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Air Traffic Management Technology Demostration-1 (ATD-1) Avionics Phase 2 Flight Test and Results

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Foreword

This NASA Technical Publication is a comprehensive report describing the design, development, and flight test of an Interval Management avionics prototype. This work was accomplished under a NASA contract to Boeing Research and Technology, with sub-contractors of Boeing Commercial Aircraft, Honeywell, United Airlines, and Jeppesen. This contractor team worked closely with members of NASA Langley Research Center's Crew Systems and Aviation Operations Branch, Systems Engineering and Engineering Methods Branch, and the Simulation Development and Analysis Branch.

People who provided exceptional contributions to this effort include: Dan Boyle, John Brown, Mary Beth Lapis, Karl Rein-Westin, Julien Scharl, Al Sipe, Paul van Tulder, George Wilber, and Barbi Withers, (Boeing); Rick Berckefeldt, Dana Clont, Craig Dowling, Jack Rahn, Craig Schimmel, Aman Singh, and Bill True (Honeywell); George Silverman, Craig Stankiewicz, and Rocky Stone (United Airlines); Sherilyn Brown, Bill Cann, Stella Harrison, Will Johnson, Missy Hill, Sean Maydwell, Mike Madson, Leighton Quon, Denise Scearce, and Nina Tappan (NASA).

Significant input to the IM procedure development, flight test design, and data analysis was provided by several FAA civil servants and contracts. The authors thank Greg Comstock, Ian Levitt, Christine Hassig, Paul von Hoene, and Lesley Weitz for their contributions throughout the duration of the ATD-1 Project.

The controllers' participation in the design and execution of the flight test was critical. On behalf of the entire NASA, Boeing, Honeywell, and United Airlines team, the authors express their gratitude for the contributions and professionalism of so many by acknowledging the leadership team of Leon Fullner and Brett Russell of Seattle Center, and Debra Hernke from Moses Lake TRACON. The flight test also benefited from the support of the FAA's Flight Technologies and Procedures Division (ASF-400), Flight Procedures Standards Branch (ASF-420) and the Flight Procedure Implementation and Oversight Branch (ASF-460).

And finally, the authors thank the immense effort of the NASA interns who contributed to the preparation for the training program and the flight test, or who contributed to the data analysis: Cristin Mayes, Joshua Milot, Ben Remy, Sandor Valenciaga, and Christine Watters.

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Abbreviations and Acronyms

ABP	Achieve-By Point
ADS-B	Automatic Dependent Surveillance–Broadcast
ARTCC	Air Route Traffic Control Center
ASG	Assigned Spacing Goal
ASTAR	Airborne Spacing for Terminal Arrival Routes
ATC	Air Traffic Control
ATD-1	Air Traffic Management Technology Demonstration–1
B-737	Boeing 737-900
B-757	Boeing 757-200
CAS	calibrated airspeed
CBT	computer-based training
CGD	configurable graphics display
CMS	Controller-Managed Spacing
ConOps	Concept of Operations
CTD	constant time delay
DTG	distance to go
EFB	electronic flight bag
ETA	estimated time of arrival
FAA	Federal Aviation Administration
F-900	Dassault Falcon 900
FAF	Final Approach Fix
FIM	Flight Deck Interval Management
FL	Flight Level
FMS	Flight Management System
FSI	Fast/Slow Indicator
FTD	Flight Test Director
GNSS	Global Navigation Satellite System
IM	Interval Management
IP	Initial Point
KBFI	Boeing Field / King County International Airport
KGEG	Spokane International Airport
KMWH	Grant County International Airport
KSEA	Seattle-Tacoma International Airport
KYKM	Yakima Air Terminal/McAllister Field
LaRC	Langley Research Center

LP	Long Pole
M	Mach
MCP	mode control panel
MOPS	Minimum Operational Performance Standards
MSI	Measured Spacing Interval
NASA	National Aeronautics and Space Administration
nmi	nautical mile
NOAA	National Oceanic and Atmospheric Administration
PBN	Performance Based Navigation
PSI	Predicted Spacing Interval
PTP	Planned Termination Point
RNAV	Area Navigation
RNP AR	Required Navigation Performance Authorization Required
SD	Standard Deviation
STA	scheduled time of arrival
STAR	Standard Terminal Arrival Route
TBO	Trajectory-Based Operation
TCAS	Traffic Alert and Collision Avoidance System
TG	trajectory generator
TMA-TM	Traffic Management Advisor with Terminal Metering
TPU	Traffic Processing Unit
TRACON	Terminal Radar Approach Control
TSAS	Terminal Sequencing and Spacing
UPS	United Parcel Service
VNAV	Vertical Navigation

Description of Terms

Term	Description
ATD-1 ConOps	
Ownship	The IM-equipped aircraft, capable of conducting an IM operation
Target	The aircraft the IM-equipped aircraft is to space behind; must be ADS-B equipped, but need not be IM equipped
Procedural constraint	An altitude or airspeed shown on the arrival or approach procedure; the IM avionics may deviate from that speed by up to 15 percent
Freeze Horizon	When crossing this line, the arriving aircraft is assigned a specific runway and its scheduled times of arrival are fixed
Top Of Descent	The aircraft's computed transition from cruise to descent
Meter Fix	A waypoint used by the ground schedule as a constraint satisfaction point; not used during ATD-1 flight test (ground elements of ATD-1 not available), earlier research typically used the TRACON boundary for arriving aircraft
Merge points	The waypoint where two aircraft trajectories merge; the first common waypoint on two different routes
Experiment Design	
Scenario	A specific operation defined by phase of flight (en route, arrival, final), lead aircraft delay (none, medium, high), type of IM operation (Maintain, Capture, Cross, Final Approach Spacing), route of flight, ABP location, amount of initial spacing error, and interval type (time or distance)
IM operation	The crew procedures and aircraft performance from when the flight crew initiate IM operation (press "Execute" on the EFB) until the operation is terminated (automatically by the IM avionics when crossing the PTP or anytime the "Terminate" button is pressed); flight crew set the IM commanded speed shown on the CGD and EFB into the MCP; four types of operations flown in the flight test: Maintain, Capture, Cross (with the ABP in one of two locations), and Final Approach Spacing
Data point	The data generated from an IM equipped aircraft during an operation
IM application	The speed control law, spacing software and logic, and the graphical interface
IM avionics prototype	The software and the hardware (EFB, CGD, TPU, cables, etc.)
IM Operation	
Assigned Spacing Goal (ASG)	The interval, in time or distance, the IM aircraft is to achieve or maintain relative to the Target aircraft; given by the controller in the ATD-1 ConOps, determined by the test matrix during the flight test

Achieve By Point (ABP)	The point on the IM aircraft's trajectory where the ASG is to be achieved; the end of the achieve stage; transition to maintain stage if ABP and PTP are not collocated, otherwise, IM operation terminates when ABP and PTP are collocated; normally the FAF (ZAVYO) and sometimes the merge point (NALTE) during this flight test
Planned Termination Point (PTP)	The limit of the IM clearance; IM operations are terminated at this point without explicit communication from controller to crew
Spacing error	The difference between the ASG and the spacing interval between the Target and Ownship; measured in time or distance; negative values indicate the spacing interval is smaller than the ASG (the aircraft are closer), positive values indicate the spacing interval is larger than the ASG (the aircraft are farther apart)
Spacing interval units	The IM operation may be conducted using time or distance; time values expressed as seconds during data entry and when shown on the EFB, while distance values were expressed as tenths of a nmi during data entry and when shown on the EFB (or as an integer if greater than or equal to 10 nmi)
Achieve stage	IM application goal is to achieve the ASG by the ABP; occurs in Cross and Final Approach Spacing operations
Maintain stage	IM application goal is to maintain the ASG until the PTP; occurs throughout the Maintain and Capture operations, and in Cross operations after the ABP when the ABP is not co-located with the PTP
Spacing Algorithm	
Trajectory-Based Operation (TBO) speed control law	Mathematical formula that calculates the IM commanded speed for the aircraft to fly to reduce the spacing error; calculates the spacing error based on both aircraft path positions, the operation's ASG, a speed correction, and the speed command as the sum of some nominal speed and the speed correction
Constant Time Delay (CTD) speed control law	Mathematical formula that calculates the IM commanded speed for the aircraft to fly to reduce the spacing error; calculates the spacing error based on the Ownship's position, the Target's time-history position, ASG, a speed correction, and the speed command as the sum of some nominal speed and the speed correction
Nominal speed profile	Speeds specified by the published arrival procedures and the airline standard operating procedure during the approach; emulates no system delay if the lead aircraft flies these speeds; shown as the black line in the case study plots
Delayed speed profile	Specific speeds flown by the lead aircraft to emulate instances where the ground system has calculated delay that must be absorbed
Control law speed	Unfiltered output from the TBO or CTD control law, prior to speed limiting or speed quantization; shown as a yellow line in case study plots

IM Instantaneous speed	The control law speed after applying speed limits (see Appendix B) and other heuristics; represents a smooth, continuous value of the aircraft's expected airspeed; indirectly shown to the flight crew as the FSI; shown as a cyan line in the case study plots
IM commanded speed	The instantaneous speed after applying quantization, a discrete number that represents the desired speed that the pilots are expected to input into the aircraft's MCP speed window; shown to the flight crew as an integer; shown as a dark blue line in the case study plots
Ownship airspeed	The IM equipped aircraft's Mach or calibrated airspeed
Wind blending	Functionality of the IM application to update the original aircraft trajectory, based on forecast winds, with winds sensed at the aircraft's current altitude

Abstract

NASA's first Air Traffic Management Technology Demonstration (ATD-1) subproject successfully completed 19 days of flight test validation in January and February 2017 of an Interval Management (IM) avionics prototype and the procedures used to conduct IM arrival and approach operations. IM is one of the three elements integrated into NASA's ATD-1 concept of operations with the subproject goal of improving aircraft efficiency and airport throughput during high-density arrival operations.

The ATD-1 concept of operations combines advanced arrival scheduling, controller decision support tools, and interval management (IM) avionics to enable merging of multiple, time-based, efficient arrival streams. IM contributes to the operation by calculating speeds that enable an aircraft to precisely achieve a specific time or distance behind another aircraft. When precise spacing intervals can be calculated, achieved, and then maintained during high-density operations, aircraft efficiency should be improved by enabling the aircraft to remain closer to the optimum descent trajectory instead of using vectors and step-down altitudes, and airport throughput should be maintained or improved by each aircraft arriving at the runway threshold closer to the assigned spacing interval.

This avionics development and flight test was conducted under a NASA contract by Boeing Research and Technology, with Boeing Commercial Aircraft, Honeywell, United Airlines, and Jeppesen as sub-contractors. The Honeywell built IM avionics were the first ever prototype built based on NASA requirements as well as developing and non-flight tested international IM standards, integrated into two test aircraft, and then flown in real-world conditions at the Grant County International Airport (KMWH). The IM prototype flown in the flight test used data from the Ownship and the assigned lead, or Target, aircraft to calculate the airspeed necessary for the Ownship to achieve the desired spacing.

The flight test demonstrated that the IM avionics prototype generally met the IM requirement for spacing accuracy. However, the control laws implemented require further development to reduce the high IM speed command rate and the number of speed reversals observed during the test. Pilots assessed the IM procedure as acceptable, and issues requiring further attention were identified.

In summary, the IM avionics prototype showed significant promise in contributing to the goals of improving aircraft efficiency and airport throughput. The flight test results also provided important data to the FAA and the working group developing the follow-on version of the international IM standards.

1 Introduction

1.1 Background

To prepare the National Airspace System for a predicted increase in traffic volume and to improve the efficiency of the air transportation system, the Airspace Operations and Safety Program in NASA's Aeronautics Research Mission Directorate created the Air Traffic Management Technology Demonstration (ATD-1) subproject. This subproject was designed to support commercial aviation stakeholders including the Federal Aviation Administration (FAA), manufacturers, and airspace users, with relevant and timely research. The NASA Langley Research Center (LaRC) Interval Management (IM) research team has been an integral part of the joint NASA Ames Research Center and LaRC effort to develop and test the ATD-1 Concept of Operations (ConOps). This ConOps integrates three separate NASA research elements (also referred to as technologies), each developed with the FAA and industry partners, to achieve high throughput, fuel-efficient arrival operations into a busy terminal airspace (refs. 1 and 2). This ConOps was developed concurrently with and kept closely aligned to the FAA concept for IM operations (refs. 3 and 4).

The first ATD-1 research element, Traffic Management Advisor with Terminal Metering (TMA-TM), generates a precise arrival schedule to the runway threshold and metering points in both Air Route Traffic Control Center (ARTCC) and Terminal Radar Approach Control Facility (TRACON) airspace. The second element, Controller-Managed Spacing (CMS), provides decision support tools to help terminal area air traffic controllers meet the schedule calculated by TMA-TM. The third element, IM, provides the speed guidance necessary to allow flight crews to manage their spacing behind the assigned Target aircraft.

The first two elements (TMA-TM and CMS) were evaluated at the FAA's William J. Hughes Technical Center in 2015 and transferred to the FAA, forming the basis of the FAA's ongoing acquisition and deployment of Terminal Sequencing and Spacing (TSAS) (ref. 5). To support the development of IM, NASA worked closely with the FAA and industry partners over the past fifteen years to contribute to an array of aircraft surveillance applications (ref. 6), safety and performance requirements for the airborne IM application (ref. 7), and the IM Minimum Operational Performance Standards (MOPS, ref. 8).

1.2 Current Operational Need

The 2015-2035 FAA Aerospace Forecast publication predicted that U.S. commercial aviation revenue passenger miles would grow on average 1.8 percent annually over twenty years (ref. 9). By 2035, U.S. commercial air carriers were projected to fly 1.71 trillion available seat-miles – approximately 167 percent of the seat-miles flown in 2015. Arrivals into high-density airports, especially during periods of peak traffic flow or inclement weather, frequently experience inefficient arrival operations due to the use of miles-in-trail restrictions and step-down descents. Current arrival operations do not always meet the airport's maximum capacity, are not always optimal in terms of aircraft fuel burn, emissions, and noise, and frequently result in high controller workload. While advanced Performance Based Navigation (PBN) procedures that can enable individual aircraft to fly more optimal descents exist at a limited number of major airports, they are not well utilized during high density operations. Shortfalls that currently preclude greater use of PBN operations include trajectories calculated by the scheduling software that terminate at the airport instead of specific runways; and a lack of controller and pilot decision support tools to better manage arrival scheduling and throughput. Furthermore, to achieve consistent use of PBN operations, technologies to precisely space aircraft will be needed to meter traffic flows in order to merge aircraft arriving from different directions.

The first two elements of the ATD-1 ConOps (TMA-TM and CMS) provide the coordinated and achievable schedule that enables deconflicted air traffic operations and improves system-level efficiency. The third element (IM) increases the likelihood that aircraft can conduct PBN procedures, which reduces fuel burn, emissions, and noise, as well as improves capacity by providing even greater precision in spacing between aircraft (refs. 10–11).

1.3 Subproject Goal and IM Flight Test Goals

The goal of the ATD-1 subproject is to increase throughput at busy airports while increasing the efficiency of aircraft arrival operations. The ATD-1 ConOps addresses the majority of the shortfalls listed above by providing deconflicted and efficient operations for multiple arrival streams of aircraft from a point prior to top of descent to the Final Approach Fix (FAF). Aircraft on these arrival streams primarily use speed control along their optimized profile descents to achieve precise schedule conformance or spacing between aircraft, thereby decreasing the number of instances when aircraft are vectored off path or required to fly level-flight segments.

During the first four years of the subproject, NASA sponsored multiple in-house simulations exploring the ConOps (refs. 12–17), a demonstration of NASA's Airborne Spacing for Terminal Arrival Routes (ASTAR) algorithm onboard Boeing's ecoDemonstrator aircraft in December 2014 (ref. 18), and a final human-in-the-loop simulation at NASA LaRC in August 2015 (refs. 19–21).

To demonstrate the feasibility of the ATD-1 ConOps in a realistic operational environment, the final activity of the subproject was to build and flight test under contract an IM avionics prototype system (NASA contract NNL13AA03B, task order NNL15AB46T). The goals of this ATD-1 Avionics Phase 2 flight test were (refs. 22–23):

- to develop an IM avionics prototype,
- to integrate that prototype into two test aircraft, and
- conduct scenarios to validate IM operations.

The Avionics Phase 2 flight test was conducted by Boeing Research and Technology, with Boeing Commercial Aircraft, Honeywell, United Airlines, and Jeppesen as subcontractors. The IM avionics created and flown in the ATD-1 flight test were the very first prototype built, and were based on two sets of requirements: 1) NASA requirements based on the ASTAR spacing algorithm (ref. 24), and 2) to the maximum extent possible, a subset of requirements derived from reference 8, which supported time- and distance-based spacing operations in the en route, arrival, and final approach environments. In preparation for the flight test conducted in early 2017, NASA and the contracting team developed comprehensive plans to use three aircraft to fly IM operations in high-altitude en route airspace, arrival operations from en route altitudes to the FAF, and operations intercepting final approach within the terminal airspace. Since the TMA-TM scheduler and CMS tools were not available for this flight test, specific speed profiles were developed for the first aircraft in the arrival stream to emulate the airspeeds expected for transport category aircraft in an integrated operational environment when delay must be absorbed (described in section 5.1).

2 ATD-1 ConOps and IM Operations

2.1 ATD-1 Concept of Operations

The ATD-1 ConOps (ref. 1) integrates advanced arrival scheduling, controller decision support tools, and aircraft avionics to enable efficient arrival operations and allow for the continued use of optimized profile descents during periods of high traffic demand. To achieve increased fuel efficiency, aircraft use optimized profile descent procedures that include a transition from the arrival procedure to the instrument approach procedure of the assigned runway (ref. 11). To achieve the goal of improved throughput at the runway threshold, the aircraft are delivered precisely to a series of meter points (more detailed explanation in Appendix A).

The three elements (or technologies) integrated into the ATD-1 ConOps are described below and shown in Figure 1:

- TMA-TM provides precise arrival scheduling in the terminal airspace
- CMS provides TRACON controllers with decision support tools that enable precise schedule conformance
- IM provides flight-deck automation that enables the flight crew to achieve or maintain precise in-trail spacing behind the Target aircraft

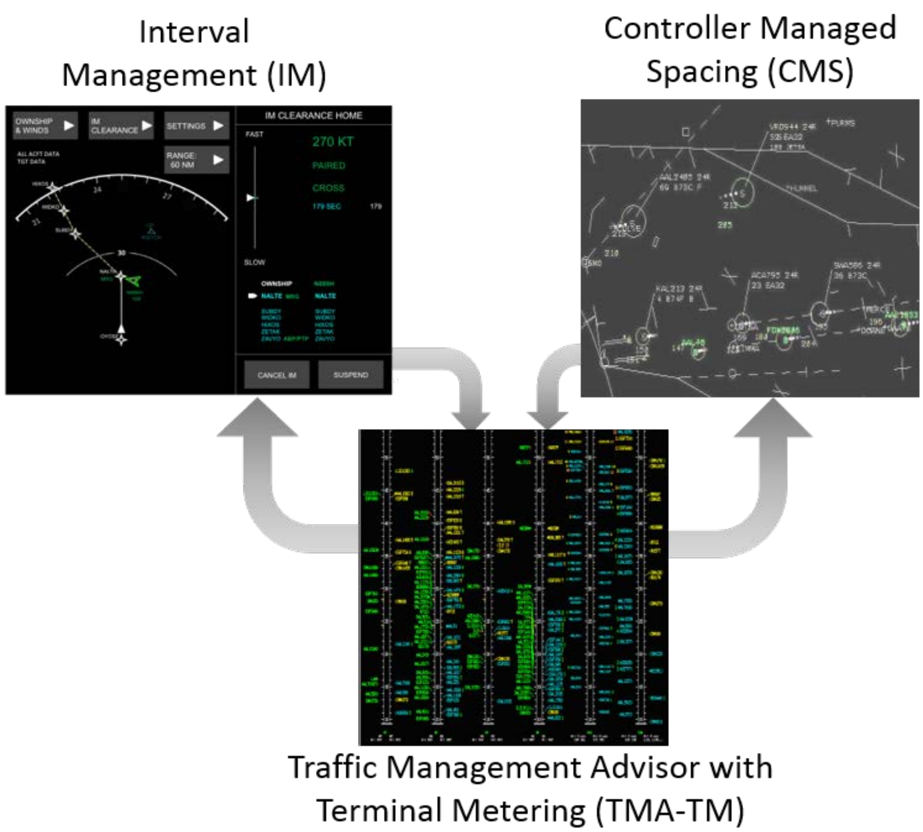


Figure 1. Integrated NASA technologies used in the ATD-1 ConOps.

When an aircraft crosses the Freeze Horizon (a pre-determined range tailored to that airport and the surrounding airspace), TMA-TM assigns the most suitable runway to that aircraft, and freezes its deconflicted scheduled times of arrival at a series of metering points, to include the meter fix, merge points, and runway threshold. It should be noted that while the schedule calculates a deconflicted time of arrival at the runway, the primary responsibility from the FAF on is the safe landing of the aircraft, that is, neither the flight crew nor the controller attempt to modify the aircraft's speed to achieve or maintain the desired spacing interval. Therefore, within the ATD-1 ConOps and the flight test, the assigned spacing interval is the interval desired at the FAF. Both en route and terminal controller meter lists, as well as schedule information used by CMS and IM, are generated from the schedule calculated by TMA-TM.

En route controllers issue the arrival procedure and the expected runway to each flight crew. When the required delay is predicted to exceed the capability of speed-only operations, the en route controller uses path stretching (vectors) or altitude step-downs to absorb the delay, and then reverts to speed-only control when it becomes feasible. Once speed-only control can provide enough control authority to achieve the schedule and the desired spacing intervals, the en route controller issues an IM clearance to the flight crew of the aircraft equipped with IM avionics. This IM clearance can include the following elements: the flight identifier (or "call sign") of the lead aircraft, i.e., the Target aircraft, that aircraft's route of flight, the Assigned Spacing Goal (ASG), the Achieve-by Point (ABP) where the spacing interval must be achieved, and the Planned Termination Point (PTP) where the IM operation is complete. The flight crew enters their route of flight and IM clearance information into the IM avionics, and then flies the speeds calculated by the avionics to either achieve or maintain the desired spacing interval behind the Target aircraft.

Terminal controllers use the scheduled times of arrival (STA) calculated by TMA-TM and displayed on their scopes, as well as the CMS graphical information and advisories, to correct the remaining schedule error of aircraft that are not conducting IM operations. The CMS displays can be used by the controller to achieve precise schedule conformance, while the IM avionics can be used by the flight crews to achieve the assigned spacing interval.

2.2 IM Operation Types

In this document, the term "procedure" is the series of sequential steps taken by the flight crews to achieve a desired result, and "operation" is used to describe the result of a flight crew procedure acting upon the aircraft systems. "Procedure" also refers to the arrival and approach procedures flown in this flight test, which are provided in Appendix D of this document.

The IM element of the ATD-1 ConOps consists of a set of ground and flight-deck capabilities used by air traffic controllers and flight crews to more efficiently and precisely manage inter-aircraft spacing. IM operations are defined in the IM operational and technical standard (ref. 7) in terms of IM clearances provided by the controller and described later in this section. These clearances include an ASG, which is a time or distance interval between the Ownship and Target aircraft. For all of the IM clearances except Maintain, the ASG provided to the flight crew by air traffic control is based on the schedule calculated by TMA-TM. For the Maintain clearance, the IM avionics establish the ASG based on its calculation of the spacing interval between the Ownship and Target aircraft when the operation is initiated. For the arrival operations in this flight test and most previous NASA research experiments, the PTP was set as the FAF. IM Operations are defined for the en route, arrival, and approach phases of flight, using both time-based and distance-based ASGs.

IM operations can be composed of an achieve stage and a maintain stage. The goal of the achieve stage is to achieve the ASG when crossing the ABP. The achieve stage uses trajectory information from the Ownship and Target aircraft to determine the spacing error; therefore, a trajectory-based control law that can support merging routes is used. The goal of the maintain stage is to maintain the ASG until the PTP. The maintain stage is designed to use state information from the Target aircraft to determine the predicted spacing error at the ABP. The state-based control law, which is used for the maintain stage of the IM operation, is limited to operations when the aircraft are in-trail (see section 2.3 and Appendix B).

