponder will be obtained using conventional radar. This radar data will be converted into ADS-B message sets and then transmitted from ground stations. Transmission of radar data over the ADS-B data link is known as Traffic Information Services – Broadcast (TIS-B). TIS-B will enable aircraft equipped with a 1090MHz ADS-B receiver to receive data concerning aircraft that are not equipped with an operable ADS-B or UAT.

- **Flight Information Services – Broadcast (FIS-B)**

Flight Information Services-Broadcast (FIS-B) is an automated, digital data link system. The system provides non-control, advisory information needed by pilots to operate more safely and efficiently in the

National Airspace System and in international airspace. FIS provides to pilots the necessary weather graphics and text, Special Use Airspace (SUA) information, Notices to Airmen (NOTAMs), and other information.

- **Cockpit Display of Traffic Information (CDTI)**

Regardless of its source, when data concerning the surrounding aircraft is displayed for pilots to use it is known as the Cockpit Display of Traffic Information or CDTI. CDTI can include the traffic's altitude, speed, direction of flight, and call sign.

- **ASTAR and IM Technologies**

IM uses ADS-B, CDTI and a unique algorithm developed at NASA's Langley Research Center known as Airborne Spacing for Terminal Arrival Routes (ASTAR). ASTAR uses 4-D trajectory modeling to compute speed guidance for the IM avionics that are used to achieve a precise time interval behind the more limiting of up to two target aircraft measured from when the aircraft cross the runway threshold. This speed guidance is based on data from the target aircraft which includes its current state (position, altitude and velocity) and its planned final approach speed. The ASTAR algorithm also considers "Ownship" (the subject-pilot-controlled simulated aircraft) configuration, stabilized approach criteria, wind profile, the planned arrival route, and planned final approach speed.

- **Air Traffic Operations Laboratory (ATOL)**

This portion of the experiment will be conducted in the Air Traffic Operations Laboratory (ATOL) at NASA's Langley Research Center. The ATOL is home to the Airspace and Traffic Operation Simulation (ATOS), a medium-fidelity, distributed simulation capability designed to explore future concepts in a rapid-prototyping environment. The ATOS system hosts twelve "Aircraft Simulation for Traffic Operations Research" (ASTOR) pilot workstations. Connected to the network are also the Integration Flight Deck (IFD) simulator and Development and Test Simulator (DTS). These fixed based cabs allow for the normal interaction of two pilots. The network also includes a simulation manager that controls time, events and simulation system modes.

- **Integration Flight Deck (IFD)**

The Integration Flight Deck (IFD) is 757-200 flight deck cab that can either be mounted on a 6 degree of freedom motion platform or used as a fixed based simulator. The IFD was the original simulator cab for NASA's 757 which was powered by Rolls-Royce RB211 engines. It was the place where NASA researchers could integrate their research project into a 757 flight deck. As a result the IFD has seen many modifications. It has a Panoramic 200°horizontal and 40° field-of-view and Heads Up Display on the Captain's side. The IFD 757 aircraft hardware is supplemented with a number of devices and displays and controls used to conduct NASA research.

- **Sequence of events**

The basic sequences of events are as follows:

1. The scenario begins at cruise altitude or on descent with autopilot and autothrottles engaged
2. The route, arrival and ILS are programmed into Route 1 of the FMC
3. The descent profile speeds of CRZ MACH/300 are programmed into the FMC descent page
4. Forecast Descent winds are programmed into the FMC for FL400, 10,000, 5,000 and 600 feet
5. The MCP altitude window is set to 2300 ft (You have already been cleared for the OPD arrival)
6. Both LNAV and VNAV PATH are active.
7. Crew will receive, load, verify, accept, and activate IM message for spacing.
8. Crew manually sets IM commanded speed in the MCP speed window
9. Crew maintains speed and ± 200 ft of VNAV profile altitude.
10. Arm approach mode between 6-2 miles of Final Approach Fix.
11. The aircraft must be fully configured and stabilized prior to 1,000 ft AGL
    Note: This is a high energy approach and configuring the aircraft in a timely fashion is essential.

IFD DISPLAYS

The Interval Management experiment will be conducted using the NASA LaRC Integrated Fixed Device (IFD) simulator. The IFD displays are shown here for content continuity purposes. See the Flight Manual Bulletin for instructions on how to operate the IFD.

IFD components include: aircraft and engine models; autopilot and autothrottle systems; Flight Management Computer (FMC) and Multi-function Control Display Unit (MCDU); Mode Control Panel (MCP); displays such as the Primary Flight Display (PFD), Navigation Display (ND), and Engine Indication and Crew Alerting System display (EICAS); and a sophisticated simulation model of ADS-B.

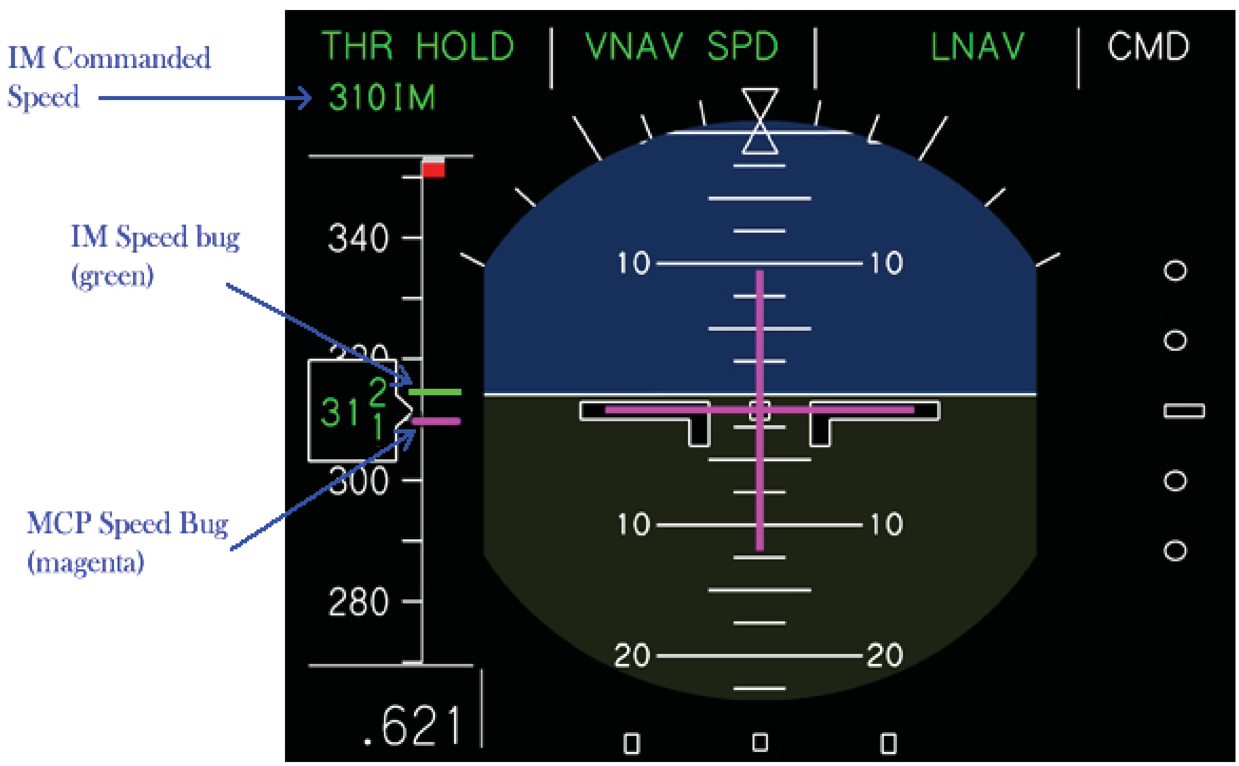
The key components for IM operations are the MCP, ND, PFD and the MCDU. As with many transport category aircraft in use today MCDU can be used to control many things such as the Flight Management Computer (FMC), the communications system or surrogate inputs from the Electronic Flight Instrumentation System, and Mode Control Panel. In addition to controlling the FMC, the ASTOR workstation also uses the MCDU to control the inputs for IM operations and initialize the ASTAR algorithm. The PFD is monitored for speed and configuration changes and the MCP is used to maneuver the aircraft.

- **Mode Control Panel (MCP)**

IM operation uses the Mode Control Panel to control the aircraft's vertical and lateral path. The IFD is operated in both LNAV and VNAV with the speed window open and the pilot manually setting the IM commanded speed.

- **Primary Flight Display (PFD)**

IM commanded speed indications are displayed on the IFD Primary Flight Display (PFD). When the MCP speed window is open with vnav engaged the mode will be VNAV SPD and the FMC will manage the aircraft speed to what is set in the MCP speed window. The crew will use speed brake and throttles as necessary to remain within ± 200 feet of the commanded vnav vertical path. The vnav mode will change to VNAV PATH with first flap extension. At this point the crew must control thrust and drag to manage the speed.



- **Navigation Display (ND)**

The Navigation Display of the IFD enables flight crews to monitor the relative position of proximate traffic, identify the target aircraft, and see how the aircraft is conforming to the IM clearance spacing. The VNAV indicator also provides the crew with feedback on how the aircraft is conforming to the optimized vertical profile.

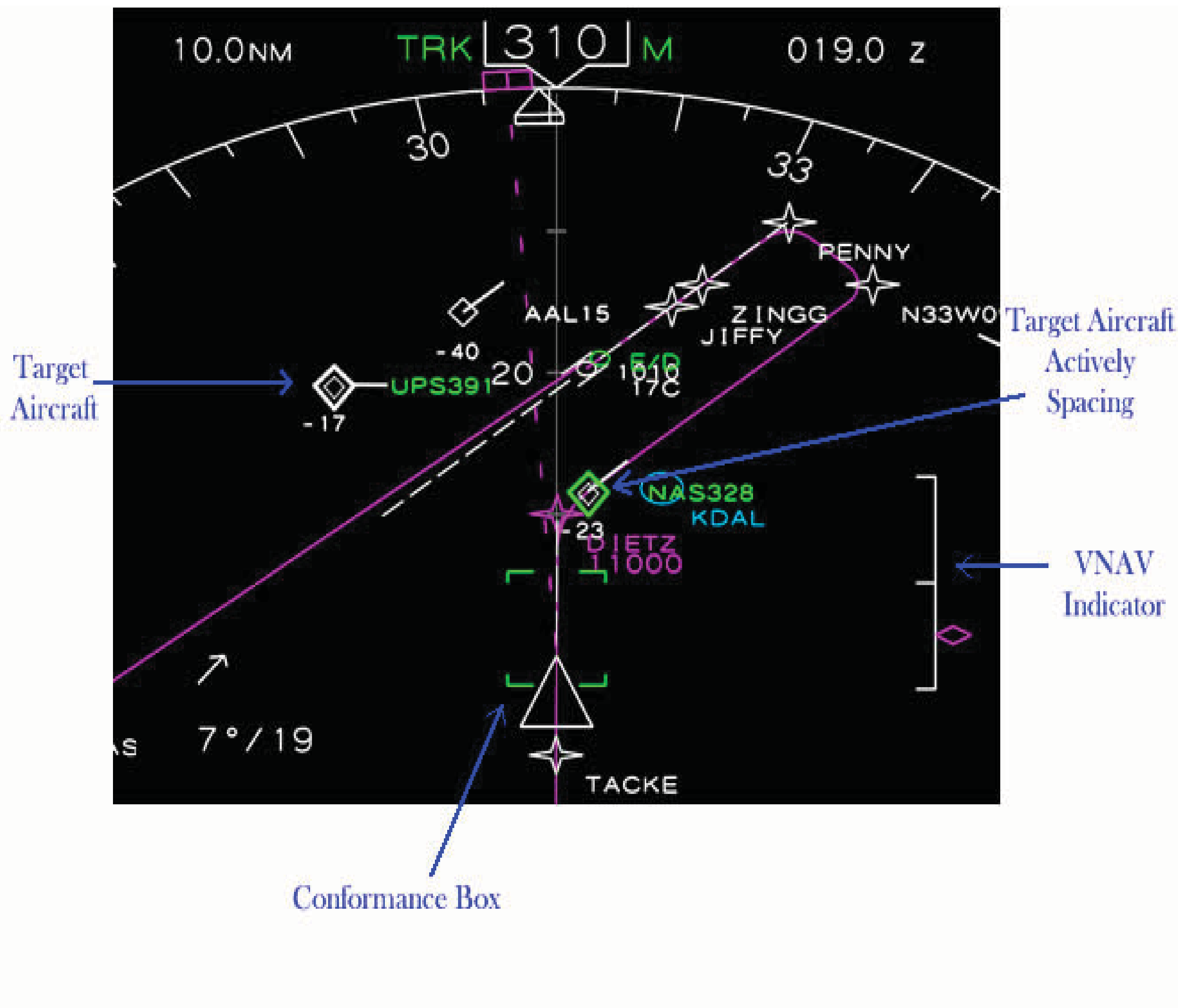
With IM in the RTA Mode
The conformance box may be shown on the ND while in RTA mode. The VNAV indicator will be present to advise the crew how the aircraft is performing with regards to the optimized vertical profile. Proximate traffic is shown for advisory purposes only.

