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Air Traffic Management Technology Demostration — 1 Research and Procedural Testing of Routes

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Abstract

NASA's Air Traffic Management Technology Demonstration – 1 (ATD-1) will operationally demonstrate the feasibility of efficient arrival operations combining ground-based and airborne NASA technologies. The ATD-1 integrated system consists of the Traffic Management Advisor with Terminal Metering which generates precise time-based schedules to the runway and merge points; Controller Managed Spacing decision support tools which provide controllers with speed advisories and other information needed to meet the schedule; and Flight deck-based Interval Management avionics and procedures which allow flight crews to adjust their speed to achieve precise relative spacing. Initial studies identified air-ground challenges related to the integration of these three scheduling and spacing technologies, and NASA's airborne spacing algorithm was modified to address some of these challenges. The Research and Procedural Testing of Routes human-in-the-loop experiment was then conducted to assess the performance of the new spacing algorithm. The results of this experiment indicate that the algorithm performed as designed, and the pilot participants found the airborne spacing concept, air-ground procedures, and crew interface to be acceptable. However, the researchers concluded that the data revealed issues with the frequency of speed changes and speed reversals.

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Abbreviations and Acronyms

ADS-B	Automatic Dependent Surveillance-Broadcast
ARC	Ames Research Center
ARTCC	Air Route Traffic Control Center
ASTAR	Airborne Spacing for Terminal Arrival Routes
ASTOR	Aircraft Simulation for Traffic Operations Research
ATC	air traffic control
ATD-1	Air Traffic Management Technology Demonstration–1
ATOL	Air Traffic Operations Laboratory
ATOS	Airspace and Traffic Operations Simulation
CGD	configurable graphics display
CMS	Controller Managed Spacing
CPDLC	Controller-Pilot Data Link Communications
DSR	Display System Replacement
DTS	Development and Test Simulator
EFB	electronic flight bag
ETA	estimated time of arrival
FAA	Federal Aviation Administration
FAF	final approach fix
FDB	full data block
FIM	Flight deck-based Interval Management
FL	flight level
FMC	flight management computer
FSF	Flight Simulation Facility
HITL	human-in-the-loop
IFD	Integration Flight Deck
IM	Interval Management
LaRC	Langley Research Center
MACS	Multi-Aircraft Control System
MCH	Modified Cooper-Harper
MCP	mode control panel
MCDU	multi-purpose control display unit
MOP	measure of performance
N	number of observations
NASA	National Aeronautics and Space Administration
OPD	optimized profile descent
p	*p*-value (note: a value < 0.05 indicates a statistically significant difference between sample means)
PBN	performance based navigation
PF	pilot flying
PHX	Phoenix Sky Harbor
PM	pilot monitoring
RAPTOR	Research and Procedural Testing of Routes
RNAV	area navigation
rTMA	research TMA-TM

SD	standard deviation
STA	scheduled time of arrival
STAR	standard terminal arrival route
STARS	Standard Terminal Automation Replacement System
TCAS	Traffic Collision Avoidance System
TMA	Traffic Management Advisor
TMA-TM	Traffic Management Advisor with Terminal Metering
TOD	top-of-descent
TRACON	Terminal Radar Approach Control
VNAV	vertical navigation
ZAB	Albuquerque Center

1 Introduction

Over the next twenty years, air traffic demand is predicted to increase by more than two percent per year [1]. Arrivals into high-density airports, especially during peak traffic periods and inclement weather, often experience significant inefficiencies due to the use of miles-in-trail procedures and step-down descents. Use of these current procedures contributes to reduced airport throughput, increased controller workload, increased arrival delay, and increased aircraft fuel burn, emissions, and noise. Although advanced arrival procedures are available, they are underutilized due to the lack of supporting technology.

The National Aeronautics and Space Administration's (NASA) Air Traffic Management Technology Demonstration – 1 (ATD-1) combines advanced ground-based and airborne scheduling and spacing technologies in order to enable efficient arrival operations in high-density terminal airspace [2] [3]. The ATD-1 integrated system consists of three core components.

- Traffic Management Advisor with Terminal Metering (TMA-TM) generates precise time-based schedules to the runway and merge points within the terminal area.
- Controller Managed Spacing (CMS) decision support tools provide controllers with speed advisories and other information needed to meet the schedule.
- Flight deck-based Interval Management (FIM) avionics and procedures allow flight crews to autonomously adjust their speed to achieve precise relative spacing.

The Traffic Management Advisor (TMA) was originally developed at NASA Ames Research Center (ARC) and is currently used at Air Route Traffic Control Centers (ARTCC) nationwide to determine an appropriate arrival schedule [4]. TMA-TM is an enhanced form of TMA that includes terminal area metering and enables the use of more efficient arrival procedures. CMS decision support tools, also developed at NASA ARC, provide controllers with the information necessary to achieve arrival schedule conformance using speed commands, thus reducing the use of tactical vectoring [5] [6]. The use of TMA-TM in conjunction with CMS tools has been assessed, and results indicate an increase in airport throughput [7] [8] [9] [10].

Interval Management (IM) is an airborne spacing concept in which the flight crew is responsible for flying their aircraft at a speed that achieves their assigned time-based spacing interval behind a target aircraft, while Air Traffic Control (ATC) remains responsible for ensuring that all aircraft maintain safe separation. In normal operations, ATC adds a spacing buffer to the separation requirement to ensure that separation is always maintained. The goal of airborne spacing is to decrease this spacing buffer by decreasing the variability of the time error associated with an aircraft's arrival at a specific point along its arrival route. The precise merging and spacing enabled by FIM avionics and flight crew procedures reduces excess spacing buffers and results in higher terminal throughput. Studies by MITRE [11] [12] [13], EUROCONTROL [14] [15] [16] [17], and NASA Langley Research Center (LaRC) [18] [19] [20] have demonstrated an increase in efficiency through the use of FIM operations.

In addition to utilizing these advanced technologies in ATD-1, aircraft will fly new, more direct Area Navigation (RNAV) routes that extend from en route airspace to the runway. Consistent use of fuel efficient descents on RNAV arrivals rather than the step-down descents used today is a key aspect for enabling broader use of Performance-Based Navigation (PBN). The Automatic Dependent Surveillance – Broadcast (ADS-B) infrastructure currently being implemented by the Federal Aviation Administration (FAA) will also be leveraged. The FIM tools will calculate speed commands using information provided by ADS-B, which is more accurate than traditional radar. The ability of flight crews to make more precise speed adjustments will enable a reduction in spacing buffers resulting in higher terminal throughput.

The ATD-1 scheduling and spacing technologies have been evaluated independently, and each has demonstrated benefits. As an integrated system, these technologies will increase throughput, reduce delay, and minimize environmental impacts. Studies at NASA ARC and LaRC to demonstrate the ATD-1 concept and validate operational feasibility indicate that the concept is viable and operations are acceptable [21] [22] [23] [24] [25]. A series of large-scale human-in-the-loop (HITL) simulations to evaluate system-level performance indicate that the ATD-1 ground-based technologies support PBN operations for high density traffic [26].

These initial studies have also revealed a number of challenges associated with the integration of the ground-based and airborne technologies. During high demand operations, TMA-TM may generate a schedule and corresponding aircraft trajectories that include a substantial amount of delay in order to ensure aircraft separation and spacing. ATC will adjust aircraft speeds and/or vector aircraft off path to adjust arrival times to meet the schedule. The FIM algorithm calculates the estimated times of arrival (ETA) for the ownship and the target aircraft, and uses the difference to calculate a commanded speed. Since aircraft conducting FIM operations have no knowledge of the delay assigned to their target aircraft, they must use the published speeds to compute the target aircraft's ETA. As a result, an aircraft performing FIM operations may follow a target aircraft with a TMA-TM generated trajectory that has substantial speed deviations from the speeds expected by the airborne spacing algorithm.

NASA's airborne spacing algorithm, Airborne Spacing for Terminal Area Routes (ASTAR), was modified to improve performance when following target aircraft with delayed trajectories. A batch simulation to investigate this new spacing algorithm with various delayed speed profiles and wind conditions indicated generally good performance. However, some types of target aircraft speed profiles were found to cause the spacing algorithm to command less than optimal speed control behavior [27].

To evaluate the performance of the new spacing algorithm with human pilots and controllers, the Research and Procedural Testing of Routes (RAPTOR) HITL simulation was conducted at NASA LaRC in 2014. The objective of this experiment was to assess if the new version of the ASTAR spacing algorithm (ASTAR-12) met the ATD-1 Project's requirements for the following ATD-1 Measures of Performance (MOP):

- Percentage of controller-interrupted FIM operations (MOP 3.3.3),
- Percentage of flight deck-interrupted FIM operations (MOP 3.4.3),
- Flight crew acceptability of FIM operations (MOP 3.4.4), and
- Flight crew workload during FIM operations (MOP 3.4.5).

This paper describes the methodology and results of the RAPTOR HITL experiment.

2 Method

2.1 Experiment and Scenario Design

The focus of the RAPTOR experiment was to assess the performance of the new ASTAR-12 airborne spacing algorithm. The airspace environment was modeled on the Albuquerque Center (ZAB) and Phoenix Sky Harbor (PHX) Terminal Radar Approach Control (TRACON) area. Each experiment scenario consisted of multiple air traffic flows involving 85 arrival aircraft flying the EAGUL FIVE and MAIER FIVE arrivals into PHX airport and landing on runway 26. Four of the arrival aircraft were flown by subject pilots operating as two-person crews. Two of these subject pilot crews flew full-scale, high fidelity fixed-base simulators, while the other two employed medium-fidelity desktop simulators. All four simulators were equipped with the ASTAR-12 (version 12.02.34) airborne spacing algorithm and a flight deck control-display interface to enable FIM operations. Four additional arrival aircraft, which served as the target aircraft for FIM operations, were flown by four confederate pilots using medium-fidelity desktop simulators. The remaining 77 arrival traffic aircraft were flown by five pseudo-pilots, each of whom operated a single station that allowed him to control the basic functions of multiple aircraft. Five recently retired air traffic controllers served as Center (ZAB 43), Center (ZAB 39), Feeder, Final, and Ghost controllers issuing speed commands, vectors, and IM clearances.

Subject aircraft performing FIM operations were expected to use the ASTAR-provided speed guidance whenever possible. This speed guidance is designed such that the spacing aircraft will achieve the assigned spacing goal behind the target aircraft at a predefined achieve-by point while remaining within 15% of the published RNAV arrival airspeed. In this experiment, the achieve-by point was the final approach fix (FAF). The FIM flight deck control-display interface shown in Figures 1 and 2 consisted of two side-mounted electronic flight bags (EFB) and configurable graphics display (CGD) devices mounted on the left and right outboard panels in the pilot's forward field-of-view.

During the RAPTOR experiment, the flight crew initially programmed ownship information into the EFBs. Confederate air traffic controllers issued the IM clearance via radio to the flight crew, who then entered the following information into the EFBs:

- Assigned spacing goal (spacing interval required at the IM achieve-by point),
- Target aircraft call sign, and
- Target aircraft flight path (arrival and transition).

After activating the FIM avionics, the flight crew flew the IM commanded speeds to achieve a precise spacing interval at the FAF.

Figure 1. Configurable graphics display

Figure 2. Electronic flight bag

Two flight scenarios were defined using the 1x2 experiment matrix shown in Figure 3 to allow an examination of two different wind fields based on actual winds recorded at PHX. The winds fields, a pairing of truth and forecast winds, were selected from a set of days that were used across the ATD-1 simulations and had been previously identified as stressing conditions. The first wind field was from 01/10/2011, while the second was from 06/12/2011. Wind error has been shown to excite the groundspeed feedback term that was added to the ASTAR-12 spacing algorithm [28], and so these two winds were carefully chosen in order to examine the spacing performance of the FIM aircraft. The wind 01/10 scenario included very strong wind conditions at altitude and light to moderate wind at the airport. Scheduling delays for the target and FIM aircraft in this scenario ranged from two to nearly five minutes. The wind 06/12 scenario included moderate winds at altitude with schedule delays ranging from 30 seconds to three minutes.

Initial conditions of the aircraft were based on actual traffic recorded at PHX on 11/14/2011 at 18:00. This West flow traffic scenario was also used in the CA-5.1 HITL simulation conducted at NASA ARC. Modifications to this traffic scenario were made based on subject matter expertise, and included the removal of turboprops on the SWIRL arrival, overflights, and departures. Only the North side of the PHX airport with arrivals to runway 26 was simulated during the RAPTOR experiment. Additional details regarding the design of the experiment scenarios and graphical representations of the standard terminal arrival routes (STARs) used during the experiment are included in Appendix A.

Forecast: 20110110/09Z Truth: 20110110/06Z	Forecast: 20110612/05Z Truth: 20110612/02Z
Wind 01/10	Wind 06/12

Figure 3. Experiment design matrix

2.2 Participants

2.2.1 Subject Pilots

Subject pilots consisted of four two-person crews of current, qualified 757/767, 777, and 787 pilots employed by major U.S. air carriers (i.e., a total of eight commercial airline pilots). All subject pilots were male and ranged from 38 to 64 years in age. On average, the pilots had 22 years of airline experience and over 12,750 hours of commercial airline flight time. To minimize potential effects associated with different airline operating procedures, all two-person crews were paired from the same airline, and the pilots flew in their current operational position (captain or first officer) using their company's standard operating procedures modified to include FIM operations. These subject pilots participated in a two-day experiment session at NASA LaRC on February 5-6, 2014.

Data were also collected from six crews of current, qualified 757/767 and 777 pilots during two single day experiment sessions conducted in January 2014. However, data collected in January were not included in formal analyses since strict adherence to the RAPTOR experiment protocol was not possible due to unexpected weather-related closings of LaRC on January 29 and 30, a required software change implemented on February 3, and changes in controller behavior observed during the experiment sessions conducted in January as compared with those conducted in February.

2.2.2 Confederate Pilots and Pseudo-Pilots

Four confederate pilots utilized medium-fidelity desktop simulators to operate four human-piloted target aircraft for FIM operations. These pilots were male and ranged from 57 to 66 years in age. They had an average of 29 years and 16,000 hours of commercial airline experience.

Five additional pseudo-pilots used desktop pseudo-pilot stations to operate 77 traffic arrival aircraft by responding to controller commands issued via radio communications. These pseudo-pilots were male and ranged in age from 61 to 70 years. On average, these pilots had 17 years of military flight experience, 19 years of commercial airline experience, and over 12,800 hours of commercial airline flight time.

2.2.3 Confederate Controllers

Five recently retired air traffic controllers served as confederate controllers. The confederate controllers included two ZAB Center controllers (sectors 43 and 39), one PHX Feeder controller, one PHX Final controller, and one Ghost controller. The three en route controllers had 25-26 years of en route ATC experience at Oakland ARTCC. The Feeder and Final controllers had 34.5 and 15 years of TRACON experience, respectively. All five controllers were trained at NASA ARC in the use of the ground-based tools and had participated in previous ATD-1 experiments.

2.3 Experiment Protocol

The subject pilots received training materials and had access to computer-based training prior to arriving at NASA LaRC. After arriving at LaRC, the pilots received six hours of classroom and hands-on training, including flying five training scenarios. The four two-person crews participated in a two-day experiment session and completed a total of four data collection flights. The first day of the experiment session began with classroom and hands-on training, and then one data collection flight was conducted. The second day consisted of the remaining data collection flights, followed by a post-experiment questionnaire and group debrief session. Each data collection flight lasted approximately 45 minutes, and pilots completed a post-run questionnaire following each flight. Post-run and post-experiment questionnaires were also administered to and feedback was collected from the confederate controllers.

Each flight crew flew both experiment scenarios twice – once with the captain as the pilot flying (PF) and the first officer as the pilot monitoring (PM), and once with the first officer as the PF and the captain as the PM – for a total of four experiment runs. The run order was partially counterbalanced, and within each crew the pilots switched PF and PM responsibilities between runs. The Center and Ghost controllers also rotated positions between runs. Additional details regarding the daily schedule and experiment run order are included in Appendix B.

2.4 Scheduling and Spacing Technologies

This experiment utilized an integrated set of ground-based and airborne technologies consisting of TMA-TM, CMS decision support tools, and FIM avionics and procedures. These scheduling and spacing technologies are described below.

2.4.1 Traffic Management Advisor with Terminal Metering

TMA-TM is an extension of the operational TMA that determines an arrival schedule based on airport conditions, airport capacity, required spacing, and weather conditions. This scheduling tool uses the predicted trajectory of each aircraft along its projected arrival route to calculate the ETA and corresponding Scheduled Time of Arrival (STA) at various meter and merge points along the aircraft flight path. The schedule is then deconflicted at each of the scheduling waypoints by delaying aircraft until they are properly spaced. The TMA-TM schedule is broadcast to the en route and TRACON controller positions for use by the CMS tools to assist the controllers in maintaining optimum flow rates to the runways.

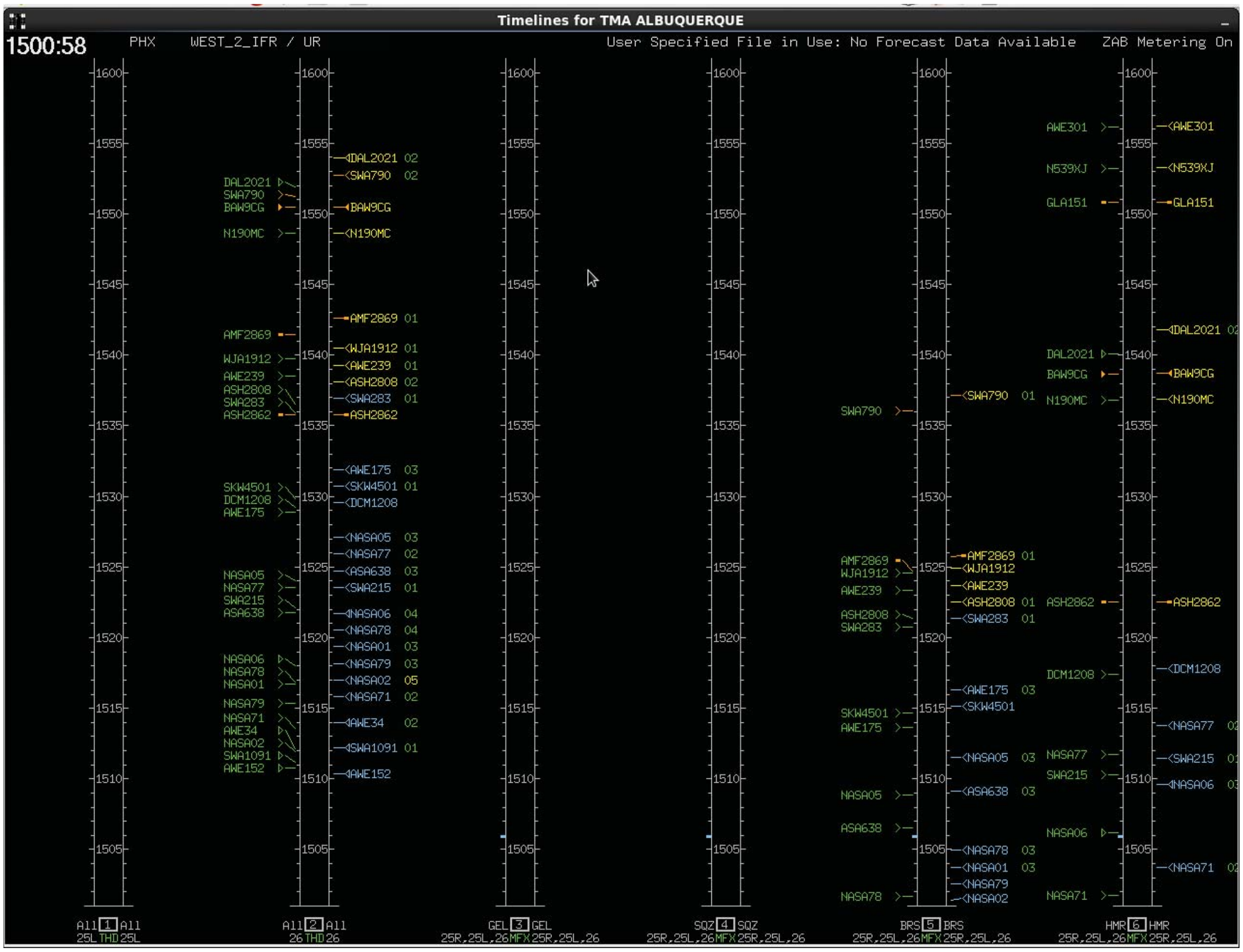

Figure 4. Traffic Management Advisor with Terminal Metering display

The research version of TMA-TM (rTMA) utilized during the RAPTOR experiment had the display shown in Figure 4 with six timelines of which three were active. The second timeline showed the arrival schedule for PHX runway 26, and the fifth and sixth timelines showed the arrival schedule for two metering fixes around the PHX TRACON. The current clock time (1500:58) appears in the upper left corner. The white numbers located in the middle of each timeline indicate minutes after the hour. As time progresses, the timelines scroll toward the bottom of the screen with the current time at the bottom and one hour in the future at the top. On the left of each timeline, each aircraft's ETA at the metering fix or runway threshold is shown in green. On the right side of each timeline, the aircraft's STA is shown in amber or cyan. As aircraft approach the airport, TMA continually recalculates the schedule based on the aircraft's current ETA until the aircraft reaches a freeze horizon set at 160 NM from each metering fix. After crossing the freeze horizon, the schedule for each aircraft remains fixed. An amber call sign indicates that an aircraft is outside of the freeze horizon, and a cyan call sign indicates that it is past the freeze horizon. If the green indicator on the left side of the timeline is below the corresponding indicator on the right, the aircraft is early; otherwise, the aircraft is late.