The achieve and maintain stages are procedurally combined into distinct IM clearances. The four clearances in the ATD-1 flight test were Maintain, Capture, Cross, and Final Approach Spacing:

- The <u>Maintain</u> clearance is used when the Ownship and Target aircraft are on a common path, and the controller wants the Ownship to maintain the current in-trail spacing interval. The algorithm determines speeds that will maintain the spacing interval until the operation terminates. Within this flight test, the Maintain clearance was used during en route and arrival operations.

- The <u>Capture</u> clearance is used when the Ownship and Target aircraft are on a common path and the controller wants the Ownship to achieve a specific ASG and then maintain it until termination. The algorithm determines speeds that will correct the initial spacing error, and then maintain the ASG until the operation terminates. This clearance is intended for use when the spacing interval between Ownship and the Target is close to the spacing interval required by either the controller or schedule. Within this flight test, the Capture clearance was used during en route and arrival operations.

- The <u>Cross</u> clearance is used when the controller wants the Ownship to achieve the ASG at the ABP, and then maintain the ASG until termination. The achieve stage is used to correct the initial spacing error by the ABP, and then transitions to the maintain stage until termination. The ASG is derived from the ground scheduling function or metering information. Within this flight test, the Cross clearance was used during arrival operations.

- The <u>Final Approach Spacing</u> clearance is used when the final controller wants to use IM to precisely achieve an ASG behind the Target aircraft on final approach. The Final Approach Spacing clearance is given to the Ownship when one aircraft was established on final, and the other aircraft was either established on final or on a vector to intercept the final approach course.

2.3 IM Speed Control Laws

Two different speed control laws were used in the IM avionics prototype (ref. 25): a Trajectory-Based Operation (TBO) speed control law and a state-based Constant Time Delay (CTD) speed control law. The TBO speed control law was used for the achieve-stage of the Cross IM operation, which is defined as the portion of the operation before the ABP, and the Final Approach Spacing IM operation. The CTD speed control law was used for the maintain stage of the Cross operation, which is defined as the portion of the operation after the ABP, the Capture operation, and the Maintain operation. These two speed control laws used by the IM prototype in this flight test were based largely on version 13 of NASA's ASTAR algorithm (ref. 24). In general, both control laws calculate a spacing error, a speed correction based on the spacing error, and the speed command as the sum of some nominal speed and the speed correction.

A brief description of the various speeds is given here and listed in the Description of Terms section of this paper. More detail about the speed control law algorithm used in the flight test is provided in reference 25, while reference 24, Appendix B, and Appendix C provide additional information about the original NASA guidance control laws.

Table 1. Description of different speeds used by IM avionics.

Nominal speed profile	Speeds specified by the published arrival procedures and the airline standard operating procedure during the approach; emulates no system delay if the Target aircraft flies these speeds; shown as the black line in the case study plots
Delayed speed profile	Specific speeds flown by the lead aircraft in the three-aircraft string to emulate instances where the ground system has calculated delay that must be absorbed
Control law speed	Unfiltered output from the TBO or CTD control law, prior to speed limiting or speed quantization; shown as a yellow line in case study plots
IM Instantaneous speed	The control law speed after applying speed limits (see Appendix B) and other heuristics; represents a smooth, continuous value of the aircraft's expected airspeed; indirectly shown to the flight crew via the FSI; shown as a cyan line in the case study plots
IM commanded speed	A discrete number that represents the desired speed that the pilots are expected to input into the aircraft's MCP speed window; calculated from the spacing error and the speed at the end of the current speed segment after applying speed limits and other heuristics (details in Appendix B); represents the aircraft's expected airspeed at the end of a speed change; shown as a dark blue line in the case study plots
Ownship airspeed	The IM equipped aircraft's Mach or calibrated airspeed

3 Facilities and Equipment

3.1 Air Traffic Facilities and Airport

Five Air Traffic Control (ATC) facilities participated in the ATD-1 flight test. The tower facilities at Boeing Field (KBFI) and Seattle-Tacoma International Airport (KSEA) coordinated with the Seattle TRACON to facilitate the setup of the first flight test scenario of the day. The Seattle ARTCC provided control for the en route scenarios and the first half of each arrival scenario. Moses Lake TRACON provided control for the second half of each arrival scenario, and facilitated the set-up of the next arrival scenario. Moses Lake TRACON also helped setup and provided control of all the Final Approach Spacing scenarios. Under the agreement with the facilities, the flight crews were allowed to implement the IM commanded speeds, which were bounded within 15 percent of the speed constraints shown on the published arrival and approach procedures.

The Grant County International Airport (KMWH), a public use airport six miles northwest of Moses Lake, WA, was chosen as the site to conduct the flight test due to its moderate to low traffic density and the facility's familiarity with conducting flight test operations. Scenarios were conducted to runway 32R (13,502 feet), and terminated at either the published decision altitude (visual conditions) or that aircraft's minimum altitude for RNP operations (instrument conditions).

3.2 Aircraft

A Honeywell owned Dassault Falcon 900 (F-900) (Figure 2, center aircraft) was used as the first aircraft in the arrival stream. It was equipped with Automatic Dependent Surveillance-Broadcast (ADS-B) Out and a Global Navigation Satellite System (GNSS). A Honeywell owned Boeing 757-200 (B-757) and a United Airlines owned Boeing 737-900 (B-737) (Figure 2, left and right aircraft) were equipped with ADS-B In/Out, GNSS, and the IM avionics prototype.

Figure 2. Aircraft used in ATD-1 flight test.

3.3 IM Avionics

The hardware associated with each IM avionic system consisted of dual UTC Aerospace Systems Smart Display G700 AB Class 3 Electronic Flight Bags (EFBs) mounted as side displays on the B-757 and B-737 flight decks (Figure 3, large orange circle). The EFBs hosted the IM application, provided the touchscreen functionality for data entry and application control, displayed the IM application data entered by the pilots, displayed the IM application processed data, and displayed other traffic in the area. The EFB also provided data to the prototype configurable graphics displays (CGDs) (Figure 3, small orange circle) via a wireless router located in the rear of the cockpit. A CGD was installed in the primary forward field-of-view of each pilot, providing speed guidance and situation awareness information. The final component was a Honeywell Traffic Processing Unit (TPU) that provided both Traffic Alert and Collision Avoidance System (TCAS) functionality and DO-317A-compliant ADS-B In track processing capability, which was utilized by the IM application running in the EFBs. Additional information about the hardware and software used in this flight test is provided in references 25–28.

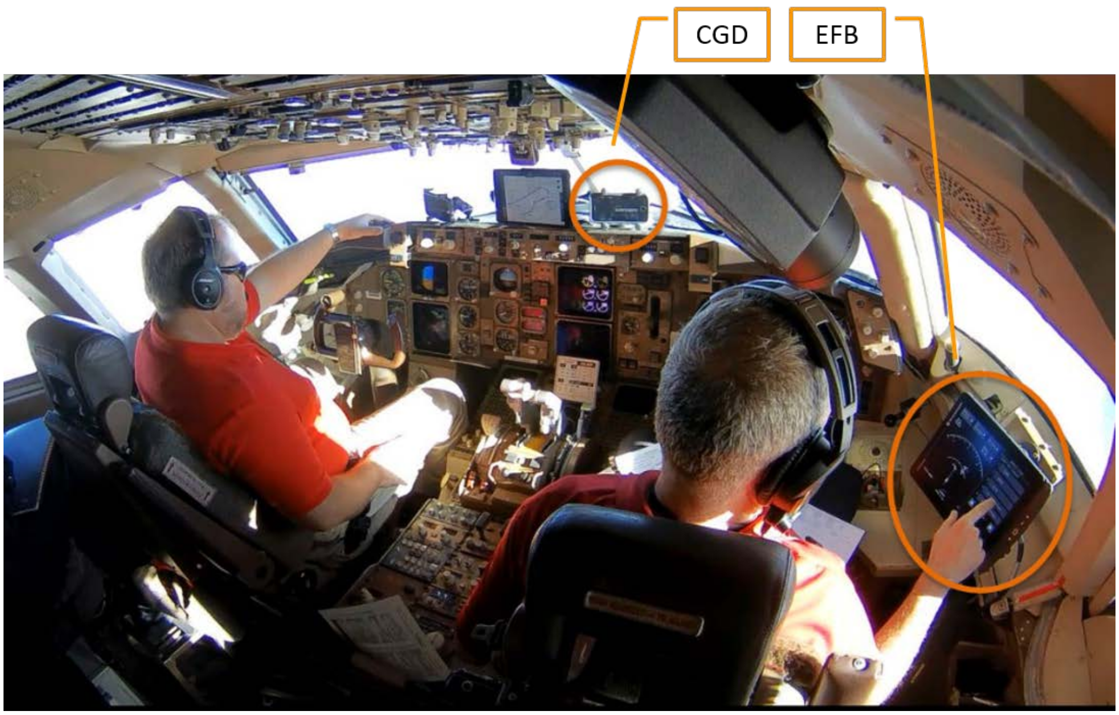


Figure 3. Honeywell B-757 cockpit location of CGD (center circle) and EFB (right circle).

After the IM avionics were initialized, one EFB was designated as the Master EFB. This EFB calculated the IM speed guidance and displayed situation awareness information to the flight crew. The data used by the IM application included Ownship state data (latitude, longitude, altitude, heading, speed, etc.) from the avionics bus, and the ADS-B state data from the Target aircraft. The flight crew was responsible for manually entering the destination airport, the Target aircraft's call sign, the Ownship's route of flight, the IM clearance type, and if required, forecast winds, the Target aircraft's route of flight, the ASG, the ABP, and the PTP. Both EFBs could be used for data entry, and the display on each EFB could be selected independently of the other. The flight crew IM procedure defined during training ensured that a single data-entry field would not be accessed simultaneously by both pilots.

Figure 4 shows the components of the IM avionics in orange, and the existing avionics that provided data to the IM avionics in light blue. The DO-317A compliant TPU was largely production standard; most importantly, the TCAS function that resides in the TPU was fully production standard, and regression testing was carried out to ensure that TCAS capabilities were unimpaired. There was no data flow from the IM prototype to the certified avionics or the aircraft systems.

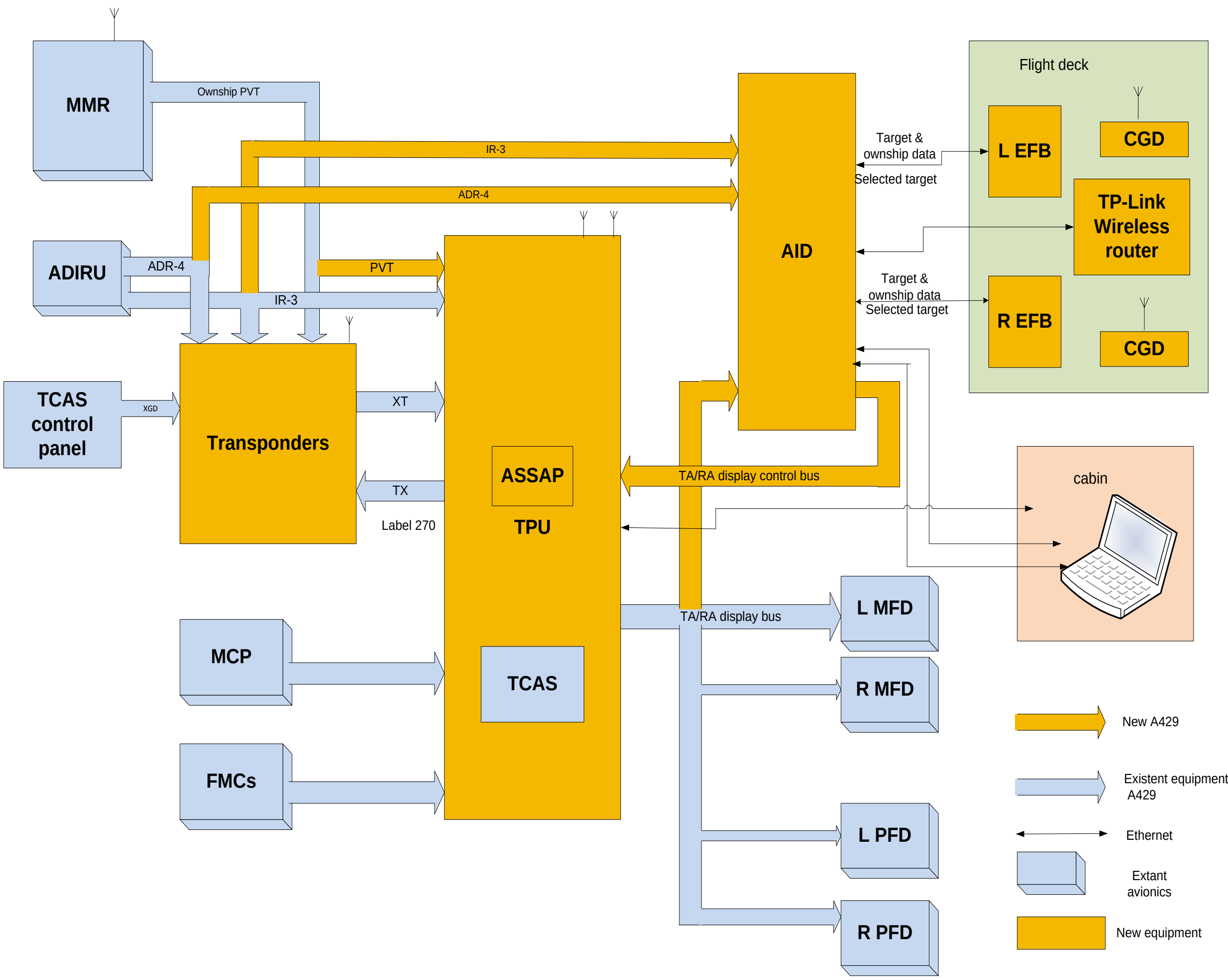


Figure 4. Configuration of IM avionics prototype hardware and software.

The IM prototype software written by the contractor team was based on NASA (ref. 24) and aviation industry standard (ref. 8) documents. The EFB and CGD displays (refs. 27 and 28) were influenced by earlier NASA designs (ref. 29).

Figure 5 illustrates the IM prototype displays where the Target is approaching NALTE and the Ownship has just passed OYOSE. The CGD repeats four essential display elements from the EFB (Fast/Slow Indicator, Progress Indicator, IM commanded speed, and IM state), and a subset of the IM avionics' status messages. The original CGD colors and font aligned with the EFB display, however, they were changed to white and a larger font size to compensate for installations above the glare shield that were exposed to direct sunlight. The numbers of the data elements in the list below correspond to the numbers shown on the EFB and CGD in Figure 5.

1) Ownship: solid white triangle shown at the bottom 1/3 of traffic display
2) Target: hollow white chevron outlined by green chevron; data tag if selected
3) Fast/Slow Indicator (FSI): Ownship's deviation from the IM instantaneous speed; always shown on both the EFB and CGD
4) Progress Indicator: shown when the Ownship is within 30 nmi of the ABP during the achieve stage, or anytime during the maintain stage; Ownship's position deviation from the ASG is labeled as Early/Late (time-based) or Near/Far (distance-based)
5) IM commanded speed: the speed displayed by the IM avionics (green on EFB and white on CGD) which the flight crew input into the mode control panel (MCP)
6) IM state: options are "OFF", "ARMED", "AVAILABLE", "PAIRED", "SUSPENDED", and "TERMINATE" (the same as 'OFF')
   - EFB: "PAIRED" shown in green, all other states in white
   - CGD: all states shown in white
7) IM clearance type: shown in green when Paired; otherwise shown in white
8) ASG: shown in seconds (time-based) or nmi (distance-based); manually entered by the flight crew; shown in cyan in Paired state only
9) Spacing Interval: the IM avionics' estimate of the spacing interval; shown in white when available; unique to the flight test and not expected to be shown on future IM avionic systems; description of calculation in Appendix B and reference 24

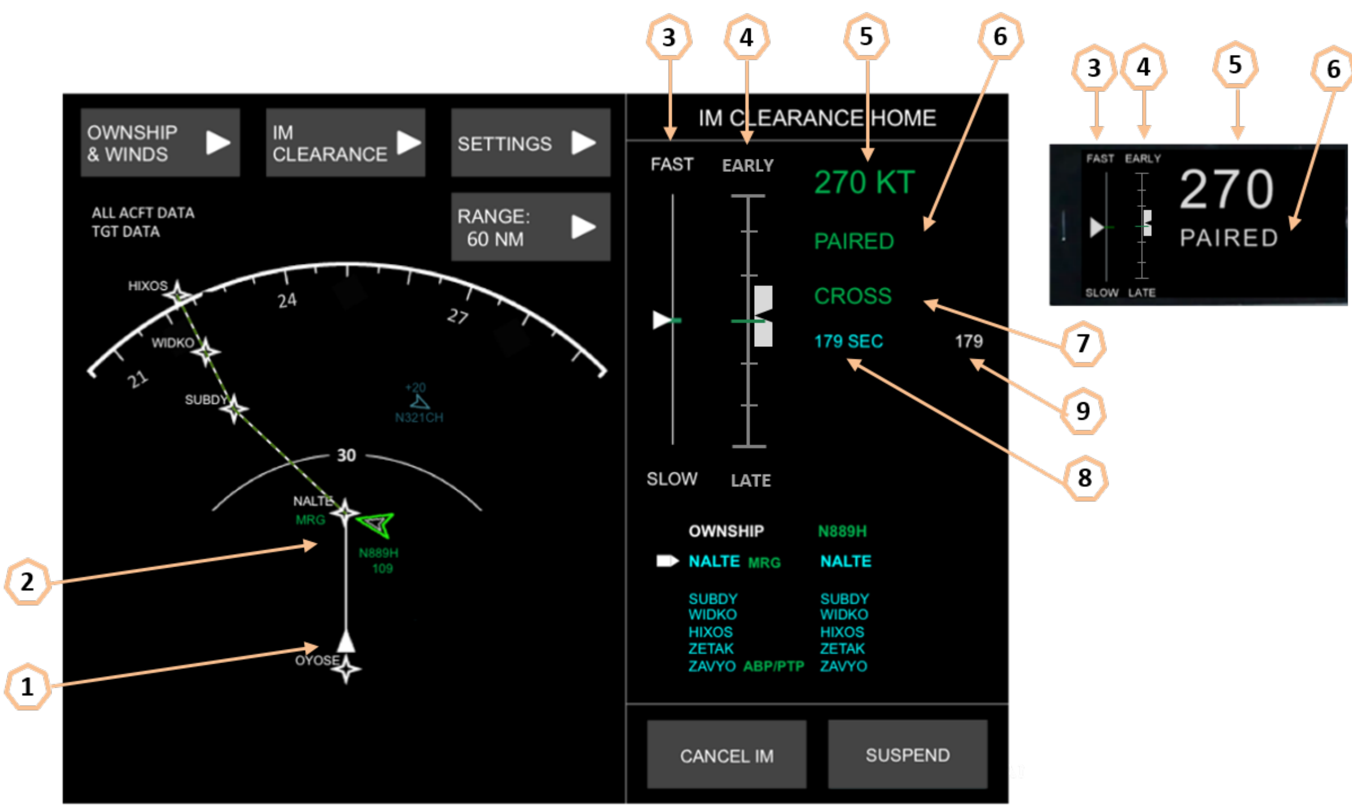


Figure 5. IM avionics prototype EFB (left) and CGD (right) displays.

4 Procedures and Test Protocol

4.1 Arrival and Approach Procedures

The PBN procedures used in the flight test consisted of Standard Terminal Arrival Routes (STARs) which were developed to connect to the existing Required Navigation Performance Authorization Required (RNP AR) instrument approach procedure at KMWH (shown in Appendix D). These STARs were developed in accordance with FAA guidance (ref. 30), and were designed to allow for various combinations of merge points and route geometries, as well as to support landing on either runway. The PBN procedures to runway 32R were used throughout the flight test since this runway had a published straight-in approach and a published RNP approach that merged at the FAF.

The legend for Figure 6 showing the STARs connecting to the runway 32R approach is as follows:

- Blue-green line: high altitude en route operations at FL350; in-trail geometries only; initiated at the waypoint ZIRAN, with the PTP at the waypoint SINGG
- Red lines: arrival operations; in-trail, medium-altitude merge (NALTE), or low-altitude merge (ZAVYO) geometries; initiated in vicinity of the waypoints SINGG, JELVO, MAHTA, or NACUN, with the PTP at ZAVYO
- Purple lines: Final Approach Spacing; in-trail or merging geometries; initiated about 25 nmi from the runway, with the PTP at 6.25 nmi from the runway threshold

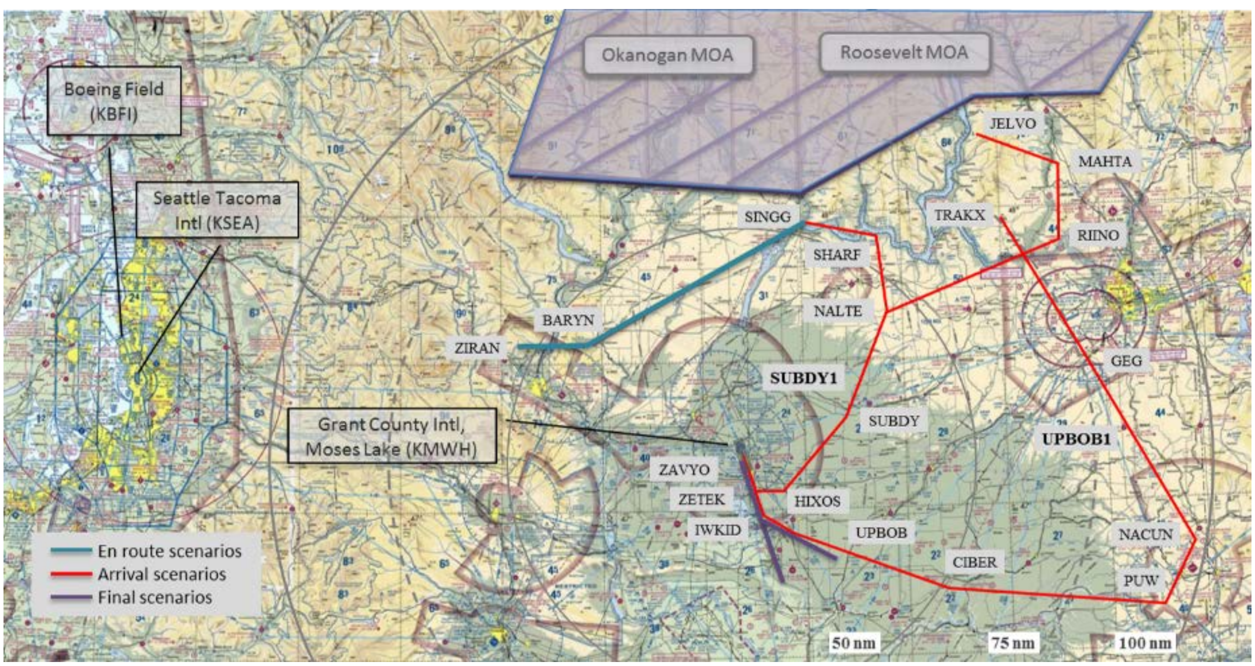


Figure 6. Airspace and routes used in ATD-1 flight test.

The en route scenarios were planned to be flown at FL350 from ZIRAN to SINGG (blue-green line), with the first arrival scenario (red line) of each day initiated shortly after the aircraft crossed

SINGG. All subsequent arrival scenarios were initiated at FL230 or FL220 to reduce transit time from the go-around point to the next start point, to avoid traffic inbound to or departing from the Seattle area, and to reduce controller workload by avoiding a handoff to a different air traffic control sector. The Final Approach Spacing scenarios (purple lines) involved only two aircraft that climbed to either 6000 (the Target) or 7000 feet (the Ownship), then proceeded to the start points which were approximately 30 nmi south of KMWH.

Hold points and IM initiation points were selected to prevent the aircraft from entering special use airspace to the north and from crossing certain sector boundaries, thus reducing the amount of coordination with air traffic control required to conduct the flight test.