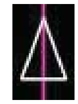
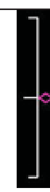
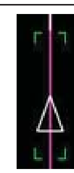
With IM in the Paired Mode

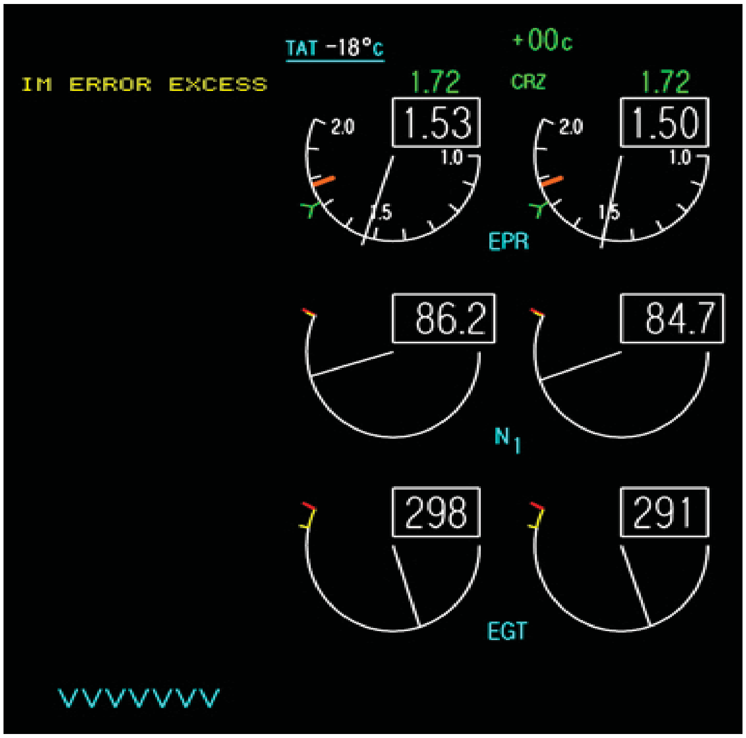
Target Aircraft will have an outer white diamond and an inner white diamond

Target Aircraft responsible for command IM speed will an outer green diamond and inner white diamond

Conformance box may be present to show conformance of IM spacing



ND Indications and Symbols	Meaning	Example
Ownship	The subject-pilot-controlled simulated aircraft	
IM Target Aircraft	When an aircraft is selected as a target aircraft, its icon on the Navigational Display is two white diamonds and its Call sign is displayed.	
IM Controlling Target Aircraft	A target aircraft that is responsible for the commanded IM speed. Its icon on the Navigation Display an outer green diamond and an inner white diamond.	
ADS-B Equipped Traffic	The altitude associated with traffic displayed on the ND can be displayed relative to own ship altitude or as the target's absolute altitude. The depicted traffic is shown as 1,300 feet above Ownship with a callsign of NAS328	
VNAV Indicator	Indicates how aircraft is conforming to vertical profile. Range is ±400 feet	
Conformance Box	Indicates how the aircraft is conforming to final interval position	



- **Engine Indication and Crew Alerting System display (EICAS)**

The Engine Indication and Crew Alerting System Display (EICAS) of the “Integrated Fixed Base (IFD) simulator enables flight crews to monitor for IM Caution, Advisory and Memo messages.

When multiple messages occur at the same time the messages are displayed in priority order of Caution, Advisory and Memo.

A table of EICAS messages and pilot actions are provided at the end of this guide.

- **Multi-function Control Display Unit (MCDU)**

The Multi-function Control Display Unit (MCDU) of the IFD enables flight crews to interact with the Flight Management Computer (FMC) and the IM avionics. IM functions are accessed through the IM button.

The FMC and IM avionics are separate pieces of equipment and as a result they have separate and distinct indications.

CAUTION:

The FMC controls the indications for LNAV and VNAV PATH for the Optimized Profile Descent (OPD) and the ASTAR Algorithm controls the indications for the Interval Management (IM) speed guidance. As a result, it is possible to be on the LNAV and VNAV PATH and off of the IM Profile.

SYSTEM DESCRIPTION

IM spacing will commence when you receive a CPDLC IM clearance from ATC. This clearance will contain the target aircraft call sign and interval value ATC desires you to achieve. This clearance may assign you one or two aircraft for spacing. The clearance may also contain an RTA to the runway threshold. You are to fly commanded speeds to meet this RTA until you are paired with at least one of your assigned target aircraft. At this time, the IM system will command a speed to meet the target aircraft interval. If there are two target aircraft, the IM system will command the speed to meet the most restrictive interval. If there is no RTA assigned in your clearance, ATC assumes that your distance to the target aircraft is within range to be paired immediately with that aircraft. Once paired to a target aircraft, the ownship speed is compared to the information known about the target aircraft and IM speed guidance is generated that will achieve the assigned spacing interval when the aircraft cross the runway threshold. At airports saturated with arrival aircraft, the greatest capacity benefits may be realized by having sequences of aircraft operating in Paired mode, with each aircraft actively spacing off the aircraft sequenced ahead of it.

Speed guidance is controlled through the MCDU and presented to the flight crew on the PFD. The IM commanded speed on the PFD will have RTA, IM, FNL, or RVT beside it to identify what is actually controlling the speed. Although IM speed guidance can be followed using manual throttle input, this experiment requires the use of the auto throttle system. The use of the auto throttle system reduces pilot workload and allows precise spacing intervals to be established. The commanded IM speed will be set manually in the MCP speed window by the pilot.

After crossing the FAF, IM Speed guidance will automatically transition to a final mode and will display a final speed which is equal to the target speed entered into the MCDU. Final mode is not pilot-selectable.

- **Mode Changes**

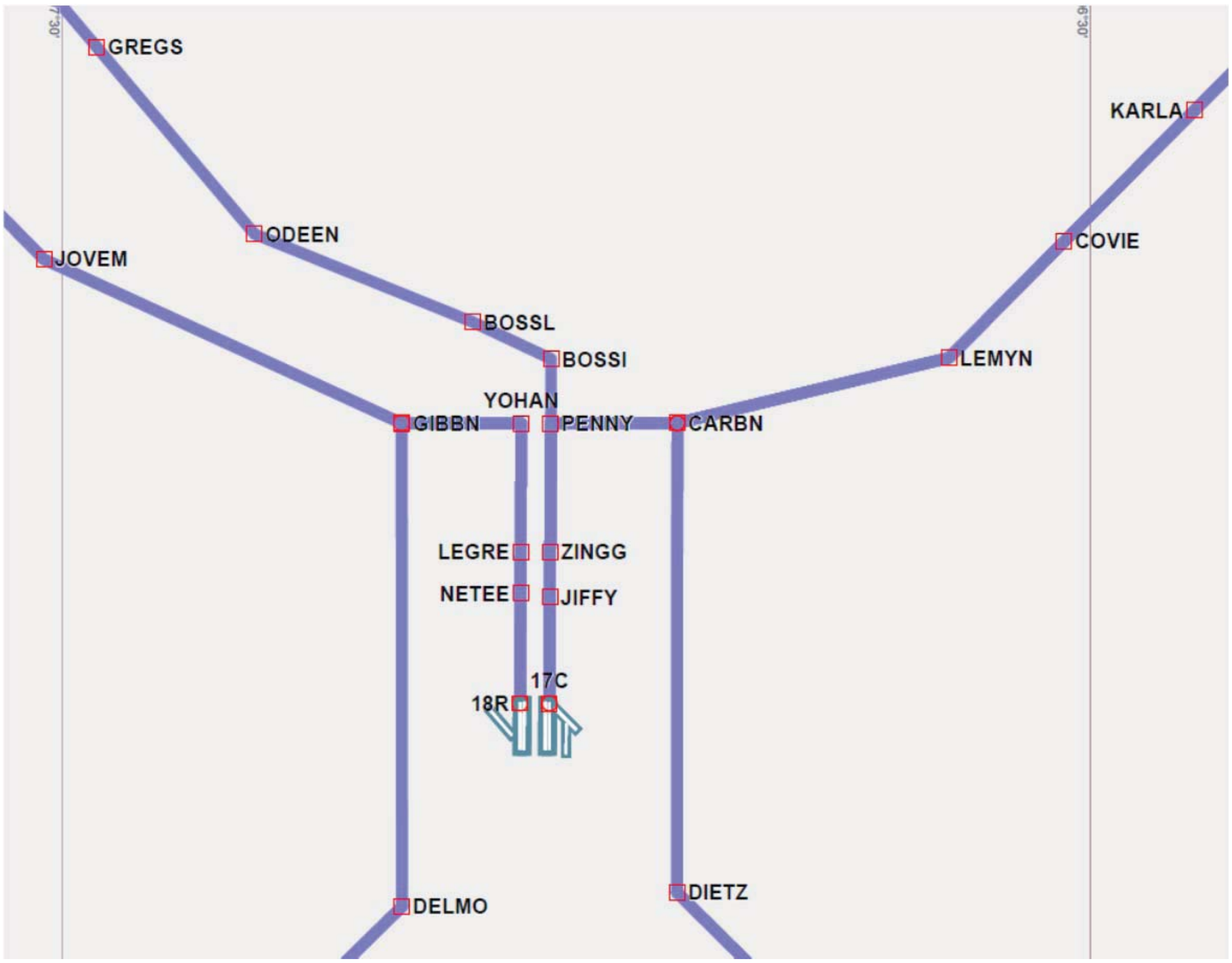
Consistent with standard flight guidance mode symbology, all Interval Management speed changes are annunciated with a green box around the commanded IM speed. The green box is displayed for 10 seconds after the mode change.

- **Speed Constraints**

The ASTAR Spacing guidance logic contains several safeguards to ensure that appropriate speed guidance is being generated. First, all Paired mode IM guidance is limited to ±10% of the Profile mode speeds. Second, all speed guidance is bounded by the aircraft flight envelope.

DETAILED PROCEDURES

This IM experiment begins at or near the Terminal area of Dallas Fort Worth Airport (KDFW). Your Optimized Profile Descent (OPD) arrival clearance will have been dynamically sent via CPDLC to your aircraft prior to Top of Descent Point. It contains required waypoints and restrictions as well as the approach you will fly. This information will already be loaded into your FMC. You have already been cleared for the OPD arrival so 2300 feet is set in your MCP altitude window.



1. The scenario begins at cruise altitude with autopilot and autothrottles engaged. LNAV and VNAV PATH will be active.
2. The route, arrival and ILS are programmed into Route 1 of the FMC
    - NOTE: ASTAR speed guidance accounts for the charted speeds on the STAR. When IM is active fly the IM guidance speeds.
3. The descent profile speeds of CRZ MACH/300 are programmed into the FMC descent page.
4. Forecast Descent winds have been programmed into the FMC for FL4000, 10,000, 5,000 and 600 feet.
5. Crew will receive a message from ATC for IM operations. (notified by ATC prompt on EICAS)

6. Crew loads IM Pages from CPDLC

Pilot Flying

Pilot Monitoring

- (PF) Press IM key on MCDU
- (PM) Press FMC/COMM key on MCDU
- (PM) Press LOAD [6L] button on MCDU

7. Verify Interval Management Clearance

- Compare IM Pages (PF) to CPDLC clearance (PM)
  - IM-S Page
    - [1L] RTA Waypoint is correct (if applicable)
    - [1R] RTA time value is correct (if applicable)
    - [2L] IM-S speed is acceptable to pilot
  - ACFT1 Page (select by pressing [4L] or NEXT PAGE button)
    - [1L] Aircraft1 Call sign is correct
    - [1R] Achieve By waypoint is correct
    - [2L] The type of spacing (Precision or NCT) is correct
    - [2R] Terminate AT waypoint is correct
    - [3L] IM-S Goal is correct
    - [3R] Aircraft1 Approach Speed is correct
    - [4L,5L] Aircraft1 routing is correct
  - ACFT2 Page (select by pressing [6L][4R] or NEXT PAGE button)
    - Verify information same procedure as ACFT1

8. Accept or Reject Interval Management Clearance

Pilot Flying

Pilot Monitoring

- Check acceptability of clearance
  - (PF) Press ACTIVATE [6R]
  - Check that there is no UNABLE IM message [3L]
  - Is the commanded speed acceptable [2L]

- If Clearance is acceptable
  - (PM) Click ACCEPT on CPDLC ATC UPLINK page [5R] (last page)
  - (PF) Activate IM Guidance
    - Press EXEC Key
    - Observe appearance of FIM Speed cue above speed tape on PFD
    - Open speed window on MCP and set FIM commanded speed
  - (PM) Inform ATC when paired with each aircraft

- If Clearance is not Acceptable
  - (PM) Press REJECT button on MCDU [5L]
  - (PF) Erase IM Guidance
    - Press ERASE [6L]

9. Amendment to IM Clearance Procedures

- CPDLC Clearance

▪ CPDLC Clearance with a second aircraft or change in spacing requirements
  - Press IM Key
  - On IM-S Page press TERMINATE [6R] button then EXEC key
  - Follow Procedures for original clearance to load, verify, and accept

- VOICE Clearance

▪ Voice Clearance for change in spacing requirements

"NASA 234 you are now cleared IM spacing 140 seconds with NASA1"

  - Press IM button on MCDU
  - Press aircraft call sign [4L][4R] of affected aircraft
  - Enter new spacing information ("s" for seconds, "m" or "nm" for miles) [3L]
  - Accept clearance by voice with ATC
  - Press EXEC Key
  - Confirm Airspeed is acceptable (if not notify ATC)

10. Arrival Interval Management Procedures

- (PF, PM) Airspeed Requirements
  - Observe and announce IM Speed changes on PFD
  - Set IM commanded speed in speed window on MCP
  - Configure aircraft as necessary to maintain IM commanded speed
  - Airspeed is safe and acceptable to the pilot for current conditions (See non normal below for action)

- (PF, PM) Vertical Path Requirements
  - Verify VNAV SPD is active mode
  - Ensure aircraft starts a descent at Top of Descent (TOD) Point
  - Use drag devices and thrust as necessary to maintain VNAV path within ±200 feet
  - Monitor that aircraft stays on path and all restrictions will be met