2.4.2 Controller Managed Spacing

CMS decision support tools provide TRACON controllers with the information needed to meet the TMA-TM generated schedule. The CMS tools used in the RAPTOR experiment were available to both the Feeder and Final controllers, and consisted of timelines, slot markers, early/late indicators, speed advisories, and sequence numbers (see Figure 5).

The schedule timelines provide graphical depictions of an aircraft's schedule conformance by displaying the relationship between each aircraft's ETA and STA to a merge point or the runway threshold. If the ETA is earlier than the STA, the aircraft needs to absorb delay; if the ETA is later than the STA, the aircraft needs to be advanced.

Slot marker circles indicate where an aircraft should be located at a given time if it were to fly the RNAV arrival, through the forecasted wind field, meeting all published speed and altitude restrictions, and arrive at its STA to the merge point or runway threshold. The relative position of the aircraft symbol and the slot marker provides a quick visual indication of how the aircraft is positioned relative to its STA. If the aircraft is on schedule, the aircraft symbol is centered within the slot marker. In this experiment, the diameter of the slot marker circle represented 15 seconds of flying time at the aircraft's current ground speed.

Early/late indicators in the aircraft full data block (FDB) enable controllers to quickly assess the schedule conformance information for that aircraft. These indicators represent the difference in minutes and seconds between the ETA and STA to the next merge point or the runway threshold. They are generated when a single speed advisory cannot be calculated to resolve schedule conformance with a 10 knot discrimination and the difference between the ETA and STA is greater than or equal to five seconds.

Speed advisories in the aircraft FDB enable controllers to formulate speed clearances for aircraft not performing FIM operations. The speed advisory is a recommended calibrated airspeed (CAS) which is predicted to place the aircraft back on schedule before reaching the scheduling fix. Speed advisories are displayed when an aircraft's ETA is more than five seconds earlier or later than its STA, and only if the predicted speed will resolve the difference between the ETA and STA by the next metering point; otherwise the early/late indicator is shown.

Sequence numbers in the aircraft FDB display the number of the aircraft in sequence to the runway.

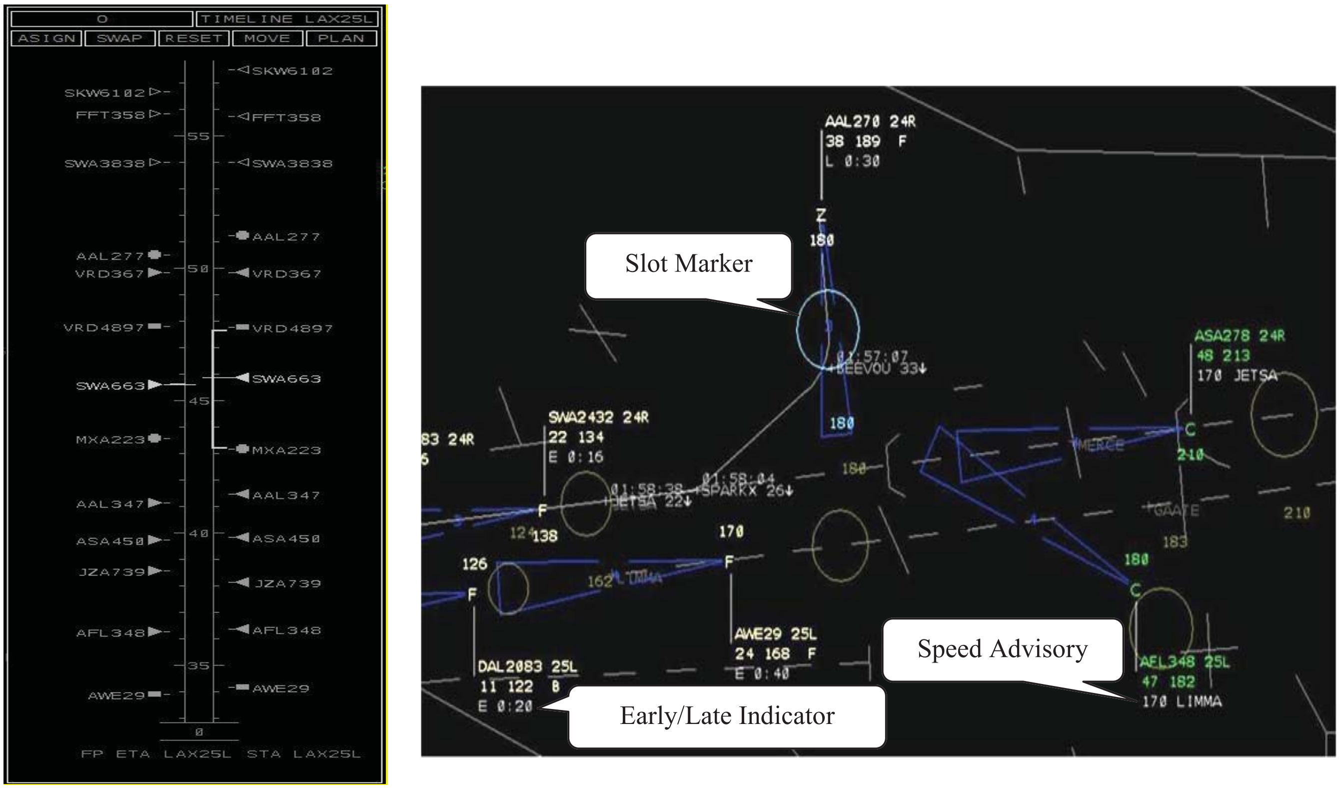

Figure 5. Controller Managed Spacing tools

2.4.3 Flight deck-based Interval Management

The FIM tools provide onboard speed guidance to the flight crew to achieve a precise spacing interval behind a target aircraft and meet the schedule set by TMA-TM. The FIM avionics include a spacing algorithm onboard the aircraft that uses information provided by ATC in the form of an IM clearance along with ADS-B data from the target aircraft to compute IM commanded speeds. The flight crew follows these speeds to achieve precise in-trail spacing at a designated achieve-by point.

In order to perform FIM operations in this experiment, all FIM aircraft were equipped with NASA LaRC's airborne spacing algorithm, ASTAR-12, and a flight deck control-display interface (see Figures 1 and 2). The ASTAR algorithm produces speed guidance by determining time-to-go until an aircraft and its target reach an achieve-by point along a 4-D trajectory. The procedure for conducting a FIM operation began when ATC provided a FIM-equipped aircraft with an IM clearance, which included the target aircraft's call sign and route, and a spacing goal computed by rTMA. The flight crew then entered this information into the interface and followed the speeds provided by the algorithm to achieve the spacing interval at the FAF.

During FIM operations, the EFB displayed the target aircraft call sign; the commanded speed required to achieve precise interval spacing behind the target aircraft; and a Fast/Slow indicator to provide trend information and guidance regarding required FIM aircraft decelerations and accelerations to conform to the ASTAR algorithm. In order to provide the pilots with required information in the forward field-of-view, the CGD supplied the following five elements during a FIM operation:

- FIM status indication of when the FIM aircraft was actively performing FIM operations,
- Target aircraft call sign,
- Commanded speed,
- Fast/Slow indicator, and
- System caution and information messages.

Upon reaching the FAF, the information on the EFBs and CGDs was turned off, and the flight crew began decelerating to their landing speed. Appendix C illustrates the use of the EFB for data entry, activation, suspension, resumption, cancellation, and termination of FIM operations. Illustrations of the information elements presented on the CGD during FIM operations are also provided.

In addition to the avionics onboard the FIM aircraft, several FIM indicators on the controller displays were also utilized during this experiment. FIM information displayed in the Meter List provided en route controllers with the information necessary to issue the IM clearance. This included the aircraft call sign, meter fix STA, meter fix delay, spacing interval in seconds, target aircraft call sign, and target aircraft route as shown in Figure 6.

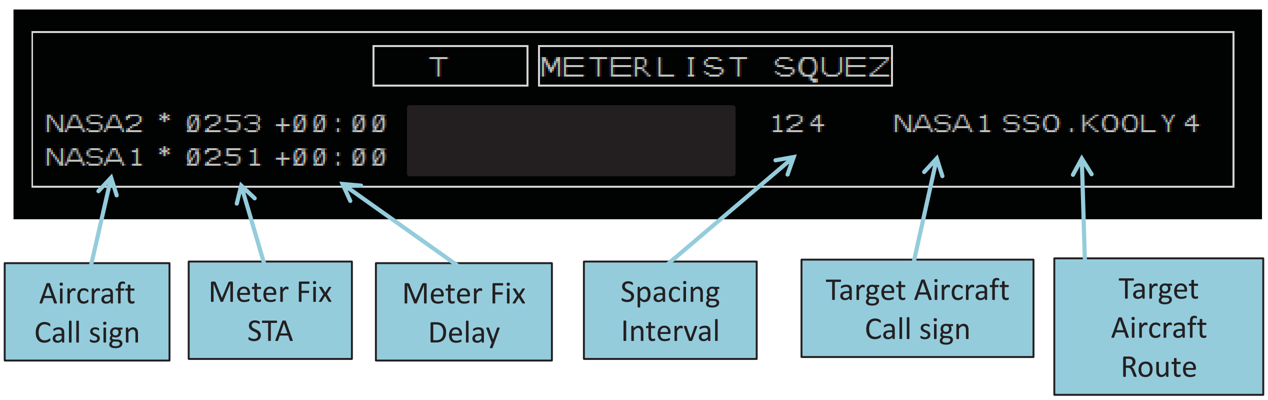

Figure 6. FIM information displayed on Meter List

FIM advisory displays to the en route controllers indicated the eligibility and status of the IM clearance. Aircraft that were FIM capable displayed a yellow "@" symbol on top of the FDB. This was changed to a magenta "@" symbol after the controller issued the IM clearance, and to a magenta "S" once the aircraft reported paired spacing (see Figure 7). On the feeder and final controller displays, aircraft that had been issued an IM clearance displayed "FIM" in the FDB, and aircraft that were currently performing FIM operations displayed "SPC" in the FDB. These symbols are shown in Figure 8.

Aircraft is FIM capable

Aircraft has been given IM clearance

Aircraft has reported paired spacing with target aircraft

Figure 7. IM clearance eligibility and status indicators for en route controllers

IM clearance not issued

Aircraft has been issued IM clearance

Aircraft has reported paired spacing with target aircraft

Figure 8. IM clearance status indicators for TRACON controllers

2.5 Facilities and Equipment

The RAPTOR experiment utilized two facilities at NASA LaRC: the Flight Simulation Facility (FSF) and the Air Traffic Operations Laboratory (ATOL). Descriptions of each facility and its equipment are provided in this section.

2.5.1 Flight Simulation Facility

During the RAPTOR scenarios, two of the four FIM aircraft were flown by subject pilots utilizing two of the full-scale simulators within the FSF – the Integration Flight Deck (IFD) and the Development and Test Simulator (DTS) [29].

2.5.1.1 Integration Flight Deck

The IFD is a full-scale simulator representative of a large commercial transport category aircraft and is driven by an appropriate aircraft dynamics mathematical model. The cockpit includes standard ship's instruments representative of a line operations aircraft, and the cockpit's visual system is a panorama system that provides 200° horizontal by 40° vertical field-of-view. During the RAPTOR experiment, one of the four subject flight crews flew the IFD, and the visual scene used was the PHX terminal environment in a daytime setting. As noted previously, the IFD simulator was equipped with the ASTAR algorithm and the prototype FIM crew interface to enable the flight crew to perform FIM operations. Figure 9 shows the positions of the EFBs and CGDs within the IFD.

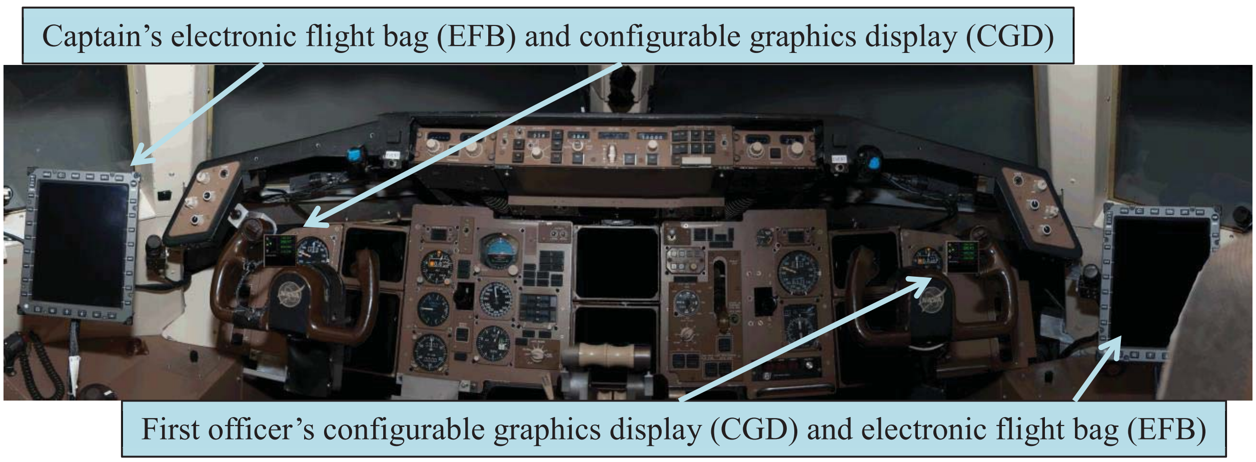

Figure 9. Integration Flight Deck equipped with the flight-deck control display interface

2.5.1.2 Development and Test Simulator

The DTS is a full-scale fixed-base simulator representative of a large generic commercial transport category aircraft, and is driven by a high-fidelity aerodynamic mathematical model. The cockpit displays are incorporated in four 17-inch displays and the visual system includes a 210° horizontal by 45° vertical out-the-window field-of-view. In order to enable the flight crew to perform FIM operations, the DTS was equipped with the ASTAR algorithm, two side-mounted EFBs, and two CGDs rendered using portions of the simulator's existing outboard heads-down displays (see Figure 10).

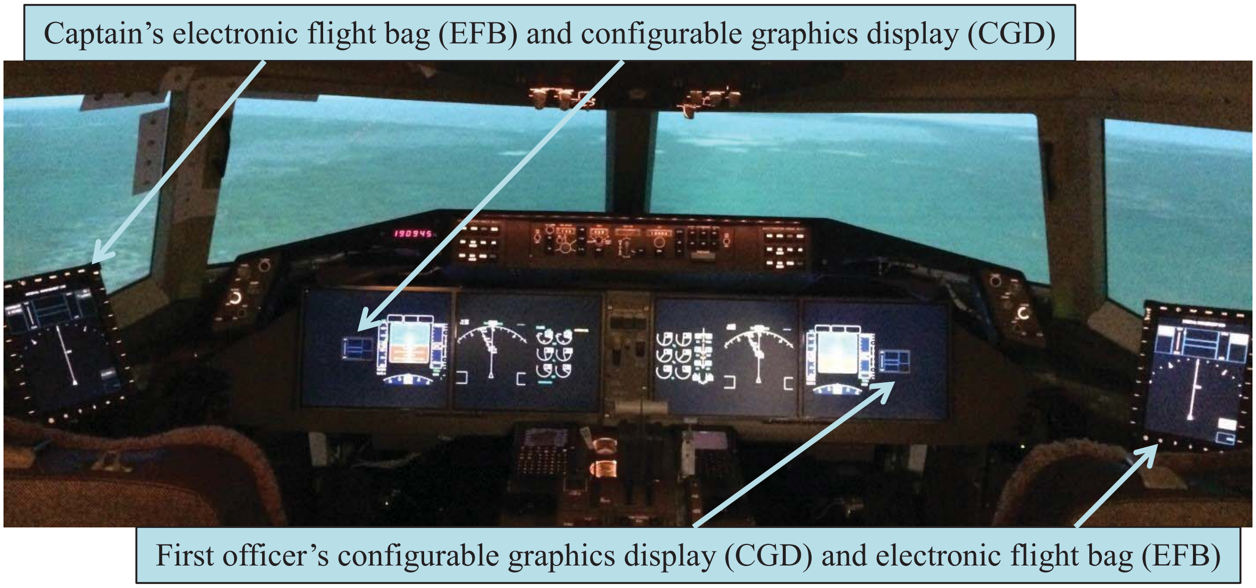

Figure 10. Development and Test Simulator equipped with the flight-deck control display interface

2.5.2 Air Traffic Operations Laboratory

The ATOL contains a network of hundreds of real-time, medium-fidelity aircraft simulators and utilizes a simulation platform, known as the Airspace and Traffic Operations Simulation (ATOS), which can be used for both batch and real-time HITL experiments. During the RAPTOR HITL experiment, two FIM aircraft, four target aircraft, and 77 traffic aircraft (total of 83 of the 85 aircraft in each scenario) were simulated in the ATOL. ATC stations within the ATOL were also utilized to enable confederate air traffic controllers to provide a realistic ATC environment.

2.5.2.1 ASTOR Stations

Each desktop aircraft simulator within the ATOL is referred to as an Aircraft Simulation for Traffic Operations Research (ASTOR) [30]. An ASTOR provides a medium-fidelity representation of a commercial transport aircraft, its flight deck systems, and the airborne components of a realistic future communications, navigation, and surveillance infrastructure. ASTORs can be configured for single-crew or dual-crew operations.

Two of the four FIM aircraft flown by subject pilots during the RAPTOR experiment were simulated using two dual-crew ASTORs. The dual-crew ASTORs were utilized in order to provide the crew interaction that is critical in today’s airlines. Each of these desktop simulators contained a high-fidelity six degree of freedom dynamics model and aircraft displays shown on three 27-inch touchscreen monitors (Figure 11). Pilots interacted with the simulators through either a mouse or touchscreen interface. In addition to normal aircraft systems, the prototype FIM crew interface was emulated on the dual-crew ASTORs to enable flight crews to perform FIM operations. The four target aircraft flown by confederate pilots were simulated using four single-crew ASTORs.

Figure 11. Dual-crew ASTOR desktop simulator displays

2.5.2.2 MACS Pseudo-Pilot Stations

The majority of the aircraft in the RAPTOR experiment were simulated using the NASA ARC Multi-Aircraft Control System (MACS) [31]. The use of MACS desktop pseudo-pilot stations allowed a single operator to control the basic functions of multiple aircraft. The 77 traffic aircraft were controlled by a group of five MACS pseudo-pilots, with three pilots working the ZAB high altitude sectors and two pilots working the PHX TRACON feeder and final sectors. Figure 12 illustrates some of the items that can be shown on a MACS pseudo-pilot display. The pseudo-pilot can take control of any active MACS aircraft by selecting it from the aircraft list with a mouse click. The aircraft's speed, heading, and altitude can be altered by entering changes in the MACS Mode Control Panel (MCP) or Multi-Purpose Control Display Unit (MCDU).

Figure 12. MACS pseudo-pilot station display

2.5.2.3 ATC Stations

ATC controller stations equipped with MACS were utilized within the ATOL to enable confederate air traffic controllers to provide a realistic ATC environment. All controller positions used standard Display System Replacement (DSR) or Standard Terminal Automation Replacement System (STARS) displays augmented with CMS tools. Five recently retired air traffic controllers served as confederate Center (ZAB 43), Center (ZAB 39), Feeder, Final, and Ghost controllers.

3 Results and Discussion

Quantitative data, audio and video recordings, and researcher observations were collected to assess the ATD-1 MOPs regarding the number of violations of separation, percentage of controller-interrupted FIM operations, FIM spacing goal conformance, and percentage of flight deck-interrupted FIM operations. To assess flight crew acceptability of FIM operations and flight crew workload of FIM operations, subjective response data were collected via electronic post-run questionnaires. The pilot and controller post-run and post-experiment questionnaires are included in Appendices D, E, F, and G.

Due to the small sample size, data from the PF and PM were combined. Data were also combined across the three different simulator types (IFD, DTS, and dual-crew ASTORs). It should be noted that a simulation artifact caused inaccurate temperature modeling which may have affected the spacing, possibly resulting in inaccurate spacing intervals and violation of separation criteria, particularly for the wind 06/12 scenario.

3.1 Number of Violations of Required Separation (MOP 3.2.1)

The separation violations recorded during the experiment are shown in Table 1. The first two columns in the Table indicate the run number and wind field of the scenario. The next four columns show the call sign and arrival route of the aircraft involved in the separation violation. The last four columns show the required horizontal separation, actual minimum horizontal and vertical separation, and location where the violation occurred. There were nine violations in total, eight of which occurred during the wind 06/12 scenario. Eight of the nine separation violations involved aircraft flown by the subject pilots.

During Run 1, the flight crew in NASA02 did not comment on the separation violation. The violation involving NASA05 corresponds to the flight deck-interrupted FIM operation discussed in Section 3.4. Additional details regarding pilot perceptions and events that occurred during the violation involving NASA06 in Run 1 are discussed in Section 3.5. The subject pilots flying NASA01 during Run 3 did not mention the separation violation, but one did comment on receiving many speed changes at low altitude, including a speed reversal. During Run 4, none of the flight crews commented on the separation violations. One of the pilots in NASA05 did mention that he had to configure the aircraft much earlier than he would have during an operational situation.