4.2 PLANET Software

The company ATMOSPHERE produces a traffic and weather software program called PLANET. This software enables the exchange of data in real time between airborne and ground users by utilizing satellite and cellular networks for ubiquitous connectivity. For this flight test, the PLANET software provided the Flight Test Director (FTD) with a visual depiction of the locations and ground speeds of the flight test aircraft, along with other information for improved situation awareness. This helped the FTD ensure that all of the flight test aircraft were properly set up before an IM operation began. ATMOSHPERE also tailored the software by enabling selectable overlays for the wind forecast, arrival and approach procedures, and the display of special use airspace. Figure 7 shows the FTD using the PLANET software, which is display on the upper left monitor.

Figure 7. FTD using PLANET software to assist in scenario setup.

4.3 Procedure to Position Aircraft

The training provided to the pilots of IM-equipped aircraft and the FTDs to position the aircraft for the next scenario (this section) and to conduct the IM operation (section 4.4) is described in Training Program for Pilots and Flight Test Directors (section 6.2).

In the ATD-1 ConOps, controllers use the TMA-TM schedule and the CMS decision support tools to ensure the aircraft are aligned so that speed control can be used to achieve the desired spacing interval. Since TMA-TM and CMS were not available for this flight test, the flight crews and the FTD used a two-part process utilizing the aircraft's Flight Management System (FMS) and the IM avionics prototype to setup the test scenarios. This two-step setup process to position the aircraft for the scenario was unique to this flight test environment.

The first part of this setup procedure was to position the aircraft in the approximate location needed for the next test run, and each aircraft's FMS was utilized for this purpose. For each run, the aircraft with the longest estimated en route time to the first waypoint common to all three aircraft was identified on the appropriate flight test card as the "LP" (or "Long Pole") for that scenario (examples shown in Figure 55 and Figure 58). The flight crew of that aircraft used the aircraft's FMS to provide the FTD with an estimated time of arrival to that waypoint after all route information and forecast winds were entered, and the aircraft was at a constant altitude, airspeed, and heading to that waypoint. The FTD used this estimated time of arrival along with the desired initial spacing error to determine a scheduled time of arrival to that waypoint for all aircraft. The flight crew entered the FTD assigned arrival time to the waypoint into the FMS, and then adjusted the aircraft's airspeed to meet that time. When changing airspeed was not sufficient, the flight crew coordinated with the controller to hold or fly a longer path to meet the time of arrival.

The second part of the procedure utilized the IM avionics prototype to calculate the ASG needed to achieve the desired initial spacing error specified in the test matrix (Table 2). As the flight crew's workload and tasks permitted, the pilot not flying the aircraft entered the IM clearance information using a temporary value for the ASG that was later replaced with the actual ASG. After the data entry was complete and the flight crew armed the IM prototype, the IM prototype displayed the spacing interval on the EFB, as shown in Figure 8, as the white '170' seconds in the right upper-middle portion of the display. The pilot then added the initial spacing error shown on the test card to the spacing interval shown on the EFB to determine the actual ASG for that scenario. Using Figure 8 and the example in Appendix E for the third aircraft (the B-757), the pilot would have added 30 seconds of spacing error from the test card to the 170 seconds shown on the EFB, then reported to the FTD that an ASG of 200 seconds would be used for that scenario. Once the ASG was calculated, the pilot entered it into the IM prototype and initialized the IM operation at the waypoint specified on the test card (MAHTA in the Appendix E example for the B-757).

An agreement was reached during the planning phase between the flight test team and the air traffic control facilities to use a minimum spacing of 150 seconds between aircraft to ensure that aircraft spacing during the scenarios was above the minimum separation criteria at all times. The agreement also called for the aircraft to remain within 210 seconds of spacing to avoid delaying other aircraft. If the calculated ASG was outside the 150 to 210 seconds range, the FTD adjusted the spacing error, and in a few circumstances, changed the IM clearance type.

Figure 8. Side-mounted EFB.

4.4 Procedure to Conduct IM Operations

The flight crew procedure to conduct IM operations was divided into two phases: 1) programming the data required for the IM operation into the avionics prototype via the EFB, and 2) entering the IM commanded speed into the MCP speed window.

In the first phase, the flight crew programmed the IM avionics using the side-mounted EFB, shown in Figure 8, to enter information about the Ownship's route and destination, forecast en route and descent winds, and the IM clearance itself. The Ownship information and winds could be entered at any time. As previously described, the FMS also needed the Ownship's route and forecast wind information to calculate a valid estimated time of arrival to the waypoint specified on the next test card. Because of this, identical information was entered separately into both the FMS and EFB prior to takeoff for the first scenario, and then also during each climb-out to set up for the next test run. (Future IM implementations are expected to be more integrated with other aircraft avionics, thereby precluding the need to enter the same data twice.) Per the flight test card, a waypoint was designated where the IM clearance would be entered by the pilot, as well as a waypoint where the IM operation would be initiated.

In the second phase, when the IM commanded speed was displayed, the flight crew entered that speed into the MCP airspeed window, similar to entering an airspeed issued via voice instruction from the controller. Even though this speed was shown on the EFB (the green 260 knots in Figure 8), the CGD located in the pilot's primary forward field of view repeated this airspeed (the white 260 knots in Figure 9) and other critical information needed to execute the IM operation.

Displaying critical information on the CGD also allowed the EFB to be used for other applications once the IM information had been entered.

Figure 9. Forward field of view mounted CGD.

The flight crew flew the arrival and approach procedures using the IM commanded speed while meeting all altitude constraints by using thrust or drag as needed. The FSI, shown as the FAST/SLOW bar in Figure 8 and Figure 9, was a secondary cue intended for the pilots to quickly compare the relationship between the IM instantaneous speed to the aircraft's current speed. After setting the IM commanded speed in the MCP speed window, the flight crew could monitor both the FSI and the aircraft's vertical deviation from the flight path to determine whether a change to either the throttle or speed brake setting was required. The flight crew configured the aircraft as the airspeed decreased below flap maneuvering speeds to achieve stabilized approach criteria by 1000 feet above ground level. A go-around was initiated at the missed approach point, where the flight crew would reprogram the FMS and EFB for the next run during climb-out.

Given the capabilities of the FMSs of the two IM-equipped aircraft, this meant the aircraft was in the Vertical Navigation (VNAV) speed mode for most of the descent, and used pitch to achieve the new IM commanded speed, i.e., increasing the descent rate to accelerate or deceasing the descent rate to decelerate. Because of the use of pitch for speed control while in descent, the aircraft would not adhere to the VNAV vertical path unless the pilot adjusted the aircraft's thrust or drag to maintain the vertical path.

4.5 Wind Forecast

The FMS and the IM avionics used a single wind forecast determined at the beginning of each flight test day. This forecast was obtained from the National Oceanic and Atmospheric Administration (NOAA) Aviation Weather Service. Since descent winds were not available for KMWH, the Yakima and Spokane International Airports' descent winds were averaged and used instead. For the IM avionics, the FL340 forecast was entered as the FL350 en route wind since no forecast was available for FL350, and forecasts for FL240, FL180, 12,000 feet, 6000 feet, and the surface were entered as those altitudes for the descent forecast. The KMWH Terminal Area Forecast winds were used for the surface winds. To standardize data entry between the three FMS types and to align with the IM avionics, the FL340 forecast was entered in the FMS as the FL350 en route wind, and the forecasts for FL180, 12000 feet, and 6000 feet were the altitudes used for the FMS descent winds since the IM avionics can accept more forecast wind altitudes than the FMS. The wind forecasts used for each day are listed in the first part of Appendix F, and the root-mean square of the along-track forecast wind error is shown in the second part of Appendix F.

4.6 Test Protocol

Both the NASA Langley Research Center and NASA Johnson Space Center Institutional Review Boards reviewed and approved the experiment protocol. Pilots acting as subjects in this flight test signed Privacy Act and Informed Consent documents.

Preparations for each flight began the previous day. By 2:00 p.m. each day, the test cards for the next day were published and sent electronically to all participants in a format tailored to their need (ATC, FTD, F-900, B-757, and B-737). Examples of these five formats are provided in Appendix E. During the day's flight debrief (generally around 4 p.m.), the FTD ensured all participants had received the electronic version of the test cards and provided paper copies to the flight crews for the following day's flight.

The FTD and all flight crews were present for each morning's 8:00 a.m. briefing, and representatives from Seattle ARTCC, Seattle TRACON, and Moses Lake TRACON called into the meeting. The briefing typically lasted 30 to 45 minutes to ensure the Honeywell aircraft at KBFI and United Airlines aircraft at KSEA could launch before 9:30 a.m. to avoid the morning departure rush at KSEA.

After the morning launch and once the aircraft were in-trail and at FL350, the flight crews of the IM-equipped aircraft initiated the en route IM operations at ZIRAN and terminated at SINGG (see Figure 6). After completing en route operations, flight crews worked with the FTD to establish the start time of the next arrival scenario. Flight crews also coordinated with ATC to maneuver their aircraft as required to achieve the start time, and then entered the data required for the next IM operation. When those tasks were complete, flight crews completed an end-of-run questionnaire for the en route IM operation.

The flight crews flew arrival scenarios to the PTP, which was always the FAF (ZAVYO). Upon reaching the FAF, the flight crews continued the descent to decision altitude, conducted a missed approach, and then proceeded to the initial point for the next scenario. Each flight crew member completed the end-of-run questionnaire for the previous run prior to commencing the next run.

After the arrival operations were complete, the F-900 returned to KBFI and the remaining flight crews coordinated with Moses Lake TRACON to set up for the Final Approach Spacing operations, if planned for that day. If none were planned, all three aircraft returned to their respective airports. During the return segment, the flight crews completed both their final end-of-run questionnaires and end-of-day questionnaires.

A debrief was held approximately 90 minutes after landing, and lasted 30 to 90 minutes depending on the activities and topics that were covered. These activities and topics included events that occurred during that day's flight, transfer and analysis of data for that day, an overview of the scenarios for the next flight, and distribution of paper copies of the test cards for the next flight.

5 Experiment Design

5.1 Lead Aircraft Profiles

Three different speed profiles were developed for each STAR. The first speed profile was a nominal profile that represented the published speeds that the lead aircraft, that is the first aircraft in the scenario, would fly if there was no controller intervention. The other two delay speed profiles represent speeds that might be flown when controllers need to delay an aircraft for flow control and separation, and were modeled using TMA's methodology for apportioning delay.

Figure 10 shows three different speed profiles that were created and intended to be flown by the aircraft leading the IM-equipped aircraft, referred to as the lead aircraft speed profile. The "No Delay" speed profiles (black lines) followed the nominal published speeds. The "Moderate Delay" speed profiles (blue lines) had a moderate amount of delay in the TRACON (approximately 20 seconds) and no delay in the Center. The "High Delay" speed profiles (red lines) had maximum delay in the TRACON (approximately 40 seconds) and moderate delay in the Center (approximately 25 seconds). Figure 10 also shows the upper and lower bounds on the speeds that the IM avionics can command (grey dotted lines) and a reference slow speed profile (solid grey line) that emulates both the slowest speed that TSAS can use when allocating delay and the slowest speed the aircraft are expected to fly in the Center airspace.

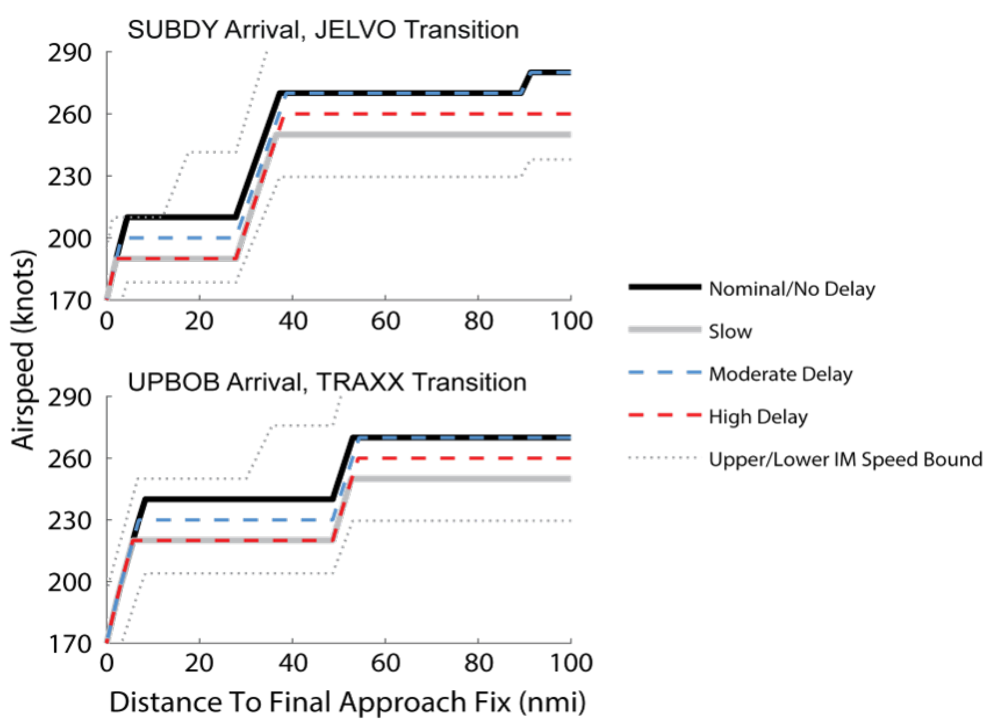


Figure 10. The delayed speed profiles flown by the lead aircraft.

When examining IM operations during arrivals, it is important to examine the impact of lead aircraft delay. When time-based metering is used, traffic flow management systems allocate delay to aircraft to deconflict them at a series of meter points. Since there is no current method of communicating trajectories between traffic flow management systems and aircraft conducting IM operations, the IM avionics use the published speeds instead of the delayed speeds to estimate the times of arrival for the Ownship and Target aircraft. This presents an unknown amount of error that was expected to affect the performance of the Cross operations and may also affect the performance of the Maintain and Capture operations.

5.2 Test Matrix for Primary Data Set

The ATD-1 flight test was designed to evaluate the prototype IM avionics' performance during three phases of flight: en route, arrival, and final approach (ref. 22). The “Scenario” column of the test matrix in Table 2 lists the 38 scenarios partitioned into three categories: the “A” high-altitude en route scenarios, the “B” arrival scenarios, and the “C” final approach scenarios; for a total of 62 unique test conditions. The “Lead Aircraft Delay” column specifies the amount of delay for the first aircraft in the arrival stream, and is based on the speed profiles described in section 5.1.

The “Geometry” column defines the routes used by the Ownship and Target aircraft during the Final Approach Spacing operations (the “C” scenarios). The aircraft were either established on final approach (a “Straight-in”, or “Str-in”), or on a heading to intercept final (“Turn”).

The first IM-equipped aircraft in the arrival stream is referred to as “IM1”, and the second IM-equipped aircraft as “IM2”. The label “T/D” refers to whether the IM clearance type is a time-based or distance-based operation.

Two replicates of each flight test scenario were planned. Therefore, each scenario was assigned a priority level (shown in the “Priority” column) and the run order was randomized within each priority level. Thus, if schedule constraints occurred during the flight test, the low priority scenarios could be removed from the test matrix. In addition, the analysis was designed to accommodate an unbalanced test matrix with unequal numbers of replicates in order to address the risk of missing data.

The spacing error sign convention predominately used in this document and in the test matrix (Table 2) follows the historical convention used by the IM research community (NASA, FAA, and the aviation industry). A positive value indicates that the spacing interval is larger than the ASG and a negative value indicates that the spacing interval is smaller than the ASG. Some materials, such as the flight test cards in Appendix E and earlier publications (refs. 26 and 32), used a reversed sign convention to simplify calculations performed by the flight crew and the FTD to determine the ASG.

Table 2. Primary test matrix.

Scenario	Lead Aircraft Delay	Geometry (Target/IM)	IM1 Clearance Type	IM1 T/D	IM1 Spacing Error	IM1 ABP	IM1 PTP	IM2 Clearance Type	IM2 T/D	IM2 Spacing Error	IM2 ABP	IM2 PTP	Priority
A01	None	n/a	CROSS	Time	–20 sec	JELVO	MAHTA	CROSS	Time	+15 sec	JELVO	MAHTA	L
A02	None	n/a	CROSS	Distance	–3 nmi	JELVO	MAHTA	CROSS	Distance	+2 nmi	JELVO	MAHTA	L
A03	None	n/a	CAPTURE	Time	–20 sec	n/a	JELVO	CAPTURE	Time	+15 sec	n/a	JELVO	H
A04	None	n/a	CAPTURE	Distance	–3 nmi	n/a	JELVO	CAPTURE	Distance	+2 nmi	n/a	JELVO	H
A05	None	n/a	MAINTAIN	Time	n/a	n/a	JELVO	MAINTAIN	Time	n/a	n/a	JELVO	M
A06	None	n/a	MAINTAIN	Distance	n/a	n/a	JELVO	MAINTAIN	Distance	n/a	n/a	JELVO	M
B01	None	n/a	CROSS	Time	+20 sec	Merge	FAF	CAPTURE	Time	–30 sec	n/a	FAF	H
B02	None	n/a	CROSS	Time	0 sec	PTP	FAF	MAINTAIN	Time	n/a	n/a	FAF	H
B03	None	n/a	CROSS	Time	–60 sec	PTP	FAF	CROSS	Time	–30 sec	PTP	FAF	H
B04	None	n/a	CAPTURE	Time	+60 sec	n/a	FAF	MAINTAIN	Time	n/a	n/a	FAF	H
B05	None	n/a	CAPTURE	Time	–60 sec	n/a	FAF	CROSS	Time	–30 sec	PTP	FAF	H
B06	None	n/a	MAINTAIN	Time	n/a	n/a	FAF	CROSS	Time	–15 sec	Merge	FAF	H
B07	Med	n/a	CROSS	Time	+20 sec	Merge	FAF	CAPTURE	Time	–30 sec	n/a	FAF	M
B08	Med	n/a	CROSS	Time	0 sec	PTP	FAF	MAINTAIN	Time	n/a	n/a	FAF	M
B09	Med	n/a	CROSS	Time	–60 sec	PTP	FAF	CROSS	Time	–30 sec	PTP	FAF	M
B10	Med	n/a	CAPTURE	Time	+60 sec	n/a	FAF	MAINTAIN	Time	n/a	n/a	FAF	M
B11	Med	n/a	CAPTURE	Time	–60 sec	n/a	FAF	CROSS	Time	–30 sec	PTP	FAF	M
B12	Med	n/a	MAINTAIN	Time	n/a	n/a	FAF	CROSS	Time	–15 sec	Merge	FAF	M
B13	High	n/a	CROSS	Time	+20 sec	Merge	FAF	CAPTURE	Time	–30 sec	n/a	FAF	H
B14	High	n/a	CROSS	Time	0 sec	PTP	FAF	MAINTAIN	Time	n/a	n/a	FAF	H
B15	High	n/a	CROSS	Time	–60 sec	PTP	FAF	CROSS	Time	–30 sec	PTP	FAF	H
B16	High	n/a	CAPTURE	Time	+60 sec	n/a	FAF	MAINTAIN	Time	n/a	n/a	FAF	H
B17	High	n/a	CAPTURE	Time	–60 sec	n/a	FAF	CROSS	Time	–30 sec	PTP	FAF	H
B18	High	n/a	MAINTAIN	Time	n/a	n/a	FAF	CROSS	Time	–15 sec	Merge	FAF	H

Scenario	Lead Aircraft Delay	Geometry (Target/IM)	IM1 Clearance Type	IM1 T/D	IM1 Spacing Error	IM1 ABP	IM1 PTP	IM2 Clearance Type	IM2 T/D	IM2 Spacing Error	IM2 ABP	IM2 PTP	Priority
B19	None	n/a	CROSS	Time	–20 sec	Merge	FAF	CROSS	Time	–15 sec	Merge	FAF	H
B20	Med	n/a	CROSS	Time	–20 sec	Merge	FAF	CROSS	Time	–15 sec	Merge	FAF	H
B21	High	n/a	CROSS	Time	–20 sec	Merge	FAF	CROSS	Time	–15 sec	Merge	FAF	H
B22	None	n/a	CROSS	Distance	–2 nmi	PTP	FAF	CROSS	Distance	–1 nmi	PTP	FAF	M
B23	Med	n/a	CROSS	Distance	–2 nmi	PTP	FAF	CROSS	Distance	–1 nmi	PTP	FAF	M
B24	High	n/a	CROSS	Distance	–2 nmi	PTP	FAF	CROSS	Distance	–1 nmi	PTP	FAF	M
C01	None	Str-in/Str-in	SPACING	Time	–15 sec	PTP	6.25						M
C02	None	Str-in/Str-in	SPACING	Distance	–1 nmi	PTP	6.25						H
C03	None	Str-in/Turn	SPACING	Time	–15 sec	PTP	6.25						M
C04	None	Str-in/Turn	SPACING	Distance	–1 nmi	PTP	6.25						H
C05	None	Turn/Str-in	SPACING	Time	–15 sec	PTP	6.25						M
C06	None	Turn/Str-in	SPACING	Distance	–1 nmi	PTP	6.25						H
C07	High	Str-in/Turn	SPACING	Distance	–1 nmi	PTP	6.25						L
C08	High	Turn/Str-in	SPACING	Distance	–1 nmi	PTP	6.25						L

5.3 Description of Scenarios

The following three sub-sections describe the scenarios planned and flown during the flight test. The four low-priority scenarios (A01, A02, C07, and C08) in Table 2 were not flown due to schedule constraints. Since the behavior of the Cross clearance is different before and after the ABP, the Cross clearance was separated into two separate experimental conditions:

- Cross-Merge: the ABP is the waypoint where the Target and Ownship routes merge, and
- Cross-FAF: the ABP is the FAF.

5.3.1 En Route Scenarios

The four high-altitude en route scenarios (A03–A06) were designed to allow an examination of test conditions with the independent variables listed below. The initial spacing error is a nested independent variable since it was only applicable for the Capture operations.

- IM clearance type
- Time- or distance-based operation
- Initial spacing error

The number of data points for the four high-altitude en route scenarios is shown in Table 3. Four replicates of each test condition were planned; however, scenario setup issues and software issues resulted in some missing data points (section 7.1.2). The two low priority scenarios planned for the Cross clearance type were not executed due to schedule constraints. The along-path distance to the PTP at initiation of the operations ranged between 71 nmi and 39 nmi. The observed initial spacing errors for the two time-based Capture scenarios were 23 and 20 seconds early, and 3.8 nmi early and 2.6 nmi late for the two distance-based Capture operations.

Table 3. En route scenarios flown.

IM Clearance Type	Time- or Distance-based Operation	Lead Aircraft Delay	*N* (Data Points)
Maintain	Time	None	4
	Distance	None	3
Capture	Time	None	2
	Distance	None	2

5.3.2 Arrival Scenarios

The 24 arrival scenarios flown during the flight test (B01–B24) were designed to evaluate the independent variables listed below. Time-or distance-based operation, initial spacing error, and ABP location are nested independent variables.

- IM clearance type
- Time- or distance-based operation
- Lead aircraft delay
- Initial spacing error
- ABP Location

The number of data points collected for the arrival scenario test conditions are shown in Table 4. Six replicates of the Maintain and Capture operations, eight replicates of the time-based Cross operations, and four replicates of the distance-based Cross operations were planned. However, scenario setup issues and software anomalies resulted in both missing and additional data points for test conditions. Although there was one Cross operation type, the data were separated into Cross-Merge and Cross-FAF categories due to the statistically and operationally significant differences in performance. The ABP was located at the medium altitude merge point (NALTE) for the Cross-Merge scenarios, and the FAF (ZAVYO) for the Cross-FAF scenarios.

Table 4. Data points of arrival scenarios flown.