- (PF, PM) Spacing Requirements
  - Aircraft stays in conformance box (if present)
  - No EICAS or status messages (See non normal below for action)

11. Final Segment Interval Management Procedures

- (PF, PM) Configuration and Energy Management
    - Extend Flaps prior to Min Flap maneuvering airspeed but no earlier than placard-5 knots
    - Maintain least amount of flaps required to maintain IM speed
    - When IM Commanded speed transitions to FNL mode
        - Gear down
        - Flaps 20
        - Target Speed set in MCP Window
        - Configure as necessary to be stable by 1000 feet AGL

- Automation Procedures
    - Aircraft will transition to VNAV PATH when flaps are extended
    - Arm approach mode between 6-2 miles prior to FAF
    - Ensure aircraft will capture both the localizer and glideslope
    - Set Target Speed in MCP speed window when IM commanded speed transitions to FNL

ALERTS: CAUTIONS, ADVISORY AND MEMOS

The IM system and its associated ASTAR algorithm have the following alerts:

Alert Level	EICAS Message	Meaning	Pilot Action
Caution	IM DISENGAGED	Loss of ownship flight path data, failure of the interface between the spacing algorithm and the aircraft avionics, ADS-B receiver failure, or other aircraft avionic failures	• Execute Terminate Spacing Procedure
Caution	IM AC 1 OFF PATH IM AC 2 OFF PATH	Target aircraft is not on the flight path given by the ATC IM clearance	• Execute Terminate Spacing Procedure • ATC may issue new clearance
Caution	IM AC 1 ADSB LOST IM AC 2 ADSB LOST	Target aircraft ADS-B information is lost	• Execute Terminate Spacing Procedure
Caution	IM ERROR EXCESS	IM spacing software determines it is not possible to meet the assigned RTA or spacing interval	• Execute Terminate Spacing Procedure • ATC may issue new clearance
Advisory	IM OWN BAD PATH	Flight path provided by aircraft avionics to the spacing algorithm is invalid or not available prior to beginning IM operations	• Flight crew verifies correct IM information
Advisory	IM OWN OFF PATH	Aircraft is greater than 2.5 nmi laterally, 6000 ft vertically, or 90 degrees of heading from the planned flight path	• Flight crew corrects to path, or updates FMS to reflect current flight path
Advisory	IM AC 1 BAD PATH IM AC 2 BAD PATH	IM spacing software has no path or an invalid flight path for that particular reference aircraft	• Flight crew verifies correct IM information
Memo	IM DRAG REQUIRED	IM spacing software determines drag is required	• Ensure thrust levers at IDLE • Deploy spoilers to return to flight path and commanded speed
Memo	IM SPEED LIMITED	Speed is constrained by profile, Mmo, Vmo	• Advisory only, no action required
Memo	IM AC 1 SPACING IM AC 2 SPACING	IM has valid data to calculate spacing	• Flight crew notifies ATC

TERMINATE SPACING PROCEDURE

Terminate due to crew preference, ATC instruction, or EICAS message. ATC issues an entire IM clearance; therefore the flight crew terminates the entire IM clearance. That is, neither ATC nor the crew can selectively cancel one of the two aircraft in a two reference aircraft IM clearance.

1) Flight crew notifies ATC they are terminating the IM clearance (time permitting, respond in same mode)
2) Flight crew flies the last IM speed (shown on the PFD with RVT) until receiving further instructions from ATC
3) (PM) Once new clearance is received from ATC pilots will terminate current IM Operation
    a. Press IM Key on MCDU
    b. ON IM-S Page press TERMINATE [6R]
    c. Press EXEC button on MCDU
4) Reload new IM clearance if available

Appendix H: Training Profiles

H.1 Basic Simulator Familiarization Training Profile

<u>Basic Simulator and Aircraft Operations</u>

- Engage LNAV & VNAV
- Change ND range scale
- MCP Speed Window:
  - VNAV PTH to VNAV SPD: open window, change speed in speed window
  - Re-engage VNAV PTH, window closes (NOTE: resolves software defect if needed)
- MCP Heading Window:
  - change setting, then SEL
  - change back to course, then LNAV PTH
- MCP Altitude Window: set to 5000 ft, then 2300 ft, then 5000 ft
  - When 5000 ft set (after sim in OPERATE), impact of not setting (aircraft flies past T/D)
- LOC and APP to be discussed during arrival phase
- PFD and ND displays (speed tape on IFD is not standard for B-757)
- MDCU:
  - Normally set by researcher between runs, however crew to check route, constraints, etc
  - LEGS, NEXT PAGE
  - PROG page
  - IM, NEXT PAGE
  - Scratch page, enter “90” into time interval
  - DESCEND NOW (IFD only)
- Radio control panel:
  - VHF L for ATC, VHF R for ATIS
    - must transmit on VHF L in IFD and DTS
  - Change frequencies (STNDBY to ACTIVE)
  - Set new frequency (load new STNDBY, then change to ACTIVE)
  - Listen to single or multiple radios
  - Microphone switch:
    - click on MIC, watch for stuck mic (ATOL)
    - two locations (IFD, DTS)
- ND control panel: ADS-B setting (Normal, Above, Below, All)
- EICAS page:
  - ENG is normal setting

- COMM for CPDLC messages (ATOL only)
  - CNCL/RECALL buttons
- Throttle, speed brake, flaps, gear:
  - Fly IM speed (within 5 knots), or data link clearance speed if no IM
  - ATOL, DTS: use of throttle and speed brake while in VNAV PTH
  - IFD: use of throttle and speed brake while in VNAV SPD
  - Flap and gear deployment to be discussed during arrival phase
- Display control panel / Simulation status panel
  - Do not change simulator until in OPERATE or directed by researcher
- Event button: location, when to use
- Review:
  - STAR (frequencies, altitude and speed constraints)
  - ILS17C(frequencies, altitude and speed constraints)
  - Aircraft Checklist (IFD and DTS only)
- Scenario admin:
  - Scenario card provides callsign, location, route
  - "Going to operate"
  - Scenario terminates: at 35 ft AGL (ATOL) or < 5 knots GS (IFD, DTS)
  - Decisions/pacing as if in operational environment

<u>CPDLC message receive and respond</u>

- Press COM button on the Display Select Panel
- Click LOAD IM-S icon on ATC UPLINK Page to load clearance into IM pages
- Press IM button on MCDU
- Verify correct data load on IM pages (refer to Pilot Procedures – ATC IM Clearance)
- ON IM-S Page press Activate [6R]
- Check that there is no EICAS cautions and speed [2L] is acceptable
- EXIT INFO on EICAS page
- Click ACCEPT on CPDLC ATC UPLINK page
  - Click CANCEL icon on ATC UPLINK Page (if applicable to clear bottom banner)
  - Click ACCEPT icon on ATC UPLINK PAGE
- Press EXEC Key (activates IM Guidance)
- Observe appearance of IM speed cue on PFD
  - Box around speed for first 10 seconds of new speed
  - Box around type of spacing for first 10 seconds, such as RTA, IM (will see in T2)
- Observe FMS Speed matches IM commanded speed on PFD
- Observe IM speed changes on PFD
- Use Thrust and Drag devices to maintain ±5 knots of IM commanded speed bug

- IM Contingency: Contact ATC
  - If RVT on PFD (triggered by EICAS message of: BAD PATH, OFF PATH)

<u>Arrival and Approach Procedures</u>

- Configure aircraft as necessary to maintain IM speed
- Configuration and Energy Management
  - Extend Flaps prior to Min Flap maneuvering airspeed but no earlier than placard-5 knots
  - Maintain least amount of flaps required to maintain IM speed
  - When IM Commanded speed transitions to FNL mode
    - Gear down
    - Flaps 20
    - Target Speed set in MCP Window
    - Configure as necessary to be stable by 1000 feet AGL

- Automation Procedures
  - Arm approach mode between 6-2 miles prior to FAF
  - Ensure aircraft will capture both the localizer and glideslope
  - Speed Window opens at glideslope capture
    - Manually set IM speed in MCP speed window
  - Set Target Speed in MCP speed window when IM commanded speed transitions to FNL

H.2 Interval Management Training Profile

<u>Start of flight</u>

- LNAV and VNAV PTH engaged
- MCP Altitude Window set to 5000 feet

<u>First IM Message (single Target aircraft)</u>

- (PM) Press ATC button on MCDU
- (PM) Press LOAD [6L] on MCDU to load clearance into IM pages
- (PF) Press IM button on MCDU
- (PF,PM) Verify correct data load on IM pages (refer to Pilot Procedures – ATC IM Clearance)
- (PF) ON IM-S Page press Activate [6R]
- (PF, PM) Check that there is no EICAS cautions and speed [2L] is acceptable
- (PM) Click ACCEPT [5R] on CPDLC ATC UPLINK Page (last page)
- (PF) Press EXEC Key (activates IM Guidance)

- (PF, PM) Observe appearance of IM speed cue on PFD
- Open MCP Speed Window and set IM commanded speed
- (PM) Observe EICAS Advisory of Spacing with AC 1
- (PM) Press IM button on MCDU
- (PM) On IM-S Page observe callsign of AC 1
- (PM) Inform ATC by voice that you are spacing off of {state callsign}
- (PF,PM) Observe and announce IM speed changes on PFD
- (PF,PM) Set IM Commanded speed in speed window on MCP
- (PF) Use Thrust and Drag devices to maintain ±200 feet of vertical profile

Second IM Message (two Target aircraft)

- (PM) Press IM key on MCDU (refer to Pilot Procedures – Amendment to IM Clearance)
- (PM) On IM-S Page press TERMINATE button[6R]
- (PM) Press EXEC key on MCDU (this will terminate ongoing IM operations)
- (PF, PM) Load, verify, accept, and execute new clearance as stated above
- (PM) Observe EICAS Advisory of Spacing with AC 1 and AC 2
- (PM) Press IM button on MCDU
- (PM) On IM-S Page observe callsigns of AC 1 and AC 2
- (PM) Inform ATC by voice that you are spacing off of {state callsigns}
- Follow speed guidance as stated above

Arrival and Approach Procedures

- Configure aircraft as necessary to maintain IM speed
- (PF, PM) Configuration and Energy Management
  - Extend Flaps prior to Min Flap maneuvering airspeed but no earlier than placard-5 knots
  - Maintain least amount of flaps required to maintain IM speed
  - When IM Commanded speed transitions to FNL mode
    - Gear down
    - Flaps 20
    - Target Speed set in MCP Window
    - Configure as necessary to be stable by 1000 feet AGL

- Automation Procedures
  - Aircraft will transition to VNAV PATH when flaps are extended
  - Arm approach mode between 6-2 miles prior to FAF
  - Ensure aircraft will capture both the localizer and glideslope
  - Set Target Speed in MCP speed window when IM commanded speed transitions to FNL

H.3 Interval Management Pilot Procedures (specific to IFD)

En route

- Fly published procedure and Econ airspeed
- Ensure LNAV and VNAV PATH are engaged
- Ensure airspeed window on MCP is closed
- Ensure 5000 ft set in MCP altitude window for OPD arrival

Receive ATC Spacing Clearance

- (PF, PM) Observe ATC prompt on EICAS
- (PM) Press FMC COMM button on MCDU
- (PM) Press LOAD [6L] on MCDU to load clearance into IM pages
- (PF) Press IM button on MCDU

Verify accuracy and acceptability of ATC Spacing Clearance

- (PF,PM) Verify correct data load on IM pages (compare IM Pages on PF MCDU to CPDLC message on PM MCDU)
  - IM-S Page
    - [1L] RTA Waypoint is correct (if applicable)
    - [1R] RTA time value is correct (if applicable)
    - [2L] IM-S speed is acceptable to pilot
  - ACFT1 Page (select by pressing [4L] or NEXT PAGE button)
    - [1L] Aircraft1 Call sign is correct
    - [1R] Achieve By waypoint is correct
    - [2L] The type of spacing (Precision or NCT) is correct
    - [2R] Terminate AT waypoint is correct
    - [3L] IM Goal is correct
    - [3R] Aircraft1 Approach Speed is correct
    - [4L,5L] Aircraft1 routing is correct
  - ACFT2 Page (select by pressing [6L][4R] or NEXT PAGE button)
    - Verify same as ACFT1

Acceptance or Rejection of Clearance

- Check acceptability of clearance
  - (PF) Press ACTIVATE [6R]
  - Check that there is no UNABLE IM message [3L]
  - Is the commanded speed acceptable [2L]
- If Clearance is acceptable
  - (PM) Click ACCEPT [5R] on CPDLC ATC UPLINK page (last page)

- (PF) Activate IM Guidance
  - Press EXEC Key
  - Observe appearance of IM Speed cue above speed tape on PFD
  - Open speed window on MCP and set IM commanded speed
- (PM) Inform ATC when paired with each aircraft

- If Clearance is not Acceptable
  - (PM) Click REJECT button on MCDU [5L] on CPDLC ATC UPLINK page (last page)
  - (PF) Erase IM Guidance
    - Press ERASE ALL [6L]

<u>Amendment to IM Clearance Procedures</u>

- (PM) CPDLC Clearance with a second aircraft or change in spacing requirements
  - Press IM key on MCDU page
  - Press TERMINATE [6R] on IM-S page
  - Press EXEC on MCDU
  - Follow Procedures for original clearance to load, verify, and accept

- (PM) Voice Clearance for change in spacing requirements
  - Press IM button on MCDU
  - Press aircraft call sign [4L][4R] of affected aircraft
  - Enter new spacing information (time, distance, type) [2L][3L]
  - Press EXEC Key

<u>Arrival IM Procedures</u>

- (PF, PM) Airspeed Requirements
  - Observe and announce IM Speed changes on PFD
  - Set IM commanded speed in speed window on MCP
  - Configure aircraft as necessary to maintain IM commanded speed
  - Airspeed is safe and acceptable to the pilot for current conditions (See non normal below for action)

- (PF, PM) Vertical Path Requirements
  - Verify VNAV SPD is active mode
  - Ensure aircraft starts a descent at Top of Descent (TOD) Point
  - Use drag and thrust as necessary to maintain VNAV path within ±200 feet
  - Monitor that aircraft stays on path and all restrictions will be met

- (PF, PM) Spacing Requirements
  - Aircraft stays in conformance box (if present)

    - No EICAS or status messages (See non normal below for action)

Final Segment IM Procedures

- (PF, PM) Configuration and Energy Management
    - Extend Flaps prior to Min Flap maneuvering airspeed but no earlier than placard-5 knots
    - Maintain least amount of flaps required to maintain IM speed
    - When IM Commanded speed transitions to FNL mode
        - Gear down
        - Flaps 20
        - Target Speed set in MCP Window
        - Configure as necessary to be stable by 1000 feet AGL

- Automation Procedures
    - Aircraft will transition to VNAV PATH when flaps are extended
    - Arm approach mode between 6-2 miles prior to FAF
    - Ensure aircraft will capture both the localizer and glideslope
    - Set Target Speed in MCP speed window when IM commanded speed transitions to FNL

Terminate IM Procedures

Terminate due to crew preference, ATC instruction, or EICAS message. ATC issues an entire IM clearance; therefore, the flight crew terminates the entire IM clearance. That is, neither ATC nor the crew can selectively cancel one of the two aircraft in a two reference aircraft IM clearance.