Table 1. Violations of required separation

Run	Wind	Aircraft1	Route1	Aircraft2	Route2	Horizontal Sep Req (NM)	Min Horizontal Sep (NM)	Min Vertical Sep (ft)	General Location
1	06/12	NASA79	MAIER	NASA02	MAIER	4.0	3.5	1300	On Final
		NASA71	MAIER	NASA06	EAGUL	2.5	2.3	800	On Final
		NASA77	EAGUL	NASA05	MAIER	2.5	2.4	820	On Final
		DCM1208	EAGUL	SKW4501	MAIER	3.0	2.9	863	Turn onto Final
3	01/10	NASA79	MAIER	NASA01	MAIER	2.5	2.4	820	On Final
4	06/12	NASA79	MAIER	NASA02	MAIER	4.0	3.5	1300	On Final
		NASA78	EAGUL	NASA01	EAGUL	4.0	3.6	1300	On Final
		NASA71	MAIER	NASA06	EAGUL	2.5	2.3	800	On Final
		NASA77	EAGUL	NASA05	MAIER	2.5	2.3	800	On Final

3.2 Percentage of Controller-Interrupted FIM Operations (MOP 3.3.3)

The number of controller-interrupted FIM operations was determined from the video and audio recordings, in addition to researcher observations. The percentage of controller-interrupted FIM operations was then computed for each scenario by

Percentage of controller-interrupted FIM operations
= 100% * number of controller-interrupted FIM ops / total number of FIM ops.

There was only one controller-interrupted FIM operation (see Table 2), which occurred during the first run of the wind 06/12 scenario. NASA01 was performing FIM operations during hand-off to final approach. The flight crew checked-in, informed the final controller that they were paired behind their target aircraft, and reported their current speed. The final controller interpreted this reported speed as having been previously commanded by the feeder controller, and responded "NASA01, Phoenix Approach, you are cleared runway 26 ILS approach resume, correction, fly normal speeds." The final controller intended the aircraft to resume FIM operations and fly the IM commanded speeds. However, the flight crew interpreted "fly normal speeds" as terminating FIM operations, so they flew the published approach for the remainder of the flight. This miscommunication resulted in an unintentional controller-interrupted FIM operation.

In order to assess the following *a priori* hypothesis,

Hypothesis 1: The rate of early FIM termination by ATC is less than 30%,

statistical analysis was performed using the binomial test of one proportion [32] to test whether the percentage of controller-interrupted FIM operations was less than or equal to 30% vs. the percentage was more than 30%. For both scenarios, the percentage of FIM operations interrupted by the controller was not significantly more than 30% ($p \geq 0.942$).

Table 2. Percentage of controller-interrupted FIM operations

Scenario	N	Number of Controller-Interrupted FIM Operations	Percentage of Controller-Interrupted FIM Operations
Wind 01/10	8	0	0.0%
Wind 06/12	8	1	12.5%

3.3 FIM Spacing Goal Conformance (MOP 3.4.1)

Descriptive statistics associated with the spacing error at the FAF for flights with interrupted FIM operations (see Sections 3.2 and 3.4), flights with uninterrupted FIM operations, and all flights combined are shown in Table 3 and histograms are shown in Figures 13, 14, and 15. The observed spacing error was within ±10 sec for all flights during the experiment, with the largest errors occurring during the wind 06/12 scenario.

In order to assess the following *a priori* hypothesis,

> Hypothesis 2: The mean spacing error at the FAF will be within ±5 seconds (sec) with a standard deviation of 5 sec,

statistical analysis was performed to test the mean and standard deviation of the spacing error using the one-sample t-test and one-sample variance test, respectively [33]. For the wind 01/10 scenario, the spacing error at the FAF had a mean within ±5 sec ($p < 0.001$) and a standard deviation significantly less than 5 sec ($p = 0.008$).

For the wind 06/12 scenario, the two flights with interrupted FIM operations resulted in the aircraft crossing the FAF 2.6 sec early and 9.7 sec late. Flights with uninterrupted FIM operations had a mean spacing error significantly less than 5 sec ($p = 0.001$), but -5 sec was not a lower bound ($p = 0.304$). The results are the same when all flights are combined with 5 sec being an upper bound on the mean spacing error ($p = 0.004$) but -5 sec not a lower bound ($p = 0.109$). The standard deviation of the spacing error at the FAF was not significantly less than 5 sec when considering either all FIM operations ($p = 0.761$) or uninterrupted FIM operations only ($p = 0.234$). This indicates that flights performing FIM operations tended to arrive early and the variability in the arrival times was slightly higher than desired.

Table 3. Descriptive statistics for spacing error at the FAF (sec)

Scenario	FIM Operations	*N*	Mean	SD	Min	Median	Max	95% CI on Mean	95% UB for SD
Wind 01/10	All	8	-1.06	2.03	-5.0	-0.8	2.1	(-2.76, 0.63)	3.64
Wind 06/12	All	8	-2.26	5.73	-9.1	-2.2	9.7	(-7.06, 2.53)	10.30
	Uninterrupted	6	-4.20	3.59	-9.1	-3.1	-0.6	(-7.96, -0.44)	7.49
	Interrupted	2	3.55	-	-2.6	3.6	9.7	-	-

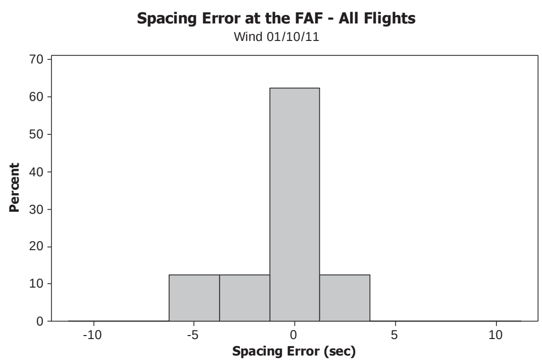

Figure 13. Spacing error at the FAF for all flights during the wind 01/10 scenario

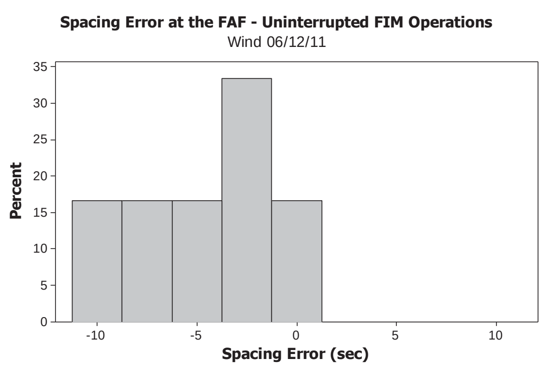

Figure 14. Spacing error at the FAF for uninterrupted FIM operations during the wind 06/12 scenario

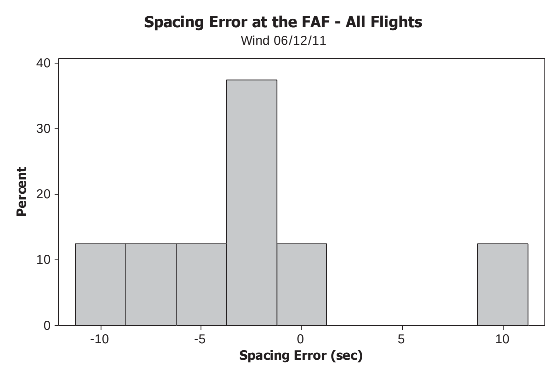

Figure 15. Spacing error at the FAF for all flights during the wind 06/12 scenario

3.4 Percentage of Flight Deck-Interrupted FIM Operations (MOP 3.4.3)

The number of flight deck-interrupted FIM operations was determined using the audio and video recordings, as well as researcher observations. A FIM operation was considered to be interrupted if it was terminated or suspended without being resumed more than 0.5 NM prior to the FAF. The percentage of flight deck-interrupted FIM operations was then computed for each scenario by

Percentage of flight deck-interrupted FIM operations
= 100% * number of flight deck-interrupted FIM ops / total number of FIM ops.

One flight deck-interrupted FIM operation occurred during the first run of the wind 06/12 scenario (see Table 4). When the flight crew in NASA05 heard the final controller slow their target aircraft to final approach speed, they estimated that they were 2.5 NM behind the target. They felt uncomfortable with this spacing and with the commanded speeds at this time, particularly with the target aircraft being slowed down. The flight crew then decided to suspend FIM operations approximately 3.2 NM prior to the FAF. They contacted the final controller and followed the suspend procedure.

In order to assess the following *a priori* hypothesis,

Hypothesis 3: The rate of early FIM termination by the flight deck is less than 30%,

statistical analysis was performed using the binomial test of one proportion to test whether the percentage of flight deck-interrupted FIM operations was less than or equal to 30% vs. the percentage was more than 30%. For both scenarios, the percentage of FIM operations interrupted by the flight deck was not significantly more than 30% ($p \geq 0.942$).

Table 4. Percentage of flight deck-interrupted FIM operations

Scenario	*N*	Number of Flight Deck-Interrupted FIM Operations	Percentage of Flight Deck-Interrupted FIM Operations
Wind 01/10	8	0	0.0%
Wind 06/12	8	1	12.5%

3.5 Flight Crew Acceptability of FIM Operations (MOP 3.4.4)

The flight crew acceptability of FIM operations was measured using a 7-point Likert rating scale, and data were collected from each of the subject pilots via electronic post-run questionnaires. In order to assess the following *a priori* hypothesis,

Hypothesis 4: Pilots will report the mean acceptability of FIM operations greater than or equal to ‘5’ (i.e., 70% of the 7-point scale where a rating of ‘5’ indicates “Slightly Agree”), data from the following items of the pilot post-run questionnaires were used.

Item 13. Please rate the overall FIM acceptability during the scenario you just completed.
Item 15 (b). I was not rushed or hurried in completing the task.
Item 15 (c). The IM commanded speeds were operationally acceptable.
Item 15 (d). The IM commanded speeds were operationally appropriate.
Item 15 (e). The frequency of the IM speed commands was acceptable at all times throughout the scenario.
Item 15 (g). The use of voice communications to provide the IM clearance(s) was acceptable in this scenario.
Item 15 (h). The amount of head down time required to input information from the IM clearance(s) into the EFB was acceptable.
Item 15 (i). During this scenario, entering IM clearance information into the EFB was easy and intuitive.
Item 15 (j). During this scenario, it was easy to obtain needed information from the IM displays.
Item 15 (l). The flight crew procedures for the events in this scenario were acceptable.

Data from the PF and PM were combined, and statistical analysis was performed using the Wilcoxon signed rank test, a nonparametric test appropriate for analyzing ordinal data with a within-subject design [32].

Questionnaire item 13 used a 7-point scale with anchor points ranging from '1' = "Completely Unacceptable" to '7' = "Completely Acceptable." Descriptive statistics associated with the pilot ratings of overall FIM acceptability are shown in Table 5, and histograms are shown in Figures 16 and 17. For both scenarios, the flight crews found the FIM operations to be acceptable ($p < 0.0005$). One pilot provided an overall FIM acceptability rating of '3' and reported inadequate separation with the target aircraft on final despite early configuration and manual speed reductions prior to the FAF. This flight corresponds to the separation violation in Run 1 of the wind 06/12 scenario with NASA06 shown in Table 1. The pilot who rated the acceptability as '4' in the wind 01/10 scenario reported an issue with no Traffic Collision Avoidance System (TCAS) display prior to top of descent which caused a distraction, and indicated that the number of speed changes was manageable but felt they increased his workload. This same pilot also reported an overall acceptability rating of '2' during a wind 06/12 scenario, but did not provide any additional details.

Table 5. Descriptive statistics for ratings of overall FIM acceptability from questionnaire item 13

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.375	0.806	4	6.5	7
Wind 06/12	16	5.938	1.526	2	6.5	7

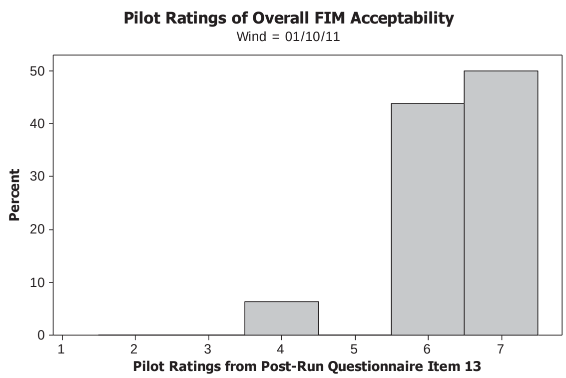

Figure 16. Pilot ratings of overall FIM acceptability during the wind 01/10 scenario

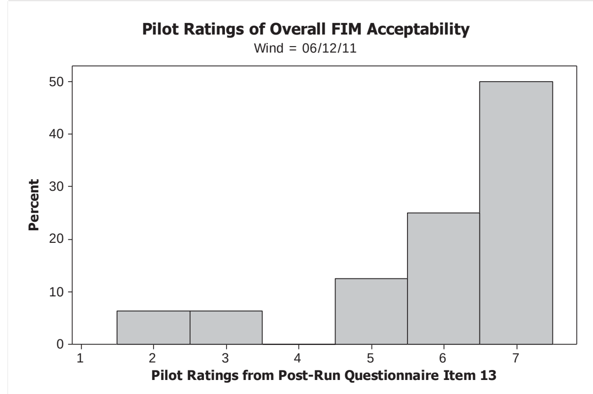

Figure 17. Pilot ratings of overall FIM acceptability during the wind 06/12 scenario

Questionnaire items 15 (b), (c), (d), (e), (g), (h), (i), (j), and (l) used a 7-point scale with anchor points ranging from '1' = "Completely Disagree" to '7' = "Completely Agree." Descriptive statistics associated with the pilots' ratings are shown in Tables 6 - 14, and histograms are shown in Figures 18 – 35.

For questionnaire item 15 (b), the flight crews found the pace of the operational task to be acceptable for both scenarios ($p < 0.0005$). The rating of '2' for the pace of the operational task was provided by the pilot who experienced the TCAS issue mentioned previously.

Table 6. Descriptive statistics for pilot acceptability ratings of FIM operations (i.e., pace of operational task) from questionnaire item 15 (b)

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.125	1.310	2	6.5	7
Wind 06/12	16	6.250	0.856	4	6	7

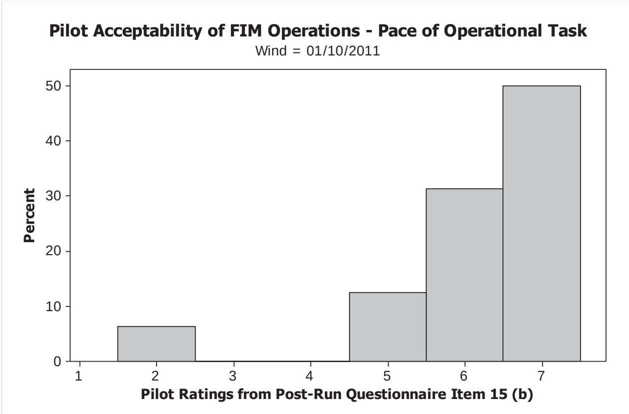

Figure 18. Pilot acceptability of FIM operations (i.e., pace of operational task) during the wind 01/10 scenario

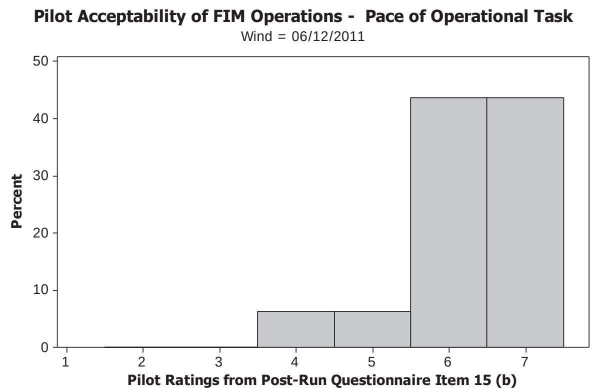

Figure 19. Pilot acceptability of FIM operations (i.e., pace of operational task) during the wind 06/12 scenario

For questionnaire item 15 (c), the flight crews found the IM commanded speeds to be operationally acceptable ($p < 0.0005$) for both wind conditions.

Table 7. Descriptive statistics for pilot ratings of IM commanded speeds' operational acceptability from questionnaire item 15 (c)

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.125	0.885	4	6	7
Wind 06/12	16	5.875	1.204	4	6	7

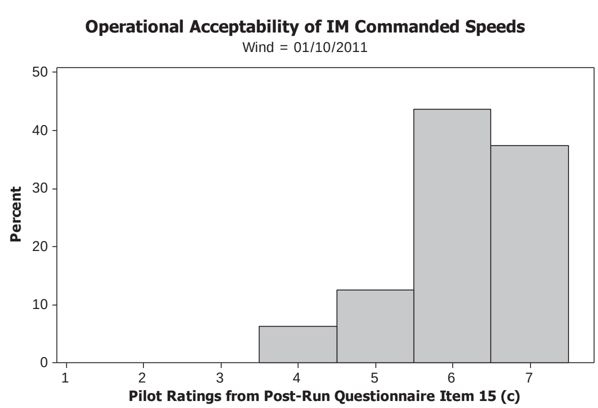

Figure 20. Operational acceptability of IM commanded speeds as perceived by pilots during the wind 01/10 scenario

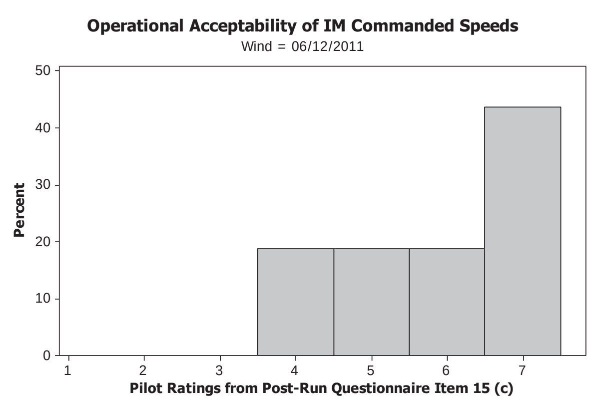

Figure 21. Operational acceptability of IM commanded speeds as perceived by pilots during the wind 06/12 scenario

For questionnaire item 15 (d), the flight crews found the IM commanded speeds to be operationally appropriate for both scenarios ($p < 0.0005$). The operational appropriateness rating of ‘2’ corresponds to the pilot who provided an overall FIM acceptability rating of ‘3’ described above due to a separation violation during Run 1 of the wind 06/12 scenario.

Table 8. Descriptive statistics for pilot ratings of IM commanded speeds' operational appropriateness from questionnaire item 15 (d)

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.125	0.885	4	6	7
Wind 06/12	16	5.750	1.483	2	6	7

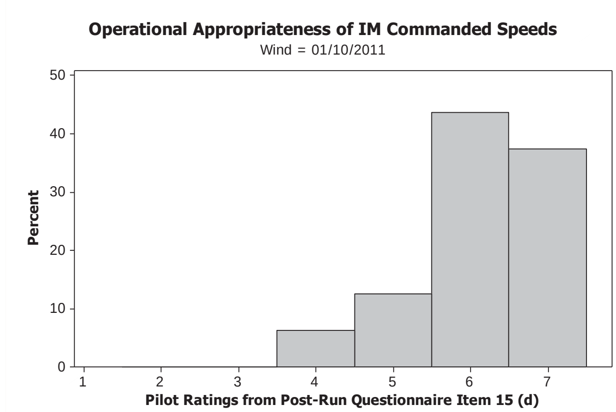

Figure 22. Pilot perceptions regarding the operational appropriateness of IM commanded speeds during the wind 01/10 scenario

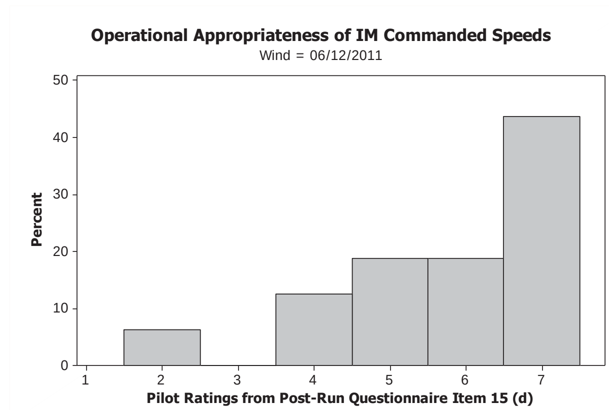

Figure 23. Pilot perceptions regarding the operational appropriateness of IM commanded speeds during the wind 06/12 scenario

For questionnaire item 15 (e), the flight crews found the IM commanded speed frequency to be acceptable for both scenarios ($p < 0.0005$).