IM Clearance Type	Time- or Distance-based Operation	Lead Aircraft Delay	*N* (Data Points)
Maintain	Time	None	6
		Medium	8
		High	4
Capture	Time	None	17
		Medium	7
		High	8
Cross-Merge	Time	None	10
		Medium	9
		High	8
Cross-FAF	Time	None	14
		Medium	11
		High	16
	Distance	None	4
		Medium	1
		High	2

The distance to go (DTG) to the PTP from the beginning of valid data for the IM operations (as defined in Appendix G) ranged from 40 nmi to 128 nmi for the arrival scenarios. The observed initial spacing error, shown in a standard box plot format in Figure 11, ranged from 96 seconds early to 84 seconds late for Capture and Cross time-based operations and from 2.9 nmi early to 4.1 nmi late for Cross-FAF distance-based operations.

Achieving the initial spacing error specified in the test matrix was challenging, resulting in initial spacing errors throughout the flight test that did not exactly align with the values specified in the test matrix. Some of the initial spacing error values exceeded what is expected operationally within the ATD-1 environment, impacting IM performance.

For the en route and arrival operations, there were instances where the initial spacing error of the Maintain operation was small (less than 10 seconds), but not zero as might be expected. This was primarily due to the time delay between when the flight crew "ARMED" the IM prototype (which generates the spacing interval) and when the flight crew pressed "EXECUTE" to initiate the IM operation. During this time period, any ground speed difference between the Ownship and Target would manifest itself as a spacing error.

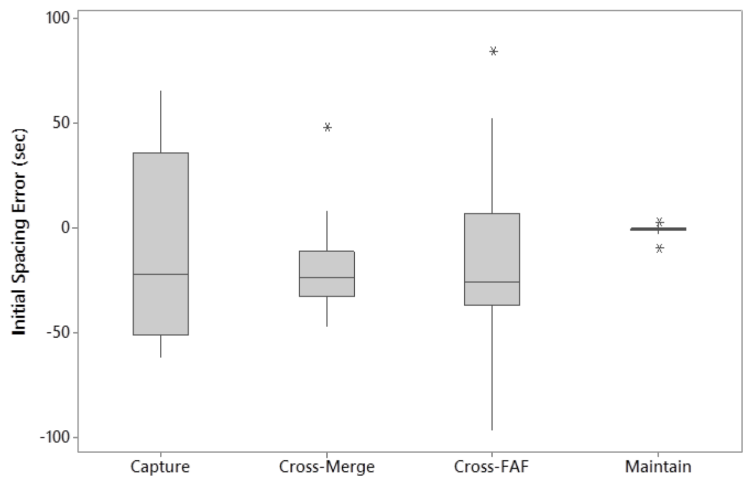


Figure 11. Initial spacing error of time-based arrival scenarios.

5.3.3 Final Approach Spacing Scenarios

The six Final Approach Spacing scenarios flown during the flight test (C01-C06) were designed to evaluate the following two independent variables:

- Time- or distance-based operation
- Geometry of the Ownship and Target aircrafts' routes

For all of the Final Approach Spacing scenarios, both the ABP and the PTP were 6.25 nmi prior to the runway threshold. Only two aircraft participated in these scenarios due to challenges with vectoring to reposition, therefore only one IM operation occurred per scenario. The two low priority scenarios planned with high lead aircraft delay were not executed due to schedule constraints. The number of data points collected for the Final Approach Spacing scenario test conditions is shown in Table 5. Four replicates of each scenario were planned; however, scenario setup issues and software anomalies resulted in missing data points. The observed initial spacing error ranged between 24 seconds early to 29 seconds late for time-based operations, and between 1.5 nmi early to 0.1 nmi early for distance-based operations.

Table 5. Final Approach Spacing scenarios flown.

<table>
<tr><th>IM Clearance Type</th><th>Time- or Distance-based Operation</th><th>Target/Ownship Geometry</th><th>N
(Data Points)</th></tr>
<tr><td rowspan="6">Final Approach Spacing</td><td rowspan="3">Time</td><td>Straight/Straight</td><td>1</td></tr>
<tr><td>Straight/Turn</td><td>1</td></tr>
<tr><td>Turn/Straight</td><td>3</td></tr>
<tr><td rowspan="3">Distance</td><td>Straight/Straight</td><td>1</td></tr>
<tr><td>Straight/Turn</td><td>1</td></tr>
<tr><td>Turn/Straight</td><td>1</td></tr>
</table>

5.4 Dependent Measures

To address the flight test goal of validating the IM avionics, both quantitative and qualitative data were collected. During each flight test run, IM avionics data, aircraft state data, and FMS data were recorded on the IM equipped aircraft (complete details available in Annex C of reference 22 and chapter 5 of reference 25). In addition, aircraft state data on the F-900 and cockpit video on the B-757 were also recorded. Metrics analyzed to assess the IM algorithm performance included the delivery accuracy at the ABP and PTP, IM commanded speed change rate, IM commanded speed reversals, magnitude of IM speed changes, and IM speed increases. Flight crews completed end-of-run and end-of-day questionnaires and participated in an interactive group debrief session.

6 Experiment Methodology

6.1 Pilot Qualifications

The pilots that participated in the flight test were selected by their respective Honeywell and United Airline flight operations departments. All of the pilots were current and qualified to fly the aircraft in the crewmember position(s) they flew during the flight test, were authorized to fly the RNP AR approaches at KMWH, and had a minimum of 50 hours of flight experience for the year prior to selection. The pilots ranged in age from 42 to 69 with an average age of 53, and had flown from 20 to 49 years with total flight times of 4,500 to 13,000 hours. Although two pilots were Test Pilot School graduates, all eight of the participating pilots (four Honeywell and four United Airlines) were experienced line pilots for their respective company.

6.2 Training Program for Pilots and Flight Test Directors

A multi-tiered training regimen was created to familiarize the pilots of the IM equipped aircraft with data entry into the IM avionics prototype and execution of the IM operations. The training also provided the pilots and the FTDs a methodology as well as practice of positioning aircraft for the next scenario. This training was conducted at NASA LaRC and incorporated computer-based training (CBT), classroom instruction, and integrated simulator training.

The first training program goal was to teach the pilots the procedure required to conduct IM operations (section 4.4). This entailed understanding the local airspace and instrument procedure, learning how to properly enter information into the IM avionics prototype, and learning how to manage the aircraft's airspeed and vertical path while conducting the IM operation. This goal was first addressed by the CBT, which was electronically sent to all pilots before arriving at NASA LaRC for the classroom and simulator training. The CBT discussed the flight test airspace, the special STARs designed for the flight test, and the four IM clearance types. The CBT included both an interactive model of the IM avionics prototype and a description of the pilot procedures to conduct an IM operation. The CBT allowed the pilots to interact with the EFB and to practice entering the required IM information, which reduced the training time necessary in the simulator. The classroom instruction included a standard brief that reviewed the information in the CBT and allowed for a more in-depth exploration of the topics and resolution of questions. The training regimen culminated with four days of interactive training using full-scale B-757 and B-737 simulators, and a separate desktop station emulating the displays expected to be available to the FTD when onboard the B-757. A recording of aircraft state data (altitude, heading, speed, etc.) of an appropriate Target flying its route for that scenario was also part of the integrated simulator training. Performance in the simulator and a final discussion session were used to validate whether the pilots had obtained sufficient proficiency in understanding the IM procedures, in particular the use of the IM commanded speed, the FSI, and the Progress Indicator.

The second training program goal was for the pilots and FTDs to practice positioning the aircraft for the next scenario (section 4.3). Since the ATD-1 ground-based components were not part of this flight test, the FTD communicated with the pilots, who in turn coordinated with controllers to efficiently position the three aircraft for each test run. This included identifying when holding was required and where that holding would occur. The test cards used during the flight test were refined during the training regimen with significant input from the pilots, including data required to assist in the correct filing and positioning of aircraft between each scenario. An important component of the scenario setup was establishing an ASG that would achieve the scenario objective while maintaining the appropriate separation between aircraft (ref. 31). When the Ownship reached its initiation point, the flight crews used the IM avionics to determine the current spacing interval. The pilots added the spacing interval to the desired spacing error shown on the flight test card to calculate the ASG used for that IM operation. If the calculated ASG was outside of the bounds defined for this flight test (150 to 210 seconds), the flight crew coordinated with the FTD who determined an alternate ASG. This process was repeated by each crew for each scenario.

6.3 Questionnaires

An end-of-run questionnaire was given to both flight crew members after completing each IM operation. The responses to the following subset of questions are included on this document:

1) Rate the overall acceptability of the IM operations
2) Rate the operational acceptability of the IM speed
3) Was any IM speed disregarded due to operational necessity?
4) Was the aircraft's energy level acceptable on final?

Those pilots were also given an end-of-day questionnaire after the final operation of the day. The responses to the following subset of questions are included in this document:

1) Describe changes you would make to the IM operation
2) Are there challenges to the implementation of IM into real-world operations?
3) Do the IM tasks integrate well with the normal operational flow of the flight deck?

In addition to the questionnaires, a debrief was held at the end of the day with all pilots, FTDs, controllers, and research team members, where issues from that day's flying or anticipated for the next fly day were discussed.

6.4 Data Collection and Delivery

Data collection was performed on-board aircraft using the following systems (refs. 25 and 26):

- EFB recording system for all IM avionics parameters (pilot entries, Ownship and Target state data, trajectories, control system details, etc.)
- TPU recording system (not used as the source for computing IM performance)
- Aircraft recording system (aircraft state, configuration, fuel, lateral and vertical deviations from FMS path when available); Honeywell systems on B-757 and F-900, flight data recorder on B-737
- Cockpit video on B-757

All data collected, except the B-757 cockpit video, included a GPS-sourced coordinated universal time stamp to enable data correlation.

7 Flight Test Results

The primary focus of the flight test analysis was the time-based arrival operations, which aligned with previous fast-time and human-in-the-loop simulations at NASA LaRC. Several reports (refs. 26 and 32) and conference papers (refs. 33–38) about this flight test have been published prior to this document, and contain additional information such as along-track wind forecast error analysis, lateral and vertical deviation from path, and generalized regression models. When appropriate, the results in this section are also compared to previous flight tests exploring spacing intervals between aircraft using similar avionics and procedures (refs. 39 and 40).

This section starts with a description of the flight test scope and the limitations on the IM operations during the flight test. This is followed by the criteria used to classify an operation as valid and the definitions of the performance metrics. The results from en route, arrival, and Final Approach Spacing operations are described, with the sub-section on arrival operations divided into time-based and distance-based operations. Within each of the four operation types, two sub-categories of data are evaluated: spacing performance and speed behavior. Where sufficient data are available (i.e., the arrival operations in section 7.5 and 7.6), the results are further sub-divided in the same sequence to allow easy comparison between operation types. Statistical analysis is only performed if sufficient data points are available; therefore several sections contain less analysis than other sections. Following the four operation categories is a section discussing pilot ratings and comments, and then a section of case studies illustrating different behaviors.

7.1 Scope and Limitations of the Flight Test

This section describes the scope of the ATD-1 flight test, and limitations to how the flight test was conducted or that impacted the quantity or quality of the data collected.

7.1.1 Scope

Tasks under the NASA contract included the development of an IM avionics prototype, and the testing of that prototype using arrival and approach procedures that mirror high-density airports to the maximum extent possible. The flight test's primary interest was algorithm performance, with secondary interest in flight crew procedures and workload when appropriate. Based on the partnerships formed by Boeing with Honeywell and United Airlines, the plan proposed by Boeing and accepted by NASA was for an eighteen-day flight test using three aircraft, of which two would be equipped with IM avionics and with the un-equipped aircraft acting as the Target aircraft. Explicitly stated in the contract was no requirement for the enhancement or refinement of the IM avionics (algorithm and message logic), and only basic IM displays and data entry pages would be developed.

7.1.2 Limitations

7.1.2.1 Timeframe for Flight Test

Based on aircraft availability and the resources committed by Honeywell and United Airlines, a six-week window was established from mid-January through the end of February, 2017. A date limit was established as the end of February, when the United Airlines aircraft returned to normal service, and six weeks was estimated as an appropriate amount of time to accomplish eighteen flight days. Although the start of the flight test window was delayed as much as possible to allow maximum time for software development, the short development time was a limitation that resulted in several known software issues existing at the start of the flight test, and several additional software issues were found during and after the flight test. Two examples of these issues were trajectory updates not occurring due to differences between the sensed winds and the wind forecast, resulting in cases where the Ownship had significantly larger wind forecast errors than if the wind blending function had worked properly (section 7.9.2.3), and deceleration or acceleration rates expected by the control law not aligning well with the aircraft's actual performance (section 7.9.3). The operational impacts of this software development limitation were that on some occasions additional speed commands were generated by the speed control law. The impact to data generation was that some portions of some runs were discarded due to software anomalies (section 7.2).

7.1.2.2 Daily Operations, Aircraft Operating Limits, Pilot Qualifications

Daily operations were created to minimize the impact to aircraft operations in the Seattle area, resulting in departing no later than 0930 PT, and returning no later than 1500 PT. This time window allowed for up to a maximum of seven IM operations per flight. No aircraft restrictions unique for conducting the IM operations existed for the flight test other than those listed in each aircraft's operating manual (airspeed, altitude, descent rate, bank angle, icing, etc.), nor were there any unique pilot qualifications required. Daily flight operations, aircraft operating limits, and pilot qualification requirements did not impact the conduct of the flight test or the data collected.

7.1.2.3 Test Site and Deployment Locations

The selection of KMWH as the test site was based on the extensive experience the Tower, TRACON, and Seattle ARTCC have with conducting flight test operations, as well as the low to medium traffic density that would allow for the facilities to support multiple approaches by a string of three-aircraft. Deployment locations (KBFI for Honeywell, and KSEA for United Airlines) were determined by proximity to the test site and availability of aircraft maintenance and support functions. The test site and deployed airfields did not impact the conduct of the flight test or the data collected.

7.1.2.4 Stand-Alone IM Operations versus Integrated ATD-1 Operations

The initial subproject plan was to conduct an integrated test of the ATD-1 concept of operations, with the TMA-TM and CMS tools available to controllers and IM avionics available to flight crews. Due to the challenges of aligning schedules between NASA, the FAA, software vendors, and airlines, the plan was modified to only controllers testing just the ground tools in 2015 (ref. 5) at the William J. Hughes FAA Technical Center, and only pilots testing just the airborne tool in 2017 during this flight test. As described below, this limitation had a profound impact on the operation of the flight test, and a significant impact on the data generated during the flight test.

Without controllers issuing IM clearances based on actual aircraft position, the FTD and flight crew had to establish scenario start times based on the aircraft's FMS estimated of time-of-arrival to the first waypoint common to all three aircraft, enter a nominal spacing interval value in the IM avionics to determine the actual spacing between aircraft, then reenter the correct ASG based on the spacing error set for that particular scenario (see section 6.2). The operational impact between the time from the end of the previous scenario to the start of the next scenario was very high-workload for the flight crew (FMS data entry, then EFB data entry twice) and FTD (calculation of arrival times for three aircraft), and sometimes caused unrealistic aircraft speeds as the pilots attempted to achieve the FTD-assigned arrival time or achieve the desired geometry (for example, the 250 knot start of a Final Approach Spacing operation in section 7.7.2). The impact to data generation was some runs had to have early portions of the data excluded from analysis due to unrealistic airspeed (Appendix G), which reduced the amount of data available for analysis.

Furthermore, without controllers directly participating in the scenarios, prior coordination between Boeing and the ATC facilities involved in the flight test resulted in an agreement that aircraft conducting IM operations would remain approximately spaced between 150 to 210 seconds to ensure remaining well clear of separation requirements. This limitation resulted in the spacing between aircraft being operationally larger than what typically occurs during high-density operations. No significant impact was observed to data generation and analysis.

7.1.2.5 IM Data Entry, Displays, and Procedures

The NASA contract for the flight test included minimal funding for software testing and a human factors design cycle, resulting in software anomalies and ambiguous displays that would have been improved (section 7.8.2.5) if there had been a larger development cycle. Furthermore, during previous NASA research (ref. 19), the flashing of the IM commanded speed on the display was used as a method to cue the flight crew that they had not set the correct airspeed in the MCP speed window within 10 seconds of the IM commanded speed being displayed on the CGD and EFB. However, for the flight test, the IM avionics prototype did not have access to the value set in the MCP speed window; therefore, the conformance logic defined in reference 8 was used to trigger the flashing of the IM speed indicating to the flight crew that the aircraft was not decelerating at a minimum rate.

The operational impact was flight crews sometimes had to reenter the IM clearance, and over the duration of the flight test, increased their use of the FSI after setting the IM commanded speed to mitigate the ambiguous displays. The impact to data generation was the flight crews reported an increase in workload due to data entry and centering the FSI, and reported what appeared to be conflicting IM guidance.

7.1.2.6 Design of Arrival and Approach Procedures

The arrival and approach procedures used in the flight test were intended to be representative of PBN procedures in place today. The arrival procedures created for the flight test (SUBDY1, UPBOB1, and NALTE1 in Appendix D) to connect to the published approach procedures were designed in accordance with FAA guidelines (ref. 30). Although testing in full-scale simulators at LaRC and United Airlines found the arrival and approach procedures acceptable for single aircraft operations, during the flight test, multiple issues were discovered when speed was used to achieve precise spacing between aircraft.

First, the large magnitude speed changes used to reduce the number of speed changes caused some of the flight crews to report, on the arrival and especially on final approach, that this could be an indication of pending insufficient separation with the Target aircraft. In reality, during the flight test, the large decelerations were due solely to how the procedure was designed (section 7.8.2.1). In the context of interpreting the flight test results reported in this document, it is important to note that all the speed change magnitudes of 20 knots or greater, and in particular the 70 knot speed changes repeatedly reported as unacceptable, are solely a function of the procedure design, and would be experienced by any aircraft, whether it was conducting an IM operation or not.

Second, the large procedural speed changes were problematic for the IM algorithm because of the way that the procedural speed changes were implemented (sections 7.9.2.2 and 7.9.3.2).

Third, the magnitude of the speed changes was large enough that the mismatch of expected versus actual aircraft deceleration coupled with pilot technique meant that the spacing error frequently increased during the deceleration (section 7.9.3).

Fourth, some of the procedural speed constraints resulted in airspeeds that were slower or faster than optimal for either that altitude or the distance from the runway (section 7.10.1).

Fifth, the combination of using speed control while meeting an altitude constraint at a waypoint close to the transition altitude (NALTE), and having different descent angles on various segments of the arrival, sometimes required the flight crew to deploy speed brakes after changing the altimeter just prior to NALTE, and then almost immediately having to add power once the shallower segment after NALTE commenced (section 7.10.2.3).

The operational impact of how the arrival and approach procedures were designed was sometimes an increase in throttle and speed brake usage was required, regardless if an IM operation was being conducted or not. Furthermore, aircraft were sometimes faster than typically flown when on final approach. The impact to the data generated was some of the flight crew reports of undesirable IM operation performance and high speed on final were due to procedure design.

7.1.2.7 Current versus Future Technologies

The final factor bounding the scope of the flight test was a subproject requirement to test the IM operations using current technologies. In a next-generation type environment with integrated avionics and data link to exchange data, as was the case in prior IM concepts, the IM software could be integrated into the FMS, the IM information could be shown on primary displays, data communication could be used to send wind forecast data and issue the IM clearances, and the Target aircraft's time-delayed trajectory could be known by the IM avionics. The operational impact would be highly beneficial, since the use of the VNAV path mode and auto-throttles would significantly reduce flight crew workload, pilot-display scan pattern would be simplified, single data entry would reduce workload, and knowledge of the Target's trajectory would allow better estimation of the spacing error. The NASA research team believes having these potential future capabilities would yield improved results compared to those obtained during this flight test.

7.2 Data Validation

NASA, Boeing, Honeywell, and the FAA jointly determined the criteria for data validity, and these criteria are defined in Appendix G. The two primary issues examined in the determination of the criteria for data validity were the impact of software anomalies and the positioning of aircraft for a run without the assistance of the controllers and the ATD-1 ground tools. The delivery accuracy metrics described below have been independently validated using ADS-B ground surveillance data. The values calculated using the flight test data and the ADS-B ground surveillance data are within 0.3 seconds for all time-based clearances.

Using these criteria for the runs conducted during the 19 flight test days, 144 data points, i.e., successful IM operations, were identified and used in the core analysis. An additional 13 data points were collected in a separate study that examined the impact of aircraft type and route design.

All quantitative data are based only on the 144 valid runs as defined by the criteria in Appendix G, as are any pilot survey data reported with statistics (sections 7.8.1 and 7.8.2.1 – 7.8.2.57.8.2.4). The remainder of the pilot survey data included comments from all 204 runs. However, since not all questionnaires were returned (98 percent return rate), not every question completed by every pilot, and some responses contained multiple comments, the number of comments reported varies to some degree.

7.3 Definition and Calculation of Metrics

The definition and methodology to calculate metrics in this paper are described in this sub-section.

7.3.1 Spacing Performance Metrics

7.3.1.1 Spacing Accuracy at the ABP and PTP

The spacing accuracy is the difference between the spacing interval and the ASG. For the achieve stage, the spacing accuracy is measured at the ABP, which was NALTE for Cross-Merge operations, ZAVYO for Cross-FAF operations, and the default 6.25 nmi from the runway threshold for Final Approach Spacing operations. For the maintain stage, it is measured at the PTP, which was always SINGG for the en route scenarios and ZAVYO for the arrival scenarios.

The spacing accuracy is the difference between the achieved spacing and the ASG. For time-based operations, the achieved spacing is the time interval between when the Target and Ownship cross the ABP or PTP. For distance-based operations, the achieved spacing is the along-path distance between the Ownship and the Target when the Target crosses the ABP or PTP.

Positive values of the spacing accuracy indicate that the achieved spacing is larger than the ASG, i.e., the Ownship is farther from the Target than specified. Negative values of the spacing accuracy indicate that the achieved spacing is smaller than the ASG, i.e., the Ownship is closer to the Target than specified. The IM tolerance described in the MOPS (ref. 8) is defined as a spacing accuracy within 10 seconds for time-based operations, or converted to the equivalent distance based on ground speed for distance-based operations, for at least 95 percent of the operations.

7.3.1.1.1 Spacing Error throughout and at the end of the Maintain Stage

The spacing error throughout the maintain stage is a measure of how well the spacing error was maintained throughout the maintain stage of IM operations. For Capture and Maintain operations, the success criterion is to maintain a spacing error within 10 seconds, or the equivalent distance, for at least 95% of the time from when the spacing error is first less than 10 seconds for time-based operations to the PTP. For Cross operations, the criterion is to maintain a spacing error within 10 seconds, or the equivalent distance, for at least 95% of the time from the ABP to the PTP. These success criteria were derived from the MOPS (ref. 8); however, the criterion for Cross operations was based on a draft version of the MOPS, which was revised for the final published version.

7.3.1.2 Capture Rate

The capture rate metric is only relevant during the maintain stage and is calculated as the difference between the initial spacing error and the 10 second threshold, divided by the time for the Ownship to reduce its spacing error to less than 10 seconds. The MOPS success criterion for the capture rate is a minimum of 3 seconds per minute (ref. 8). The capture rate was only applicable to Capture operations which started with a spacing error greater than 10 seconds.

7.3.2 Speed Behavior Metrics

7.3.2.1 Number of IM Speed Changes

The IM commanded speed is the speed value displayed by the IM avionics prototype to the flight crew. It is a discrete number that represents the desired speed that the pilots are expected to input into the aircraft's MCP speed window. The number of IM speed changes is the total number of times the IM commanded speed changed, including the first speed at the initiation of the IM operation and the transition from Mach to calibrated airspeed.

7.3.2.2 IM Speed Command Rate

The IM speed command rate is calculated by dividing the number of IM speed changes by the duration of the IM operation in time. For distance-based operations, the IM speed command rate also includes the portion of the IM operation after the Target aircraft crosses the PTP (which was not included in the calculations performed in refs. 32 and 33).

7.3.2.3 IM Speed Reversals

An IM speed reversal is a trend change that occurs when an IM commanded speed increase is followed by a speed decrease, or an IM commanded speed decrease is followed by an increase.

7.3.2.4 Magnitude of IM Speed Change

The magnitude of an IM speed change is the difference between the previous IM commanded speed and the new IM commanded speed.