1) Flight crew notifies ATC they are terminating the IM clearance (time permitting, respond in same mode)
2) Flight crew flies the last IM speed (shown on the PFD with RVT) until receiving further instructions from ATC
3) (PM) Once new clearance is received from ATC pilots will terminate current IM Operation
    a. Press IM Key on MCDU
    b. ON IM-S Page press TERMINATE [6R]
    c. Press EXEC button on MCDU
4) Reload new IM clearance if available

Table 19. Non-Normal IM Procedures

Alert Level	EICAS Message	Meaning	Pilot Action
Caution	IM DISENGAGED	Loss of ownship flight path data, failure of the interface between the spacing algorithm and the aircraft avionics, ADS-B receiver failure, or other aircraft avionic failures	Execute Terminate Spacing Procedure
Caution	IM AC 1 OFF PATH IM AC 2 OFF PATH	Target aircraft is not on the flight path given by the ATC IM clearance	Execute Terminate Spacing Procedure ATC may issue new clearance
Caution	IM AC 1 ADSB LOST IM AC 2 ADSB LOST	Target aircraft ADS-B information is lost	Execute Terminate Spacing Procedure
Caution	IM ERROR EXCESS	IM spacing software determines it is not possible to meet the assigned RTA or spacing interval	Execute Terminate Spacing Procedure ATC may issue new clearance
Caution	IM OWN BAD PATH	Flight path provided by aircraft avionics to the spacing algorithm is invalid or not available prior to beginning IM operations	Flight crew verifies correct IM information
Caution	IM OWN OFF PATH	Aircraft is greater than 2.5 nmi laterally, 6000 ft vertically, or 90 degrees of heading from the planned flight path	Flight crew corrects to path, or updates FMS to reflect current flight path
Caution	IM AC 1 BAD PATH IM AC 2 BAD PATH	IM spacing software has no path or an invalid flight path for that particular reference aircraft	Flight crew verifies correct IM information
Advisory	IM DRAG REQD	IM spacing software determines drag is required	Ensure thrust levers at IDLE Deploy spoilers to return to flight path and commanded speed
Advisory	IM SPD LIMITED	Speed is constrained by profile, Mmo, Vmo	Advisory only, no action required
Advisory	IM AC 1 SPACING IM AC 2 SPACING	IM has valid data to calculate spacing	Flight crew notifies ATC

Appendix I: Spacing Interval Error Results

Table 20 contains the average and route mean square (in seconds) for the spacing interval error for the piloted aircraft at the runway threshold (listed in arrival sequence for that scenario).

Table 20. Spacing Error Average and Route Mean Square, all Platforms

	ABSOLUTE (RTA)							RELATIVE (RTA+FIM)						
Error	Sim	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**	Sim	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**
None	A10	A	-4.5	-2.2	-4.4	**-3.7**	**3.8**	A04	B	-4.2	1.0	-7.6	**-3.6**	**5.0**
	IFD	A (Cpt)	4.0	1.8	-2.8	**1.0**	**3.0**	A10	B	-1.1	-1.5	4.5	**0.6**	**2.8**
	A09	A	-11.0	-2.8	-3.6	**-5.8**	**6.9**	DTS	B (Cpt)	0.0	-4.1	2.4	**-0.6**	**2.7**
	DTS	A (Cpt)	3.0	-1.1	0.7	**0.8**	**1.9**	IFD	B (Cpt)	0.1	6.8	-4.0	**1.0**	**4.6**
	A05	A	-1.8	-3.7	-4.4	**-3.3**	**3.4**	A09	B	-5.6	-1.0	-4.9	**-3.8**	**4.3**
	A04	A	-16.3	-1.9	-8.6	**-8.9**	**10.7**	A05	B	-1.5	-5.7	-6.2	**-4.5**	**4.9**
		Avg	**-4.4**	**-1.6**	**-3.8**	**-3.3**			**Avg**	**-2.0**	**-0.8**	**-2.6**	**-1.8**	
		RMS	**12.0**	**3.4**	**6.7**		**5.8**		**RMS**	**4.2**	**5.8**	**7.3**		**4.2**
Wind	DTS	C (Cpt)	5.0	3.6	6.8	**5.1**	**5.3**	A05	D	4.8	-9.2	0.6	**-1.3**	**6.0**
	A09	C	7.6	5.2	-2.3	**3.5**	**5.5**	DTS	D (Cpt)	-0.6	3.9	6.1	**3.1**	**4.2**
	A05	C	3.0	5.0	4.4	**4.1**	**4.2**	IFD	D (Cpt)	4.4	-1.6	-0.7	**0.7**	**2.7**
	A10	C	4.9	5.1	5.1	**5.0**	**5.0**	A04	D	-4.1	2.8	2.3	**0.3**	**3.2**
	A04	C	-2.6	2.6	-0.2	**-0.1**	**2.1**	A10	D	2.0	0.4	1.6	**1.3**	**1.5**
	IFD	C (Cpt)	6.4	-8.7	5.0	**0.9**	**6.9**	A09	D	NA	7.6	0.2	**3.9**	**4.4**
		Avg	**4.1**	**2.1**	**3.1**	**3.1**			**Avg**	**1.3**	**0.7**	**1.7**	**1.2**	
		RMS	**7.4**	**7.6**	**6.4**		**5.0**		**RMS**	**4.6**	**7.5**	**3.9**		**4.0**
Wind	DTS	G (FO)	6.8	4.9	3.2	**4.9**	**5.2**	A05	H	3.7	1.8	-0.6	**1.6**	**2.4**
	A09	G	4.1	3.5	-1.8	**2.0**	**3.3**	DTS	H (FO)	3.1	-1.7	3.8	**1.7**	**3.0**
	A05	G	2.8	3.7	8.8	**5.1**	**5.7**	IFD	H (FO)	-0.2	4.3	-1.9	**0.7**	**2.7**
	A10	G	5.0	5.6	3.0	**4.5**	**4.6**	A04	H	-3.6	-4.4	-7.8	**-5.2**	**5.5**
	A04	G	1.9	3.2	4.8	**3.3**	**3.5**	A10	H	1.6	-2.5	3.4	**0.8**	**2.6**
	IFD	G (FO)	6.6	2.5	2.8	**3.9**	**4.4**	A09	H	-1.3	7.7	5.8	**4.0**	**5.6**
		Avg	**4.5**	**3.9**	**3.5**	**3.9**			**Avg**	**0.6**	**0.9**	**0.4**	**0.6**	
		RMS	**6.9**	**5.7**	**6.6**		**4.5**		**RMS**	**3.6**	**6.0**	**6.4**		**3.9**
Offset	DTS	J (Cpt)	-5.1	2.9	3.1	**0.3**	**3.8**	A05	K	1.7	1.9	0.3	**1.3**	**1.5**
	A09	J	-4.4	-2.9	-8.3	**-5.2**	**5.6**	DTS	K (Cpt)	-6.5	-1.4	0.8	**-2.4**	**3.9**
	A05	J	-0.7	-2.6	-3.1	**-2.1**	**2.3**	IFD	K (Cpt)	3.6	-7.8	-4.4	**-2.9**	**5.6**
	A10	J	-3.1	-2.7	-3.9	**-3.2**	**3.2**	A04	K	-8.7	-2.4	-5.0	**-5.4**	**6.0**
	A04	J	-6.3	-3.0	-5.3	**-4.8**	**5.0**	A10	K	-6.4	-2.3	-3.3	**-4.0**	**4.3**
	IFD	J (Cpt)	1.4	3.2	-1.1	**1.1**	**2.1**	A09	K	-1.5	-3.2	-6.6	**-3.7**	**4.3**
			-3.0	**-0.8**	**-3.1**	**-2.3**				**-3.0**	**-2.5**	**-3.0**	**-2.8**	**2.8**
		Avg	**5.7**	**4.1**	**6.6**		**3.9**		**Avg**	**7.7**	**5.4**	**5.7**		**4.5**

Table 20. Spacing Error Average and Route Mean Square (concluded)

	ABSOLUTE (RTA)							RELATIVE (RTA+FIM)						
Error	Sim	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**	Sim	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**
Offset	DTS	L (FO)	0.0	-1.6	-1.6	**-1.1**	**1.3**	A05	M	-2.4	1.9	2.3	**0.6**	**2.2**
	A09	L	-2.9	-4.0	-4.3	**-3.7**	**3.7**	DTS	M (FO)	0.3	-4.4	0.1	**-1.3**	**2.5**
	A05	L	-7.2	-3.0	-2.0	**-4.1**	**4.6**	IFD	M (FO)	5.0	-0.2	-4.3	**0.2**	**3.8**
	A10	L	-3.5	-3.4	-2.8	**-3.2**	**3.2**	A04	M	-4.8	-6.3	-5.0	**-5.3**	**5.4**
	A04	L	-7.9	-3.5	-1.6	**-4.3**	**5.0**	A10	M	-1.5	-0.9	-1.9	**-1.4**	**1.5**
	IFD	L (FO)	8.2	0.4	-0.3	**2.7**	**4.7**	A09	M	-2.8	-2.2	0.4	**-1.5**	**2.0**
		Avg	**2.2**	**2.5**	**2.1**	**-2.3**			**Avg**	**-1.0**	**-2.0**	**-1.4**	**-1.5**	
		RMS	**8.2**	**4.1**	**3.4**		**4.0**		**RMS**	**4.6**	**4.8**	**4.2**		**3.2**

Table 21 provides the subset of this data for the IFD only, Table 22 the data for the DTS only, and Table 23 combines the data from the IFD and DTS. Table 24 presents data by individual subject pilot or crew, and Table 25 provides a comparison of single versus two-crew simulators. All data is in seconds.

Table 21. Spacing Error Average and Route Mean Square, IFD only

	ABSOLUTE (RTA)						RELATIVE (RTA+FIM)					
Error	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**
None	A (Cpt)	4.0	1.8	-2.8	**1.0**	**3.0**	B (Cpt)	0.1	6.8	-4.0	**1.0**	**4.6**
Wind	C (Cpt)	6.4	-8.7	5.0	**0.9**	**6.9**	D (Cpt)	4.4	-1.6	-0.7	**0.7**	**2.7**
	G (FO)	6.6	2.5	2.8	**3.9**	**4.4**	H (FO)	-0.2	4.3	-1.9	**0.7**	**2.7**
Offset	J (Cpt)	1.4	3.2	-1.1	**1.1**	**2.1**	K (Cpt)	3.6	-7.8	-4.4	**-2.9**	**5.6**
	L (FO)	8.2	0.4	-0.3	**2.7**	**4.7**	M (FO)	5.0	-0.2	-4.3	**0.2**	**3.8**

Table 22. Spacing Error Average and Route Mean Square, DTS only

	ABSOLUTE (RTA)						RELATIVE (RTA+FIM)					
Error	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**
None	A (Cpt)	3.0	-1.1	0.7	**0.8**	**1.9**	B (Cpt)	0.0	-4.1	2.4	**-0.6**	**2.7**
Wind	C (Cpt)	5.0	3.6	6.8	**5.1**	**5.3**	D (Cpt)	-0.6	3.9	6.1	**3.1**	**4.2**
	G (FO)	6.8	4.9	3.2	**4.9**	**5.2**	H (FO)	3.1	-1.7	3.8	**1.7**	**3.0**
Offset	J (Cpt)	-5.1	2.9	3.1	**0.3**	**3.8**	K (Cpt)	-6.5	-1.4	0.8	**-2.4**	**3.9**
	L (FO)	0.0	-1.6	-1.6	**-1.1**	**1.3**	M (FO)	0.3	-4.4	0.1	**-1.3**	**2.5**