Table 9. Descriptive statistics for pilot perceptions regarding the acceptability of IM commanded speed frequency from questionnaire item 15 (e)

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.063	1.063	4	6	7
Wind 06/12	16	5.813	0.981	4	6	7

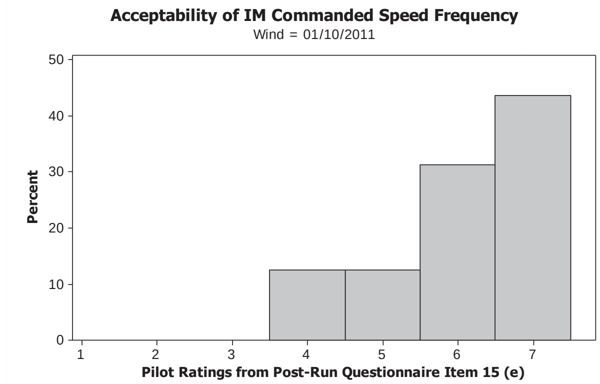

Figure 24. Pilot perceptions regarding the acceptability of IM commanded speed frequency during the wind 01/10 scenario

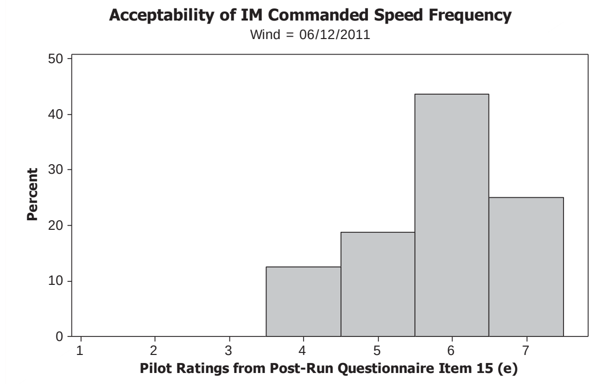

Figure 25. Pilot perceptions regarding the acceptability of IM commanded speed frequency during the wind 06/12 scenario

For questionnaire item 15 (g), the flight crews found the use of voice communications to provide IM clearance(s) to be acceptable for both the wind 01/10 and 06/12 scenarios ($p < 0.0005$).

Table 10. Descriptive statistics for pilot perceptions regarding the use of voice communications to provide IM clearance(s) from questionnaire item 15 (g)

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.500	0.632	5	7	7
Wind 06/12	16	6.375	0.719	5	6.5	7

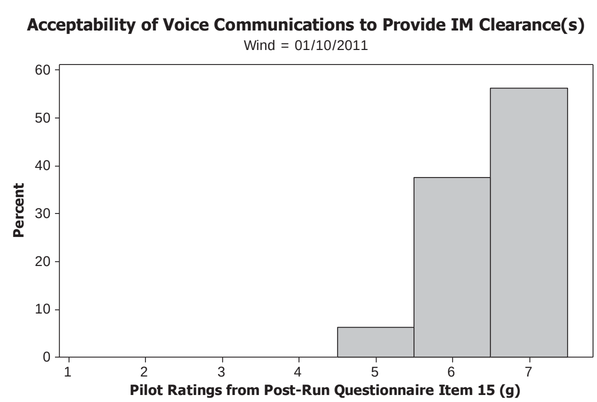

Figure 26. Pilot perceptions regarding the use of voice communications to provide IM clearance(s) during the wind 01/10 scenario

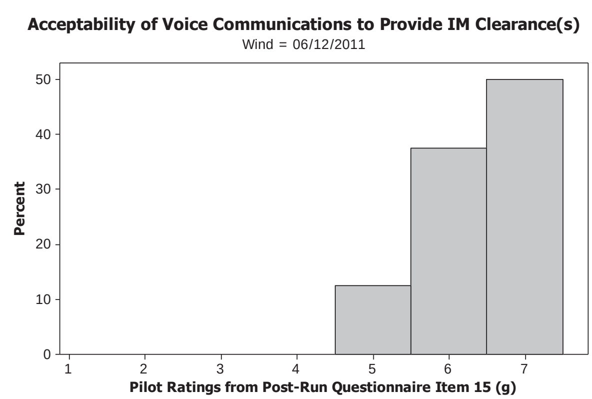

Figure 27. Pilot perceptions regarding the use of voice communications to provide IM clearance(s) during the wind 06/12 scenario

For questionnaire item 15 (h), the flight crews found the head down time required by EFB interactions to be acceptable for both scenarios ($p < 0.0005$).

Table 11. Descriptive statistics for the acceptability of the head down time required by EFB interaction from questionnaire item 15 (h)

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.375	0.619	5	6	7
Wind 06/12	16	6.438	0.727	5	7	7

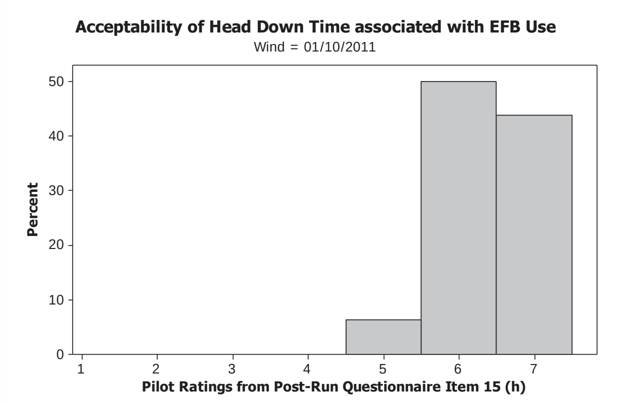

Figure 28. Acceptability of head down time required by EFB interactions during the wind 01/10 scenario

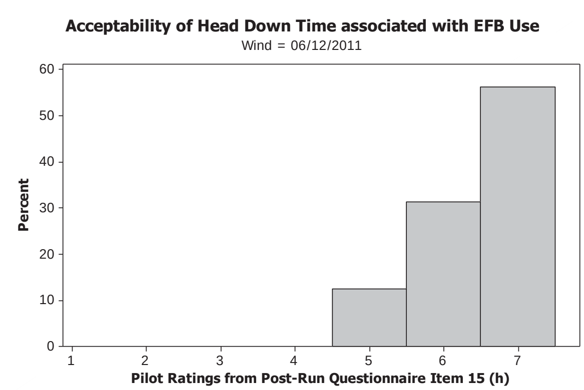

Figure 29. Acceptability of head down time required by EFB interactions during the wind 06/12 scenario

For questionnaire item 15 (i)**,** the flight crews found that entering IM clearance information into the EFB was easy and intuitive for both wind conditions ($p < 0.0005$). The pilot who provided a data entry intuitiveness rating of ‘2’ indicated he had an issue entering the target aircraft call sign into the EFB.

Table 12. Descriptive statistics for the acceptability of entering IM clearance information into the EFB from questionnaire item 15 (i)

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.500	0.632	5	7	7
Wind 06/12	16	6.313	1.401	2	7	7

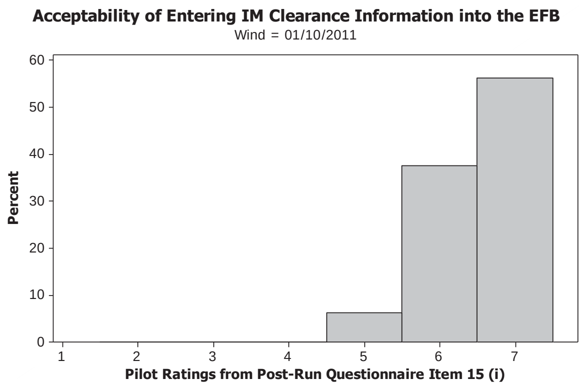

Figure 30. Acceptability of entering IM clearance information into the EFB during the wind 01/10 scenario

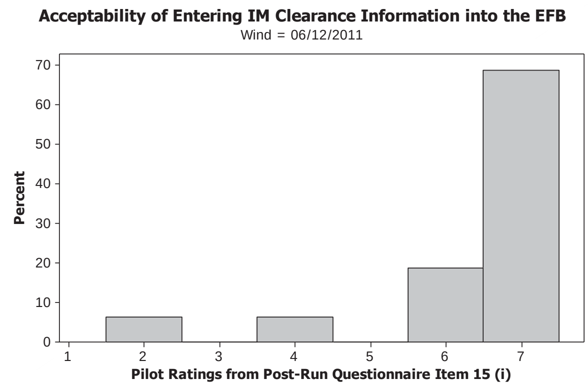

Figure 31. Acceptability of entering IM clearance information into the EFB during the wind 06/12 scenario

For questionnaire item 15 (j), the flight crews found that obtaining information from IM displays was easy for both scenarios ($p < 0.0005$).

Table 13. Descriptive statistics for pilot perceptions regarding the ease of obtaining information from IM displays from questionnaire item 15 (j)

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.438	0.727	5	7	7
Wind 06/12	16	6.625	0.619	5	7	7

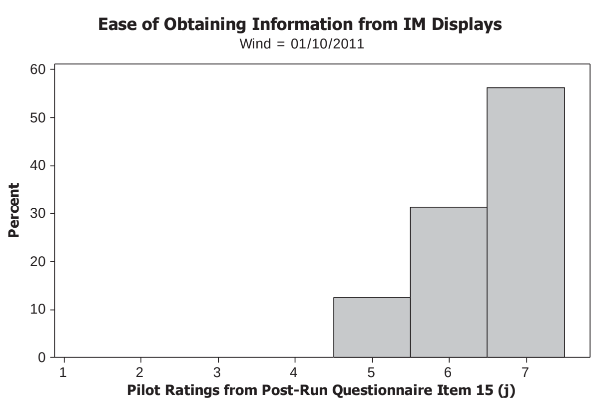

Figure 32. Pilot perceptions regarding the ease of obtaining information from IM displays during the wind 01/10 scenario

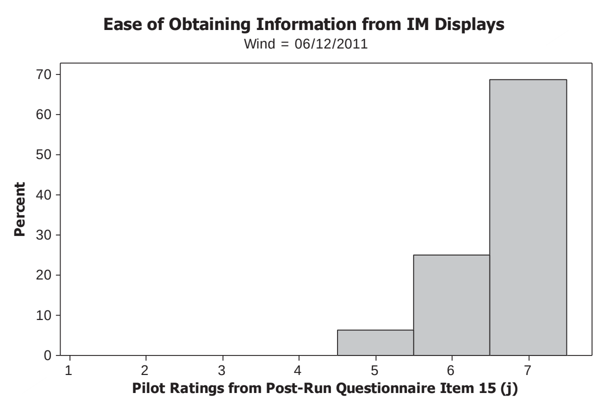

Figure 33. Pilot perceptions regarding the ease of obtaining information from IM displays during the wind 06/12 scenario

For questionnaire item 15 (l), the flight crews found the FIM procedures to be acceptable for both scenarios ($p < 0.001$).

Table 14. Descriptive statistics for pilot perceptions regarding the acceptability of the flight crew procedures from questionnaire item 15 (l)

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	6.438	0.727	5	7	7
Wind 06/12	16	6.188	0.834	5	6	7

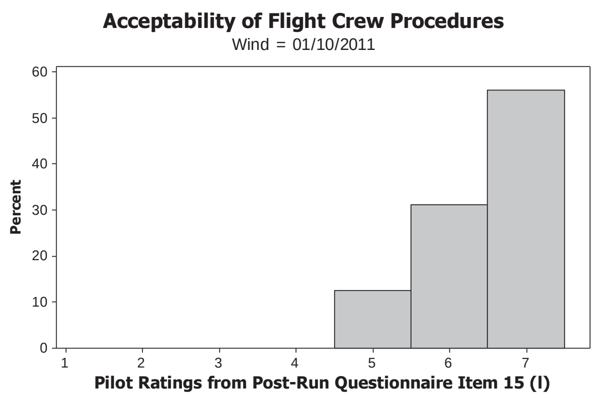

Figure 34. Acceptability of flight crew procedures used during the wind 01/10 scenario

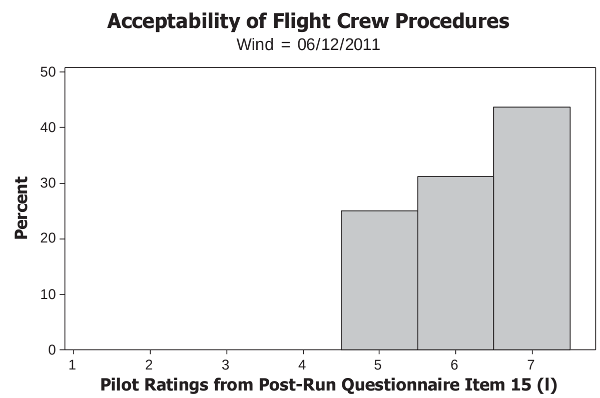

Figure 35. Acceptability of flight crew procedures used during the wind 06/12 scenario

3.6 Flight Crew Workload of FIM Operations (MOP 3.4.5)

In order to assess the flight crew workload of FIM operations, the Modified Cooper-Harper (MCH) subjective workload rating scale was used [34]. Data were collected from each of the subject pilots via electronic post-run questionnaires in order to assess the following *a priori* hypothesis,

> Hypothesis 5: Pilots will report the mean MCH workload ratings with FIM operations less than or equal to “3.”

A rating of “3” on the MCH rating scale indicates that the instructed task is fair and/or has mild difficulty, and acceptable operator mental effort is required to attain adequate system performance. Descriptive statistics associated with the pilot workload ratings are shown in Table 15 and histograms of the data are shown in Figures 36 and 37. Data from the PF and PM were combined, and statistical analysis was performed using the Wilcoxon signed rank test. For both scenarios, the flight crews found the workload level experienced during FIM operations to be acceptable ($p \leq 0.002$).

Table 15. Descriptive statistics for flight crew workload ratings

Scenario	*N*	Mean	SD	Min	Median	Max
Wind 01/10	16	1.81	0.75	1	2	3
Wind 06/12	16	1.94	0.85	1	2	3

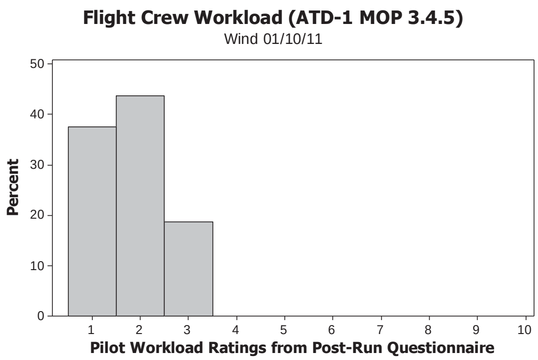

Figure 36. Flight crew workload for the wind 01/10 scenario

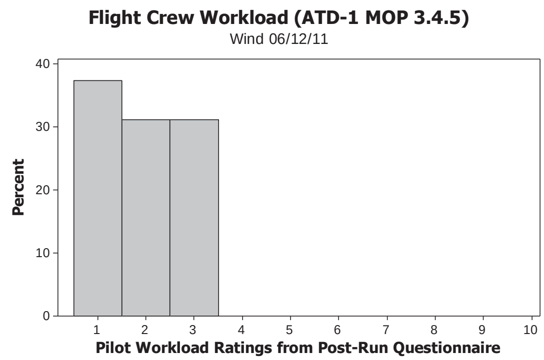

Figure 37. Flight crew workload for the wind 06/12 scenario

4 Conclusions

NASA has developed an integrated set of scheduling and spacing technologies, consisting of TMA-TM, CMS decision support tools, and FIM avionics and procedures. Previous studies have identified a number of challenges associated with the integration of these ground-based and airborne technologies. The ASTAR spacing algorithm was recently modified to address some of these air-ground challenges.

The RAPTOR experiment described in this document was designed to assess the performance of the modified ASTAR spacing algorithm. ASTAR-12 was previously evaluated in a batch study using deterministic scripted scenarios based on assumptions made without realistic data involving human participation. The RAPTOR experiment provided the first opportunity to integrate ASTAR-12 with the ground-based tools. This simulation utilized an unscripted environment, and some of the initial assumptions made regarding the compatibility between the FIM and ground-based tools were found to be in need of revision. For instance, during the batch study it was assumed that target aircraft would fly within 10 knots of their expected published speed while on final approach because all allocated delay was supposed to be absorbed prior to the final approach. However, there were a number of cases in RAPTOR where the speed deviation on final approach was greater than 10 knots.

Due to the design of ASTAR-12, the behavior of the FIM aircraft is highly coupled to the behavior of the target aircraft. If a target aircraft is slowed by ATC, the FIM aircraft is also expected to slow down. Depending on the point where these decelerations occur on the arrival, they can cause speed reversals and a high frequency of low magnitude speed changes, both of which are inefficient and undesirable.

Overall, the pilots reported the FIM concept, procedures, operations, and crew interface to be acceptable. However, the data indicate that there were some issues with the frequency of speed changes, speed reversals, and lower than expected speeds issued to the target aircraft by ATC prior to the FAF. Some of the unacceptable ratings from the pilot participants may have been influenced by simulation artifacts, including display of the target aircraft on the runway causing pilots to perceive a separation violation, and unrealistic deceleration rates for some aircraft. Inaccurate temperature modeling may also have affected the spacing, possibly resulting in incorrect spacing intervals.

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Appendix A: Simulated Airspace and Scenario Design

The Research and Procedural Testing of Routes (RAPTOR) experiment scenarios consisted of 85 arrival aircraft which initialized at various points within Albuquerque Center (ZAB) and Phoenix Sky Harbor (PHX) Terminal Radar Approach Control (TRACON) airspace. All inbound aircraft approached the PHX airport via the EAGUL FIVE and MAIER FIVE standard terminal arrival routes (STARs) and landed on runway 26 (see Figure A-1).

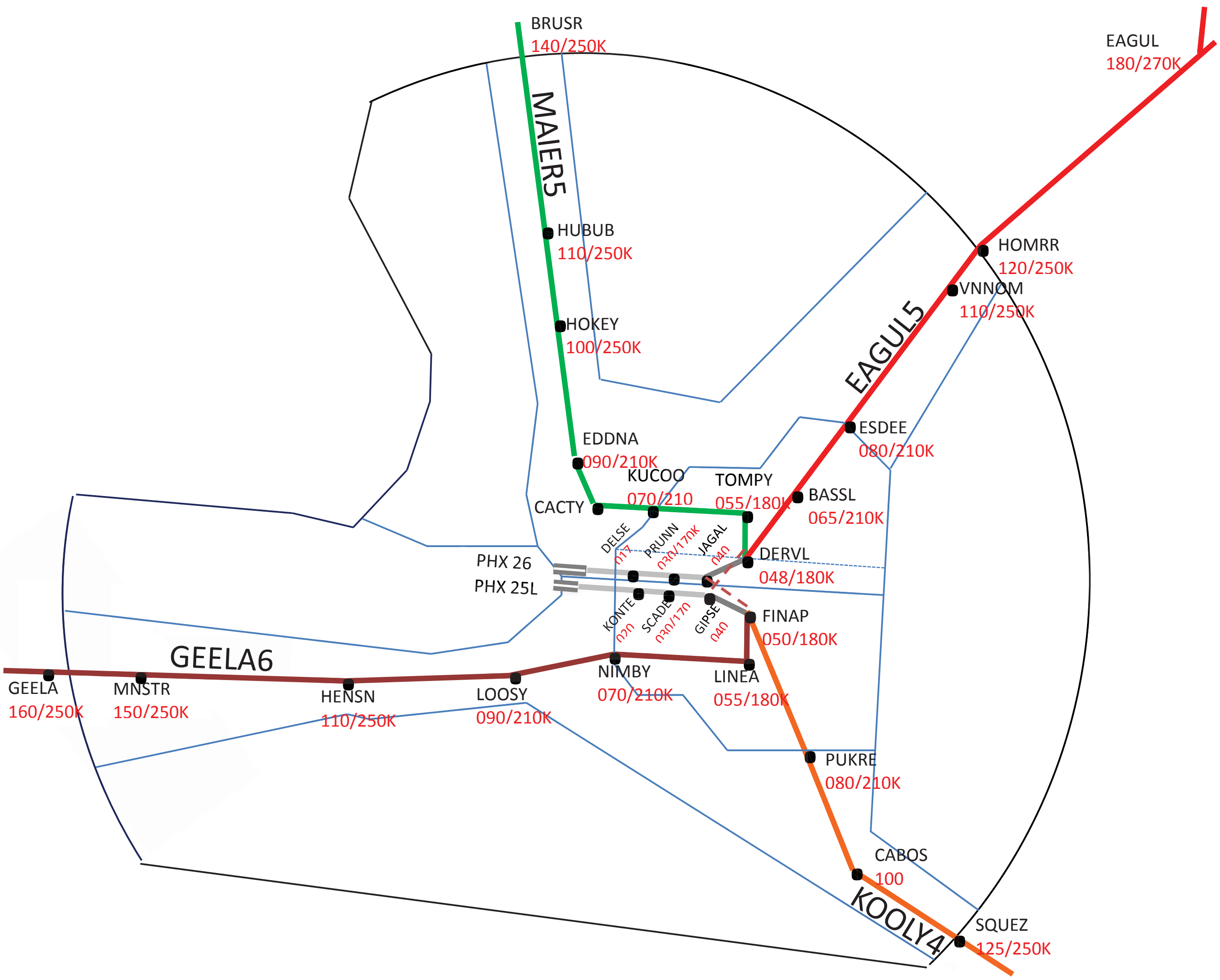


Figure A-1. Simulation airspace

The primary focus of the experiment was on four pairs of aircraft conducting Flight deck-based Interval Management (FIM) operations. Each pair consisted of a target and a following aircraft that used the FIM tools and procedures to achieve an assigned spacing goal at the final approach fix (FAF). The four FIM aircraft in the experiment were flown by subject pilots utilizing the Integration Flight Deck, the Development and Test Simulator, and two dual-crew Aircraft Simulation for Traffic Operations Research (ASTORs). The four target aircraft were flown by four recently retired commercial airline pilots utilizing four single crew ASTORs. Five pseudo-pilots operated Multi-Aircraft Control System (MACS) pseudo-pilot stations to control the 77 traffic arrival aircraft.