7.4 En Route Operations

7.4.1 Spacing Performance

The eleven (N = 11) en route operations consisted of six time-based and five distance-based operations. The length of the en route operations ranged from 39 nmi to 71 nmi and typically required less than 9 minutes to complete. The initial time-based spacing errors ranged from 23 seconds early to 20 seconds early (a range of three seconds), and distance-based spacing errors ranged from 3.8 nmi early to 2.6 nmi late.

Figure 12 illustrates that all of the spacing errors at the PTP for the six time-based en route operations were well within the 10 second IM tolerance for both the Maintain and Capture operations (ref. 8). The average spacing error at the PTP for time-based en route scenarios was 2.8 seconds early with a standard deviation of 2.1 seconds. Both the maintain stage performance and the capture rate were examined to determine if they met the IM tolerance specified in reference 8. All of these operations maintained the spacing error within 10 seconds for at least 95 percent of the duration of the maintain stage.

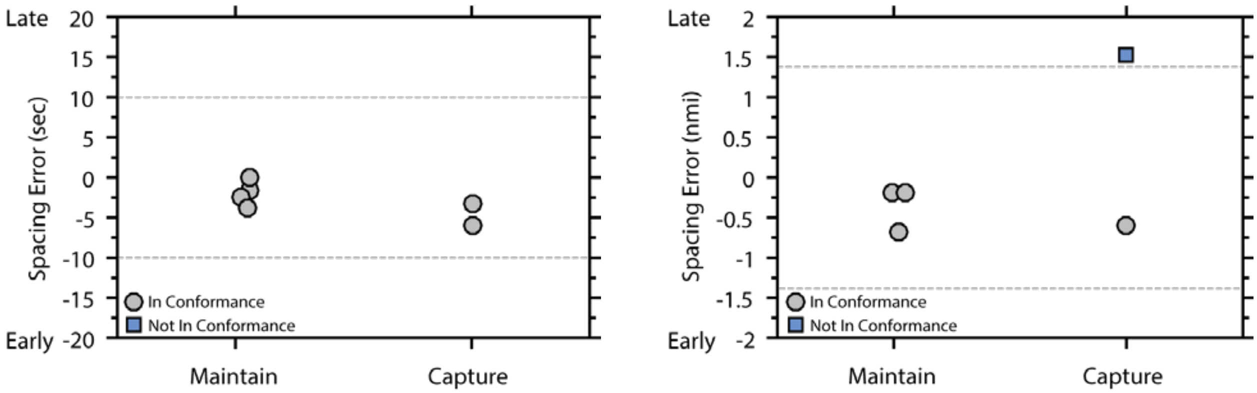


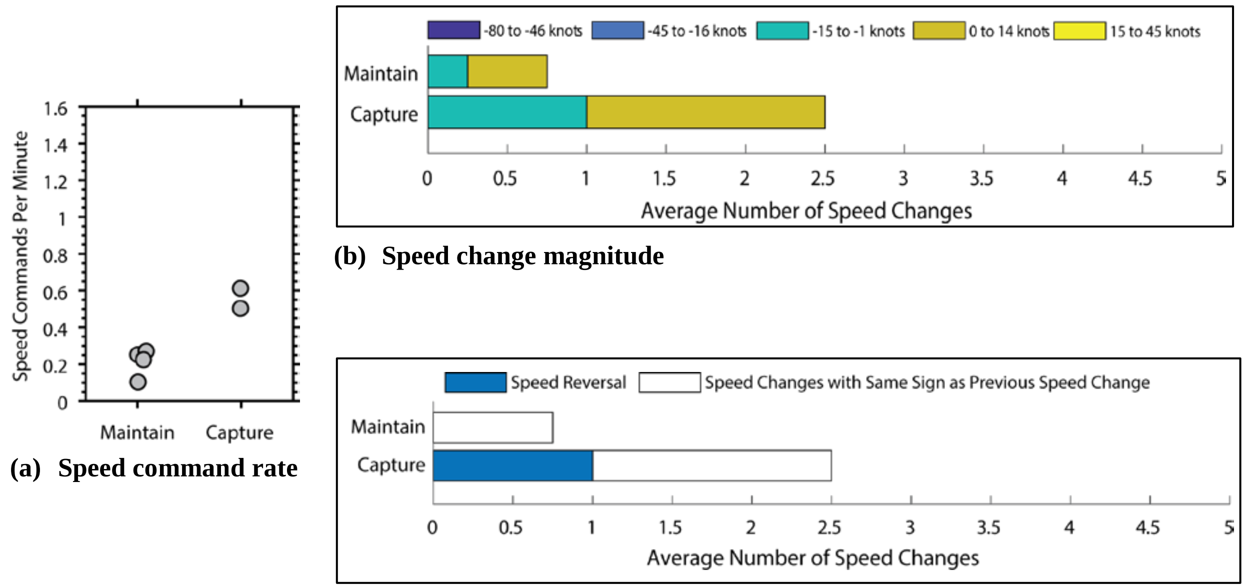
Figure 12. Spacing accuracy for time- (left) and distance-based (right) en route operations.

Figure 12 also illustrates that four out of five spacing errors at the PTP for the distance-based en route operations were within the distance-based equivalent of the 10 second IM tolerance, which ranged from 1.3 to 1.6 nmi depending on the ground speeds of the aircraft. On average, the spacing error at the PTP was 0.03 nmi with a standard deviation of 0.9 nmi. The one aircraft noted as not achieving the IM tolerance was 0.1 nmi outside the criterion and in the process of capturing the ASG. This aircraft was also unable to achieve a spacing error within 10 seconds at the PTP. Both the maintain stage performance and the capture rate were examined to determine if they met the IM tolerance specified in reference 8. All four of the distance-based operations that contained a maintain stage were able to maintain the spacing error within 10 seconds 95 percent of the time.

7.4.2 Speed Behavior

Since there were only 11 en route IM operations, all of which were of fairly short duration, there is not sufficient data to draw definitive conclusions about the IM speed behavior during these operations. Nevertheless, the data presented in this section are intended to describe the speed behavior that was observed. Figure 13 shows the IM speed command rate, the speed change magnitude, and the number of speed reversals for time-based en route operations. Figure 14 shows the same metrics for distance-based en route operations. As noted in section 7.1.2.6, speed changes larger than 20 knots, and in particular the 70 knot speed changes, are a function of the arrival or approach procedure design, and would be experienced by any aircraft regardless if conducting an IM operation or not.

For en route operations, the speed command rate was always less than one speed command per minute. Since the length of the en route IM operations was relatively short, the speed command rate may have been higher than would be observed during longer cruise operations. Some other notable trends are that all of the speed changes for the en route operations had a magnitude of 15 knots or less (most were 10 knot speed increases or decreases), and the distance-based operations had relatively low percentage of speed reversals.

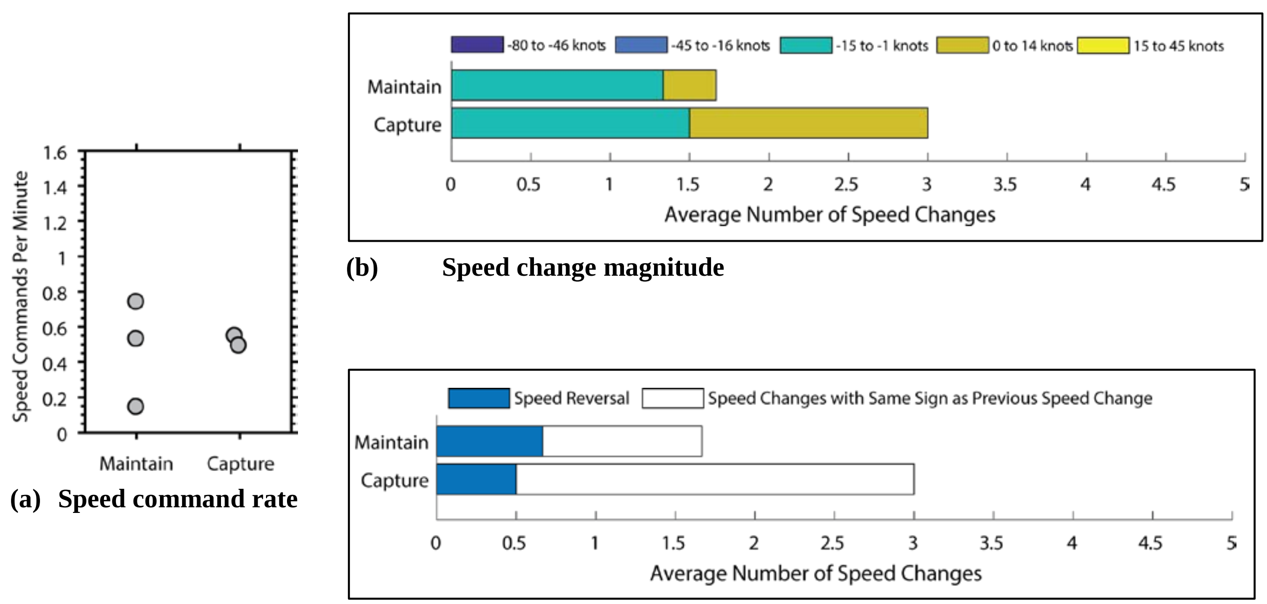


(a) **Speed command rate**

(b) **Speed change magnitude**

(c) **Speed reversals**

Figure 13. Speed behavior for time-based en route operations.



(a) **Speed command rate**

(b) **Speed change magnitude**

(c) **Speed reversals**

Figure 14. Speed behavior for distance-based en route operations.

7.5 Arrival Operations, Time-Based

7.5.1 Spacing Performance

7.5.1.1 Spacing Accuracy at the End of the Achieve stage

Figure 15 and Table 6 show spacing performance at the ABP for the Cross-Merge and Cross-FAF operations, with the dotted line representing the desired IM tolerance. The average spacing accuracy of the 25 Cross-Merge operations (*N* = 25) was -1.65 seconds with a standard deviation of 6.24 seconds. The average spacing accuracy of the 41Cross-FAF operations (*N* = 41) was 6.24 seconds, with a standard deviation of 8.28 seconds. The two Cross-Merge operations that began after the Ownship crossed the ABP are not included in this analysis.

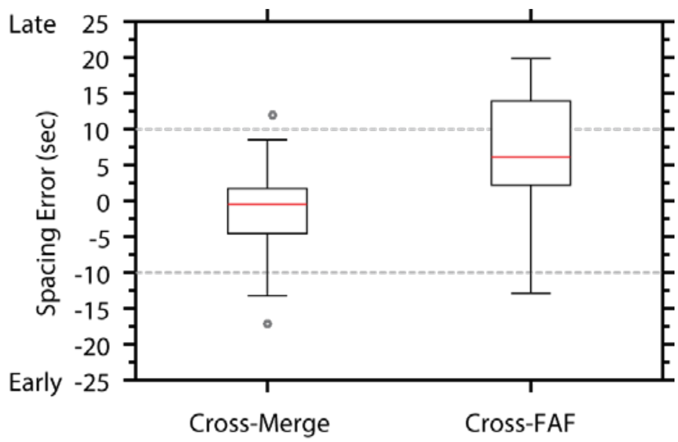


Figure 15. Achieve stage spacing accuracy for time-based arrival operations.

Table 6. Achieve stage spacing accuracy for time-based arrival operations.

Clearance Type	*N*	Mean (sec)	SD (sec)
Cross-Merge	25	-1.65	6.24
Cross-FAF	41	6.24	8.28

Of the 25 Cross-Merge operations, four had spacing errors greater than 10 seconds (16 percent). Two of these cases involved conditions at initiation that would not be expected operationally. In both of these cases, the IM operation started within 25 nmi of the ABP, with spacing errors of 19 and 28 seconds early. The Target aircraft had a ground speed 40 knots slower than predicted for the initial 5 to 10 nmi of the operation, likely because it was operating at slower speeds in order to set up the scenario. The Target aircraft's speed deviation caused the spacing error to increase to a value that was unable to be solved by the ABP, resulting in spacing errors at the ABP of 17 seconds early and 13 seconds early. The other two outliers for the Cross-Merge operations appeared to be normal operations with adequate speed control authority to resolve the spacing error. These two cases had spacing accuracies of 12 seconds early and 13 seconds late at the ABP.

Of the 41 Cross-FAF operations, 17 had spacing errors at the ABP greater than 10 seconds (41 percent). Two primary causes were identified for the poor spacing performance. First, there was a software implementation error that was identified after the flight test that prevented the IM avionics prototype from consistently incorporating sensed wind information into the Ownship's and Target aircraft's trajectory predictions. This resulted in cases where the Ownship had significantly larger differences between the predicted headwind and actual headwind than it would have had if the software implementation error had not occurred. Second, there were differences between the speeds flown by the Ownship and the speeds expected by the IM avionics during the deceleration segment prior to the FAF. These differences were caused by a combination of large procedural speed changes and functionality that provided procedural speed changes as a single speed command. The case studies in sections 7.9.2.2, 7.9.2.3, 7.9.3.2, and 7.9.3.3 provide examples of these behaviors.

Further analysis of the 17 cases was conducted to determine those cases where the wind blending software implementation error was a significant contributing factor and those cases where differences between the speeds flown by the Ownship and the speeds expected by the IM avionics was a significant contributing factor. For trajectory-based IM operations, Ownship or Target aircraft speed deviations from the nominal ground speed caused the spacing error to change. For this analysis, the ground speed deviations of the IM and Target aircraft were decomposed into several contributing factors. These contributing factors included Ownship and Target headwind error, Ownship and Target altitude error, Target aircraft airspeed deviation, and Ownship airspeed deviation from the FSI. The ground speed components were then integrated to determine the impact of each of the errors over the last 10 nmi prior to the FAF. The results of this analysis indicated that the Ownship's speed deviation from the expected speed was the primary contributing factor for 9 out of the 17 cases (53%), the wind blending software implementation error was the primary contributing factor for 4 out of the 17 cases (24%), and both the Ownship's speed deviation and wind blending software implementation error were significant contributing factors for 2 out of the 17 cases (12%).

7.5.1.2 Spacing Accuracy at the End of the Maintain Stage

In this flight test, every Maintain, Capture, and Cross-Merge scenario with a maintain stage terminated at ZAVYO (the FAF).

Figure 16 and Table 7 show that the accuracy of the arrival scenarios was better than the IM success criterion at the PTP (shown as dotted lines in Figure 16) for the Maintain, Capture, and Cross-Merge operations. All time-based Maintain, Capture, and Cross-Merge arrivals had spacing errors within 10 seconds when they crossed ZAVYO, indicating that the IM tolerance was met. For each operation, the average spacing error was less than 2 seconds and the standard deviation was less than 3 seconds. This indicates the ability of those operations to precisely meet the ASG at the PTP. These results are consistent with a field evaluation conducted by the United Parcel Service (UPS), The MITRE Corporation, and the FAA in 2010 (ref. 39). They found that all of the aircraft who followed the IM speed commands were able to obtain spacing accuracies within 8 seconds.

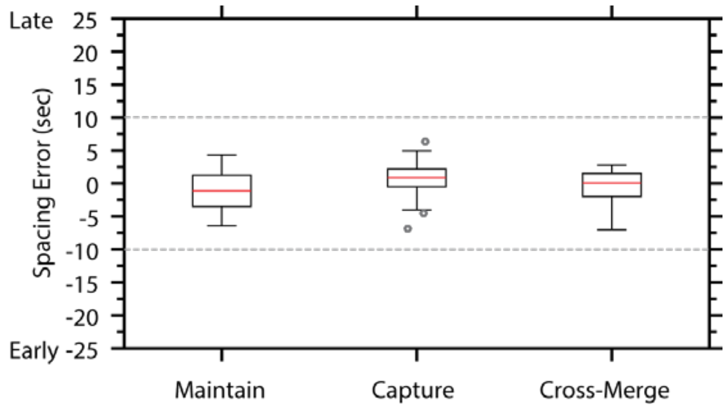


Figure 16. Maintain stage spacing accuracy for time-based arrival operations.

Table 7. Maintain stage spacing accuracy for time-based arrival operations.

Clearance Type	*N*	Mean (sec)	SD (sec)
Maintain	18	-1.13	2.99
Capture	32	0.55	2.63
Cross-Merge	27	-0.47	2.45

7.5.1.3 Spacing Error Throughout Maintain Stage

Of the 77 operations that contained a maintain stage, 13 did not meet the IM tolerance. Of these 13 cases, 7 occurred during the 270 to 210 knot deceleration on the SUBDY1 arrival (black line in Figure 10), and were due to the Ownship and Target aircraft not decelerating at the same rate. Three of these cases were Cross-Merge operations where the spacing error at the ABP was greater than 10 seconds, resulting in spacing errors at the beginning of the maintain stage that were not within 10 seconds. There was one Cross-Merge case where the spacing error was not within 10 seconds due to both the deceleration from 270 knots to 210 knots on the SUBDY1 arrival and a spacing error at the ABP that was not within 10 seconds. The remaining two cases were a Cross-Merge operation that began after the ABP with an initial spacing error greater than 10 seconds, and a Maintain operation where spacing error increased as the Ownship decelerated toward its initial IM commanded speed. Analysis of these cases revealed that the maintain stage performance generally met the IM tolerance, although deceleration segments should be considered when designing arrival and approach procedures for use with IM.

7.5.1.4 Capture Rate

Only Capture operations with initial spacing errors greater than 10 seconds were examined in the evaluation of the capture rate. The data from the time-based Capture operations indicated that 3 of the 30 Capture operations did not meet the success criterion. The first two cases had capture rates of 1.6 and 2.5 seconds per minute. For both cases, the Ownship was the last aircraft in the three aircraft string, the lead aircraft (first aircraft) flew a high delay speed profile, and the Target (second aircraft) had an early initial spacing error. The Ownship was speed limited by the ±15 percent speed bounds applied around the published speeds, indicating that there was not enough speed control authority to capture the ASG at the desired rate. The third case had a capture rate of 2.8 seconds per minute, just missing the success criterion. As in the previous two cases, the Ownship was the last aircraft in the string, the lead aircraft (first aircraft) flew a medium delay speed profile, and the Target aircraft had an early initial spacing error. The IM avionics were again at the ±15 percent speed limit during the initial portion of the operation. Therefore, in all of the cases where there was sufficient speed control authority, the IM avionics prototype met the capture rate criterion.

7.5.2 Speed Behavior

7.5.2.1 Rate of Speed Commands

For current day arrival operations when speed control is not being used to achieve a precise spacing interval between aircraft, the rate of speed changes is driven by the number of speed constraints on the published procedure, regulatory restrictions, company operating procedures, and controller instructions. This method of approximating the speed change rate of arrival operations with no attempt to achieve precise spacing between aircraft, when used on the KMWH procedures shown in Appendix D, produces approximately 0.25 changes per minute. The number of speed changes during higher-density operations when precise spacing intervals are desired would be expected to be higher, regardless of whether the speed command was generated by a ground-based system or airborne-based system.

The mean IM speed command rate for all time-based arrival operations was 0.57 speed commands per minute (approximately one per two minutes), which is higher than the value estimated in the previous paragraph. Figure 17 and Table 8 show the IM speed command rate by IM operation type. From top to bottom in Table 8, the most likely cause of the high speed command rate for the Maintain operations (CTD control law) is that both the Target aircraft's ground speed and the spacing error are used to determine the value of the speed command. Therefore, a change to the Target's ground speed, headwind, or spacing error can result in a speed change. The Capture operation also used the CTD speed control law, but there were heuristics used when the IM aircraft is capturing the desired spacing goal to minimize the speed command rate. These heuristics are not used in the maintain stage because of the need to maintain the spacing interval within a 10 second tolerance around the ASG. The Cross-FAF operation, which used the TBO speed control law exclusively throughout the entire operation, had the lowest speed command rate. The Cross-Merge operations used the TBO speed control law for the first portion of the arrival and the CTD speed control law for the second part; therefore, its speed command rate was higher than the Cross-FAF operations.

There are three possible reasons why TBO speed control law had fewer speed changes than the CTD speed control law. First, the TBO speed control law was prohibited from commanding a speed change above the final nominal speed (170 knots) during the deceleration to the FAF to ensure the Ownship could achieve a stable approach. Second, the TBO speed control law is less susceptible to variations in the Target aircraft ground speed when close to the FAF. Third, cases where the Ownship was speed limited within ±15 percent of the nominal speed profile for a large portion of the operation may have reduced the number of speed commands.

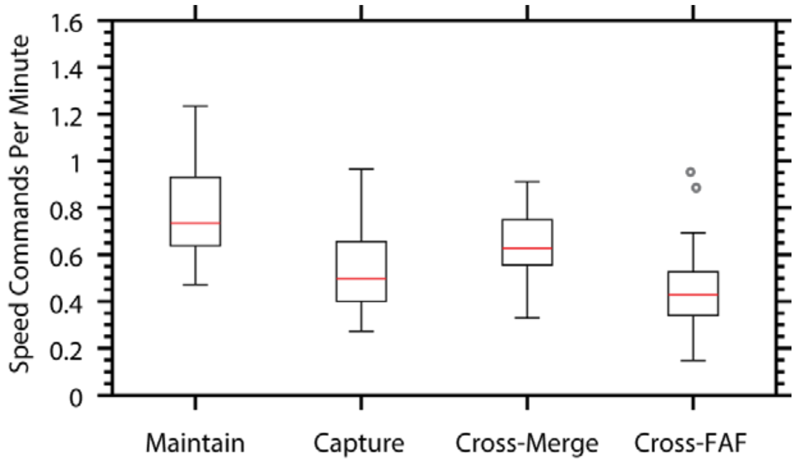


Figure 17. IM speed command rate for all time-based arrivals.

Table 8. IM speed command rate for all time-based arrivals.

Clearance Type	*N*	Mean (number/min)	SD (number/min)
Maintain	18	0.80	0.23
Capture	32	0.54	0.18
Cross-Merge	27	0.64	0.15
Cross-FAF	41	0.45	0.15

The 0.80 changes per minute experienced in this flight test during the maintain stage was higher than the UPS flight trails where the speed command rate during the maintain stage was approximately 0.60 to 0.33 (ref. 39).

7.5.2.2 Rate of Speed Reversals

Because pilot comments indicated that the IM commanded speed reversals reduced the acceptability of the IM operation, the number of speed reversals was examined in order to understand how frequently they occurred. While some speed reversals may be required to meet the desired spacing accuracy, they should be minimized to the extent possible in order to maximize the efficiency of the IM operation and to provide predictable speeds to the pilots.

The blue portion of each bar in Figure 18 shows the number of speed reversals observed for all time-based arrival operations in the flight test. From top to bottom, the number of speed reversals (and the percentage of the total number of speed changes) was 8.4 (51 percent) for Maintain operations, 4.4 (44 percent) for Capture operations, 5.1 (45 percent) for Cross-Merge operations, and 2.8 (39 percent) of Cross-FAF operations.

The relatively high percentage of speed changes that were reversals for all IM clearance types supports the pilot feedback that the number of IM commanded speed reversals was too high. While it may not always be possible to avoid speed changes and reversals while meeting the spacing accuracy criterion, the IM spacing algorithm should ideally be designed to avoid speed reversals unless absolutely necessary.

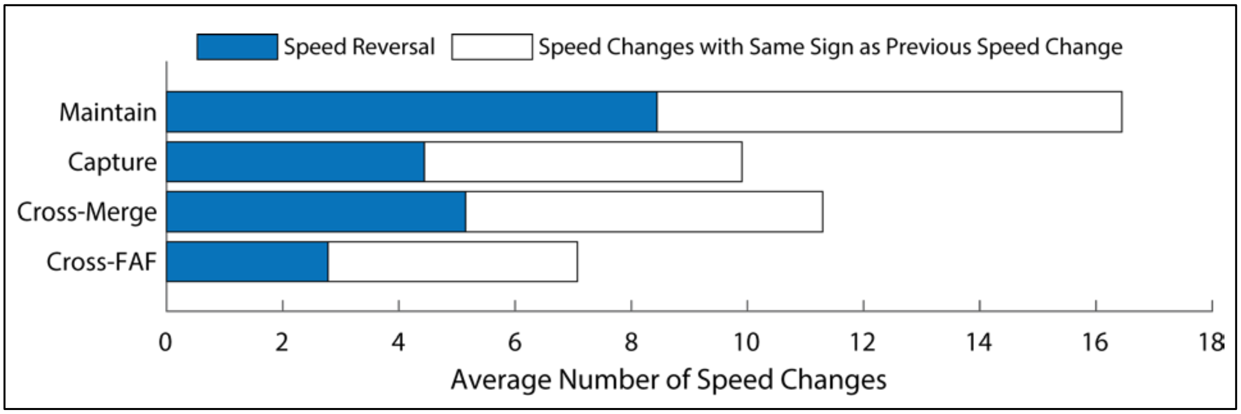


Figure 18. Speed reversals observed by IM operation type.