Table 23. Spacing Error Average and Route Mean Square, IFD and DTS

	ABSOLUTE (RTA)						RELATIVE (RTA+FIM)					
Error	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**	Scenario	Week 1	Week 2	Week 3	**Avg**	**RMS**
None	A	3.5	0.3	-1.1	**0.9**	**2.5**	B	0.1	1.4	-0.8	**0.2**	**3.8**
Wind	C	5.7	-2.6	5.9	**3.0**	**6.1**	D	1.9	1.2	2.7	**1.9**	**3.5**
	G	6.7	3.7	3.0	**4.4**	**4.8**	H	1.5	1.3	1.0	**1.2**	**2.9**
Offset	J	-1.9	3.0	1.0	**0.7**	**3.1**	K	-1.5	-4.6	-1.8	**-2.6**	**4.8**
	L	4.1	-0.6	-1.0	**0.8**	**3.5**	M	2.7	-2.3	-2.1	**-0.6**	**3.2**

Table 24. Spacing Error Average and Route Mean Square, by Flight Crew

		ABSOLUTE (RTA)				RELATIVE (RTA+FIM)			
Error	Platform	Scen.	Week 1	Week 2	Week 3	Scen.	Week 1	Week 2	Week 3
None	A04	A	-16.3	-1.9	-8.6	B	-4.2	1.0	-7.6
Wind	A04	C	-2.6	2.6	-0.2	D	-4.1	2.8	2.3
Wind	A04	G	1.9	3.2	4.8	H	-3.6	-4.4	-7.8
Offset	A04	J	-6.3	-3.0	-5.3	K	-8.7	-2.4	-5.0
Offset	A04	L	-7.9	-3.5	-1.6	M	-4.8	-6.3	-5.0
		Avg	**-7.8**	**-0.7**	**-2.7**	**Avg**	**-6.3**	**-2.3**	**-5.8**
		RMS	**8.7**	**2.9**	**5.0**	**RMS**	**5.4**	**3.8**	**5.9**
None	A05	A	-1.8	-3.7	-4.4	B	-1.5	-5.7	-6.2
Wind	A05	C	3.0	5.0	4.4	D	4.8	-9.2	0.6
Wind	A05	G	2.8	3.7	8.8	H	3.7	1.8	-0.6
Offset	A05	J	-0.7	-2.6	-3.1	K	1.7	1.9	0.3
Offset	A05	L	-7.2	-3.0	-2.0	M	-2.4	1.9	2.3
		Avg	**-1.0**	**-0.1**	**0.9**	**Avg**	**1.6**	**-2.3**	**-0.9**
		RMS	**3.8**	**3.7**	**5.1**	**RMS**	**3.1**	**5.0**	**3.0**
None	A09	A	-11.0	-2.8	-3.6	B	-5.6	-1.0	-4.9
Wind	A09	C	7.6	5.2	-2.3	D	NA	7.6	0.2
Wind	A09	G	4.1	3.5	-1.8	H	-1.3	7.7	5.8
Offset	A09	J	-4.4	-2.9	-8.3	K	-1.5	-3.2	-6.6
Offset	A09	L	-2.9	-4.0	-4.3	M	-2.8	-2.2	0.4
		Avg	**-1.6**	**-0.2**	**-5.0**	**Avg**	**-2.8**	**2.2**	**-1.3**
		RMS	**6.7**	**3.8**	**4.6**	**RMS**	**3.3**	**5.1**	**4.5**
None	A10	A	-4.5	-2.2	-4.4	B	-1.1	-1.5	4.5
Wind	A10	C	4.9	5.1	5.1	D	2.0	0.4	1.6
Wind	A10	G	5.0	5.6	3.0	H	1.6	-2.5	3.4
Offset	A10	J	-3.1	-2.7	-3.9	K	-6.4	-2.3	-3.3
Offset	A10	L	-3.5	-3.4	-2.8	M	-1.5	-0.9	-1.9
		Avg	**-0.3**	**0.6**	**-0.7**	**Avg**	**-1.3**	**-1.7**	**1.1**
		RMS	**4.2**	**4.0**	**3.9**	**RMS**	**3.2**	**1.7**	**3.1**

Table 24. Spacing Error Average and Route Mean Square (concluded)

		ABSOLUTE (RTA)				RELATIVE (RTA+FIM)			
Error	Platform	Scen.	Week 1	Week 2	Week 3	Scen.	Week 1	Week 2	Week 3
None	IFD	A (Cpt)	4.0	1.8	-2.8	B (Cpt)	0.1	6.8	-4.0
Wind	IFD	C (Cpt)	6.4	-8.7	5.0	D (Cpt)	4.4	-1.6	-0.7
Wind	IFD	G (FO)	6.6	2.5	2.8	H (FO)	-0.2	4.3	-1.9
Offset	IFD	J (Cpt)	1.4	3.2	-1.1	K (Cpt)	3.6	-7.8	-4.4
Offset	IFD	L (FO)	8.2	0.4	-0.3	M (FO)	5.0	-0.2	-4.3
		Avg	**6.6**	**-0.2**	**0.9**	**Avg**	**3.2**	**0.4**	**-3.8**
		RMS	**5.8**	**4.4**	**2.9**	**RMS**	**3.4**	**5.1**	**3.4**
None	DTS	A (Cpt)	3.0	-1.1	0.7	B (Cpt)	0.0	-4.1	2.4
Wind	DTS	C (Cpt)	5.0	3.6	6.8	D (Cpt)	-0.6	3.9	6.1
Wind	DTS	G (FO)	6.8	4.9	3.2	H (FO)	3.1	-1.7	3.8
Offset	DTS	J (Cpt)	-5.1	2.9	3.1	K (Cpt)	-6.5	-1.4	0.8
Offset	DTS	L (FO)	0.0	-1.6	-1.6	M (FO)	0.3	-4.4	0.1
		Avg	**2.4**	**2.2**	**3.0**	**Avg**	**-0.9**	**-1.9**	**3.3**
		RMS	**4.6**	**3.1**	**3.7**	**RMS**	**3.2**	**3.4**	**3.4**

Table 25. Spacing Interval Error, by Single and Two-Crew Simulators

	ABSOLUTE (RTA)			RELATIVE (RTA+FIM)		
Error	Scenario	Single-Crew	Two-Crew	Scenario	Single-Crew	Two-Crew
None	A	-5.4	0.9	B	-2.8	0.2
Wind	C	3.2	3.0	D	0.814	1.9
	G	3.7	4.4	H	0.3	1.2
Offset	J	-3.8	0.7	K	-2.9	-2.6
	L	-3.8	0.8	M	-1.9	-0.6
	Avg	**-1.2**	**2.0**	**Avg**	**-1.3**	**0.0**
	RMS	**4.9**	**4.2**	**RMS**	**4.1**	**3.7**

Appendix J: FIM Speed Change Results

Table 26 tabulates the number of speed changes for each aircraft (listed in arrival sequence), for every scenario.

Table 26. FIM Speed Changes, by Simulator

	ABSOLUTE (RTA)							RELATIVE (RTA+FIM)						
Error	Scen	Sim	Call sign	Week 1	Week 2	Week 3	**Avg**	Scen	Sim	Call sign	Week 1	Week 2	Week 3	**Avg**
None	A	A10	094	10	11	10	**10.3**	B	A04	094	8	11	8	**9.0**
	A	IFD	163	9	7	7	**7.7**	B	A10	163	14	10	9	**11.0**
	A	A09	557	8	8	8	**8.0**	B	DTS	557	8	7	11	**8.7**
	A	DTS	328	14	9	9	**10.7**	B	IFD	328	10	9	9	**9.3**
	A	A05	472	9	8	14	**10.3**	B	A09	472	10	12	12	**11.3**
	A	A04	701	9	8	9	**8.7**	B	A05	701	7	9	11	**9.0**
Wind	C	DTS	094	12	9	12	**11.0**	D	A05	094	21	19	14	**18.0**
	C	A09	163	17	18	18	**17.7**	D	DTS	163	18	13	16	**15.7**
	C	A05	557	23	23	25	**23.7**	D	IFD	557	17	15	19	**17.0**
	C	A10	328	15	15	15	**15.0**	D	A04	328	14	10	13	**12.3**
	C	A04	472	15	14	17	**15.3**	D	A10	472	12	12	14	**12.7**
	C	IFD	701	21	18	21	**20.0**	D	A09	701	20	19	22	**20.3**
Wind	G	DTS	094	13	12	11	**12.0**	H	A05	094	19	20	17	**18.7**
	G	A09	163	18	18	15	**17.0**	H	DTS	163	14	14	17	**15.0**
	G	A05	557	22	24	23	**23.0**	H	IFD	557	18	14	21	**17.7**
	G	A10	328	16	15	15	**15.3**	H	A04	328	13	14	15	**14.0**
	G	A04	472	17	15	16	**16.0**	H	A10	472	12	14	12	**12.7**
	G	IFD	701	21	21	20	**20.7**	H	A09	701	21	20	21	**20.7**
Offset	J	DTS	094	10	9	9	**9.3**	K	A05	094	15	12	14	**13.7**
	J	A09	163	11	9	10	**10.0**	K	DTS	163	13	12	15	**13.3**
	J	A05	557	10	11	11	**10.7**	K	IFD	557	16	14	15	**15.0**
	J	A10	328	9	9	7	**8.3**	K	A04	328	12	13	15	**13.3**
	J	A04	472	12	11	12	**11.7**	K	A10	472	12	11	15	**12.7**
	J	IFD	701	10	13	15	**12.7**	K	A09	701	12	11	14	**12.3**
Offset	L	DTS	094	7	9	9	**8.3**	M	A05	094	15	13	13	**13.7**
	L	A09	163	10	11	11	**10.7**	M	DTS	163	12	12	10	**11.3**
	L	A05	557	11	11	10	**10.7**	M	IFD	557	16	15	14	**15.0**
	L	A10	328	8	9	11	**9.3**	M	A04	328	11	16	12	**13.0**
	L	A04	472	12	9	12	**11.0**	M	A10	472	16	11	11	**12.7**
	L	IFD	701	20	12	9	**13.7**	M	A09	701	10	12	13	**11.7**

Table 27 and Figure 22 contain statistical analysis of the number of speed changes by scenario condition (control method and error type).

Table 27. Analysis of Speed Changes, by Condition

Error	Control	Error × Control
$p < 0.0005$	$p = 0.032$	$p < 0.0005$
No Error condition had the lowest number of changes, and the wind condition had the highest.	More speed changes occurred when the "IM-S" Control Method was experienced.	The effect of Error Type on the total number of speed changes was dependent upon Control Method used.
None (Error #1): $M = 9.500$, $SD = 1.920$, $N = 36$ [C]	RTA (Control #1): $M = 12.922$, $SD = 4.662$, $N = 90$ [A]	None / RTA: $M = 9.278$, $SD = 1.994$, $N = 18$ [C]
Wind (Error #2): $M = 16.676$, $SD = 3.691$, $N = 71$ [A]	RTA+FIM (Control #2): $M = 13.618$, $SD = 3.453$, $N = 89$ [B]	None / RTA+FIM: $M = 9.722$, $SD = 1.873$, $N = 18$ [C]
Offset (Error #3): $M = 11.792$, $SD = 2.461$, $N = 72$ [B]		Wind / RTA: $M = 17.222$, $SD = 3.986$, $N = 36$ [A]
		Wind / RTA+FIM: $M = 16.114$, $SD = 3.323$, $N = 35$ [A]
None < Offset < Wind	*RTA < RTA+FIM*	Offset / RTA: $M = 10.444$, $SD = 2.298$, $N = 36$ [C]
		Offset / RTA+FIM: $M = 13.139$, $SD = 1.807$, $N = 36$ [B]

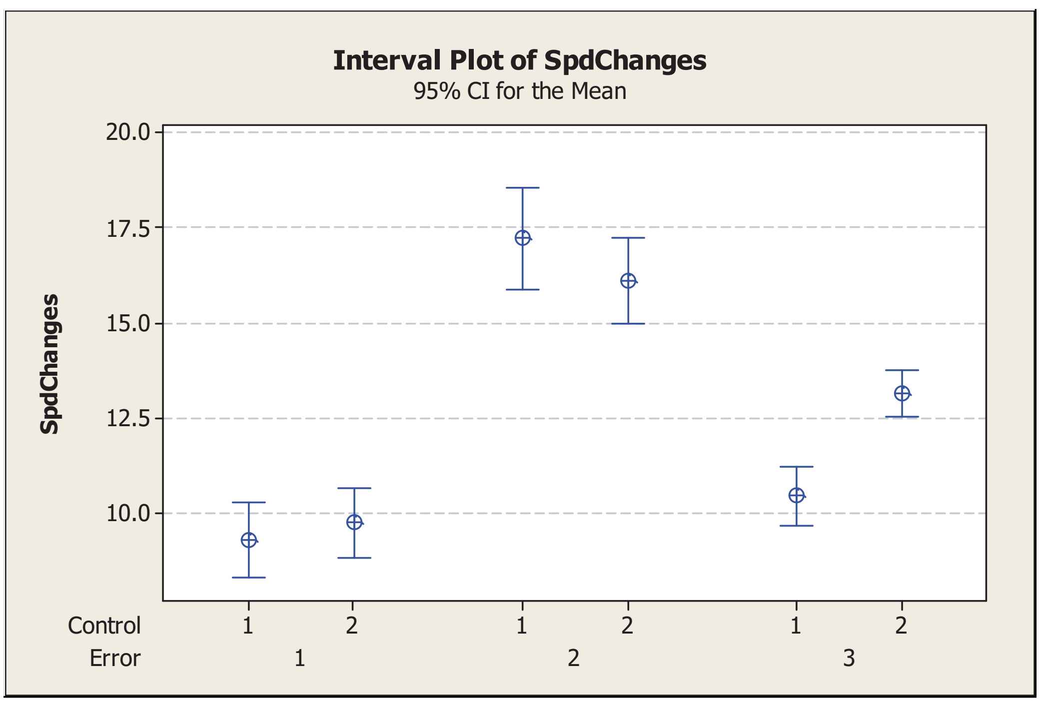


Figure 55. Plot of Speed Changes, by Condition

Appendix K: CPDLC Message Results

Table 28 shows the flight crew Read (outlined in blue) and Respond (outlined in red) time in seconds to the Controller-Pilot Datalink Communications (CPDLC) message clearance, sorted from longest to shortest Respond time. The Message Received column is the time from scenario start until the CPDLC chime and EICAS message were presented to the crew. All times are based from when the CPDLC chime occurred until that a button was pushed by the flight crew. For example, the first row indicates it took the flight crew 22.0 seconds to read the CPDLC button to read the message, and 99.2 seconds to respond to it. See Table 2 for the description of Scenario (error source, control method, and replicate number), Figure 4 for a review of crew CPDLC procedures, and Figure 34 for required communication performance.