A.1 Training Scenarios

Prior to arriving at NASA Langley Research Center, the subject pilots received a minimum of 30 minutes of computer-based training, in addition to a Pilot's Users Guide on FIM operations. After their arrival, the pilots attended a two-hour training class to familiarize them with the FIM concept of operations, terminology used for voice communications, and operation of the related equipment. Upon completion of the classroom training, the pilots flew five training scenarios with NASA instructors. The first four scenarios included only the FIM and target aircraft without active air traffic controllers or MACS pseudo-pilots. The fifth run was a fully integrated scenario with all participants in the loop.

A.1.1 Training Scenario #1

The first training scenario was a nominal run to provide practice in basic operational procedures. Both the target and the FIM aircraft flew the same arrival but started on different transitions (see Figure A-2). The target was within Automatic Dependent Surveillance-Broadcast (ADS-B) range at the start of the scenario and remained on path and at a stable speed for the duration of the run.

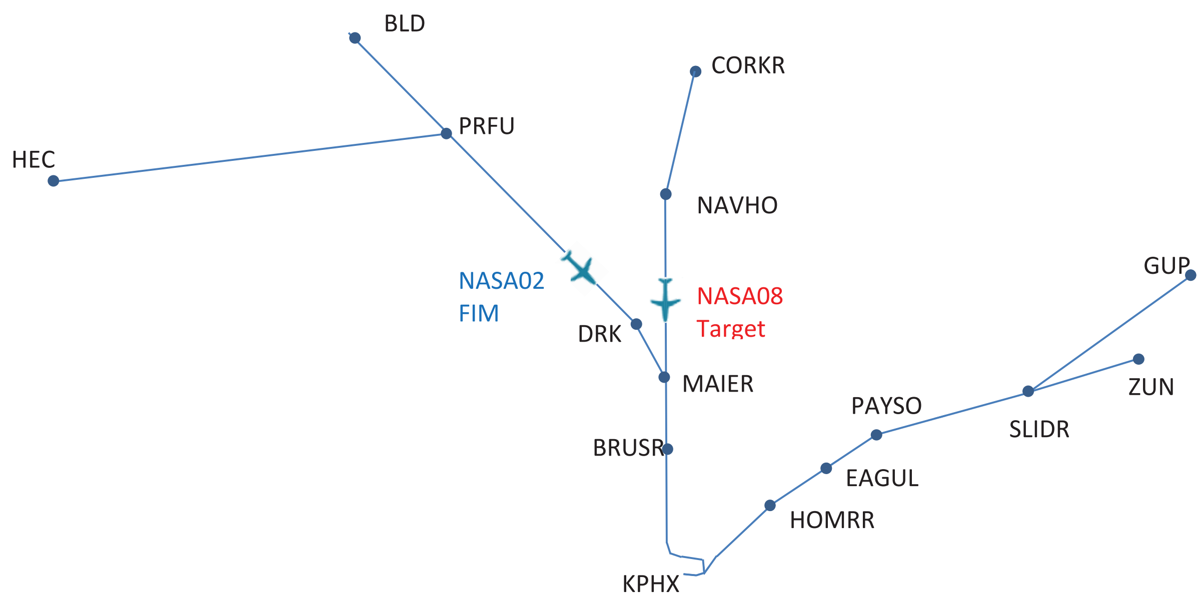


Figure A-2. Training scenario #1

A.1.2 Training Scenario #2

For the second training scenario, the target aircraft flew the EAGUL arrival and the FIM aircraft flew the MAIER arrival, as shown in Figure A-3. The target aircraft was positioned such that it remained outside of ADS-B range for approximately eight minutes. For simulation purposes, the maximum ADS-B reception range was assumed to be 120 NM with perfect reception at lesser ranges. After activating the Interval Management (IM) clearance, the crew received a message stating “IM Target No ADS-B” until the target closed to within 120 NM. Once this point was reached, the crew began to receive speed commands from the FIM algorithm.

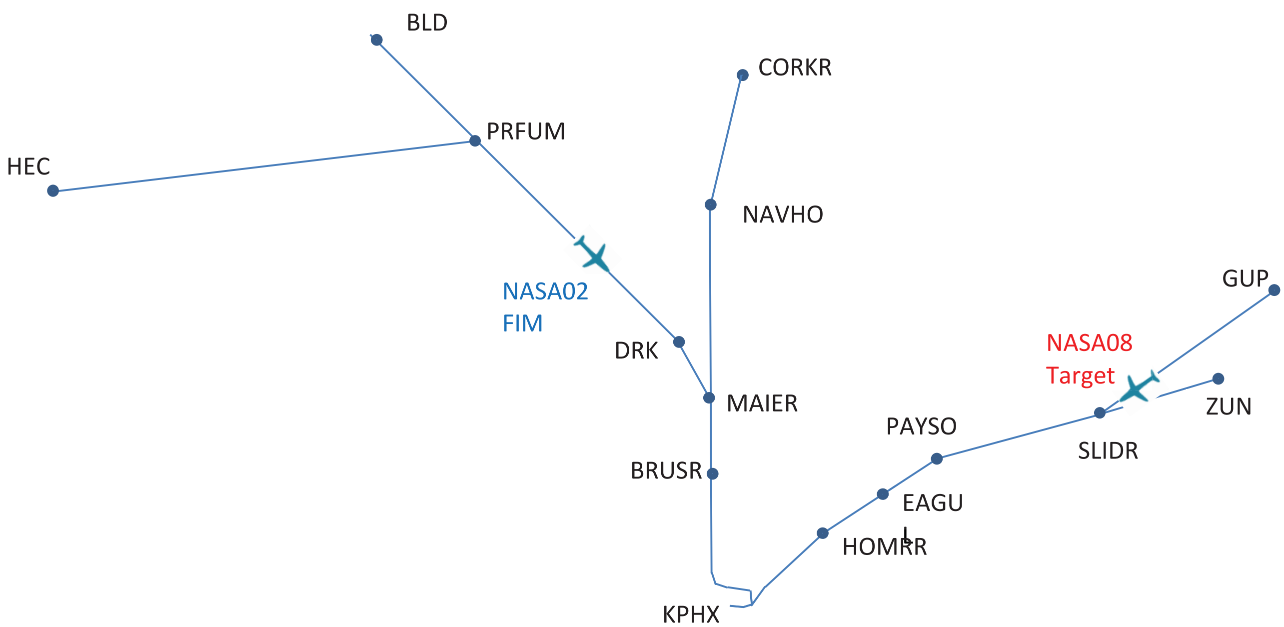


Figure A-3. Training scenario #2

A.1.3 Training Scenario #3

For the third training scenario, both aircraft started in trail on the EAGUL arrival at flight level (FL) 360 (see Figure A-4). The FIM aircraft was positioned too close to the target, requiring Air Traffic Control (ATC) to vector the aircraft for sequencing. Prior to reaching SLIDR, the FIM aircraft was instructed to turn 30 degrees right, descend to FL240, and slow to 270 knots to attain spacing behind the preceding aircraft. After the FIM aircraft completed the turn, the instructor issued an IM clearance. Since the aircraft was no longer on the planned arrival, the FIM algorithm displayed an "Ownship off path" error message to the flight crew. Next, the crew was instructed to proceed direct to PAYSO to demonstrate the algorithm's Direct-To logic. When the algorithm was engaged, proceeding from a location off of the arrival direct to any point on the arrival caused the airborne spacing algorithm to create a new arrival path and allow immediate paring with the target.

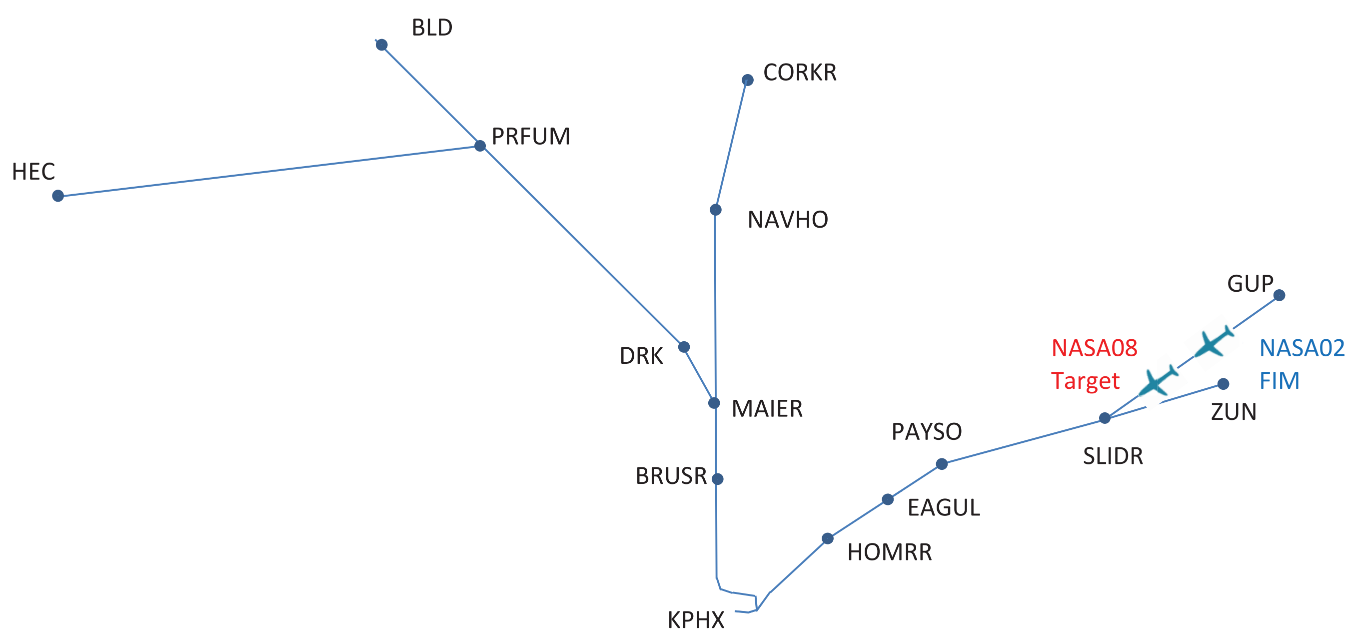


Figure A-4. Training scenario #3

A.1.4 Training Scenario #4

For the fourth training scenario, both aircraft initialized in trail on the EAGUL arrival at FL360, as shown in Figure A-5. The instructor issued an IM clearance for NASA02 to follow 140 seconds behind NASA08. After the aircraft began FIM operations, the target aircraft was instructed to turn 20 degrees right for sequencing. When the target deviated more than 2.5 NM off of the planned arrival path, the FIM algorithm disengaged and displayed a "Target off path" error message to the flight crew. At this point the target aircraft was instructed to proceed from its present position direct to EAGUL to demonstrate that the airborne spacing algorithm would re-engage once the target was again positioned within 2.5 NM of the planned arrival path. A revised spacing goal of 110 seconds was also issued to the FIM crew to allow them to practice clearance amendments.

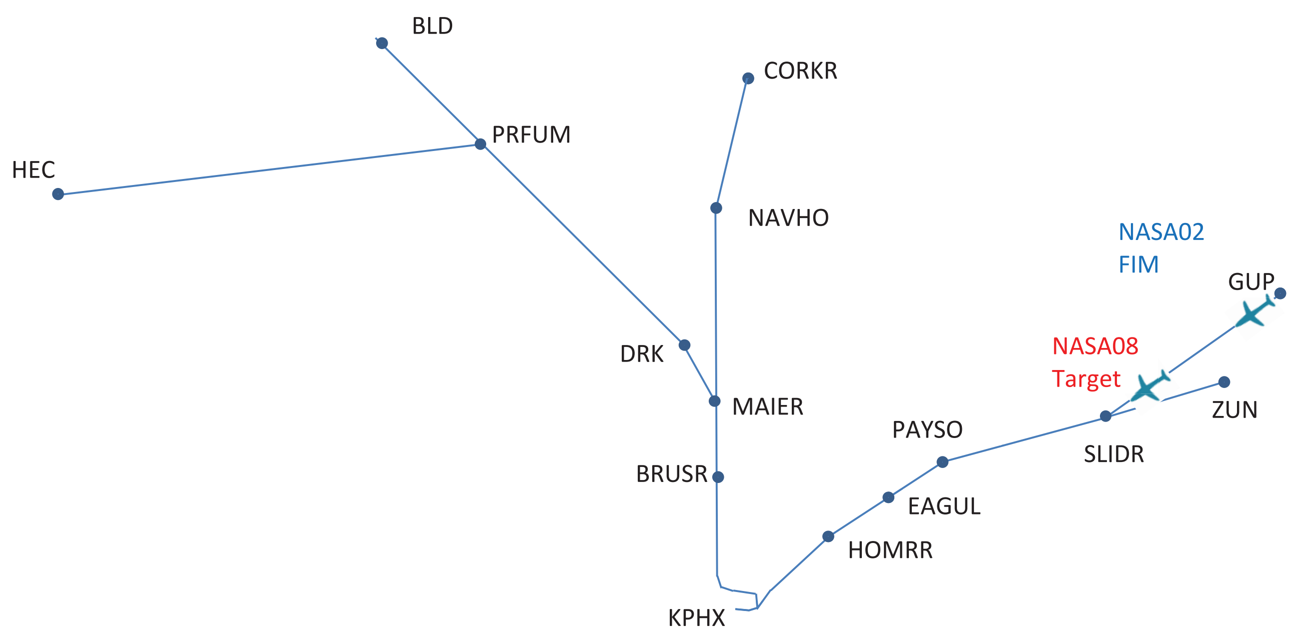


Figure A-5. Training scenario #4

A.1.5 Training Scenario #5

The last training scenario was a fully integrated run with the subject pilots, pseudo-pilots, and air traffic controllers in the loop. This run was the same as the RAPTOR data collection wind 06/12 scenario except that the starting positions for the FIM aircraft were scrambled so that the crews flew a different arrival with a different target than during the data collection run. Starting positions for the subject aircraft are shown in Figure A-6 with the target and FIM aircraft pairs indicated by matching colors on the call sign labels.

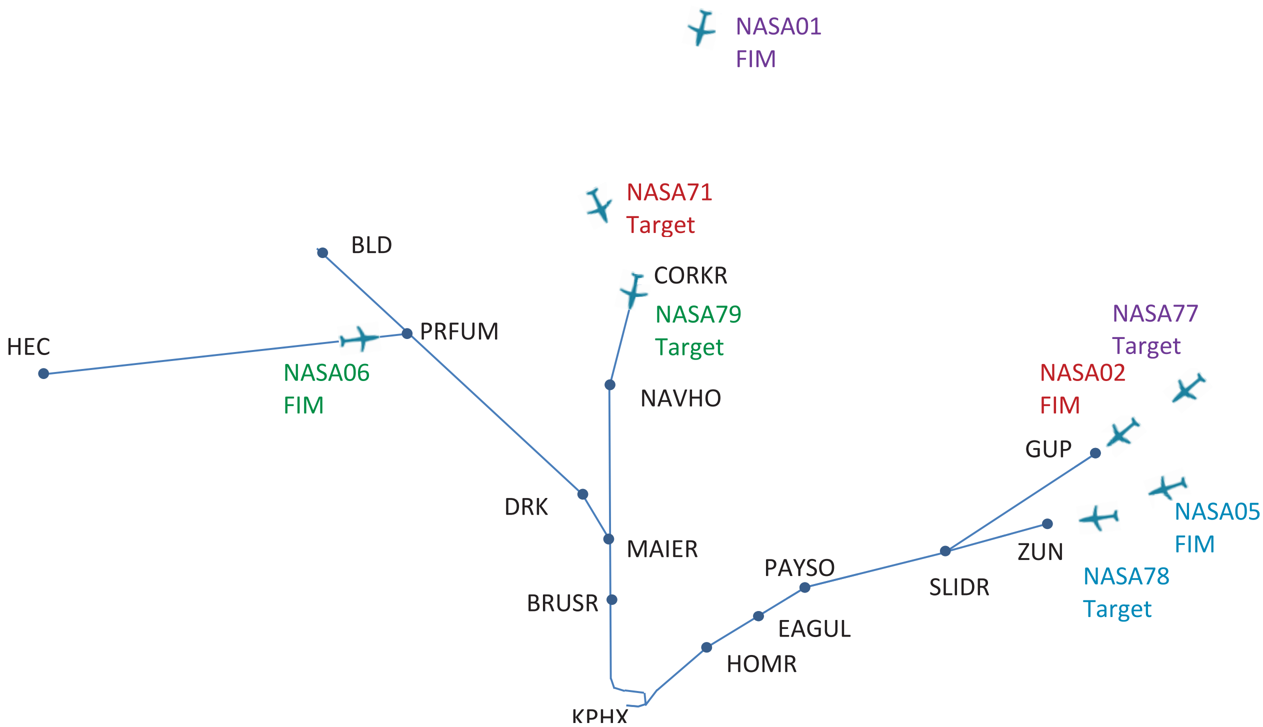


Figure A-6. Training scenario #5 initial positions and FIM pairs

A.2 Data Collection Scenarios

During planning for the RAPTOR experiment, several different scenarios were designed and tested. Two scenarios were selected for the final data collection runs based on the West flow traffic recorded at PHX on 11/14/2011 at 18:00 with the 01/10/2011 and 06/12/2011 winds. The FIM pairings were chosen by running a MACS scenario generated from the live traffic recording to observe how Traffic Management Advisor with Terminal Metering (TMA-TM) scheduled the arrival sequence. The FIM pairs were then selected from the arrival stream to provide a sampling of different target/following aircraft types with starting positions within a few minutes of the TMA-TM freeze horizon. The selected pairs were converted from MACS aircraft to ASTORs to take advantage of the ASTOR's higher fidelity flight model and provide human-piloted targets for the four subject FIM aircraft.

A.2.1 Wind 01/10 Scenario

The RAPTOR wind 01/10 scenario included very strong wind conditions at altitude and light to moderate wind at the airport. TMA-TM scheduling delays for the target/FIM aircraft ranged from two to nearly five minutes. Starting positions for the subject aircraft are shown in Figure A-7. The target and FIM aircraft for each pair are indicated by matching colors on the call sign labels in the diagram.

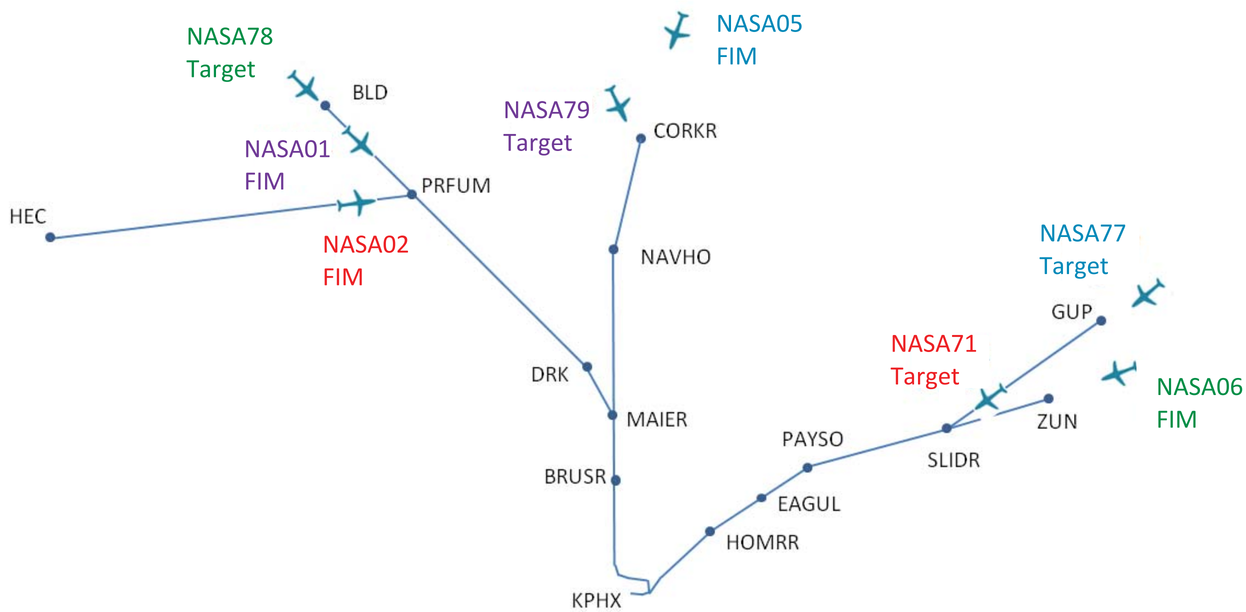


Figure A-7. Wind 01/10 scenario initial positions and FIM pairs

A.2.2 Wind 06/12 Scenario

The RAPTOR wind 06/12 scenario included moderate winds at altitude with TMA-TM schedule delays ranging from 30 seconds to three minutes. Starting positions for the subject aircraft are shown in Figure A-8. The target and FIM aircraft for each pair are indicated by matching colors on the call sign labels in the diagram.