7.5.2.3 Magnitude of Speed Change

Figure 19 shows the magnitude of the IM speed changes by IM operation type, with negative values (all shades of blue) indicating a speed decrease and positive numbers (all shades of yellow) indicating a speed increase.

Three observations can be made about the data shown in Figure 19. First, the relative proportions of the speed magnitudes are roughly similar across the four IM operation types. Second, the majority of speed change magnitudes were between –15 and +15 knots. Third, the large speed decreases were almost always associated with the published procedure, such as the 270 to 210 knot speed decrease on SUBDY1 and the 240 to 170 knot speed decrease on UPBOB1 (see Figure 10).

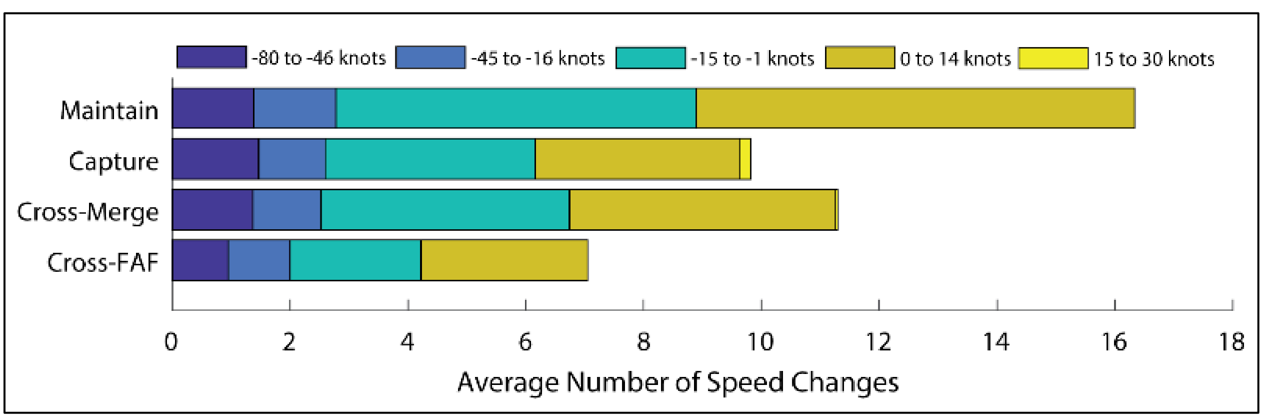


Figure 19. Magnitude of speed change by IM operation type.

As expected, the number of speed increases (yellow bars) in Figure 19 aligns closely with the number of speed reversals in Figure 18. In general, the magnitude of the IM speed changes was rated by the pilots as acceptable, except for the large-magnitude speed changes caused by the design of the arrival procedures, which they reported as difficult to control. Some pilots suggested no speed change magnitudes of greater than 40 knots on arrival and 20 knots on approach as a desirable characteristic for normal operations.

7.5.2.4 Use of Speed Brake

The results of the ATD-1 flight test were examined to gain an understanding of how pilots managed the energy of their aircraft during IM operations. Of particular interest was the total amount of time and the location speed brakes were deployed throughout each IM operation. Consistent use of speed brakes could indicate less than ideal procedure design, winds that were not predicted accurately, or energy management issues caused by the speeds that were commanded by the IM avionics. The results presented in this section are limited to the time-based arrival operations for the B-737, since speed brake data were not available for the B-757.

First, speed brake deployment was examined for each run. Figure 20 graphs the cumulative distribution of the speed brake usage as a function of the total time the speed brakes were deployed. The results indicate that 12 percent of the operations had no speed brake use, 50 percent of the operations deployed the speed brakes for 2 minutes or less, and 10 percent of the operations deployed the speed brakes for 5.5 minutes or more.

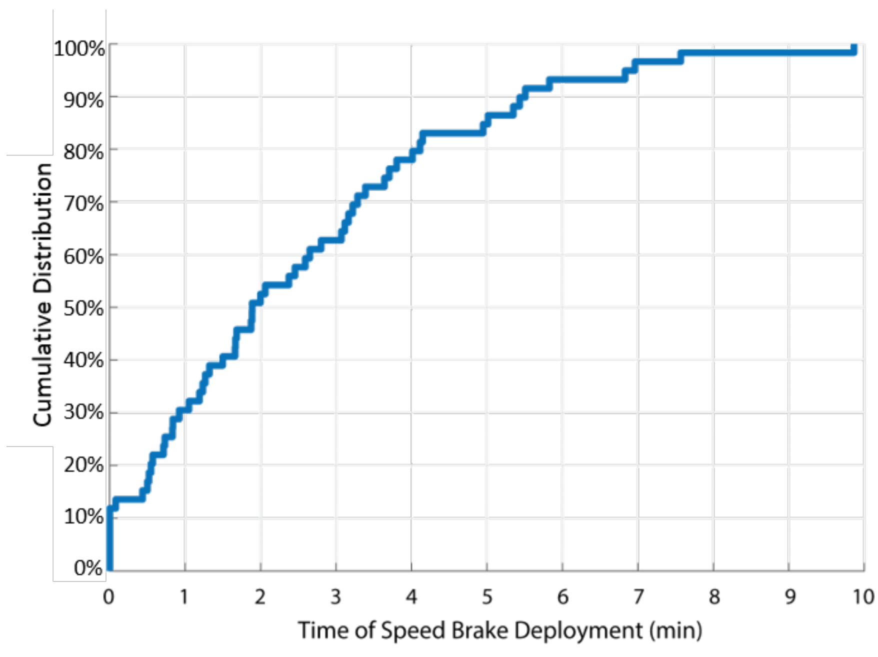


Figure 20. Cumulative probability distribution of speed brake deployment time.

Next, the data were examined to determine if there were particular locations on the flight test routes where speed brakes were commonly used and the magnitude of their use at these locations. Figure

21 shows the speed brake deployment as a function of the distance-to-go on the three flight test routes. The height of each bar on the graph indicates the percentage of runs where speed brakes were deployed, and is broken into four categories that indicate the magnitude of speed brake deployment. The dark blue regions indicate the percentage of operations where the speed brake lever extended between 0 to 25 percent of its full range, the light blue regions indicate the percentage of operations where the speed brake lever extended between 25 to 50 percent the green regions indicate the percentage of operations where the speed brake lever extended between 50 to 75 percent, and the yellow regions indicate the percentage of operations where the speed brake lever extended between 75 to 100 percent (i.e., speed brakes fully deployed).

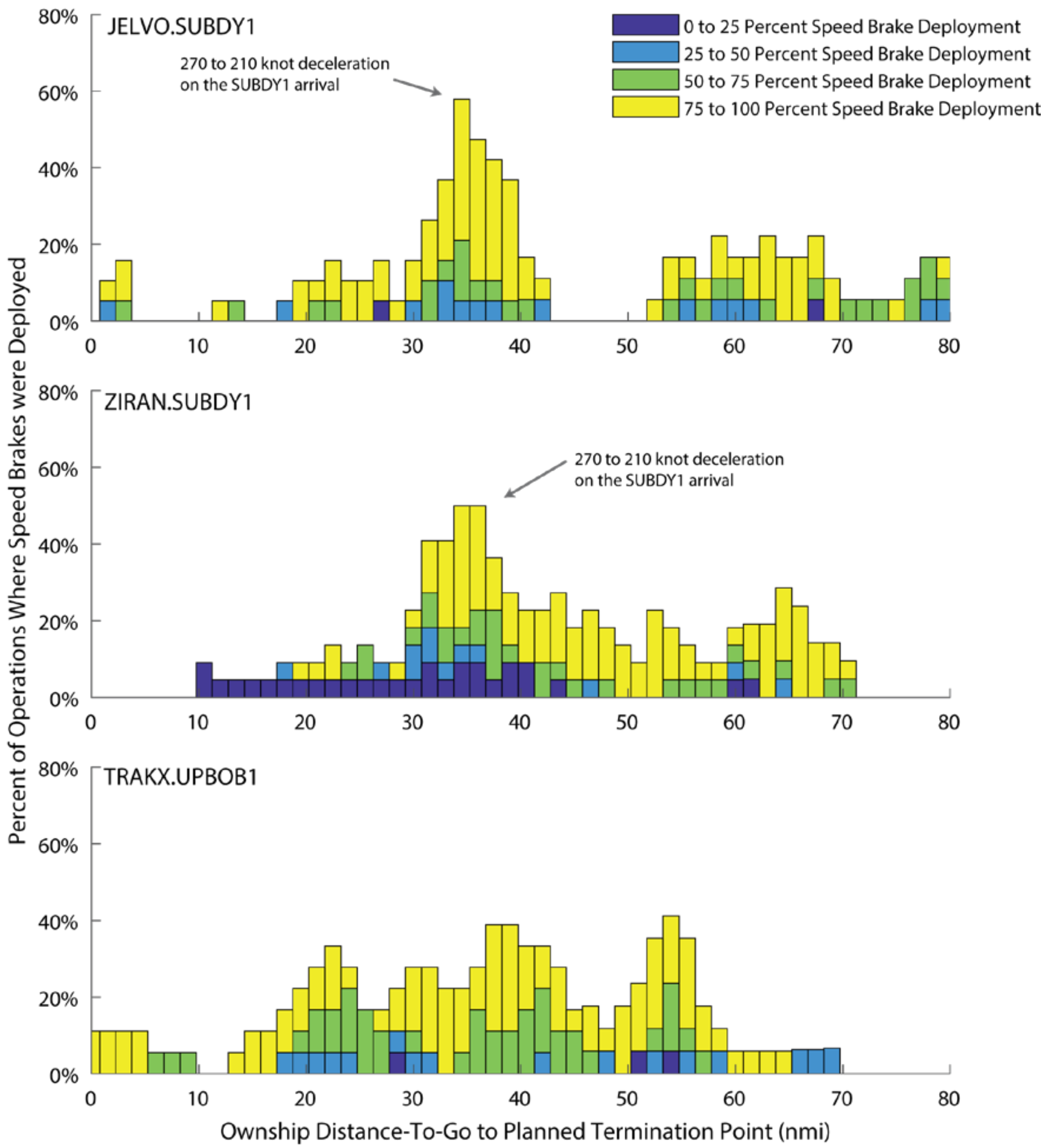


Figure 21. Speed brake deployment along the flight path.

The data for both transitions of the SUBDY1 arrival also indicate that 50 to 60 percent of the aircraft used speed brakes between 30 and 40 nmi prior to the PTP. This is the region where there was a procedural speed change from 270 knots to 210 knots, suggesting that it was difficult for the pilots to maintain a desirable amount of energy when flying that deceleration segment. The trend is less clear for the UPBOB1 arrival. Unlike the SUBDY1 arrival, the speed brake use was spread out over a larger portion of the IM operation.

7.6 Arrival Operations, Distance-Based

7.6.1 Spacing Performance

All seven distance-based arrival scenarios (*N* = 7) were Cross operations with the ABP and PTP co-located at the FAF (i.e., Cross-FAF). The length of these operations ranged from 41 nmi to 99 nmi, with initial spacing errors from 2.9 nmi early to 4.1 nmi late. As illustrated in Figure 22, the distance-based arrival operations achieved the desired spacing performance at the PTP for only three out of seven distance-based arrival scenarios.

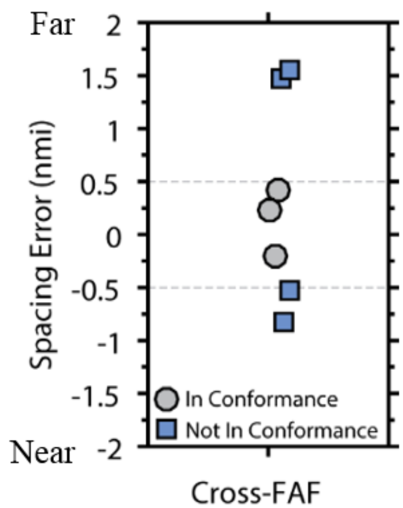


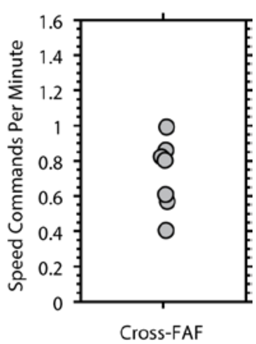
Figure 22. Spacing accuracy for distance-based arrival operations.

The two cases with a spacing error of 1.5 nmi late occurred on a day with strong winds at low altitude. As the Target flew around the radius-to-fix turn to final, the wind it experienced changed from a 60 knot headwind to a 10 knot tailwind. At approximately the same time, the spacing error began to diverge from zero. A similar increase in spacing error was observed for the time-based Cross-FAF scenarios conducted on the same day; however, in the time-based case the Ownship was able to correct the spacing error after the Target aircraft crossed the PTP.

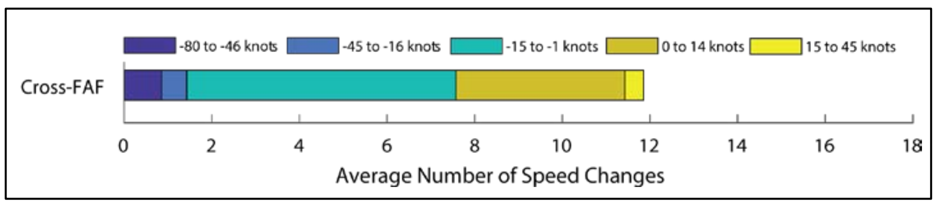
7.6.2 Speed Behavior

Figure 23 shows the commanded speed change rate, the speed change magnitude, and the number of speed reversals for the distance-based arrival operations. For the distance-based arrival operations, the speed command change rate ranged from 0.4 to 1.0 speed commands per minute. On average there were 4.0 speed reversals for the Cross-FAF operations.

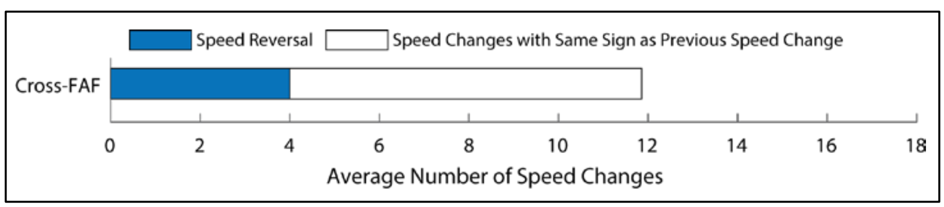
During distance-based operations, the IM performance is measured when the Target aircraft crosses the PTP. After the Target aircraft crossed the PTP, there was an average of 3.7 additional speed commands provided to enable the Ownship to match the ground speed of the Target aircraft at the PTP. The speed command rate presented in this paper includes those additional speed commands. The reason for the large number of speed changes that occurred after the Target aircraft crossed the PTP is not entirely understood; however, the software error that prevented sensed winds from being blended with the wind forecast, and the ground speed matching algorithm itself may have been contributing factors.



(a) Speed rate



(b) Speed change magnitude



(c) Speed reversals

Figure 23. Speed behavior for distance-based arrival operations.

7.7 Final Approach Operations

The eight (N = 8) Final Approach Spacing operations consisted of five time-based and three distance-based operations. The length of these operations ranged from 14 nmi to 32 nmi, with the initial time-based spacing errors ranging from 23 seconds early to 29 seconds late, and distance-based spacing errors ranging from 1.5 nmi early to 0.1 nmi early.

7.7.1 Spacing Performance

Figure 24 shows that the spacing error at the PTP for all time-based (left plot) and distance-based (right plot) Final Approach Spacing operations was less than the 10 second IM tolerance (approximately 0.5 nmi at final approach speed). The average time-based spacing error was 3.3 seconds (SD = 4.2 seconds), and 0.09 nmi (SD = 0.25 nmi) for the distance-based operations. The one time-based case that marginally met the IM tolerance was due to the Ownship flying an average of 9.8 knots slower than the desired speed (shown on the fast/slow indicator) throughout the final deceleration, which contributed to the Ownship having a larger spacing interval at the PTP.

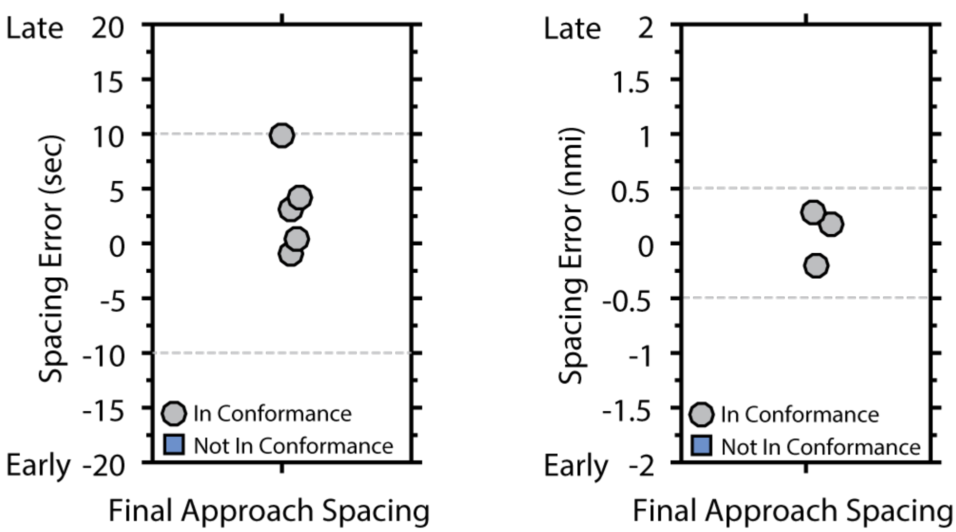
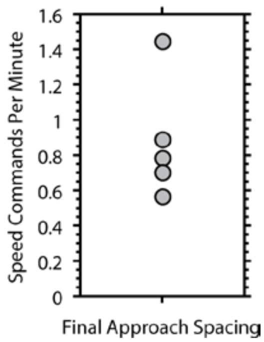


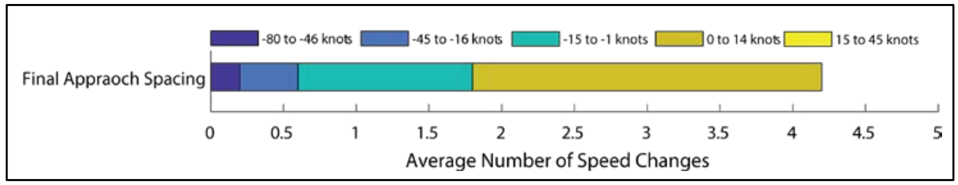
Figure 24. Spacing accuracy for time- (left) and distance-based (right) final operations.

7.7.2 Speed Behavior

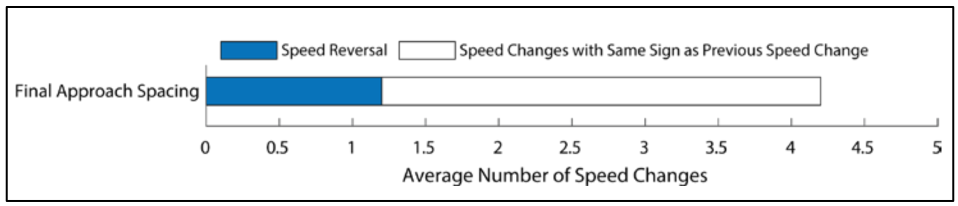
Since there were only eight Final Approach Spacing operations, there is not enough data to draw conclusions regarding speed behavior of the Final Approach Spacing IM operations. Figure 25 shows the commanded speed change rate, the speed change magnitude, and the number of speed reversals for time-based Final Approach Spacing operations. Figure 26 shows the same metrics for distance-based Final Approach Spacing operations.



(a) Speed rate

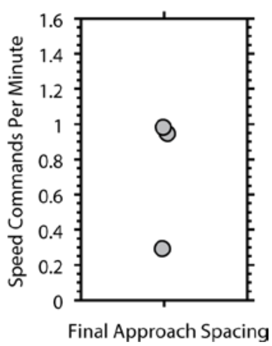


(b) Speed change magnitude

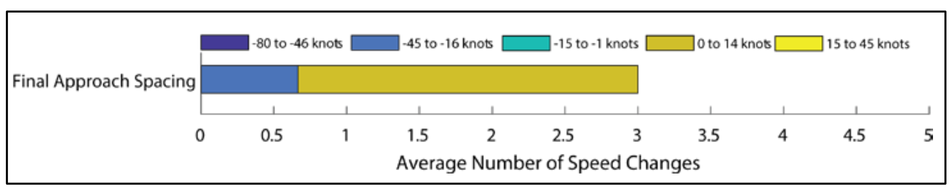


(c) Speed reversals

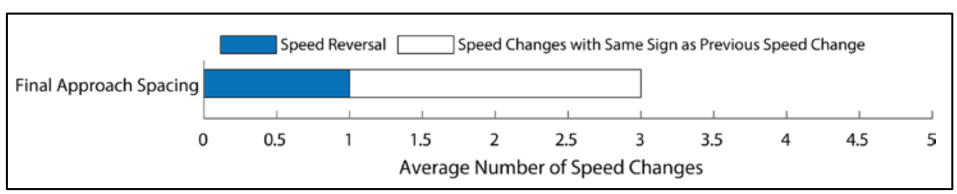
Figure 25. Speed behavior for time-based Final Approach Spacing operations.



(a) Speed rate



(b) Speed change magnitude



(c) Speed reversals

Figure 26. Speed behavior for distance-based Final Approach Spacing operations.

For the Final Approach Spacing, the speed command rate for time-based operations ranged from 0.6 to 1.4 speed commands per minute and from 0.3 to 1.0 speed commands per minute for distance-based operations. There was an average of 2.4 speed increases for time-based arrivals and 2.3 for distance-based operations. There was an average of 1.2 speed reversals (29 percentage) for the time-based Final Approach Spacing operations, and 1.0 speed reversals (33 percent) for the distance-based operations.

Two interesting observations about the Final Approach Spacing behavior were the 50 knot speed decrease during the time-based operations (Figure 25) and no 10 knot speed decreases during the distance-based operations (Figure 26). The 50 knot speed change from 210 to 160 knots during the time-based operations was to conform to the assumed procedural deceleration required to match the 170 knot speed constraint at the default PTP. Although there was a 50 knot speed reduction this run was relatively normal and consistent with the MOPS requirements for aircraft that are at ~210 knots when turning onto final. The lack of any 10 knot speed change during the three distance-based operations was a statistical anomaly due to the small sample size.

7.8 Subjective Data

7.8.1 Pilot Ratings

Pilot acceptability of the IM operation and the IM speeds displayed by the avionics prototype were measured using a 7-point Likert rating scale of 1 (“Completely Unacceptable”) to 7 (“Completely Acceptable”). Data were collected during the end-of-run questionnaires, and statistical analysis was performed using the Wilcoxon signed rank test (ref. 41) to assess the hypotheses that pilots would report the mean operational acceptability of the IM operation and the acceptability of the IM speeds as greater than or equal to ‘5’.

- The mean acceptability ratings for all IM operation types were statistically significantly greater than 5 ($p \leq 0.018$), indicating that flight crews found the operations to be acceptable overall (column #1 in Table 9).
- The mean acceptability ratings for the IM speeds for all IM operation types were statistically significantly greater than 5 ($p \leq 0.025$), indicating that flight crews found the IM speeds to be acceptable overall (column #2 in Table 9).