The legend for the Note column is after the table. Three runs were dropped from this analysis (not included in table). They were due to: (1) pilot manually load FIM clearance into the spacing software, (2) pilot flew the FIM speeds but could not find the ACCEPT button to respond to ATC, and (3) equipment failure in the Development and Test Simulator (DTS).

Table 28. CPDLC Message Respond Time, from Slowest to Fastest

Group	Scenario	Callsign	Simulator	Message received (chime, light)	READ (push button)	LOAD (enter clnc)	ACTIVATE (start algorithm)	RESPOND (accept to ATC)	EXEC (display speeds)	Note
3	J	NAS094	DTS	14.6	22.0	48.6	58.4	99.2	82.0	1
2	B	NAS328	IFD	14.2	6.2	18.6	44.8	83.8	70.8	
3	B	NAS557	DTS	99.0	7.4	41.0	59.6	82.0	84.6	
2	A	NAS163	IFD	88.8	16.6	29.0	34.0	79.6	70.2	1
2	M	NAS163	DTS	129.6	14.2	45.0	51.2	78.2	80.2	
2	B	NAS701	A05	130.0	8.8	19.8	54.4	76.0	85.2	
2	M	NAS557	IFD	139.6	2.6	14.4	36.4	74.6	55.0	1
3	L	NAS701	IFD	169.2	6.6	13.8	20.2	73.4	53.8	1
2	K	NAS094	A05	15.0	4.2	19.0	47.0	73.4	84.2	
2	M	NAS094	A05	15.2	12.0	24.4	46.0	73.4	80.0	
3	A	NAS328	DTS	14.4	7.2	21.4	32.0	72.0	60.6	1
3	M	NAS163	DTS	129.6	6.6	41.6	45.2	70.0	72.0	
2	H	NAS163	DTS	89.8	3.4	32.2	37.2	68.2	69.2	
2	C	NAS701	IFD	129.8	9.6	25.6	34.6	66.4	57.4	1
3	J	NAS557	A05	140.0	18.8	24.2	27.8	66.4	69.0	
2	K	NAS557	IFD	139.6	3.2	23.0	29.2	66.4	55.6	1
3	C	NAS094	DTS	9.8	13.2	23.2	30.6	64.8	71.6	
1	A	NAS163	IFD	89.6	5.0	26.2	39.8	64.4	65.8	
2	J	NAS701	IFD	169.6	4.8	25.6	40.6	63.4	54.0	1
1	H	NAS163	DTS	89.4	9.6	13.2	41.6	63.2	63.0	2

Table 28. CPDLC Message Respond Time (continued)

Group	Scenario	Callsign	Simulator	Message received (chime, light)	READ (push button)	LOAD (enter clnc)	ACTIVATE (start algorithm)	RESPOND (accept to ATC)	EXEC (display speeds)	Note
3	J	NAS472	A04	160.0	6.4	18.8	40.8	62.2	76.4	
2	H	NAS557	IFD	99.8	4.0	20.2	27.6	61.0	47.0	1
3	K	NAS163	DTS	129.6	7.0	33.8	39.0	60.8	67.0	
2	H	NAS094	A05	10.0	9.6	24.8	35.6	59.6	72.4	
1	K	NAS328	A04	20.2	5.8	30.6	37.0	59.4	57.4	2
3	A	NAS163	IFD	89.4	2.4	6.4	10.8	58.4	12.6	1
1	J	NAS472	A04	160.0	23.0	30.6	15.8	57.4	58.6	
1	A	NAS701	A04	130.0	21.2	24.6	14.0	56.8	61.2	
3	L	NAS472	A04	160.0	4.0	11.6	13.4	56.8	35.6	1
3	D	NAS163	DTS	89.6	4.8	18.0	32.4	56.4	62.4	
2	J	NAS557	A05	140.0	7.8	17.2	30.2	54.6	64.8	
1	M	NAS328	A04	20.0	9.6	23.4	18.4	53.8	47.4	2
2	C	NAS094	DTS	9.8	10.2	22.2	33.4	52.2	53.8	
3	H	NAS163	DTS	89.2	3.8	22.6	26.0	52.0	54.4	
3	L	NAS094	DTS	14.2	12.4	22.0	27.4	51.8	56.4	
2	D	NAS328	A04	15.0	5.8	9.0	21.4	51.6	46.0	2
3	D	NAS328	A04	15.0	3.2	8.8	29.8	51.4	74.4	4
1	H	NAS557	IFD	99.2	21.0	21.0	29.0	51.2	52.8	
3	B	NAS094	A04	10.0	6.0	30.0	46.4	50.6	54.8	
2	D	NAS701	A09	130.0	4.8	20.8	26.2	50.6	59.6	
2	D	NAS557	IFD	99.4	3.0	21.2	25.8	50.0	33.6	1
2	J	NAS094	DTS	14.6	4.6	15.6	26.6	49.4	51.4	
1	D	NAS557	IFD	98.8	5.2	14.4	17.6	49.2	51.0	
1	D	NAS328	A04	15.0	5.4	19.6	13.0	49.0	51.8	
2	D	NAS094	A05	10.0	5.0	13.4	27.2	49.0	59.0	
1	K	NAS557	IFD	139.0	9.4	29.0	32.2	49.0	52.6	
2	B	NAS557	DTS	99.4	4.2	12.6	28.8	48.6	50.0	
1	J	NAS557	A05	140.0	8.0	17.0	24.2	48.2	52.0	
1	M	NAS557	IFD	139.6	2.8	21.4	24.4	48.2	49.2	
3	A	NAS094	A10	10.2	8.2	15.6	27.2	48.0	49.0	
1	C	NAS472	A04	120.2	17.0	25.4	11.8	48.0	49.8	
3	B	NAS472	A09	120.0	3.4	17.8	24.6	47.6	48.8	
1	B	NAS328	IFD	14.6	5.4	21.4	23.0	47.6	48.8	
3	A	NAS701	A04	130.2	3.4	13.6	37.8	47.4	65.8	
2	H	NAS472	A10	120.0	16.4	18.2	24.8	47.4	48.6	
3	K	NAS557	IFD	139.6	2.2	15.8	21.2	47.4	41.4	
2	H	NAS328	A04	15.0	7.8	11.6	35.6	46.6	50.0	

Table 28. CPDLC Message Respond Time (continued)

Group	Scenario	Callsign	Simulator	Message received (chime, light)	READ (push button)	LOAD (enter clnc)	ACTIVATE (start algorithm)	RESPOND (accept to ATC)	EXEC (display speeds)	Note
1	G	NAS094	DTS	8.8	3.0	6.2	22.2	46.2	43.6	2
1	B	NAS094	A04	10.0	5.0	15.2	9.0	46.0	47.4	
2	B	NAS163	A10	90.0	4.0	11.2	18.6	46.0	47.6	
3	M	NAS557	IFD	139.6	2.0	11.4	17.8	45.8	40.2	2
3	J	NAS163	A09	130.0	4.4	14.4	24.4	45.6	47.4	
1	H	NAS328	A04	15.0	13.0	21.8	25.6	44.8	481.6	4, 5
2	B	NAS472	A09	120.0	7.8	18.8	23.4	44.2	49.0	
2	K	NAS163	DTS	129.6	3.2	15.2	18.4	44.0	46.0	
2	J	NAS163	A09	130.0	6.2	13.0	18.0	43.8	48.2	
2	K	NAS701	A09	170.2	2.8	17.8	22.6	43.8	52.6	
2	G	NAS557	A05	100.2	6.2	13.2	18.8	43.0	50.6	
2	L	NAS094	DTS	14.2	6.4	14.0	17.4	42.8	43.6	
2	A	NAS094	A10	10.0	14.6	17.6	22.8	42.6	44.0	
3	G	NAS094	DTS	9.0	7.6	17.2	20.4	42.4	43.4	
3	G	NAS701	IFD	129.0	3.4	9.4	14.8	42.4	36.8	2
2	A	NAS472	A05	120.0	3.2	10.2	22.6	42.0	47.2	
1	G	NAS701	IFD	128.8	3.0	15.2	18.0	41.6	42.8	
3	H	NAS094	A05	10.0	6.2	15.0	22.2	41.6	45.8	
1	J	NAS701	IFD	168.8	5.6	12.2	19.4	41.6	42.6	
3	K	NAS328	A04	20.2	3.6	9.4	16.0	41.6	55.0	
1	K	NAS163	DTS	129.0	8.2	12.0	17.2	41.6	43.2	
3	D	NAS701	A09	130.0	7.2	12.8	20.2	41.4	42.4	
2	D	NAS472	A10	120.0	4.4	11.6	20.2	41.4	43.2	
2	M	NAS701	A09	170.2	5.2	14.6	18.6	41.4	47.4	
3	B	NAS701	A05	130.0	4.6	15.0	21.6	41.2	50.2	
3	C	NAS472	A04	120.0	4.2	18.0	19.6	41.2	43.2	
3	G	NAS472	A04	119.8	3.2	16.0	18.6	41.0	59.6	4
3	D	NAS557	IFD	99.6	2.0	14.0	18.2	41.0	38.8	2
3	C	NAS701	IFD	129.8	3.0	12.6	17.6	40.4	38.4	2
3	J	NAS701	IFD	169.6	2.6	11.2	17.2	40.4	39.4	2
1	G	NAS472	A04	120.0	6.6	14.0	18.0	40.2	36.8	2
1	B	NAS701	A05	130.0	3.6	6.8	16.2	40.0	41.2	
1	D	NAS094	A05	10.0	4.6	10.2	14.6	40.0	40.8	
2	D	NAS163	DTS	89.2	3.6	16.4	19.6	40.0	41.2	
2	A	NAS328	DTS	14.0	5.0	16.8	19.8	39.8	41.4	
2	J	NAS328	A10	20.0	6.4	12.2	18.0	39.8	43.0	
2	G	NAS094	DTS	9.6	4.2	12.8	16.2	39.6	40.0	

Table 28. CPDLC Message Respond Time (continued)

Group	Scenario	Callsign	Simulator	Message received (chime, light)	READ (push button)	LOAD (enter clnc)	ACTIVATE (start algorithm)	RESPOND (accept to ATC)	EXEC (display speeds)	Note
1	L	NAS328	A10	20.0	5.8	7.2	11.4	39.6	41.6	
2	C	NAS328	A10	15.0	5.6	12.2	19.0	39.4	41.2	
2	C	NAS163	A09	90.0	3.6	8.6	12.4	39.2	43.2	
1	L	NAS557	A05	140.0	6.6	9.4	17.2	39.2	40.2	
1	L	NAS701	IFD	168.8	2.6	8.4	14.0	39.2	41.6	
3	A	NAS557	A09	100.2	8.6	14.6	18.6	38.8	41.8	
3	H	NAS557	IFD	99.2	2.6	9.8	14.2	38.8	35.2	2
2	B	NAS094	A04	10.0	2.4	8.6	15.4	38.6	36.0	2
1	G	NAS557	A05	100.0	11.6	13.6	16.0	38.2	39.8	
2	J	NAS472	A04	160.0	3.4	10.6	13.8	38.2	44.0	
2	L	NAS557	A05	139.8	5.0	9.6	17.0	38.2	43.8	
1	M	NAS163	DTS	129.6	2.8	10.0	12.6	38.2	33.0	2
3	B	NAS328	IFD	14.2	5.8	10.8	16.6	38.0	19.0	1
1	A	NAS557	A09	100.0	6.6	13.6	18.8	37.8	39.4	
1	L	NAS094	DTS	13.8	5.2	8.0	16.0	37.8	38.0	
3	B	NAS163	A10	90.0	4.2	14.4	16.6	37.4	41.8	
1	C	NAS701	IFD	129.8	6.6	12.8	15.8	37.4	38.4	
2	C	NAS557	A05	100.0	7.0	10.0	17.6	37.2	43.4	
3	C	NAS557	A05	100.2	3.8	12.4	16.6	37.2	39.2	
3	C	NAS163	A09	90.0	7.2	13.2	15.6	37.2	39.0	
3	H	NAS472	A10	120.0	3.2	9.4	14.4	37.2	35.0	2
1	C	NAS557	A05	100.0	7.0	9.2	14.2	37.0	38.2	
3	D	NAS472	A10	120.0	4.2	7.6	15.4	37.0	38.4	
3	L	NAS328	A10	20.0	9.0	11.8	19.4	37.0	38.0	
3	D	NAS094	A05	10.0	3.4	10.6	15.2	36.8	42.4	
3	K	NAS094	A05	15.2	2.6	12.6	16.6	36.8	46.0	
2	M	NAS328	A04	20.2	6.0	8.4	13.6	36.6	35.2	2
3	G	NAS557	A05	99.8	4.2	12.0	17.4	36.4	37.6	
3	H	NAS701	A09	130.0	8.0	12.4	17.0	36.4	44.4	
3	L	NAS163	A09	130.0	7.6	13.2	16.6	36.4	37.4	
1	M	NAS094	A05	15.0	4.8	13.4	14.8	36.2	37.2	
3	A	NAS472	A05	120.0	4.6	10.8	16.0	35.8	63.2	4
1	D	NAS163	DTS	89.0	2.6	8.2	11.4	35.8	36.4	
1	J	NAS094	DTS	13.8	3.8	10.8	13.6	35.6	37.2	
1	L	NAS472	A04	160.0	4.8	12.8	15.2	35.4	36.4	
3	M	NAS701	A09	170.0	8.0	12.6	16.2	35.2	36.2	