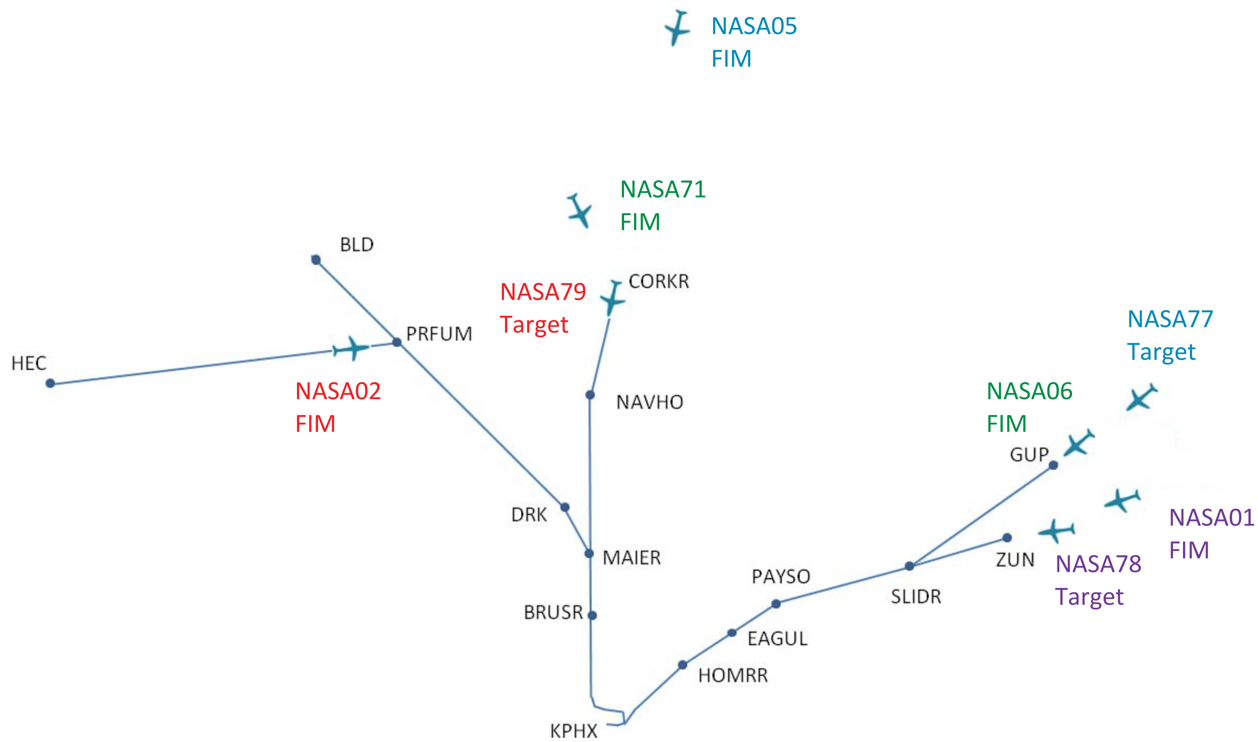


Figure A-8. Wind 06/12 scenario initial positions and FIM pairs

Appendix B: Experiment Schedule and Run Order

Each two-person crew (with both members employed by the same airline) participated in a two-day experiment session. Every crew flew each scenario twice – once with the captain as the pilot flying (PF) and the first officer as the pilot monitoring (PM), and once with the first officer as the PF and the captain as the PM. Therefore, each crew flew a total of four experiment runs. Since each pilot flew each scenario, this was a within-subject experiment design. Counterbalancing was used to determine the run order of the scenarios, and the pilots switched responsibilities between runs, resulting in the run order shown in Table B-1.

Table B-1. Experiment run order

Run	Scenario	PF and PM
Run 1	Wind 06/12	Captain as PF and First Officer as PM
Run 2	Wind 01/10	First Officer as PF and Captain as PM
Run 3	Wind 01/10	Captain as PF and First Officer as PM
Run 4	Wind 06/12	First Officer as PF and Captain as PM

One group of five recently retired air traffic controllers served as confederate controllers actively controlling the aircraft. This included two Center controllers (ZAB Sectors 43 and 39), one PHX Feeder controller, one PHX Final controller, and one Ghost controller. All controllers were trained at NASA Ames Research Center in the use of the ground-based tools and had participated in previous ATD-1 experiments. The Center and Ghost controllers rotated positions between runs as shown in Table B-2.

Table B-2. Rotation of controllers

Run	Ghost	Center Sector 43	Center Sector 39	Feeder	Final
Run 1	A	B	C	D	E
Run 2	B	C	A	D	E
Run 3	C	A	B	D	E
Run 4	A	B	C	D	E

Each pilot participated in a two-day experiment session with the schedule shown in Figure B-1. The pilot participants received training material and access to computer based training prior to arriving at NASA Langley Research Center. They also received approximately six hours of classroom and hands-on training after arrival, including flying five training scenarios prior to commencing data collection. The first day of the experiment session began with classroom and hands-on training, and then one data collection flight was conducted. The second day consisted of the remaining data collection flights, followed by a post-experiment questionnaire and group debrief session. Pilots also completed post-run experiment questionnaires following each data collection run. Post-run and post-experiment questionnaires were administered to and feedback was collected from the confederate controllers.

Figure B-1. Daily experiment schedule

Day #1
Intro Brief
Classroom Training
Training Scenarios
Lunch
Training Scenarios
Data Collection Run #1

Day #2
Data Collection Run #2
Data Collection Run #3
Lunch
Data Collection Run #4
Post-Experiment Questionnaire
Debrief

Appendix C: FIM Crew Interface and Procedures

C.1 Overview of Interface and Procedures

The prototype Flight deck-based Interval Management (FIM) crew interface consists of two side-mounted electronic flight bags (EFB) and configurable graphics display (CGD) devices mounted on the left and right outboard panels in the pilot's forward field-of-view. Pilots use the EFB for data entry, as well as to activate, amend, suspend, resume, and cancel the FIM operation, while the CGD is used for conformance monitoring.

The CGD displays five pieces of information in the pilot's forward field-of-view (see Figure C-1).

1) CMD SPD displays the Interval Management (IM) commanded speed in Mach or knots. When an IM speed change occurs, the speed is shown in reverse video for 10 seconds. If the pilot does not respond within 10 seconds, the commanded speed blinks until the speed is set in the Mode Control Panel (MCP).

2) The status box displays the current status of the FIM operation: CALCULATING, SPACING, or SUSPENDED.

3) The target aircraft call sign is displayed when receiving Automatic Dependent Surveillance – Broadcast (ADS-B) information.

Figure C-1. Information elements displayed on the CGD

4) The Fast / Slow indicator displays the difference between the actual and instantaneous Interval Management (IM) commanded airspeed. During deceleration this value may be used to see how closely the FIM aircraft is to the desired deceleration rate.

5) System caution and information messages are displayed in the message box.

Figure C-2. Information elements displayed on the EFB

The EFB enables data entry and displays the information shown in Figure C-2.

1) CMD SPD displays the current IM commanded speed the aircraft should fly in order to achieve the spacing goal.

2) The Fast / Slow indicator displays speed conformance information. The deviation of the actual speed from the instantaneous commanded speed is shown.

3) The status box displays the current status of the IM operation, including CALCULATING, SPACING, and SUSPENDED.

4) The message box displays caution and information messages generated by the FIM system.

5) The Situation Display shows the location of the target and other ADS-B out aircraft. The ownship aircraft is shown as a white triangle centered in the display. The target aircraft is shown as two chevrons with the inner chevron white and the outer green. The target aircraft's information block is also displayed with call sign and altitude information. Other ADS-B out aircraft are shown as blue chevrons.

6) OWN INFO allows the pilot to enter ownship information into the FIM system.

7) Next Waypoint displays the next waypoint on the arrival that the aircraft will fly over. This field is for information only and cannot be modified by the pilot.

8) Descent Forecast Winds allows the pilot to enter up to eight altitude winds for the arrival. This information may be entered manually or uploaded with an Aircraft Communications Addressing and Reporting System (ACARS) or Controller-Pilot Data Link Communications (CPDLC) message.

9) IM GOAL allows the pilot to enter the assigned spacing goal.

10) TGT ACFT allows the pilot to select and identify the target aircraft to space behind.

11) TGT RTE allows the pilot to enter the target aircraft's arrival routing, transition, and approach so that the FIM system knows the target's ground track.

12) Using the ZOOM IN and ZOOM OUT buttons changes the range on the EFB's situation display.

13) The bezel buttons on the top of the EFB:
    - MENU displays the EFB software's Main Menu
    - BACK returns to previous main page
    - PGUP and PGDN cycles through pages if more than one is needed to display information
    - XFR is inoperative
    - ENTER button enters inputted information into the FIM system

The FIM system provides commanded speeds for the pilot to fly in order to achieve a precise interval behind the target aircraft to the final approach fix (FAF). Pilot actions are essentially the same as for current day operations. He or she flies the commanded speeds while maintaining the vertical profile to meet all restrictions. The main difference is that the commanded speeds come from the FIM avionics instead of the controller.

If Air Traffic Control (ATC) expects the pilot to fly FIM procedures, the controller will issue an IM clearance. This clearance will contain the spacing interval to achieve, the target aircraft's call sign, and the target aircraft's arrival routing. An aircraft is considered paired with a target aircraft once valid ADS-B information from that target aircraft is received, and a commanded airspeed is displayed. Once paired with a target aircraft, an IM commanded speed is generated for the pilot to fly that will achieve the assigned spacing goal when the aircraft crosses the FAF. The system is designed for limited airspeed changes and to conform as closely as possible to an Optimized Profile Descent (OPD). At airports saturated with arrival aircraft, the greatest capacity benefits may be realized by having sequences of aircraft operating in IM mode, with each aircraft actively spacing behind the aircraft ahead of it.

Speed guidance is displayed on the EFB in the CMD SPD block and is duplicated on the CGD located in the pilot's forward field-of-view. The aircraft's airspeed is controlled by setting the IM commanded speed in the MCP speed window. The pilot flying will fly the arrival and instrument approach on autopilot. The use of the autopilot system reduces pilot workload and allows precise spacing intervals to be established. For a majority of the descent, the aircraft will descend in vertical navigation (VNAV) SPD mode with the throttles in the HOLD mode. To ensure the predictability of vertical paths during FIM operations, flight crews will be required to modulate thrust and drag to stay on the IM speed profile and the OPD path. The aircraft will pitch to maintain the speed window's set speed. Throttles and drag devices will be used to nominally maintain the aircraft within ±400 feet of the VNAV path. After crossing the FAF, IM speed guidance will be removed from the display, and the pilot will configure the aircraft for landing.

An overview of the procedures to perform IM operations is as follows.

1. Program flight management computer (FMC) with arrival routing, VNAV descent, and forecast winds. Tune radios.
2. Load ownship information into EFB
3. Load descent forecast winds into EFB
4. Load assigned spacing goal into EFB
5. Load target aircraft call sign into EFB
6. Load target aircraft arrival routing into EFB
7. Activate IM in EFB
8. Fly IM commanded airspeed on arrival while maintaining VNAV path
9. At FAF configure airplane for landing

Details on loading information into the EFB, as well as the activation, suspension, resumption, and cancellation of FIM operations are provided below.

C.2 Load Ownship Information into EFB

Ownship information is typically programmed earlier in the flight. Figures C-3 through C-8 illustrate the procedure for loading the ownship route information into the EFB.

Press the OWN INFO button to enter the ownship route information.

Figure C-3. Load ownship information

Enter information into the scratch pad and load into the fields.

CRZ ALT: Three number value (e.g. 350) for expected altitude at Top of Descent (TOD)

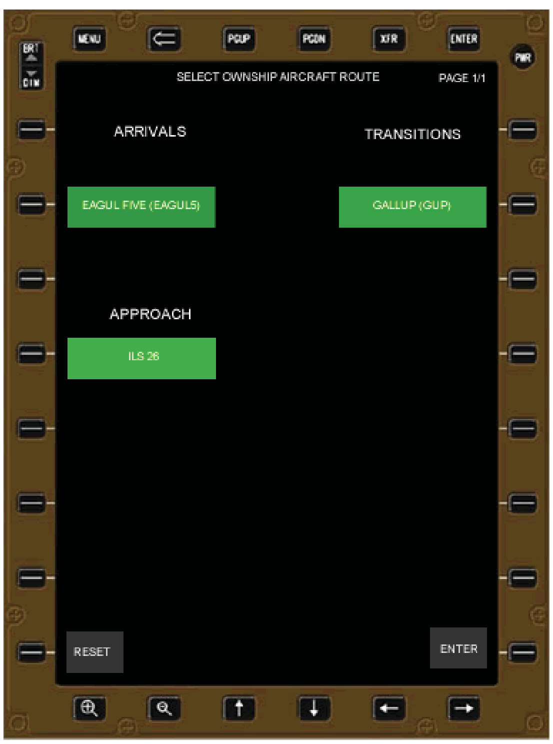
CRZ MACH: Two number value (e.g. 80) for expected Mach within 100 miles of TOD

DES MACH/CAS: Two number slash three number value (e.g. 80/300) for descent Mach and crossover CAS

Figure C-4. Load ownship cruise altitude, cruise Mach, and descent Mach/CAS transition

Enter the arrival airport's ICAO identifier in the DEST AIRPORT block. Then the OWNSHIP RTE button will appear. Press the OWNSHIP RTE button to input the ownship's arrival, transition, and approach to the airport.

Figure C-5. Load the ownship arrival airport



Select the arrival, transition, and approach by touching the screen or using the bezel buttons. The RESET button may be pressed to start over if a mistake was made. The ENTER button will appear when all the information is selected. Press the ENTER button to finish inputting the ownship route information and return the EFB to the OWNSHIP INFO page.

Figure C-6. Load the ownship arrival, transition, and approach to the airport

Route now appears in the OWNSHIP RTE block. Once all required information is entered, an ENTER button appears. Press the ENTER button to input the information and return the EFB to the Interval Management Main Page.

Figure C-7. Enter the ownship route information

OWN INFO block displays ownship route to indicate that ownship information has been entered.

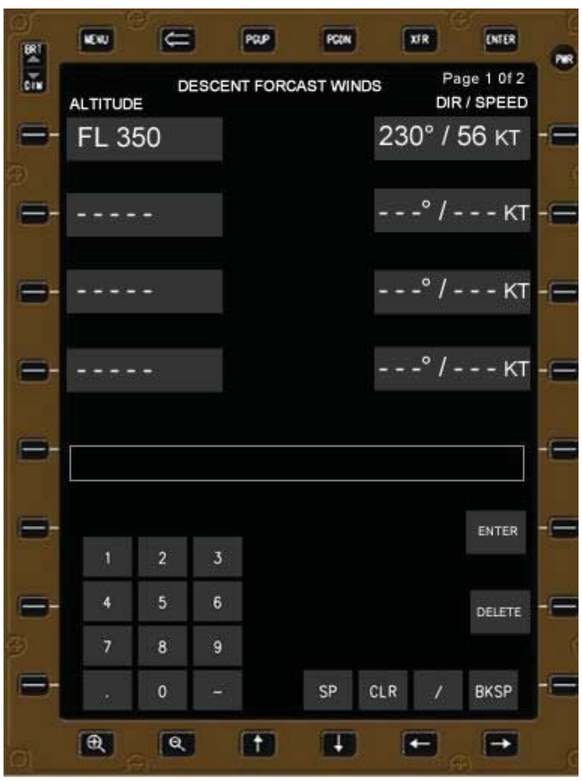
Figure C-8. Interval Management Main Page with ownship route information

C.3 Load Descent Forecast Winds into EFB

For FIM operations to work efficiently, accurate wind information must be available. In practice, this wind forecast will be provided by the aircraft's company and will be at altitudes that have major wind shifts. The wind information may be uploaded or entered manually as illustrated in Figures C-9 through C-11.

Press the DES FCST WINDS block to enter the descent forecast winds.

Figure C-9. Load the descent forecast winds



Enter the altitude into the scratchpad. Three number values will be interpreted as Flight Levels while four and five number values will be entered as MSL altitudes. Enter the value by pressing the altitude block or the adjacent bezel button. The BKSP button will erase one number while the CLR button will clear the whole scratchpad. To delete a value already loaded into the field, press the DELETE button and then the desired field.

Enter the direction and speed values separated by a slash. Enter the value by pressing the associated DIR/SPEED block or the adjacent bezel button.

Press the ENTER key located on the touchscreen or the top of the EFB to return to the EFB Interval Management Main Page.

Figure C-10. Load the wind direction, speed, and altitudes

There are two Descent Forecast Winds Pages allowing a total of eight altitude winds for the descent to be entered. Use the PGUP and PGDN buttons located on the top of the EFB to switch between pages.

Figure C-11. Switch between pages on the EFB

C.4 Load Assigned Spacing Goal and Target Aircraft Information into EFB

An example of an IM clearance issued by ATC over the radio is given below.

> *'NASA 12, when able space 90 seconds behind Delta Alpha Lima 877 on EAGUL 5 Zuni Transition. Report paired.'*

Figures C-12 through C-20 illustrate the procedure for loading the assigned spacing goal, target aircraft call sign, and target aircraft arrival routing information provided in the clearance.

Press the IM GOAL button to enter the assigned spacing goal.

Figure C-12. Load the assigned spacing goal

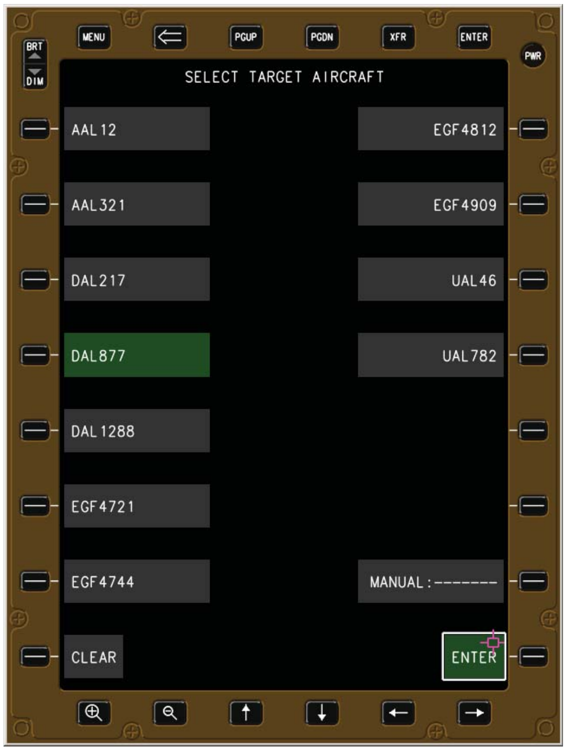
Enter value in scratchpad and then press ENTER.

IM GOAL: Two number value (e.g. 90)

Figure C-13. Enter the assigned spacing goal

The IM GOAL now shows 90 seconds. To enter the target aircraft call sign press the TGT ACFT block on the touchscreen or the bezel button located beside it.

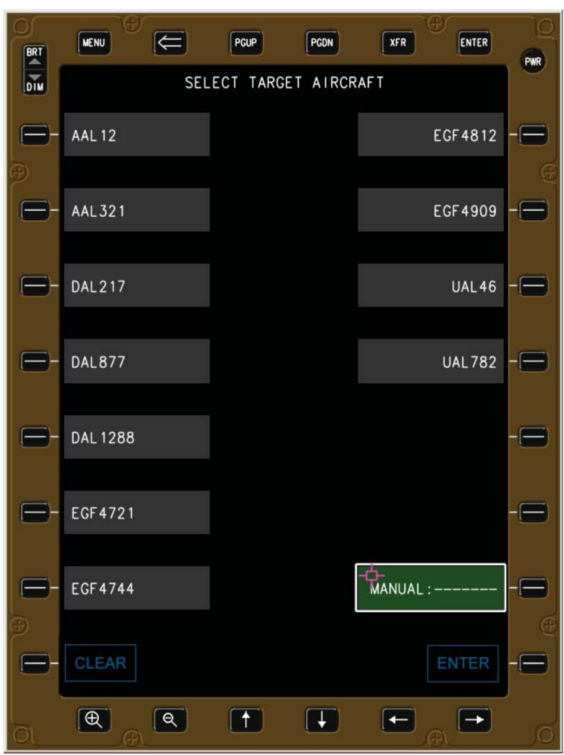
Figure C-14. Load the target aircraft call sign



The Target Aircraft page lists all the aircraft within ADS-B range sorted alphabetically. If there are more aircraft than can fit on one page, the PGUP and PGDN buttons can be used. Select the target aircraft by either pressing on the touchscreen or pressing the bezel button located beside it.

Once a call sign is selected, the ENTER and CLEAR buttons will be active. Pressing the CLEAR button will clear the selection. Pressing the ENTER button will enter the call sign into the FIM system and return to the Interval Management Main Page.

Figure C-15. Select the target aircraft call sign from the list of aircraft within ADS-B range



If the target aircraft is not in ADS-B range, the pilot may enter it manually by pressing the MANUAL button.