Pilot acceptability of the aircraft’s energy level on final was rated using a “Yes” (“Acceptable”) or “No” (“Unacceptable”) response. Pilots must execute a “go-around” if stabilized approach criteria are not met at 1000 feet above ground level (from airlines’ Operations Specification manual to comply with FAA Order 8900.1), and a generally accepted goal is for less than 1 percent of approaches to require a “go-around” instead of landing. Since unacceptably high energy levels on final would not meet stabilized approach criteria and would require the flight crew to execute a “go-around,” the researchers and participating pilot subject matter experts set a subjective criterion of greater than 95 percent of the responses must be “Yes” for the operation to be acceptable. (Note: reference 8 assumes pilots will stop following the IM commanded speed when the aircraft must decelerate to achieve stabilized approach criteria, however, the research team has observed in both simulation experiments and the flight test that this is not always done by the pilots.)

- Fewer than 95 percent of the responses reported that the energy level on final was acceptable; therefore, the IM operations did not meet the criterion (column #3 in Table 9).

Table 9. Rating statistics for responses to IM operation, IM speed, and energy on final.

Scenario	Clearance Type	*N*	#1. IM Operation		#2. IM Speed		*N*	#3. Energy on final acceptable			
			Mean	SD	Mean	SD		Yes	(%)	No	(%)
En route	Maintain	13	6.6	0.5	6.7	0.5	n/a	n/a	(-)	n/a	(-)
	Capture	6	6.5	0.5	6.5	0.5					
Arrival	Maintain	31	5.9	1.1	5.5	1.3	26	18	(70)	8	(30)
	Capture	58	6.1	0.7	5.9	0.9	53	44	(83)	9	(17)
	Cross	137	5.9	1.0	5.6	1.2	147	129	(88)	18	(12)
Final Approach	Final *	15	6.3	0.8	6.5	0.5	15	13	(87)	2	(13)

* Note: The Final Approach Spacing concept of operations as described in reference 7 has the controller issue the clearance once the Ownship is on final or on an intercept to final. During the flight test, the pilots entered the IM information into the avionics well prior to that point. Several pilots speculated that their acceptability ratings may have been lower if they had to enter the IM information at the later point specified in reference 7; however, they acknowledged that a suitably designed interface that required minimum time and effort for data entry could alter their opinion.

7.8.2 Pilot Comments

Responses associated with surveys that used numerical ratings (sections 7.8.2.1 – 7.8.2.4) are based on surveys only from valid runs, while the remaining responses used surveys from both valid and invalid runs. Some pilots provided multiple comments in the response, therefore, there is not always a one-to-one correlation between the rating and the comment, and the number of comments can exceed the total number of responses.

7.8.2.1 Acceptability of the IM operation

While the ratings given by the pilots in the previous section indicated that the IM operations were acceptable, the written comments associated with those ratings made it clear that as flown in this flight test, the IM operations were not always acceptable for normal daily airline operations. Case studies discussing the issues with the high speed command rate and expected deceleration rate are discussed in section 7.9. For the 260 ratings given to the question regarding the acceptability of the IM operation, the responses associated to those ratings are grouped below in categories, with the number of times the comment was made given on the left. Comments not core to the IM operation, e.g., software issues or scenario set up error, are not listed.

- 24 Great run, good run, or performed as desired.
- 10 Too many IM speed changes; excessive use of throttle and speed brake.
- 8 Large magnitude IM speed change (due to procedure design) or speed reversal.
- 5 Expected deceleration rate did not always appear to be accurate.
- 3 IM speed too fast to ensure stabilized approach, challenging remaining on VNAV Path.
- 1 Speed increase required raising flaps

7.8.2.2 Acceptability of the IM speed

The comments given by the pilots for the acceptability of the IM speeds were very similar to the comments about the acceptability of the IM operation. For the 260 ratings given to the question regarding the acceptability of the IM speed, the responses associated to those ratings are grouped below in categories, with the number of times the comment was made given on the left. The remaining comments were not core to IM operation and are not listed.

- 17 Large magnitude IM speed change (due to procedure design), particularly on approach
- 15 Too many IM speed changes and/or excessive use of throttle/speed brake
- 4 IM speed too fast on final
- 4 Fast/Slow Indicator did not appear to be consistent with other indications

7.8.2.3 IM speed not followed

Of the 261 “Yes” or “No” responses to the question of if any IM commanded speed was disregarded during the IM operation, 243 (93%) ratings were “No” and 18 (7%) were “Yes”. Interestingly, the two pilots in the same flight crew for the same run frequently did not give the same response. Comments associated with this question are listed below.

- 3 IM commanded speed not appropriate (too fast, too slow, etc.)

- 2 Used different speed to resolve vertical flight path error or meet altitude constraint, or resolve IM spacing error quicker
- 2 Used different speed for turbulence

7.8.2.4 Energy On Final Acceptable

Of the 241 ratings given by the pilots about the aircraft's energy state on final being acceptable or not (section 7.8.1), the Maintain operations were rated approximately twice as often as unacceptably high as the other type of IM operations. Comments associated with the "No" ratings are given below.

- 11 Too fast and/or significant speed reduction on final
- 2 Early gear or excessive speed brake deployment required due to significant IM speed reduction on final
- 1 Delayed flap or gear deployment to assist in flying faster than normal IM speed

7.8.2.5 Conducting the IM Procedure

Many comments for this end-of-run questionnaire question were heavily influenced by the previously noted modifications to the IM procedure, where the flight crews increased their use of the FSI to compensate for the difference between the rate of deceleration expected by the IM prototype and the actual rate of deceleration of the aircraft. The issues described in this section were accentuated by the design of the arrival and approach procedures, which had large speed changes, causing the aircraft to be slightly faster than normal just prior to the FAF (see section 7.10.1 for more details). While the pilot comments are valid and need to be addressed in future research and testing, care must be exercised to ensure that comments are properly attributed to the root cause, such as route design, limitations of the particular IM avionics retrofit installation, the design of the IM displays, or control law implementation.

Regarding the Final Approach Spacing operations, it should be reiterated that the pilots entered IM clearance information into their avionics earlier than they would be expected to during future Final Approach Spacing operations, and that the IM displays and data entry procedures were not as mature as a future certified system would be. Therefore, the ratings and comments about Final Approach Spacing may be useful for identifying further research, but should not be used to infer the acceptability and usability of mature final Approach Spacing operations specified in reference 8 for Final Approach Spacing. Some issues were identified by the flight crews about the IM operation:

- Using the VNAV speed intervene mode to conduct an IM operation increases workload compared to current day procedures if flown using VNAV path. This workload increase was due to the need for the pilot to intervene with throttles or speed brakes to maintain vertical path while achieving the IM commanded speed.
  - Furthermore, the VNAV speed intervene mode removes the protection to meet certain altitude constraints, allowing the aircraft to be above the altitude constraint (section 7.10.2.1).
  - In particular, decelerations in the VNAV speed intervene mode just prior to an altitude constrained waypoint may not be acceptable due to the loss of altitude protection.

- However, while using the VNAV path mode to conduct IM operations would be lower workload than the VNAV speed mode when there are few IM commanded speed changes and the flight crew has time to enter airspeed into the flight management system, typically above 10,000 feet mean sea level, the VNAV path mode would arguably be higher workload or less acceptable if either of those two conditions were not met.

Large magnitude speed changes were difficult to execute. It should be noted that the large speed changes were driven by the design of the published procedures and are not a typical characteristic of IM operations.

- In current day operations, large magnitude speed changes are frequently assumed to be the results of a pending loss of separation with the preceding aircraft. The large decelerations intentionally designed into the custom arrival procedures used during the flight test were sometimes misinterpreted as issues with maintaining separation with the Target aircraft (from verbal comments in-flight and during debrief).
- No foreknowledge of the next IM speed meant that the flight crew could only be reactive, which was especially challenging when configuring the aircraft for landing.
- Constantly monitoring and responding to the FSI in addition to setting the IM commanded speed in the MCP speed window is very labor intensive and not desirable for normal operations. It should be noted that the fast/slow indicator was included on the display to help pilots track the speeds desired by the speed control law during large procedural deceleration segments.
- The workload to enter the forecast wind, Ownship route information, and IM clearance data required for the IM operation, is very high for typical airline operations. This issue would have been mitigated in part by a more intuitive data entry design and software robust to data entry errors.

7.8.2.6 Changes to the IM operation

Responses to the end-of-day questionnaire question about desired end-of-run to the IM operations reiterated comments from the end-of-run questionnaire. Most frequently listed were a desire for fewer speed changes, small speed changes, and no speed changes that require raising the flaps. Other comments noted that the IM software should be embedded into the existing aircraft avionics to reduce workload related to IM data entry, enable the use of VNAV path mode and the auto-throttles, and to simplify pilot scan pattern. Remaining comments included more appropriate airspeeds on the arrival and approach procedures, as well as larger altitude windows to increase aircraft performance and reduce the use of throttles and speed brakes to achieve the constraints.

7.8.2.7 Challenges to IM implementation

The majority of the responses to the possible challenges to implementing IM procedures into real-world operations were related to the frequency of IM speed changes (IM spacing control law), the magnitude of the IM speed changes (arrival and approach procedure design), and the high workload associated with data entry (IM displays and software). A few responses also highlighted the increased workload associated with operating the aircraft in the VNAV speed mode, particularly when a speed change happens just prior to an altitude constrained waypoint, and not having a consistent and predictable schedule for landing gear and flap deployment.

7.8.2.8 Integrating IM tasks into normal operations

Responses to the end-of-day questionnaire question of if the tasks required to conduct IM operations integrated well with normal flight deck tasks were approximately split with 25 “Yes” and 31 “No”. The “No” comments were overwhelmingly about either the workload was too high for IM data entry, or the workload was too high to fly the IM operations due to the frequency of speed changes and maintaining vertical path while achieving the IM speed.

7.9 Case Studies

This section contains case studies based on runs that occurred during the flight test that highlight various spacing algorithm behaviors. The first case study is an example of desirable speed behavior and spacing performance. The remaining case studies are examples of undesirable speed behavior or poor spacing performance, with an explanation of the root cause.

All of the case studies in this section use a common case study plot format, with some case studies utilizing supplemental plots to provide further explanation. Each of the common case study plots has two panels in a single column. The top panel colored lines to show various airspeeds: black is the ‘Ownship Nominal Speed Profile’ (the published arrival and approach procedure), red is the ‘Ownship Airspeed’, and blue the ‘IM Commanded Speed.’ These speeds are described in the Description of Terms section and section 2.3 of this paper). In operations using the TBO control law, yellow is the ‘Control Law Speed’ and cyan is the ‘Instantaneous Speed’, while in operations using the CTD control law, grey is the ‘Target Aircraft Time History Airspeed’. The green line in the bottom panel shows the ‘Spacing Error’, with negative values indicating that the spacing interval is less than the ASG, i.e., the Ownship is ahead of the desired location in the arrival stream. Positive values indicate that the spacing interval is greater than the ASG, i.e., the Ownship is behind the desired location in the arrival stream.

7.9.1 Nominal IM Operation

This case study is an example of a nominal Cross operation with an initial spacing error close to zero and no lead aircraft delay, i.e., the Target aircraft flew the published speeds. This particular operation was chosen because the pilots indicated that the speed behavior was acceptable and the spacing algorithm achieved the ASG within the desired spacing accuracy.

During this scenario, the sequence of arrivals was the F-900 on the ZIRAN.SUBDY1 arrival with no delay and the B-757 on the JELVO.SUBDY1 arrival conducting a Cross operation with no initial spacing error. The Cross operation was initiated just after the F-900, the Target, crossed SINGG and the B-757, the Ownship, crossed RIINO. The routes merged at NALTE (53 nmi from the PTP). The ABP and PTP were coincident with the FAF; therefore, the TBO speed control law was used throughout the entire operation.

In Figure 27, the spacing error was close to zero for the entire operation and the Target aircraft flew the nominal speeds; therefore, the only speeds that were commanded to the flight crew were procedural speed changes. At the end of the scenario, there was a small difference between how the flight crew flew the deceleration to the FAF and the nominal speed profile, causing the spacing error to increase from 2 seconds early to 6.1 seconds late. Nevertheless, the spacing accuracy at the ABP was within the 10 second IM tolerance.

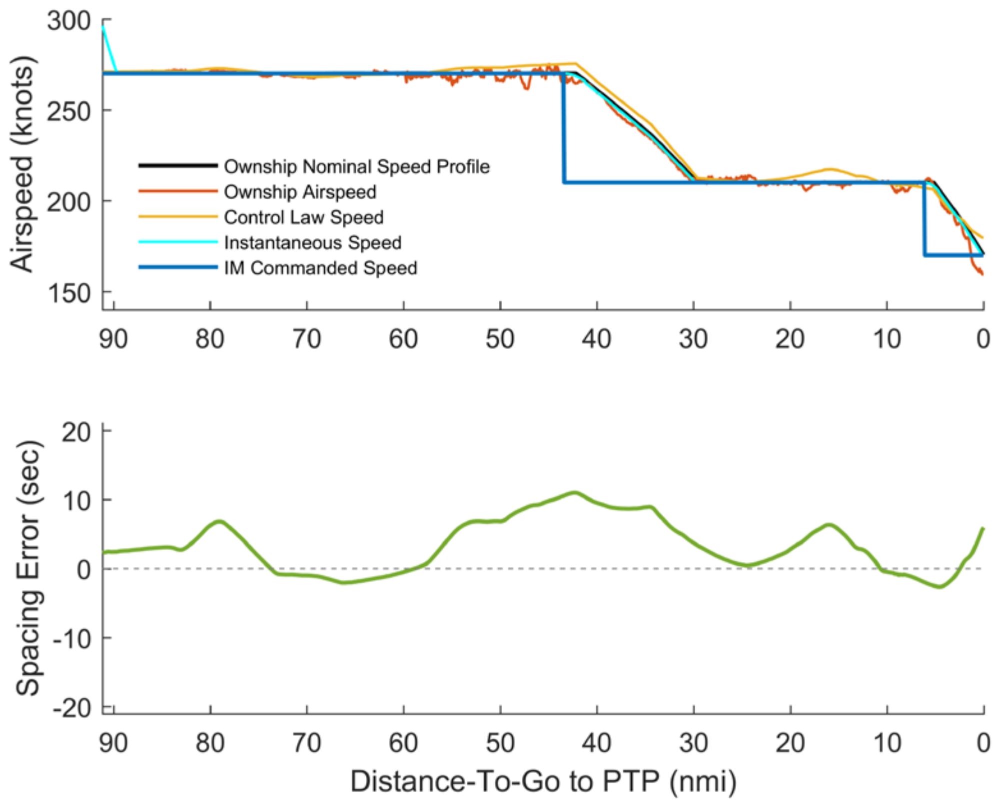


Figure 27. Nominal IM Cross operation with aircraft merging at 53 nmi.

Both pilots rated the acceptability of the IM commanded speeds in this scenario as acceptable (6 on the 7-point Likert scale). However, one of the pilots remarked that the IM speed change from 270 to 210 knots was very large, while the other pilot remarked that the energy level on final was too high. Since the speed commands followed the nominal speed profile (i.e., the published speeds), the large speed change was caused by the design of the arrival and approach procedures, and not the fact that the aircraft was spacing.

This case study is an example of ideal speed behavior and shows the IM performance that can be attained if the IM operation is set up with a small initial spacing error and if the winds and the Target aircraft's airspeed closely match the nominal speed profile and the wind data used by the IM avionics. Some of the desirable attributes in this regard are a low number of speed commands while keeping the spacing error relatively close to zero (within 10 seconds).

7.9.2 Control Law Design and Implementation

7.9.2.1 IM Speed Increases when Capturing the ASG

One source of speed increases and speed reversals during Capture operations was how the ASG was attained. This case study is an example of an arrival operation where the IM commanded speed decreased to correct an early initial spacing error and then increased back to the Target aircraft's time-history speed as the spacing error was resolved.

The Target aircraft is performing a Cross operation with the ABP approximately 53 nmi from the PTP, while the Ownship begins in-trail with the Target aircraft. In this example, the IM equipped aircraft had 35 seconds of spacing error to correct at the beginning of the IM operation, as shown by the green line in Figure 28. Since the CTD speed control law was used, the spacing error was corrected by commanding a slower IM commanded speed (blue line) than the Target aircraft's time history airspeed (grey line), which is defined as the ground speed that the Target aircraft was flying when it was at the Ownship's current position, converted to an airspeed.

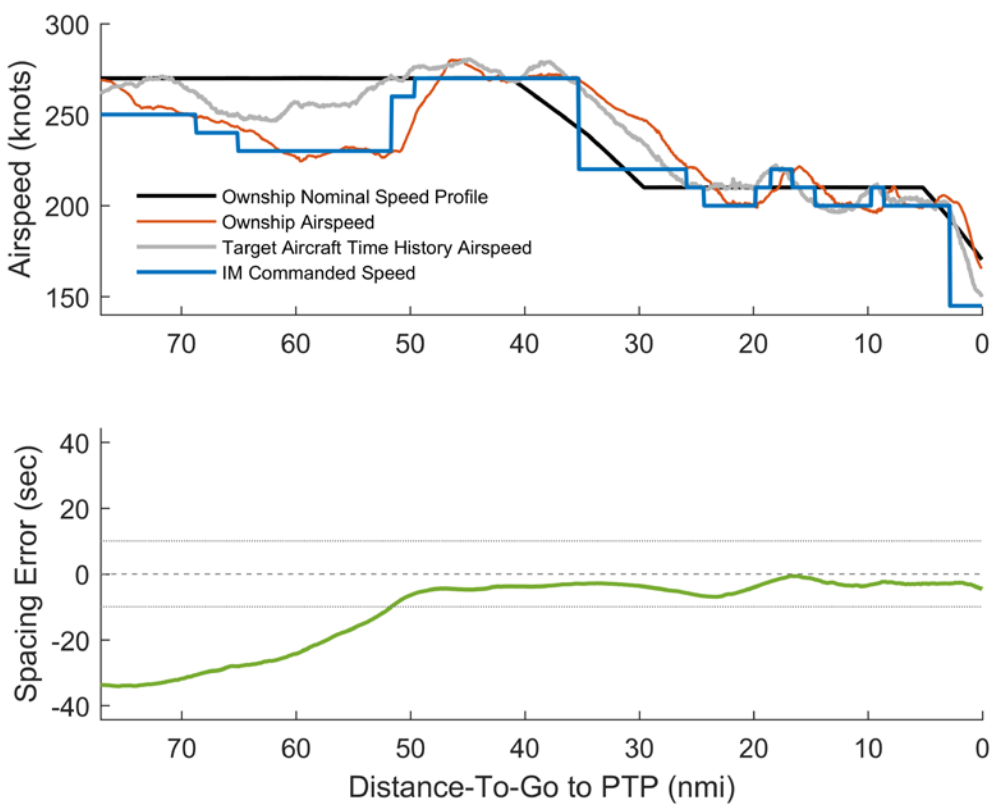


Figure 28. IM speed increases when capturing the ASG.

Due to the initial spacing error and changes in the Target aircraft's time-history airspeed, the IM commanded speed changed from 250 to 240 then 230 knots between 70 and 65 nmi from the PTP. As the spacing error was resolved and the Target aircraft's time-history airspeed increased, the IM commanded speed increased from 230 to 260 knots, then again to 270 knots.

This case study shows how the process of capturing the ASG and the Target aircraft's speeds can contribute to speed increases and speed reversals. While these speed changes are needed to meet the spacing accuracy specified by reference 8, pilot comments indicated that they are undesirable. Additionally, these speed reversals can propagate through a string of aircraft that are conducting either Capture or Maintain operations since the commanded speed is a combination of the speed flown by the Target aircraft and the speed control required to resolve the spacing error. In examining the Target's airspeed in this case study, the Target aircraft had 8 airspeed reversals that occurred during its maintain stage, with these airspeed reversals contributing to the number of IM commanded speed reversals for the Ownship.

7.9.2.2 Speed Increases and Poor Spacing Towards End of Operation

This case study is an example where the difference between the control law speed and the Ownship's airspeed during the deceleration to the ABP caused poor spacing performance. In this case, the actual spacing between the aircraft was less than the ASG at the beginning of the deceleration to the ABP. The large 70 knot procedural deceleration on the UPBOB1 arrival, combined with the Ownship slowing quickly and then flying significantly slower than the IM instantaneous speed, resulted in a rapidly changing spacing error. This spacing error change itself led to increases of the IM commanded speed prior to the end of the operation.

Figure 29 shows the sequence of events that contributed to poor spacing performance at the ABP and Figure 30 shows the full set of plots for this case study. When the deceleration to the FAF began, the spacing error was approximately -20 seconds. The proportional speed control law used by the IM avionics prototype during the 20 nmi prior to the ABP uses the current state of the spacing error to determine the amount of speed control required. In this case, the speed control law determined that -20 knots of speed control was required to resolve the spacing error (step 1 in Figure 29).

When the deceleration began, the IM commanded speed changed from 220 knots to 150 knots (the 170 knot profile speed at the ABP and –20 knots of speed control). At that time, the spacing error began to rapidly diminish, causing the control law speed and instantaneous speed to trend toward the nominal speed profile, and the IM commanded speed to trend toward 170 knots, the nominal speed at the end of the deceleration segment (steps 2 and 3 in Figure 29). Since the flight crew was trying to achieve the IM commanded speed, they continued their deceleration.

By the time the Ownship was approximately 5 nmi from the ABP, the spacing error was zero (top right panel of Figure 30). After the Target aircraft crossed the ABP the Ownship's speed should have been equal to the nominal speed to keep the spacing error close to zero. In this case, the Ownship's speed was significantly slower than the nominal speed, causing the spacing error to overshoot to a value of 15.5 seconds (step 4 in Figure 29). To mitigate this issue, the IM instantaneous speed was depicted on the IM avionics prototype's display as the FSI; however, the FSI was unintuitive and difficult for some pilots to follow. As a result, there were several instances where the pilots ignored the instantaneous speed shown on the FSI and continued decelerating toward the IM commanded speed. On the other hand, there were other pilots who became very adept at following the FSI and consistently achieved very low spacing errors at the ABP and PTP at the cost of increased workload to intervene with throttle and speed brake (see case study in section 7.9.4).

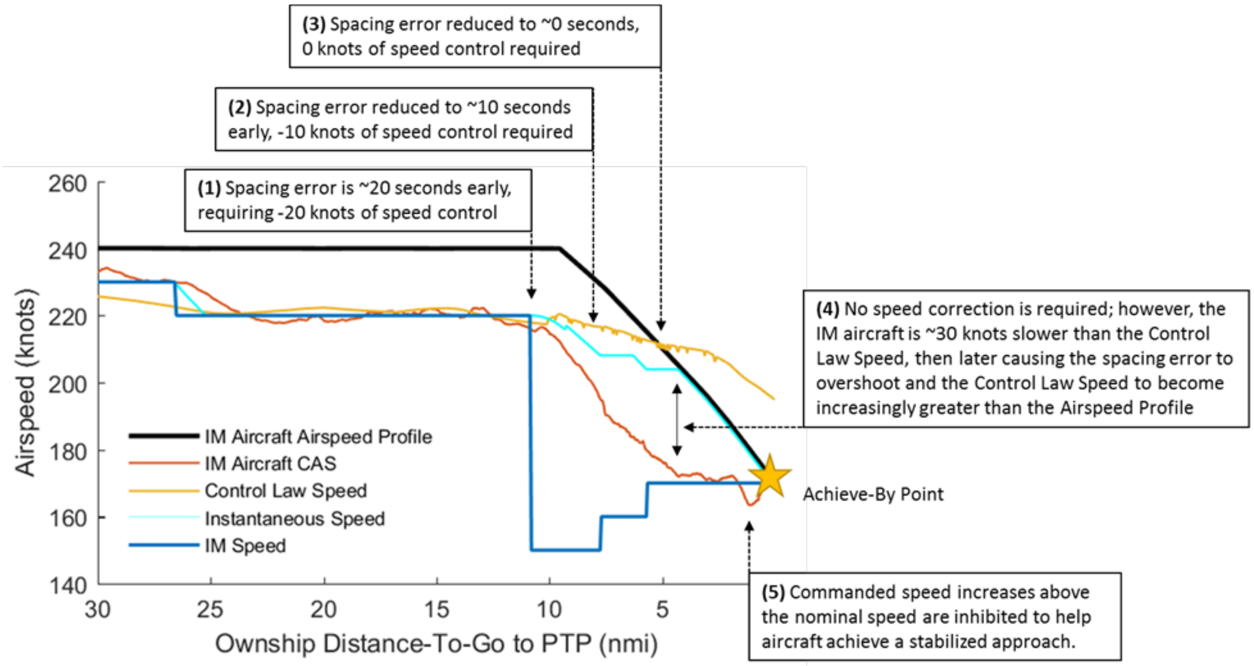


Figure 29. Sequence of events leading to poor spacing behavior.