Table 28. CPDLC Message Respond Time (continued)

Group	Scenario	Callsign	Simulator	Message received (chime, light)	READ (push button)	LOAD (enter clnc)	ACTIVATE (start algorithm)	RESPOND (accept to ATC)	EXEC (display speeds)	Note
1	C	NAS328	A10	15.2	4.6	10.4	15.2	35.0	36.0	
3	G	NAS163	A09	89.8	6.0	12.6	15.6	34.8	36.2	
3	C	NAS328	A10	15.0	6.4	13.2	16.2	34.8	36.2	
3	M	NAS328	A04	20.0	3.2	9.4	11.6	34.8	55.0	4
3	M	NAS472	A10	160.0	3.6	8.6	13.0	34.8	36.0	
2	K	NAS472	A10	160.0	6.4	11.6	14.4	34.6	35.6	
3	G	NAS328	A10	15.0	7.0	9.8	14.6	34.2	35.6	
2	A	NAS701	A04	130.0	3.4	6.0	12.0	34.0	31.8	2
1	A	NAS094	A10	10.0	5.4	7.8	12.4	34.0	36.6	
2	G	NAS472	A04	120.0	5.4	8.0	12.0	34.0	32.0	2
3	L	NAS557	A05	140.0	3.8	11.2	15.2	34.0	38.6	
2	C	NAS472	A04	119.8	3.6	8.0	12.0	33.8	38.4	
2	G	NAS328	A10	15.2	5.2	10.0	13.4	33.6	35.2	
2	H	NAS701	A09	130.0	7.8	14.6	36.6	33.6	62.0	4
3	K	NAS472	A10	160.2	3.4	9.0	13.2	33.2	34.0	
2	L	NAS163	A09	129.8	3.0	7.0	10.8	33.0	37.2	
1	A	NAS472	A05	120.0	12.6	15.6	28.4	32.8	39.4	
2	M	NAS472	A10	160.2	5.8	9.4	12.8	32.6	33.2	
1	M	NAS701	A09	170.0	4.0	8.0	9.4	32.4	28.0	2
1	G	NAS163	A09	90.0	4.8	8.2	9.8	32.2	34.0	
1	D	NAS472	A10	120.0	4.0	6.0	11.0	31.6	34.0	
3	K	NAS701	A09	170.2	3.6	7.6	10.6	31.6	29.6	2
1	K	NAS701	A09	170.2	1.8	8.4	12.4	31.4	33.0	
3	M	NAS094	A05	15.2	2.6	8.2	12.2	30.8	32.2	
1	K	NAS472	A10	160.2	2.6	5.0	9.6	30.8	34.0	
2	A	NAS557	A09	100.0	3.0	8.6	11.8	30.6	35.6	
1	G	NAS328	A10	15.0	4.2	8.6	10.4	30.6	29.2	2
1	J	NAS328	A10	20.0	4.4	7.0	10.6	30.6	31.8	
2	L	NAS472	A04	160.0	3.4	6.4	9.8	30.4	28.8	2
1	B	NAS557	DTS	99.8	3.0	5.8	8.8	30.2	31.4	
1	H	NAS701	A09	130.0	2.6	8.6	10.8	29.8	31.2	
1	L	NAS163	A09	130.0	3.0	7.2	8.6	29.8	30.8	
2	L	NAS328	A10	20.0	4.4	7.0	11.0	29.8	31.0	
2	G	NAS163	A09	90.2	2.6	6.4	10.0	29.6	33.4	
1	M	NAS472	A10	160.0	3.4	6.8	9.6	29.4	32.8	

Table 28. CPDLC Message Respond Time (concluded)

Group	Scenario	Callsign	Simulator	Message received (chime, light)	READ (push button)	LOAD (enter clnc)	ACTIVATE (start algorithm)	RESPOND (accept to ATC)	EXEC (display speeds)	Note
1	J	NAS163	A09	130.0	3.0	7.0	8.6	28.8	29.8	
2	K	NAS328	A04	20.0	2.6	5.6	10.0	28.8	32.2	
1	C	NAS163	A09	90.2	3.2	8.0	9.4	27.8	29.2	
1	B	NAS163	A10	90.0	3.2	4.8	8.4	27.6	30.2	
1	H	NAS472	A10	120.0	4.0	6.8	8.2	27.6	28.6	
1	D	NAS701	A09	130.0	2.4	6.2	7.6	27.4	29.4	
1	B	NAS472	A09	120.0	1.4	3.4	7.2	26.8	28.0	
1	H	NAS094	A05	10.0	2.2	4.0	8.0	26.6	35.0	
1	K	NAS094	A05	15.2	9.2	12.8	19.2	25.8	34.6	
1	C	NAS094	DTS	9.8	5.2	5.2	11.8	19.0	33.8	4
2	L	NAS701	IFD	169.4	3.2	34.0	40.6	16.0	61.0	4
2	G	NAS701	IFD	129.8	2.6	45.8	56.2	11.6	76.2	4, 6

NOTES:

1) Flight crew completed steps out of sequence; FIM was executed (display FIM speed on PFD and ND) well prior to sending ACCEPT message to ATC. Appears to be a lack of understanding or training by the flight crew, but not considered an operational issue for controllers or pilots.

2) Flight crew completed steps out of sequence; FIM was executed (display FIM speed on PFD and ND) just prior to sending ACCEPT message to ATC. Appears to have been an incorrect sequence of button pushes by the pilot, and is not an operational issue for controllers or pilots.

3) Flight crew did not send an ACCEPT message to ATC in a timely fashion. Appears to have been either caused by the pilot believing a message response had been sent or forgot to send a message response (even though the EICAS message remained on). This could be an operational issue for controllers.

4) Flight crew did not EXECUTE the FIM clearance in a timely manner, resulting in a FIM speed available on the MCDU, but not shown on the PFD or ND. This would only become an operational problem if the flight crew were expecting the FIM speed to be shown on the PFD or ND, and did flew the published speed instead.

5) Video review of this run indicated the pilot was very proficient (the seventh of ten runs), and flew the correct FIM speed based on the MCDU display.

6) Second run for this pilot; he accidentally accepted the FIM clearance prior to loading and activating the clearance into the spacing software. He immediately recognized the error, and went back to load and activate the FIM clearance.

Appendix L: Post-Run Questionnaire Results

The first part of this Appendix contains data for post-run questions appropriate for data analysis. The second part contains a list of comments from various parts of the questionnaire. Light gray shading indicates data not relevant for that cell.

- Question #3: Select the average workload experienced during the scenario using the Modified Cooper-Harper scale of 1 (easily attainable) to 10 (cannot be accomplished).

Table 29. Mean and Standard Deviation for Average Workload

By Condition						
	RTA, No Error	RTA, Wind Error	RTA, Offset Error	RTA+FIM, No Error	RTA+FIM, Wind Error	RTA+FIM, Offset Error
Median	1.8958	1.8542	1.8958	1.8542	2.0625	1.8125
Sum of Ranks	84.5	76.0	90.0	80.5	100.0	73.0
By Control Method						
	RTA	RTA+FIM				
Mean	1.95	1.98				
Stand Dev	0.87	0.86				
By Error Type						
	No Error	Wind Error	Offset Error			
Mean	1.88	2.02	1.96			
Stand Dev	0.84	0.85	0.89			
By Simulator						
	ATOL	DTS	IFD			
Mean	2.23	1.65	1.77			
Stand Dev	0.97	0.71	0.59			
By PF/PM						
	Pilot Flying	Pilot Monitor				
Mean	1.85	1.57				
Stand Dev	0.63	0.65				

- Question #5: Select the peak workload experienced during the scenario using the Modified Cooper-Harper scale of 1 (easily attainable) to 10 (cannot be accomplished).

Table 30. Mean and Standard Deviation for Peak Workload

By Condition						
	RTA, No Error	RTA, Wind Error	RTA, Offset Error	RTA+FIM, No Error	RTA+FIM, Wind Error	RTA+FIM, Offset Error
Median	2.3750	2.0000	2.2083	1.9583	2.4167	2.0417
Sum of Ranks	91.0	68.5	93.0	73.0	105.0	73.5
By Control Method						
	RTA	RTA+FIM				
Mean	2.30	2.33				
Stand Dev	1.03	1.00				
By Error Type						
	No Error	Wind Error	Offset Error			
Mean	2.15	2.39	2.33			
Stand Dev	1.07	0.93	1.05			

Table 30. Mean and Standard Deviation for Peak Workload (concluded)

By Simulator						
	ATOL	DTS	IFD			
Mean	2.63	1.90	2.12			
Stand Dev	1.02	0.92	0.88			
By PF/PM						
	Pilot Flying	Pilot Monitor				
Mean	2.18	1.83				
Stand Dev	0.87	0.91				

- Question #7a: How much attention was required (demand) on a scale of 1 (low) to 7 (high).

Table 31. Mean and Standard Deviation for Attention Required

By Control Method						
	RTA	RTA+FIM				
Mean	2.64	2.79				
Stand Dev	1.47	1.47				
By Error Type						
	No Error	Wind Error	Offset Error			
Mean	2.31	2.85	2.78			
Stand Dev	1.29	1.42	1.57			
By Simulator						
	ATOL	DTS	IFD			
Mean	3.25	2.42	1.95			
Stand Dev	1.51	1.41	0.93			
By PF/PM						
	Pilot Flying	Pilot Monitor				
Mean	2.43	1.93				
Stand Dev	1.28	1.09				

- Question #7b: How much spare attention was available on a scale of 1 (low) to 7 (high).

Table 32. Mean and Standard Deviation for Supply of Attention

By Control Method						
	RTA	RTA+FIM				
Mean	5.22	5.11				
Stand Dev	1.52	1.52				
By Error Type						
	No Error	Wind Error	Offset Error			
Mean	5.25	5.00	5.28			
Stand Dev	1.59	1.54	1.46			
By Simulator						
	ATOL	DTS	IFD			
Mean	4.71	5.23	6.00			
Stand Dev	1.40	1.81	0.97			
By PF/PM						
	Pilot Flying	Pilot Monitor				
Mean	5.57	5.67				
Stand Dev	1.32	1.66				

- Question #7c: How much understanding of events on a scale of 1 (low) to 7 (high).

Table 33. Mean and Standard Deviation for Understanding of Events

By Control Method						
	RTA	RTA+FIM				
Mean	6.24	6.29				
Stand Dev	0.93	0.86				
By Error Type						
	No Error	Wind Error	Offset Error			
Mean	6.23	6.24	6.31			
Stand Dev	0.93	0.84	0.93			
By Simulator						
	ATOL	DTS	IFD			
Mean	6.13	6.45	6.35			
Stand Dev	1.00	0.57	0.92			
By PF/PM						
	Pilot Flying	Pilot Monitor				
Mean	6.38	6.42				
Stand Dev	0.72	0.81				

The following scale was used for responses shown in Table 34 and Table 35.

- 1 to 2: completely disagree or moderately disagree
- 2 to 3: moderately disagree to slightly disagree
- 3 to 4: slightly disagree or neutral
- 4 to 5: neutral to slightly agree
- 5 to 6: slightly agree to moderately agree
- 6 to 7: moderately agree to completely agree

Questionnaire responses shown in Table 34 and Table 35 use the following scale:

- 1 to 2: completely disagree or moderately disagree
- 2 to 3: moderately disagree to slightly disagree
- 3 to 4: slightly disagree or neutral
- 4 to 5: neutral to slightly agree
- 5 to 6: slightly agree to moderately agree
- 6 to 7: moderately agree to completely agree

- Question #9: How acceptable were the FIM operations on a scale of 1 to 7.