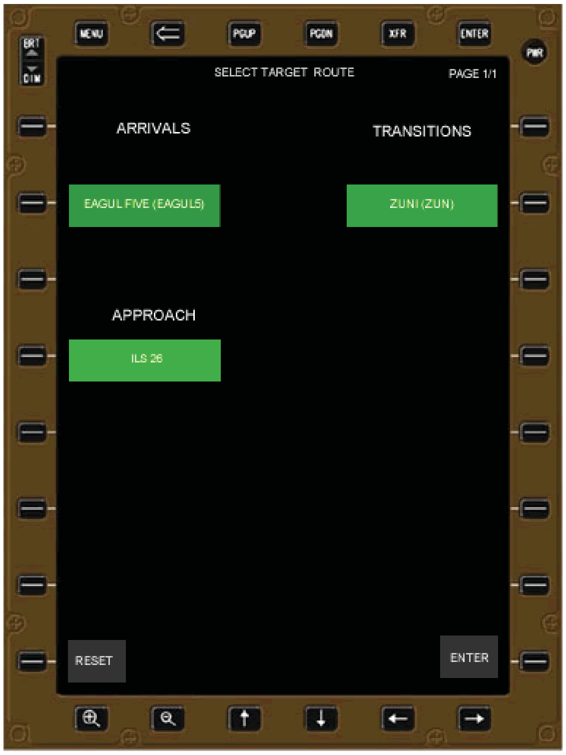
Figure C-16. Manually load the target aircraft call sign

Enter the call sign of the target aircraft. The input can be cleared by using the CLR button located on the bottom row of the keyboard. The CANCEL button will cancel the input and return to the Target Aircraft Page. Pressing the ENTER button will enter the call sign into the FIM system and return to the Interval Management Page

Figure C-17. Manually enter the target aircraft call sign

The target aircraft call sign is now shown in the TGT ACFT block. To enter the target aircraft's route press the TGT RTE block or the bezel button located beside it.

Figure C-18. Load the target aircraft route information



Select the target aircraft's arrival, transition, and approach in the same manner as the ownship route information was selected.

Once all items are selected, an ENTER button appears. Press the ENTER button to input the target aircraft's route into the FIM system and return to the main Interval Management Main Page.

Figure C-19. Select target aircraft route information

The target aircraft's arrival and transition is shown in the TGT RTE block.

Figure C-20 Interval Management Main Page with assigned spacing goal, target aircraft call sign, and target aircraft route information

C.5 Activate IM System

When all the required information has been entered into the FIM system, the ACTIVATE button on the EFB will become selectable as shown in Figure C-21. Once the information has been verified by both pilots, the ACTIVATE button is pressed to begin performing FIM operations. If the IM clearance specified initializing spacing over a waypoint, pressing ACTIVATE is delayed until the aircraft is crossing that waypoint.

Figure C-21. Activate the IM operation

The FIM system will initially need time to compute speed commands. During this period, CALCULATING will be displayed on the EFB (see Figure C-22). The TGT ACFT and TGT RTE input fields turn into labels, and cannot be changed. The OWN INFO and IM GOAL fields can be changed if the original IM clearance is amended. The NEXT WPT field displays the next waypoint the ownship will fly over on the arrival. The CGD located in the pilot's forward field-of-view will also become active displaying CALCULATING and the target aircraft's call sign. The call sign is shown in white to indicate the target aircraft is not yet paired and no commanded speed is shown.

Figure C-22. Calculating initial speed command

Once a commanded speed has been calculated, the ownship and target aircraft will be paired, and a commanded speed will appear as shown in Figure C-23. The pilot will then open the MCP speed window and fly this speed. The Fast / Slow indicator appears to provide speed conformance information. The CGD will also change to indicate the paired status. SPACING will appear in the Status block, and the target aircraft's call sign will turn green. A commanded speed will appear and the Fast / Slow indicator will be presented graphically on the left side. Once paired, the pilot may fly the FIM operation using the CGD exclusively.

Figure C-23. Information displayed on the EFB and CGD while performing FIM operations

C.6 Arrival Interval Management Procedures

- (PF, PM) Airspeed Requirements
    - Observe and announce IM Speed changes and mode changes on CGD/EFB
        - Speed changes will highlight for 10 seconds and then will blink if not set
    - Set IM commanded speed in speed window on MCP
    - Maintain ±10 knots of IM commanded speed during speed changes

    NOTE: *When IM is active, fly the IM commanded speed and disregard any charted speeds on the arrival. Use the FAST/SLOW indicator for deceleration/acceleration rate guidance.*

    - 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 TOD Point
    - Use drag devices and thrust as necessary to maintain VNAV path within ±400 feet (PF)
    - Monitor that aircraft stays on path and all restrictions will be met

- (PF, PM) Spacing Requirements
    - No Caution messages on EFB (See non normal below for action)
    - Notify ATC when initially spacing behind target aircraft
    - Notify each new ATC check in with “Paired with”
    - Notify ATC if no longer IM spacing

C.7 Final Segment Interval Management Procedures

- (PF, PM) Configuration and Energy Management
  - Extend Flaps as necessary
  - VNAV PTH will engage at flap extension
  - Maintain least amount of flaps required to maintain IM speed and vertical path

  NOTE: *IM commanded speed may increase above current flap max speed. Reduction of flaps may be required.*

  - When IM commanded speed blanks at the FAF
    - Gear down
    - Target Speed set in MCP Window
    - Configure as necessary to be stable by 1000 feet AGL

- Automation Procedures
  - Aircraft will transition to VNAV PTH when flaps are extended
  - Arm approach mode between 6-2 miles prior to FAF
  - Ensure aircraft will capture both the localizer and glideslope

  NOTE: *If aircraft is on VNAV PTH profile the aircraft will be on or slightly below glideslope when established on final*

  - Set Target Speed in MCP speed window when crossing the FAF and IM Commanded Speed is removed from the EFB and CGD.

C.8 Amendment of Spacing Goal

ATC may amend the IM clearance with a new assigned spacing goal. The procedure for amending the spacing goal in the EFB is illustrated in Figure C-24.

ATC may amend the IM clearance with a new IM GOAL.

Press IM GOAL and enter the new value into the system. The other pilot will check the new value after it has been entered.

Figure C-24. Amend the assigned spacing goal

C.9 Suspend and Resume

ATC may need to suspend FIM operations for a period of time. If a Suspend Instruction, such as

'NASA 6, suspend interval spacing and slow 10 knots'

is issued, the flight crew will assume that FIM operations will resume at a later time. ATC may later issue a Resume Instruction such as the example given below.

'NASA 6, when able, resume interval spacing with DAL877'

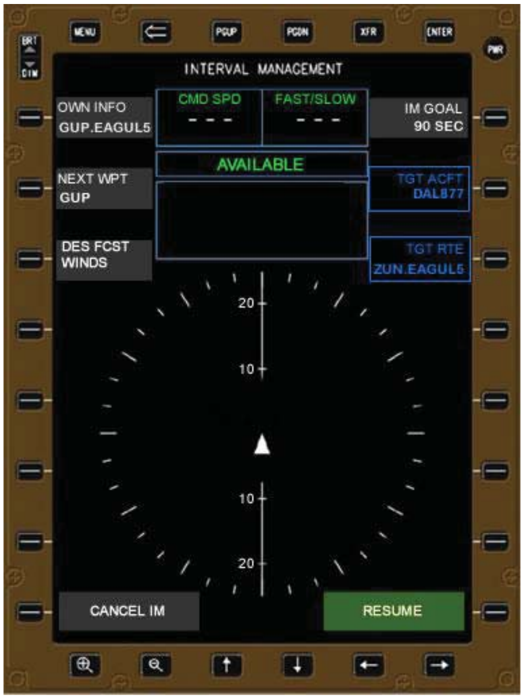
The procedure for suspending and resuming IM spacing is illustrated in Figures C-25 through C-28.

Upon receiving a Suspend Instruction, press the SUSPEND button on the Interval Management Main Page.

Figure C-25. Suspend IM spacing

All speeds are removed from the EFB and CGD and SUSPENDED is displayed in the Interval Management Main Page Status Box. Follow ATC instruction for airspeed.

Figure C-26. Interval Management Main Page with IM spacing suspended



Upon receiving a Resume Instruction, press the RESUME button on the Interval Management Main Page.

Figure C-27. Resume IM spacing

All IM airspeed information is displayed on the EFB and CGD. Follow the CMD SPD at this time.

Figure C-28. Interval Management Main Page with IM spacing resumed

C.10 Unable Spacing

If the CMD SPD disappears from the interface due to a caution (see Figure C-29), the flight crew flies the current airspeed and advises ATC. ATC will determine the appropriate action. If ATC instructs, “advise when able to resume spacing,” the crew will monitor the CMD SPD block. If a value returns to the block the crew will advise ATC and follow instructions. Once the CMD SPD returns, the flight crew reports to ATC that they are able to space behind the target aircraft. ATC may then instruct the aircraft to resume spacing.

Figure C-29. Unable spacing due to target off path

C.11 Cancel Spacing

ATC may cancel the IM clearance, which will be followed by airspeed/heading instructions or a new IM clearance. The procedure for cancelling IM spacing using the EFB is illustrated in Figures C-30 and C-31.

Upon receiving a Cancel Instruction, press the SUSPEND button on the Interval Management Main Page.

Figure C-30. Cancel IM spacing by first suspending FIM operations

Press the CANCEL IM button to cancel the IM clearance. This will remove all information from all fields. A new clearance will have to be entered to Activate Interval Spacing.

Figure C-31. Cancel IM clearance

C.12 Alerts: Cautions, Advisory, and Memos

The IM system and its associated ASTAR algorithm have the set of alerts shown in Table C-1.

Table C-1. IM system 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	Fly Current Airspeed and advise ATC “Unable Spacing due equipment failure”
Caution	IM TGT OFF PATH	Target aircraft is not on the flight path given by the ATC IM clearance	Fly Current Airspeed and advise ATC “Unable Spacing due to Target off path”
Caution	IM TGT ADSB LOST	Target aircraft ADS-B information is lost	Fly Current Airspeed and advise ATC “Unable Spacing due to Target ADS-B Loss”
Caution	IM OWN OFF PATH	Aircraft is greater than 2.5 NM laterally, 6000’ vertically, or 90 degrees of heading from the planned flight path	Fly Current Airspeed and advise ATC “Unable Spacing due to Ownship off path”
Advisory	IM SPD LIMITED	IM would command a different speed but is limited by the 15% constraint	Advisory only. No crew action.

Appendix D: Pilot Post-Run Questionnaire

1. **What is your name? ________________________________**

   **Names will be removed and replaced with coded ID numbers.

2. **Please select the scenario you just completed from the list below:**
   - Training
   - Scenario 1
   - Scenario 2
   - Scenario 3
   - Scenario 4

3. **Please select your role during the scenario you just completed from the list below:**
   - Pilot Flying
   - Pilot Not Flying / Pilot Monitoring

4. **Please select your role during the scenario you just completed from the list below:**
   - Captain
   - First Officer

5. **What was your call sign during the previous run?**
   - NASA01
   - NASA02
   - NASA05
   - NASA06

6. **Even though errors may be large or frequent, can instructed task be accomplished most of the time?**
   - Yes
   - No

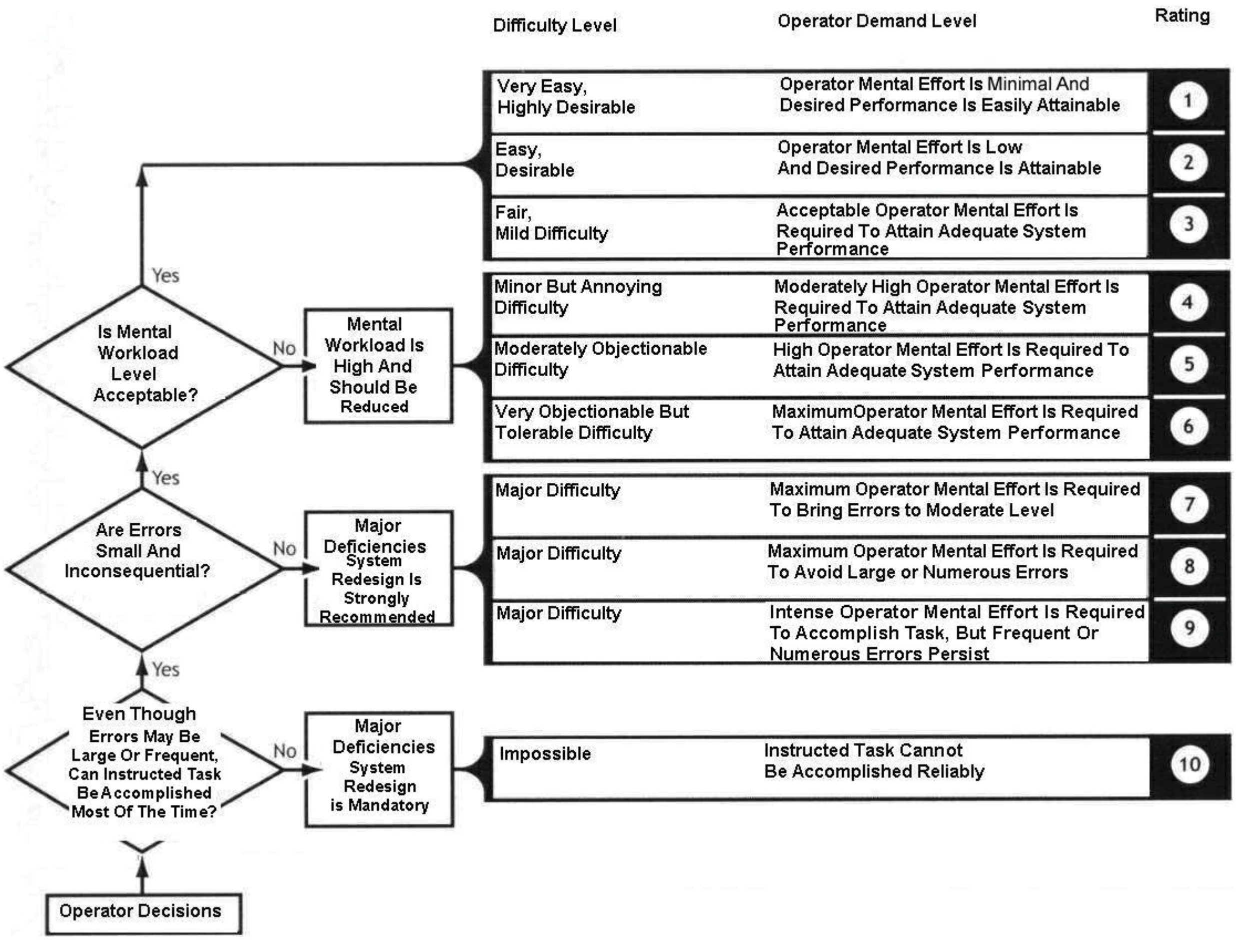
7. **[If pilot responded 'Yes' to Item 6] Are errors small and inconsequential?**
   - Yes
   - No

8. **[If pilot responded 'No' to Item 7] Given that major deficiencies exist and system redesign is strongly recommended, please choose one of the following ratings:**
   - Major difficulty / maximum operator mental effort is required to bring errors to moderate level
   - Major difficulty / maximum operator mental effort is required to avoid large or numerous errors
   - Major difficulty / intense operator mental effort is required to accomplish task, but frequent or numerous errors persist

9. **[If pilot responded ‘Yes’ to Item 7] Is mental workload level acceptable?**
    - Yes
    - No

10. **[If pilot responded ‘No’ to Item 9] Given that mental workload is high and should be reduced, please choose one of the following ratings:**
    - Minor but annoying difficulty / moderately high operator mental effort is required to attain adequate system performance
    - Moderately objectionable difficulty / high operator mental effort is required to attain adequate system performance
    - Very objectionable but tolerable difficulty / maximum operator mental effort is required to attain adequate system performance

11. **[If pilot responded ‘Yes’ to Item 9] Given that mental workload level was acceptable, please choose from one of the following:**
    - Very easy / highly desirable / operator mental effort is minimal and desired performance is easily attainable
    - Easy, desirable / operator mental effort is low and desired performance is attainable
    - Fair, mild difficulty / acceptable operator mental effort is required to attain adequate system performance



12. Follow the flow chart above to select the <u>peak</u> workload you experienced during each segment of flight during the scenario you just completed. Rating of your peak workload level:

	1	2	3	4	5	6	7	8	9	10
>18,000ft (cruise, initial descent)	○	○	○	○	○	○	○	○	○	○
18,000–11,000 (descent, approach check)	○	○	○	○	○	○	○	○	○	○
11,000–5,000 (TRACON, low altitude merge)	○	○	○	○	○	○	○	○	○	○
<5,000 (final approach, configure aircraft)	○	○	○	○	○	○	○	○	○	○

13. Please rate the overall FIM acceptability during the scenario you just completed.

Completely Unacceptable						Completely Acceptable
1	2	3	4	5	6	7

14. Please rate the FIM acceptability during each segment of flight during the scenario you just completed.

	Completely Unacceptable 1	2	Moderately Acceptable 3	4	Very Acceptable 5
>18,000 ft (cruise, initial descent)	○	○	○	○	○
18,000–11,000 (descent, approach check)	○	○	○	○	○
11,000–5,000 (TRACON, low altitude merge)	○	○	○	○	○
<5,000 ft (final approach, configure aircraft)	○	○	○	○	○

15. **Respond to each of the statements shown below using a scale ranging from "1" (Completely Disagree) to "7" (Completely Agree).**

	Completely Agree 1	2	3	4	5	6	Completely Disagree 7
Relevant information, including operational plans, decisions, and changes in aircraft state, were effectively communicated between yourself and your crew member.	○	○	○	○	○	○	○
I was not rushed or hurried in completing the task.	○	○	○	○	○	○	○
The IM commanded speeds were operationally acceptable.	○	○	○	○	○	○	○
The IM commanded speeds were operationally appropriate.	○	○	○	○	○	○	○
The frequency of the IM speed commands was acceptable at all times throughout the scenario.	○	○	○	○	○	○	○
I understood why the IM speed commands were provided (i.e. the IM commanded speeds made sense).	○	○	○	○	○	○	○
The use of voice communications to provide the IM clearance(s) was acceptable in this scenario.	○	○	○	○	○	○	○
The amount of head down time required to input information from the IM clearance(s) into the EFB was acceptable.	○	○	○	○	○	○	○
During this scenario, entering IM clearance information into the EFB was easy and intuitive.	○	○	○	○	○	○	○
During this scenario, it was easy to obtain needed information from the IM displays	○	○	○	○	○	○	○
The flight crew procedures for the events in this scenario were complete.	○	○	○	○	○	○	○
The flight crew procedures for the events in this scenario were acceptable.	○	○	○	○	○	○	○

16. Did the procedures contain missing steps?

- Yes
- No

17. Did the procedures contain extra steps that were unnecessary?

- Yes
- No

18. Were the procedural steps logical and easy to follow?

- Yes
- No

19. Please briefly explain any undesirable ratings from the statements above.

____
____
____
____

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

____
____
____
____

21. 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: Pilot Post-Experiment Questionnaire

1. **What is your name? ________________________________**

   **Names will be removed and replaced with coded ID numbers.

2. **What was your call sign during the experiment?**
   - NASA01
   - NASA02
   - NASA05
   - NASA06

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
Workload Required	1	2	3	4	5	6	7

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:**

   ____
   ____
   ____
   ____

5. **Did you receive adequate training with respect to flying the simulator?**
   - Yes
   - No. If not, please briefly describe how simulator training can be improved.

   Make a comment on your choice here:

   ____
   ____
   ____
   ____

6. **Did you receive adequate training with respect to the IM spacing procedure and the spacing tool?**
    - Yes
    - No. If not, please briefly describe how IM procedures or spacing tool training can be improved.

    Make a comment on your choice here:

    ____
    ____
    ____
    ____

7. **Did you receive adequate training with respect to the entry and interpretation of information presented on the EFB?**
    - Yes
    - No. If not, please briefly describe how EFB training can be improved.

    Make a comment on your choice here:

    ____
    ____
    ____
    ____

8. **Did you receive adequate training with respect to the interpretation of information presented on the CGD in the forward field of view?**
    - Yes
    - No. If not, please briefly describe how CGD training can be improved.

    Make a comment on your choice here:

    ____
    ____
    ____
    ____

Interval Management Procedures

The following questions are intended to gather your feedback about the procedures used for each aspect of the IM operation that was tested (note that the last question asks about the general IM procedures).

9. **Were the procedures for terminating an IM operation complete, accurate, and logical?**
   - Yes
   - No. Please provide any suggestions regarding the way(s) in which the procedures for terminating the IM operation may be improved.

   Make a comment on your choice here:

   ____
   ____
   ____
   ____

10. **Were the procedures for suspending and then resuming an IM operation complete, accurate, and logical?**
   - Yes
   - No. Please provide any suggestions regarding the way(s) in which the procedures for suspending the IM operation may be improved.

   Make a comment on your choice here:

   ____
   ____
   ____
   ____

11. **Were the procedures for amending the IM spacing goal complete, accurate, and logical?**
   - Yes
   - No. Please provide any suggestions regarding the way(s) in which the procedures for amending the IM spacing goal may be improved.

   Make a comment on your choice here:

   ____
   ____
   ____
   ____

12. Were the procedures for reacting to the loss of your lead aircraft's ADS-B signal complete, accurate, and logical?

- Yes
- No. Please provide any suggestions regarding the way(s) in which the procedures for reacting to the loss of your lead aircraft's ADS-B signal may be improved.

Make a comment on your choice here:

13. Were the general (nominal) IM procedures complete, accurate, and logical?

- Yes
- No. Please also provide any suggestions regarding the way(s) in which the general IM procedures may be improved.

Make a comment on your choice here:

14. Was the IM phraseology used in this experiment correct and intuitive?

- Yes
- No. If "no," why not, and what could be done to improve the phraseology?