Table 34. Mean and Standard Deviation for Acceptability of FIM Operation

	IFD	DTS	ATOL	RTA + FIM	RTA	PF	PM	No Error	Wind Error	Offset Error
I was aware of commanded speed changes within an appropriate timeframe.	6.53 0.70	6.52 0.62	5.61 1.44	6.05 1.21	6.08 1.21	6.63 0.55	6.42 0.74	5.96 1.15	6.02 1.26	6.17 1.19
I was able to implement the speed changes within an appropriate timeframe when the speed window was open.	6.60 0.69	6.38 0.90	5.63 1.30	6.08 1.12	6.04 1.21	6.58 0.62	6.40 0.96	6.10 1.13	5.93 1.25	6.17 1.08
The commanded speed was operationally acceptable and appropriate.	6.22 1.11	6.43 1.06	5.78 1.43	5.96 1.22	6.14 1.37	6.13 1.20	6.52 0.93	6.54 0.62	5.75 1.53	6.10 1.22
The frequency of speed commands was acceptable at all times throughout the scenario.	5.68 1.47	6.15 1.16	5.50 1.52	5.63 1.42	5.78 1.47	5.70 1.50	6.13 1.13	6.35 0.91	5.23 1.56	5.86 1.39
I was able to predict when speed changes would occur, before they were given.	5.15 1.40	5.87 1.14	5.22 1.42	5.40 1.36	5.33 1.40	5.47 1.26	5.55 1.40	5.46 1.32	5.13 1.42	5.55 1.33
I maintained adequate awareness of my lead aircraft throughout the scenario.	6.38 0.90	6.20 1.16	5.52 1.33	6.28 0.93	5.53 1.41	6.28 1.01	6.30 1.08	5.90 1.31	5.88 1.25	5.94 1.24
The events I experienced in this scenario are operationally realistic.	6.48 0.65	6.68 0.85	6.07 0.88	6.42 0.63	6.23 1.03	6.58 0.59	6.58 0.91	6.33 0.75	6.26 0.90	6.39 0.88
The flight crew procedures for this event are operationally feasible.	6.58 0.70	6.73 0.45	6.22 0.71	6.38 0.72	6.49 0.65	6.60 0.69	6.72 0.45	6.48 0.65	6.43 0.64	6.43 0.75
The amount of head down time required to respond to CPDLC messages was acceptable.	6.52 0.79	6.63 0.55	5.80 1.48	6.22 1.15	6.16 1.28	6.60 0.81	6.55 0.53	6.10 1.34	6.32 1.11	6.09 1.25
The time take to review and respond to CPDLC clearances did not detract from your ability to complete other critical tasks.	6.47 0.81	6.73 0.66	5.72 1.50	6.20 1.19	6.12 1.34	6.58 0.89	6.62 0.58	6.06 1.39	6.26 1.15	6.10 1.30

- Question #10: How acceptable was the FIM spacing tool on a scale of 1 to 7.

Table 35. Mean and Standard Deviation for Acceptability of FIM Spacing Tool

	IFD	**DTS**	**ATOL**	**RTA + FIM**	**RTA**	**PF**	**PM**	**No Error**	**Wind Error**	**Offset Error**
There was a time in the scenario where you thought it was unsafe to fly the commanded speed.	1.45 1.16	1.01 0.13	1.41 0.76	1.35 0.84	1.29 0.78	1.22 0.78	1.25 0.91	1.23 0.59	1.48 1.10	1.21 0.46
There was a time in the scenario where you thought the commanded speed would not get you to the runway threshold at the correct time.	1.55 1.10	1.17 0.69	1.56 0.92	1.47 0.99	1.45 0.88	1.40 0.89	1.32 0.98	1.50 1.13	1.52 0.97	1.38 0.77
The FIM commanded speed interrupted you while you were in the process of completing other critical tasks.	2.20 1.27	1.65 0.94	3.18 1.73	2.48 1.55	2.63 1.64	2.00 1.25	1.85 1.04	2.42 1.49	2.63 1.56	2.55 1.69
There was a time in the scenario where the spacing tool behaved in an unexpected manner.	2.15 1.46	1.67 1.39	2.23 1.73	2.12 1.57	2.02 1.62	2.15 1.61	1.67 1.20	1.60 1.35	2.48 1.76	1.89 1.44
There was a time in the scenario where you felt that the commanded speed or other information available from the spacing tool conflicted with other information available through ATC, CDTI, voice comm., etc.	1.93 1.27	1.33 0.91	1.78 1.26	1.68 1.18	1.74 1.23	1.65 1.20	1.62 1.09	1.60 1.23	1.92 1.39	1.55 0.95
There was a time in the scenario where you felt uncomfortable with the commanded speed.	1.67 1.43	1.10 0.30	1.71 1.31	1.56 1.24	1.53 1.17	1.40 1.08	1.37 1.07	1.40 0.96	1.74 1.50	1.43 0.94
There was a time in the scenario where you felt frustrated by the spacing tool.	2.20 1.52	1.63 1.29	2.66 1.75	2.08 1.49	2.50 1.75	1.97 1.41	1.87 1.40	1.73 1.16	2.69 1.80	2.17 1.58

This portion of the Appendix contains selected comments from various post-run questions. This format is used since the subject pilots tended to record their responses in several locations.

- *"Spent more head down time than was comfortable after FIM clearance was received but waiting for software to calculate a speed. No one was watching the aircraft."*
- *"Felt that an enormous amount of attention was required to stay on the vertical path while maintaining the required speed."*
- *"Drag Required message on EICAS triggered when aircraft already slowing. Other times the message seemed inappropriate, and the crew disregarded it."*
- *"Using both MCDUs at the same time to interact with CPDLC and FIM software was a bit confusing."*
- *"Not able to predict when the next FIM speed change would occur."*
- *"Workload for FIM operation seemed to peak as aircraft is intercepting the glideslope and the crew configuring the flaps."*
- *"RTA only scenario was easier than previous RTA+FIM scenario."*
- *"Changes to FIM speed were not always noticed, need more alerting. As a consequence, spent more time than normal monitoring airspeed and indications."*
- *"Too many FIM speed reversals (speed up followed by a slow down)."*
- *"I am getting used to the FIM procedures and speed changes, and can more easily anticipate what it is doing and what it will do."*
- *"Frequency changes and traffic point outs were realistic, and caused some distraction."*
- *"Need to smooth out number of FIM speed changes."*
- *"CPDLC procedures requires too many steps. Needs to be streamlined."*
- *"Not operationally realistic to command a speed up that also requires the flaps to be raised (very occasional okay, but not routinely)."*
- *"Do not understand why speed were what they were, and why it changed so often."* [Note: A review of these comments show almost all were written during Wind Error scenarios where a significant wind shear occurred on the turn to final.]
- *"I think it would help scan/awareness if the FIM speed command box flashed as well as boxed during the ten second speed change command. This would aid in drawing attention to the box. It just doesn't stand-out enough for me from the other autoflight green command lights on the PFD."*
- *"We get better flying the FIM procedures the more we repeat them. I wonder how a line crew would do after training, and then not actually seeing a FIM approach for months, then being called on to do one."*

Appendix M: Post-Experiment Questionnaire Results

The first part of this Appendix contains data for post-experiment questions appropriate for data analysis. The second part contains excerpts of comments collected from the pilots.

- Question #3: Select the average workload experienced during the scenario using the Modified Cooper-Harper scale of 1 (easily attainable) to 10 (cannot be accomplished).

Table 36. Mean and Standard Deviation of Overall Workload

	ATOL	DTS	IFD	All
3. Was the workload required to operate the simulator much less than, the same as, or greater than the workload required to fly an actual aircraft?	4.08 1.68	4.33 1.03	4.50 0.84	4.25 1.33

- Question #7: How much additional workload do you think would be required to conduct FIM procedures while flying Optimized Profile Descents using a scale of 1 (much more) to 7 (much less)?

Table 37. Mean and Standard Deviation of Additional Workload due to FIM Operations

	ATOL	DTS	IFD	All
7. In a real world environment, how much additional workload do you think would be required to carry out the spacing procedures while flying the Optimized Profile Descent (OPD) compared to current step-down procedures?	3.67 1.78	4.33 1.03	3.83 0.75	3.88 1.39

- Question #9: How difficult do you think it will be for a typical flight crew to learn and integrate FIM procedures into their current daily operations using a scale of 1 (very difficult) to 7 (very easy)?

Table 38. Mean and Standard Deviation of Learning FIM Operations

	ATOL	DTS	IFD	All
9. How difficult do you think it would be for a typical flight crew to learn and integrate the IM spacing procedures into their current daily operational flight procedures?	4.83 1.47	4.00 1.90	4.67 1.51	4.58 1.56

- Question #10: What is your overall assessment of the safety of the FIM procedures compared to current day operations using a scale of 1 (not safe at all) to 7 (much more safe).

Table 39. Mean and Standard Deviation of Safety of FIM Procedures

	ATOL	DTS	IFD	All
10. Given the experience with FIM that you gained during this simulation, what is your overall assessment of the safety of the spacing procedure compared with current day operations?	4.92 1.24	5.17 0.75	4.50 1.22	4.88 1.12

- Question #12: Impact to operations when electronic data tags do not match the voice callsign on a scale of 1 (insurmountable issue) to 5 (not an issue at all).

Table 40. Mean and Standard Deviation of Data Tag and Voice Callsign Confusion

	ATOL	DTS	IFD	All
12. ATC controllers are accustomed to aircraft callsign data tags they see on their radar scope not matching the respective voice callsign or airline name (examples include Airtran Airways has a "TRS" data tag but pronounced "Citrus", and Express Jet Airlines has a "BTA" data tag but pronounced "JetLink"). Was it an issue to correlate verbal ATC instructions with the CPDLC instructions?	3.50 1.09	3.67 1.03	4.00 0.89	3.67 1.01

- Question #25a: The FIM spacing tool behaves in a predictable manner using a scale of 1 (completely disagree) to 7 (completely agree).

Table 41. Mean and Standard Deviation of Spacing Tool Predictability

	ATOL	DTS	IFD	All
25a. Based on my experience during this simulation, the spacing tool behaves in a predictable manner.	6.08 0.51	6.00 0.63	6.00 0.63	6.04 0.55

- Question #25b: It is important to be able to predict changes to the FIM Commanded Speed using a scale of 1 (completely disagree) to 7 (completely agree).

Table 42. Mean and Standard Deviation of Speed Change Predictability

	ATOL	DTS	IFD	All
25b. It is important to be able to predict changes to the commanded speed before they occur.	5.58 1.24	5.83 1.17	4.83 1.47	6.04 0.55

- Question #25c: The use of CPDLC messages was operationally acceptable as simulated in this experiment on a scale of 1 (completely disagree) to 7 (completely agree).

Table 43. Mean and Standard Deviation of Use of CPDLC Acceptability

	ATOL	DTS	IFD	All
25c. The use of CPDLC messages were operationally acceptable as simulated in this experiment.	6.17 1.03	6.67 0.52	6.00 1.55	6.25 1.07

A list of the post-experiment comments are given below.

- *"I believe the scenarios to be very realistic. I did feel that the several speed changes during the final phase was annoying, however I also realized with the IM spacing, that this may be necessary to "keep the gap" correct. I can tell you that my task saturation was very high at the beginning of the training and very low at the end."*
- *"The scenarios were well thought out and reasonably realistic. Having this many pilots and controllers working together, improved the realism of the scenarios immensely."*
- *"The most confusing and distracting part of flight in the terminal area is the volume of radio traffic. There was very little traffic on the radio in these scenarios."*
- *"Having more information on the spacing tool would help me do my job better. I believe a little more time spent on briefing or teaching the pilots the why, what, were, when and how would be more beneficial."*
- *"No training should be required to perform the scenarios with level of experience we have."*
- *"Do not believe that data tags (as seen on controller scopes and cockpit avionics) that are different than the voice callsigns is an issue."*
- *"Procedure of setting speed in Mode Control Panel (MCP) added to workload, especially in weather conditions."*

- *“Need clearance to intercept the glideslope further out if the arrival connects to an approach. Should also try some scenarios using Area Navigation (RNAV) approaches.”*
- *“Consider slower decel rates below 250 knots. Also need better speed alerting, especially when MCP speed window is open.”*
- *“The Flight deck Interval Management (FIM) conformance box gave me a general idea where I was, but not enough to tell me exactly where I was. I found myself using the IM page on the Flight Management Computer (FMC) to determine the number of seconds I was ahead/behind. Having that data alongside own aircraft on the Navigation Display (ND) might be more beneficial.”*
- *“I couldn't make out the conformance box. It was difficult to see on my display and it was further hidden by mileage on the route or by airports (blue circles) that we flew over. I don't think it added anything to make the system better. In my opinion, it was a nuisance.”*
- *“Once I'm below 10,000 ft MSL, I really don't want to be bothered by Controller-Pilot Datalink Communications (CPDLC) messages, especially if the weather is bad or there is high terrain in the area.”*
- *“The deceleration commands should accommodate the flap extension schedule speeds of the aircraft. For example, the Boeing 747-400 aircraft takes a long time to get to flaps 5, but then quickly extends flaps after that. So, the large deceleration to final approach speed should commence with flaps 5 or more, not from a speed where flaps 1 would be appropriate. Ideally, once below 10,000 feet, I would like to see only 3 commands, one for roughly 240 knots, one for roughly 200 knots, and one for final approach speed.”*
- *“I liked the target speed trend green "equals sign" on the speed tape. This helped me determine and adjust target deceleration/acceleration rates which allowed for smoother transitions and fewer self-inflicted FIM generated speed changes.”*

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The predicted increase in the number of commercial aircraft operations creates a need for improved operational efficiency. Two areas believed to offer increases in aircraft efficiency are optimized profile descents and dependent parallel runway operations. Using Flight deck Interval Management (FIM) software and procedures during these operations, flight crews can achieve by the runway threshold an interval assigned by air traffic control (ATC) behind the preceding aircraft that maximizes runway throughput while minimizing additional fuel consumption and pilot workload. This document describes an experiment where 24 pilots flew arrivals into the Dallas Fort-Worth terminal environment using one of three simulators at NASA's Langley Research Center. Results indicate that pilots delivered their aircraft to the runway threshold within +/- 3.5 seconds of their assigned time interval, and reported low workload levels. In general, pilots found the FIM concept, procedures, speeds, and interface acceptable. Analysis of the time error and FIM speed changes as a function of arrival stream position suggest the spacing algorithm generates stable behavior while in the presence of continuous (wind) or impulse (offset) error. Concerns reported included multiple speed changes within a short time period, and an airspeed increase followed shortly by an airspeed decrease.

15. SUBJECT TERMS

Air Traffic Operations Laboratory; Cockpit Displays; Controller-Pilot Datalink; Dependent Parallel Runways; Flight deck Interval Management

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