Make a comment on your choice here:

15. How difficult do you think it would be for a typical crew to learn and integrate the IM spacing procedures into their current daily operational flight procedures?

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

16. Briefly describe any challenges involved with integrating the IM procedures with existing procedures.

____
____
____
____

17. 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

18. In general, did you find the process of entering IM clearance information into the EFB easy and intuitive?

- Yes
- No. If “no,” what can be done to improve the process of loading information into the EFB?

Make a comment on your choice here:

____
____
____
____

19. Did the CGD and EFB provide you with the information you needed/desired to safely and correctly conduct IM, and was this information easy to obtain when needed?

- Yes
- No. If “no,” what information was missing, or how can the information be presented better?

Make a comment on your choice here:

____
____
____
____

20. Did following the IM commanded speed and procedure ever cause unexpected or undesired behavior?

- Yes. If "yes," please explain what the unexpected or undesired behavior was.
- No

Make a comment on your choice here:

21. Did you find the responsibility of using onboard automation to achieve a spacing interval behind a lead aircraft acceptable (when ATC is responsible for separation)?

- Yes
- No. If "no," why not, and what could be done to make the responsibility or workload acceptable?

Make a comment on your choice here:

22. Did you find your level of engagement with the IM automation acceptable (i.e., the level of decision making ability you had, and your understanding of the reasoning behind IM speeds that were commanded)?

- Yes. Please explain.
- No. Please explain.

Make a comment on your choice here:

23. Did the IM commanded speeds make sense?

- Yes
- No

Make a comment on your choice here:

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

Appendix F: Controller Post-Run Questionnaire

1. **What is your name? ________________________________**

   **Names will be removed and replaced with coded ID numbers.

2. **Please select the scenario you just completed from the list below:**
   - Training
   - Scenario 1
   - Scenario 2
   - Scenario 3
   - Scenario 4

3. **Which position did you work in this scenario?**
   - Center North (ZAB 36/43)
   - Center North (ZAB 93/39)
   - Feeder North
   - Final North
   - Ghost

4. **How mentally demanding was the task?**

Very Low						Very High
1	2	3	4	5	6	7

5. **How hurried or rushed was the pace of the task?**

Very Low						Very High
1	2	3	4	5	6	7

6. **How hard did you have to work to accomplish your level of performance?**

Very Low						Very High
1	2	3	4	5	6	7

7. **How insecure, discourage, irritated, stressed, and annoyed were you?**

Very Low						Very High
1	2	3	4	5	6	7

8. How physically demanding was the task?

Very Low						Very High
1	2	3	4	5	6	7

9. How successful were you in accomplishing what you were asked to do?

Good						Poor
1	2	3	4	5	6	7

10. Were the ATD-1 operations in this last run safe?
- Yes
- No

11. [If controller responded 'Yes' to Item 10] Did the ATD-1 operations function adequately, so that you had a tolerable workload?
- Yes
- No

12. [If controller responded 'No' to Item 11] Given that you think the ATD-1 operations were not adequate, were the operations controllable?
- Barely controllable, needs extreme amounts of controller compensation
- Marginally controllable, needs considerable controller compensation
- Controllable, needs some controller compensation

13. [If controller responded 'Yes' to Item 11] Are the ATD-1 operations satisfactory without improvement?
- Yes
- No

14. [If controller responded 'No' to Item 13] How much, if at all, did you have to compensate for the tools to make the ATD-1 operations work? (In these situations "compensation" means how much did you have to work to counterbalance or offset less desirable actions from the tools?)
- Extensive compensation required to maintain adequate performance
- Considerable compensation required to maintain adequate performance
- Moderate compensation required to maintain adequate performance

15. [If controller responded 'Yes' to Item 13] How close to a desired level of performance were the ATD-1 operations in this run?
- Moderate controller compensation needed to reach desired performance
- Minimal controller compensation required to reach desired performance
- Realistic ATC emulation performance with no controller correction

16. **[If controller responded 'No' to Item 10] Please describe any events you saw in the last run that were unsafe.**

____
____
____
____

17. **Did you have any problems in this run? Please note why and which aircraft were the issue.**

____
____
____
____

18. **Did you have to maneuver any non-FIM aircraft to accommodate a FIM-equipped aircraft? Please note how many you had to move and describe why.**
    - Yes
    - No

    Make a comment on your choice here:

____
____
____
____

19. **Did you have to change the way you worked to manage the FIM aircraft?**

    Please choose all that apply:

- ☐ Changed my general scan of the FIM aircraft (compared with non-FIM aircraft)
- ☐ Changed the way I monitored separation of the FIM aircraft (compared with non-FIM aircraft)
- ☐ Changed the way I monitored the FIM aircraft spacing (compared with non-FIM aircraft)
- ☐ Issued different types of clearances to the FIM aircraft (compared with non-FIM aircraft)
- ☐ Issued more clearances to the FIM aircraft (compared with non-FIM aircraft)
- ☐ Considered different types of solutions to FIM aircraft problems (compared with non-FIM aircraft)
- ☐ No change required
- ☐ Other: ____________________

20. **Did you encounter any problems as a result of the target aircraft arriving on a different route from its following FIM (self-spacing) aircraft?**
    - Yes
    - No

    Make a comment on your choice here:

    ____
    ____
    ____
    ____

21. **How manageable was the size of the delay / advance that was required for your non-FIM (CMS) aircraft to meet the schedule?**

Very manageable			Somewhat manageable			Not at all manageable
1	2	3	4	5	6	7

22. **[If controller responded 'Center North (ZAB 36/43)' or 'Center North (ZAB 93/39)' to Item 3] How manageable was the size of the delay / advance that was required for the FIM-equipped aircraft to meet the plus or minus 60 sec limit required to issue the FIM (self-spacing) clearance?**

Very manageable			Somewhat manageable			Not at all manageable
1	2	3	4	5	6	7

23. **Which of these available tools did you actively use in the last run?**

    Please choose all that apply:
    - ☐ Meterlist with FIM information
    - ☐ Delay in the meterlist
    - ☐ Delay countdown timer
    - ☐ Runway identifier in data block
    - ☐ FIM spacing designator
    - ☐ Route display
    - ☐ J-rings to 5 NM
    - ☐ Slot marker
    - ☐ Speed advisory
    - ☐ Timeline on your scope
    - ☐ Spacing cones (bats)
    - ☐ Other: ________________________

24. [If controller responded 'Center North (ZAB 36/43)' or Center North (ZAB 93/39)' to Item 3] How useful were the CMS tools for managing the FIM aircraft? (e.g., giving you information about the FIM aircraft or helping you to space non-FIM aircraft around them.)

Please choose the appropriate response for each item:

	Not useful at all (ignored) 1	2	3	Somewhat useful 4	5	6	Very useful (essential) 7
Delay in the meterlist	○	○	○	○	○	○	○
Delay countdown timer	○	○	○	○	○	○	○
FIM designators	○	○	○	○	○	○	○
Runway identifier	○	○	○	○	○	○	○
FIM-specific meterlist information	○	○	○	○	○	○	○
All-aircraft meterlist information	○	○	○	○	○	○	○

25. [If controller responded 'Feeder North' or 'Final North' to Item 3] How useful were the CMS tools for managing the FIM aircraft (e.g., giving you information about the FIM aircraft or helping you to space non-FIM aircraft around them.)

Please choose the appropriate response for each item:

	Not useful at all (ignored) 1	2	3	Somewhat useful 4	5	6	Very useful (essential) 7
Speed advisories	○	○	○	○	○	○	○
Slot markers	○	○	○	○	○	○	○
Delay countdown timer	○	○	○	○	○	○	○
Timelines	○	○	○	○	○	○	○
FIM designators	○	○	○	○	○	○	○
Spacing cones (bats)	○	○	○	○	○	○	○

26. Did you issue any of the types of clearances listed below? Please note the aircraft call sign (if you can) as well as where and why you took this action in the box on the right.

Please choose all that apply and provide a comment:

- ☐ Suspended FIM spacing ______________________
- ☐ Resumed FIM spacing ______________________
- ☐ Decided not to issue a FIM clearance ______________________
- ☐ Cancelled FIM spacing ______________________
- ☐ None ______________________
- ☐ Other: ______________ ______________________

27. Did you have to re-issue the IM clearance? If so, please note the ACID(s) and the reason(s) why.

Aircraft 1 (ID and why) ______________________
Aircraft 2 (ID and why) ______________________
Aircraft 3 (ID and why) ______________________
Aircraft 4 (ID and why) ______________________
No, I didn't have to reissue ______________________

28. How many vectoring maneuvers did you issue to FIM aircraft in this run? (A vector away from a route and a second vector back onto the route counts as one maneuver.)

	None	1 or 2 vector maneuvers	3-5 vector maneuvers	6-10 vector maneuvers	More than 10 vector maneuvers
Before IM spacing engaged	○	○	○	○	○
When the FIM-equipped aircraft was suspended	○	○	○	○	○
After FIM spacing was terminated	○	○	○	○	○

29. In general, was the FIM pilot's intent clear? (i.e., Did you have enough information about the status of the FIM operations?)

- Intent / plan was always clear (had enough information)
- Intent / plan was usually clear
- Intent / plan was sometimes clear
- Intent / plan was occasionally clear
- Intent / plan was not at all / never clear (not enough information)

Make a comment on your choice here:

____

____

____

____

30. Did being responsible for maintaining safe / standard separation for FIM aircraft but not managing their spacing affect your monitoring load?

Monitoring load was greatly reduced			No change in monitoring load			Monitoring load was greatly increased
1	2	3	4	5	6	7

31. [If controller responded 'Center North (ZAB 36/43)' or Center North (ZAB 93/39)' to Item 3] Please rate how accurately the FIM displays (S & ®) reflected the status of the FIM aircraft as they entered your sector.

Very accurate			Somewhat accurate			Very inaccurate
1	2	3	4	5	6	7

32. [If controller responded 'Center North (ZAB 36/43)' or Center North (ZAB 93/39)' to Item 3] Please rate how accurately the FIM displays (S & ®) reflected the status of the FIM aircraft as they left your sector.

Very inaccurate			Somewhat accurate			Very accurate	
1	2	3	4	5	6	7	N/A

33. If applicable, why was the status indicator inaccurate as the FIM aircraft left your sector?

- I didn't update the status (please say why)
- There wasn't a code for the state of the FIM aircraft
- The status of the FIM aircraft was changing
- Other

Make a comment on your choice here:

____

____

____

____

34. Did having FIM aircraft change the amount of coordination you engaged in with the controllers upstream and downstream of you?

Much less coordination			No change / the same level of coordination			Much more coordination
1	2	3	4	5	6	7

35. Was there anything that happened in this run that we forgot to ask about? What would you have liked to see happen differently, if anything?

____

____

____

____

Appendix G: Controller Post-Experiment Questionnaire

1. **What is your name? ________________________________**

   **Names will be removed and replaced with coded ID numbers.

2. **Which position did you work in this scenario?**
   - Center
   - Feeder/Final

3. **During which year did you retire? _______________**

4. **Which aircraft did you pay the most attention to during the experiment? Please note why this type of aircraft required more attention from you.**

   Please choose all that apply and provide a comment.

   - ☐ All aircraft equally ______________________
   - ☐ Non-FIM (RNAV) aircraft ______________________
   - ☐ FIM aircraft that were in paired spacing mode ______________________
   - ☐ FIM aircraft that were suspended or terminated ______________________
   - ☐ Other: ____________________________ ______________________

5. **Did the speed profile that the FIM aircraft followed fit with your strategy for working the non-FIM equipped (RNAV) traffic? Why or why not?**

   ____
   ____
   ____
   ____

6. **If you had seen a FIM aircraft that was in IM spacing mode and you slowed its lead, what would you expect to see the FIM aircraft do?**

   ____
   ____
   ____
   ____

7. **What was your plan B if the FIM aircraft did not do as you expected in the example above?**

   ____
   ____
   ____
   ____

8. To what degree did you accommodate the FIM aircraft? Please note why you selected this rating.

Not at all			Sometimes			Always
1	2	3	4	5	6	7

Make a comment on your choice here:

____
____
____
____

9. In what ways would you like to change the FIM operations / aircraft behavior, and why?

____
____
____
____

10. Did the winds in this simulation affect the behavior of the FIM aircraft or the FIM tools?

	Always	Often	Sometimes	Occasionally	Never	N/A
FIM aircraft	○	○	○	○	○	○
FIM spacing interval	○	○	○	○	○	○

11. What impact did the wind variation have on the speed / time advisories and the information given by the tools?

____
____
____
____

12. Is there a wind condition that could be problematic for the FIM concept?

- Yes
- No
- N/A

Make a comment on your choice here:

____
____
____
____

13. Please comment on your thoughts of the FIM aircraft sharing routes with the non-FIM equipped (RNAV) aircraft.

____
____
____
____

14. How did you handle your traffic as it crossed your merge point?

____
____
____
____

15. What information would you like to know about the lead aircraft? How would you like this information to be displayed?

____
____
____
____

16. What procedure would you suggest for coordination when the lead is in a different sector from the FIM aircraft?

____
____
____
____

17. [If controller responded 'Center' to Item 2] This simulation used a procedure where you conditioned the FIM traffic to be within a 60 second "window" of their meterfix STA before you engaged FIM spacing. Was this possible? If so, how successful was it?

- Very easy to achieve 60 sec conditioning
- Easy to achieve 60 sec conditioning
- 60 sec conditioning was available
- Hard to achieve 60 sec conditioning
- Very hard to achieve 60 sec conditioning
- Impossible to achieve 60 sec conditioning

Make a comment on your choice here"

____
____
____
____

18. How well did the FIM aircraft conditioning work for you?

- Conditioning worked very well
- Conditioning worked well
- Conditioning sometimes worked
- Conditioning only worked occasionally
- Conditioning did not work
- Impossible to achieve 60 sec conditioning

Make a comment on your choice here”

19. How timely / appropriate was the reaction of the system to the speed adjustments of the self-spacing (FIM) aircraft? (e.g., When a self-spacing aircraft was flying at a faster speed than its target, how quickly did it adjust to a matching speed?)

Poor timing / slow reaction			Reasonably timely			Very good timing / fast reaction
1	2	3	4	5	6	7

20. In addition to standard separation, there is a 0.3 NM buffer. Was the 0.3 NM buffer adequate? Please explain.

- Yes
- No
- N/A

Make a comment on your choice here:

21. [If controller responded ‘Feeder/Final’ to Item 2] Was the final approach fix the best point by which the FIM aircraft should achieve their spacing?

No, not at all			Sometimes			Yes, always
1	2	3	4	5	6	7

22. [If controller responded 'Feeder/Final' to Item 2] Was it clear whether the FIM aircraft were going to meet their time at final approach fix targets?

Never clear			Sometimes clear			Always clear	
1	2	3	4	5	6	7	N/A

23. [If controller responded 'Feeder/Final' to Item 2] Did you modify where you handed off your aircraft to the Tower with the final approach fix as the FIM achieve-by point? Was it earlier or later than you would have normally made the handoff at PHX?

- Handoff was much earlier than normal
- Handoff was earlier than normal
- Handoff was the same
- Handoff was later than normal
- Handoff was much later than normal

24. Was the transfer of spacing responsibility from you (controller) to the FIM aircraft, and back, clear?

- Yes, always
- Yes, usually
- Sometimes
- Occasionally
- No

Make a comment on your choice here:

____
____
____
____

25. When FIM aircraft were in your sector, how acceptable was it for you to be responsible for maintaining safe / standard separation between these aircraft (but not managing their spacing)?

	Not at all acceptable		Moderately acceptable		Very acceptable
	1	2	3	4	5
FIM aircraft spacing behind FIM aircraft on the same route	○	○	○	○	○
FIM aircraft spacing behind a FIM aircraft on a different route	○	○	○	○	○
FIM aircraft spacing behind a CMS aircraft on the same route	○	○	○	○	○
FIM aircraft spacing behind a CMS aircraft on a different route	○	○	○	○	○

26. How would you change flight deck interval management (FIM) to be most helpful to a controller?

____
____
____
____

27. **Do you think the phraseology you used during the experiment was satisfactory? Please refer to the phraseology sheet for exact clearance.**

	Not at all clear or concise 1	2	3	Moderately clear, OK length 4	5	6	Very clear and concise 7	N/A
IM clearance	○	○	○	○	○	○	○	○
Amendments to IM clearance	○	○	○	○	○	○	○	○
IM engagement status reporting as paired	○	○	○	○	○	○	○	○
Check in with TRACON	○	○	○	○	○	○	○	○
IM operations status reporting	○	○	○	○	○	○	○	○
IM clearance suspension	○	○	○	○	○	○	○	○
IM clearance resumption	○	○	○	○	○	○	○	○
Descent clearance	○	○	○	○	○	○	○	○
IM engagement status reporting unable	○	○	○	○	○	○	○	○

28. **Can you suggest changing the phraseology of the FIM clearances in any way to make them more clear and / or concise?**

____

____

____

____

29. [If controller responded 'Feeder/Final' to Item 2] What did you think of the check in by the FIM aircraft? How could it be made more concise? Did it give you enough information?

- Always too long
- Sometimes too long
- Just the right length
- Sometimes too short or brief
- Always too short or brief

Make a comment on your choice here:

30. Was the use of the FIM status symbology useful?

- Yes
- No
- N/A

Make a comment on your choice here:

31. When FIM operations were involved, were coordination requirements different? If so, did you have to coordinate more or less?

- Yes
- No
- N/A

Make a comment on your choice here:

32. Could you have worked the FIM aircraft under current day / baseline conditions, i.e., without CMS tools?

Not at all			Somewhat / sometimes			Definitely
1	2	3	4	5	6	7

33. Were there any tips about managing FIM aircraft that you discovered for yourself that should be built into training for future studies?

____

____

____

____

34. Please rate the usability of the following tools for working the FIM aircraft. “Usability” is how logical the functions and button presses associated with the tools are.

	Not at all usable			Somewhat usable			Very usable	
	1	2	3	4	5	6	7	N/A
Slot markers	○	○	○	○	○	○	○	○
Timelines	○	○	○	○	○	○	○	○
Speed advisories	○	○	○	○	○	○	○	○
Early / late indicators	○	○	○	○	○	○	○	○
Spacing designators	○	○	○	○	○	○	○	○
Cones	○	○	○	○	○	○	○	○

35. Please rate the usability of the following tools for working the FIM aircraft. "Usability" is how logical the functions and button presses associated with the tools are.

	Not at all usable 1	2	3	Somewhat usable 4	5	6	Very usable 7	N/A
Meterfix STA	○	○	○	○	○	○	○	○
Delay time on aircraft target	○	○	○	○	○	○	○	○
Spacing designators	○	○	○	○	○	○	○	○
Lead aircraft information in the meterlist (call sign, route)	○	○	○	○	○	○	○	○
FIM delay in the meterlist	○	○	○	○	○	○	○	○
FIM interval to the leader in the meterlist	○	○	○	○	○	○	○	○
FIM achieve-by point and time in the meterlist	○	○	○	○	○	○	○	○

36. How confident were you that the controller tools and FIM tools were providing accurate information?

	Not at all confident 1	2	3	Moderately confident 4	5	6	Very confident 7	N/A
Slot markers	○	○	○	○	○	○	○	○
Timelines	○	○	○	○	○	○	○	○
Speed advisories	○	○	○	○	○	○	○	○
Early / late indicators	○	○	○	○	○	○	○	○
Spacing designators	○	○	○	○	○	○	○	○
Meter STA	○	○	○	○	○	○	○	○
Delay on the aircraft target	○	○	○	○	○	○	○	○
Lead aircraft information in meterlist (call sign, route)	○	○	○	○	○	○	○	○
FIM delay in the meterlist	○	○	○	○	○	○	○	○
FIM interval to leader in the meterlist	○	○	○	○	○	○	○	○
FIM achieve-by point and time in the meterlist	○	○	○	○	○	○	○	○

37. What information should the tools have provided to you that they did not? Please consider information presented on your visual display and via voice.

____
____
____
____

38. [If controller responded 'Feeder/Final' to Item 2] Do you think you could have given fewer speed corrections to keep the aircraft in their spacing "slots"?

- Yes
- No

39. Is there something that we didn't ask above that you would like to comment on? Please note this, or anything you observed in the runs this week that you'd like us to know about.

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14. ABSTRACT
NASA's Air Traffic Management Technology Demonstration – 1 (ATD-1) will operationally demonstrate the feasibility of efficient arrival operations combining ground-based and airborne NASA technologies. The ATD-1 integrated system consists of the Traffic Management Advisor with Terminal Metering which generates precise time-based schedules to the runway and merge points; Controller Managed Spacing decision support tools which provide controllers with speed advisories and other information needed to meet the schedule; and Flight deck-based Interval Management avionics and procedures which allow flight crews to adjust their speed to achieve precise relative spacing. Initial studies identified air-ground challenges related to the integration of these three scheduling and spacing technologies, and NASA's airborne spacing algorithm was modified to address some of these challenges. The Research and Procedural Testing of Routes human-in-the-loop experiment was then conducted to assess the performance of the new spacing algorithm. The results of this experiment indicate that the algorithm performed as designed, and the pilot participants found the airborne spacing concept, air-ground procedures, and crew interface to be acceptable. However, the researchers concluded that the data revealed issues with the frequency of speed changes and speed reversals.

15. SUBJECT TERMS
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