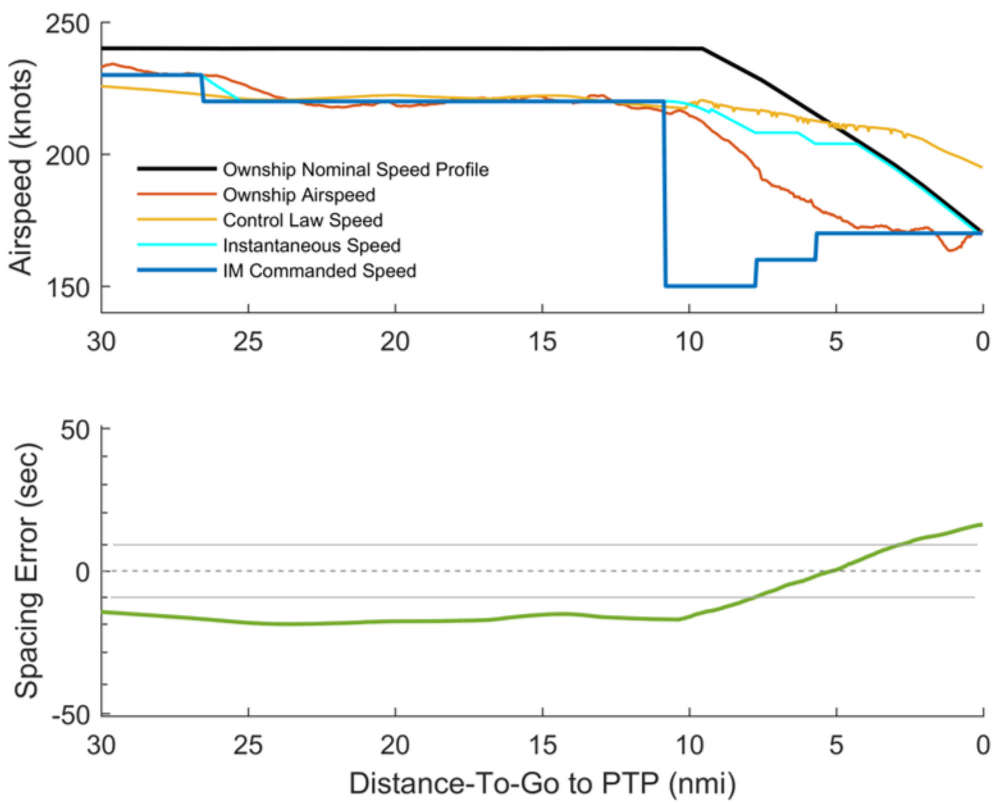


Figure 30. Differences between expected and actual aircraft deceleration.

At the very end of the operation, the IM commanded speed was inhibited from increasing above the nominal speed profile in order to ensure that the pilots could achieve a stabilized approach at the FAF, which was also the ABP (step 5 in Figure 29).

While the FSI displayed the difference between the instantaneous speed and the aircraft's current speed, it can be seen in Figure 29 and Figure 30 that the aircraft's speed did not track the IM instantaneous speed, even at the start of the deceleration, and got progressively worse over the next 5 nmi. The large 70 knot procedural deceleration on the UPBOB1 arrival, combined with a changing spacing error, caused this speed difference problem. From this case study, it can be seen that large procedural speed changes without close adherence to some instantaneous speed guidance can lead to large spacing errors. Conversely, close adherence to some instantaneous speed guidance may lead to an unacceptable level of pilot workload according to the subject pilot responses.

It should also be noted that there were cases, unique to the TBO control law, where the spacing error and instantaneous speed changed during a procedural deceleration segment, causing conflicts between the FSI and the speed conformance monitoring function defined by reference 8. The operation shown in Figure 30 is an example of this issue. The speed conformance monitoring function uses a generic rate of acceleration or deceleration that is not based on the control law speed to determine if the flight crew has implemented the IM commanded speed. In these cases, the FSI showed the correct control response unless the IM commanded speed was limited. However, the flat segments in the IM instantaneous speed (for example, the cyan line in Figure 30 from 8 to 6 nmi) that occurred when the IM commanded speed changed violated the rate of deceleration assumed by the conformance monitoring function defined in reference 8, and made the FSI difficult to follow and unintuitive to pilots. As the flight test progressed, some pilots recognized that following the FSI often resulted in better spacing performance and began to more assertively use the FSI when conducting IM operations.

7.9.2.3 Wind Blending

This case study shows the impact of the software implementation error that prevented trajectory updates to reflect differences between the truth and forecast winds. NASA's version of the ASTAR algorithm updates the trajectories of both the Ownship and Target aircraft if the difference between the blended wind forecast and sensed winds is greater than 4 knots. The IM prototype would have also used this logic; however, a software implementation error prevented the Ownship and Target aircraft trajectories from being updated due to discrepancies between the sensed winds and forecast winds (see the 4-D Path Generation sub-section of Appendix B in this document for more details). The sensed winds were still blended with the forecast and were used if the trajectories were updated for any other reason (for example, a large altitude deviation).

The case study shown in Figure 31 is an example where the software implementation error was the primary contributing factor to poor spacing accuracy at the ABP. The Cross-FAF operation (with routes merging at NALTE, but the ABP set as ZAVYO) started with a small spacing error, which was maintained until the Ownship was 10 nmi from the ABP. After the Target aircraft crossed the ABP, the spacing error diverged to a value of approximately –12.9 seconds.

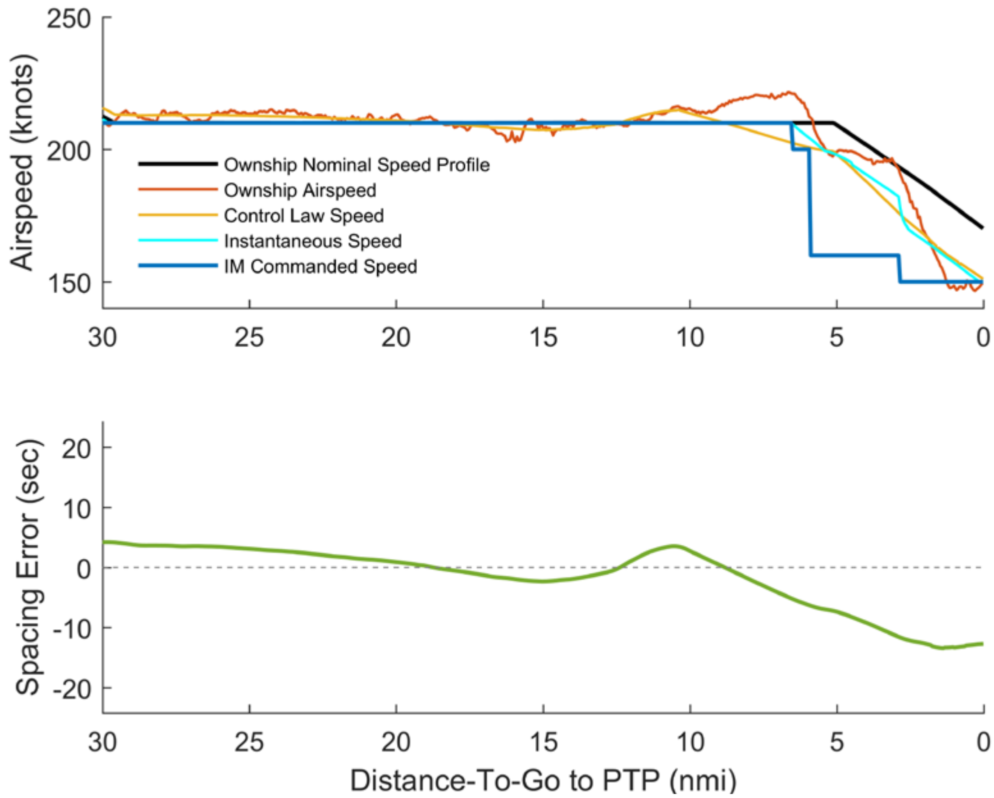


Figure 31. Impact to spacing accuracy from difference between forecast and actual wind.

The plot in Figure 32 shows the headwind error of the Ownship and Target aircraft, which is defined as the difference between the forecast and the sensed headwind. For this case study, the error increased after the aircraft were within 30 nmi of the PTP, and the error was different for each of the two aircraft. Positive headwind deviations indicate that there was a larger headwind than expected (i.e., the aircraft's ground speed was slower than expected) and negative values indicate that there was a smaller headwind than expected (i.e., the aircraft's ground speed was faster than expected).

Between 30 and 15 nmi from the PTP, the Target's headwind error canceled out the Ownship's headwind error, reducing its impact on the spacing error. This cancellation effect was a consequence of the aircraft being on a common path and the same wind error being used to calculate both the Ownship's and the Target's estimated time of arrival (ETA), with these ETAs then being used to calculate the spacing error. As a result, the spacing error remained close to zero and the IM commanded speed followed the nominal speed profile. After the Target aircraft crossed the ABP, its crossing time was used as the basis for the spacing error. Therefore, the Target's speed and headwind error were no longer incorporated into the spacing error calculation. The Target's headwind error no longer canceled the Ownship's headwind error, causing the spacing error to diverge from zero.

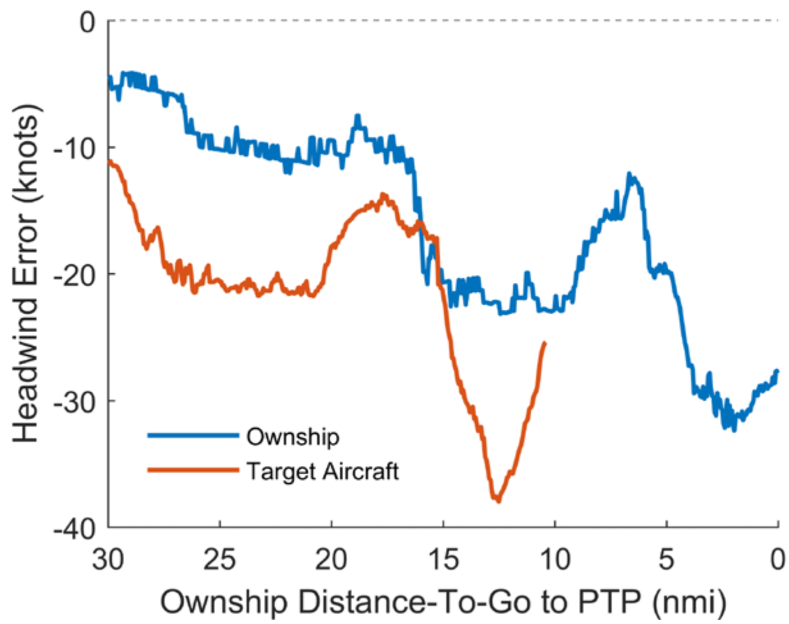


Figure 32. The Ownship and Target aircraft's headwind error.

While the behavior in this case study was largely caused by the software implementation error, it highlights certain items that should be considered. First, this case study demonstrates the importance of the requirement to update the trajectory due to differences between the forecast wind and the winds sensed by the Ownship. Secondly, the locations where the winds were selected likely contributed to the large headwind errors. Within the flight test, the forecast winds were defined at the altitudes of FL350, FL240, FL180, 12,000 feet, 6000 feet, and the surface. Sampling the wind forecast at the location and altitude of the ABP would have likely reduced the magnitude of the headwind error when the Ownship and Target aircraft were close to the ABP (the FAF).

7.9.3 Expected versus Actual Rate of Deceleration

This section provides three case studies of when a difference between the deceleration expected by the control law was different than the aircraft's actual deceleration, what the root cause was, and the impact this difference had to the IM operation itself.

7.9.3.1 Deceleration During En Route Operations

The case study portrayed in Figure 33 is an example where the actual deceleration of the Ownship, when operating at the en route altitude of FL350, was considerably less than expected by the speed control law. In this particular Capture operation, the IM avionics expected the deceleration from 0.74M to 0.71M to occur over 8 nmi (approximately 55 seconds), whereas the Ownship's actual deceleration took just over 20 nmi (approximately 2 minutes and 15 seconds), apparently due to the aircraft's auto-throttle response. The result is no significant change occurred to the spacing error over the first 25 nmi or half of the IM operation, where the spacing error should have been reduced over this interval.

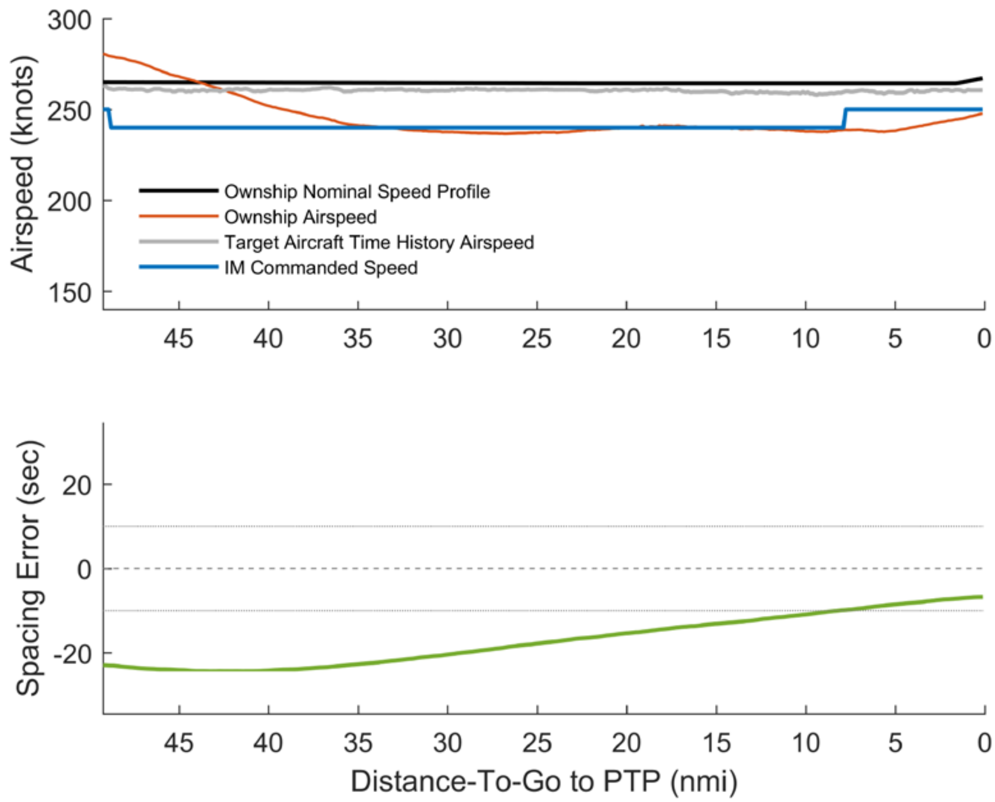


Figure 33. Example of expected versus actual rate of deceleration.

7.9.3.2 Rate of Deceleration During Arrival Operations

One factor that contributed to poor spacing performance at the ABP was the difference between how quickly the Ownship decelerated to the IM commanded speed and the deceleration of the control law speed. Figure 34 shows a case study where differences between the deceleration of the Ownship and the deceleration expected by the spacing algorithm resulted in a 17.8 second spacing error at the ABP. The IM operation began 46 nmi prior to the ABP with an initial spacing error of –30 seconds, i.e., a spacing interval 30 seconds less than the ASG. The spacing error was reduced to zero by the time the Ownship was approximately 25 nmi from the ABP. Just before the last deceleration segment began at approximately 10 nmi from the ABP, the spacing error was close to zero and the IM commanded speed was equal to the nominal speed profile. The IM commanded speed changed from 240 to 170 knots to comply with the published speeds on the UPBOB1 arrival (Figure 10), and the Ownship began decelerating toward the commanded speed at a rate that was greater than both the nominal speed profile and the control law speed. This caused the spacing error to increase from approximately 0 seconds to 17.8 seconds. In order to ensure that the pilots could achieve a stabilized approach, commanded speed increases above the nominal speed were inhibited, resulting in a discrepancy between the control law speed and the instantaneous speed. It should be noted that the control law speed would have been approximately equal to the nominal speed profile if the Ownship had decelerated at the same rate as the nominal speed profile, since the spacing error would have remained close to zero.

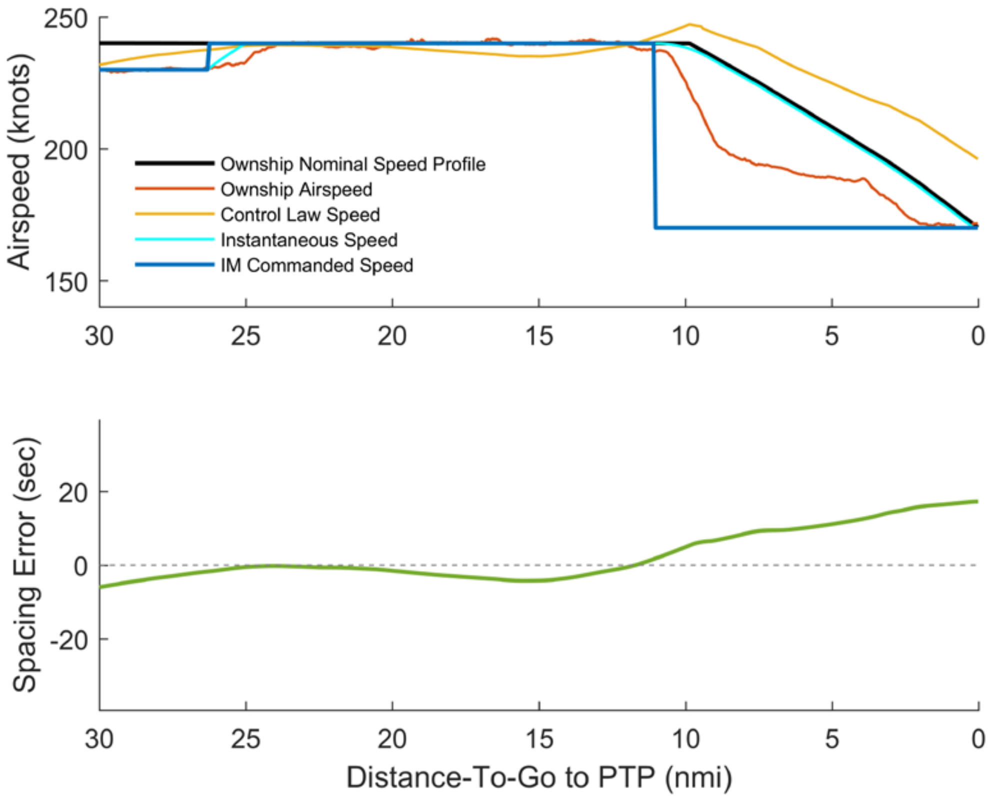


Figure 34. Impact of expected versus actual rate of deceleration.

In this case, the impact of the difference between the aircraft's deceleration and the nominal deceleration was amplified by the large, 70 knot speed change on the UPBOB1 arrival, similar to the example of section 7.8.2.3. Reducing the size of the speed change prior to the ABP would reduce the impact of differences in the deceleration rates expected by the control law speed compared to the Ownship's actual performance. The IM avionics prototype used in this flight test did not consider the aircraft type or configuration when determining the deceleration due to cost and schedule constraints in its development. Using a simple dynamic model of the Ownship to generate its trajectory may reduce the discrepancy between the deceleration assumed by the nominal speed profile and flown by the Ownship.

It may also be worthwhile reconsidering how the IM commanded speed should be determined during a procedural deceleration. The IM avionics prototype used in this flight test and NASA's ASTAR spacing algorithm provide a single speed change when there is a procedural deceleration. The reason for this behavior is to minimize the number of speed changes that are presented to the flight crew, which was a requirement in the ASTAR design. However, the Ownship has limited ability to react to IM commanded speed changes that are provided during the deceleration segment unless a secondary speed cue, such as the instantaneous speed, is provided to the flight crew. While the instantaneous speed was provided to the flight crew in the form of a FSI, the FSI display and the instantaneous speed in the calculation FSI were not intuitive and were difficult for the pilots to follow as reported on the end-of-run surveys. Alternatively, the IM speed could be provided in 10 or 20 knot increments instead of providing a single speed change for the entire deceleration segment. This approach would provide the ability to make corrections for spacing error in the middle of a large deceleration segment; however, it would likely result in additional IM speed commands that the flight crew would need to implement (see Appendix C for further discussion).

7.9.3.3 Following and Not Following the FSI

Although intervening with throttle and speed brake to center the FSI increased the flight crew's workload to some extent, responding to the FSI directly appeared to have improved the spacing accuracy at the PTP, while not responding to the FSI appeared to have degraded the spacing accuracy at the PTP in this case study. The two figures in this section are from the same day, flown by the same crew in the same aircraft, while conducting the same type of IM operation on the same routes (the B-737 on the UPBOB1 conducting a Cross-FAF operation behind the B-757 on the SUBDY1).

Figure 35 illustrates an operation where at 11 nmi DTG, the IM commanded speed changed from 240 knots to 170 knots, and the pilot adjusted the throttles so the FSI remained almost centered during the deceleration (the Ownship airspeed remained close to the instantaneous speed), which caused the spacing error to go from –2 seconds at 11 nmi to no error at the PTP.

Figure 36 illustrates an operation where at 11 nmi DTG, the IM commanded speed changed from 240 knots to 170 knots, and the pilot adjusted the throttles to idle, which caused the FSI to indicate "FAST" (the Ownship airspeed was faster than expected by the instantaneous speed), which caused the spacing error to go from +1 seconds at 11 nmi to +19 seconds at the PTP.

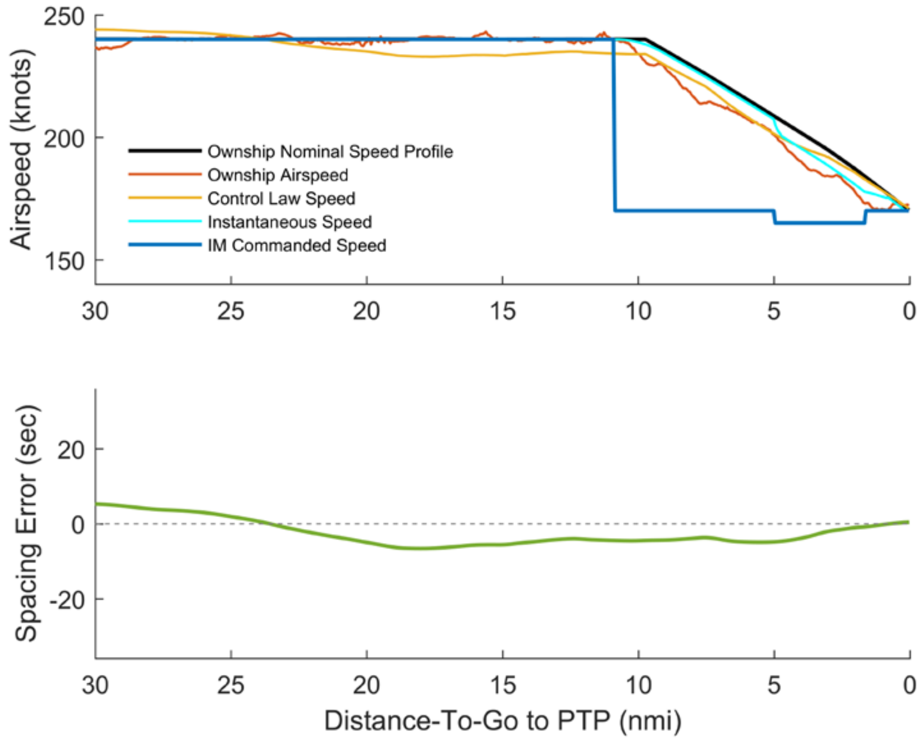


Figure 35. Pilot technique incorporating the FSI.

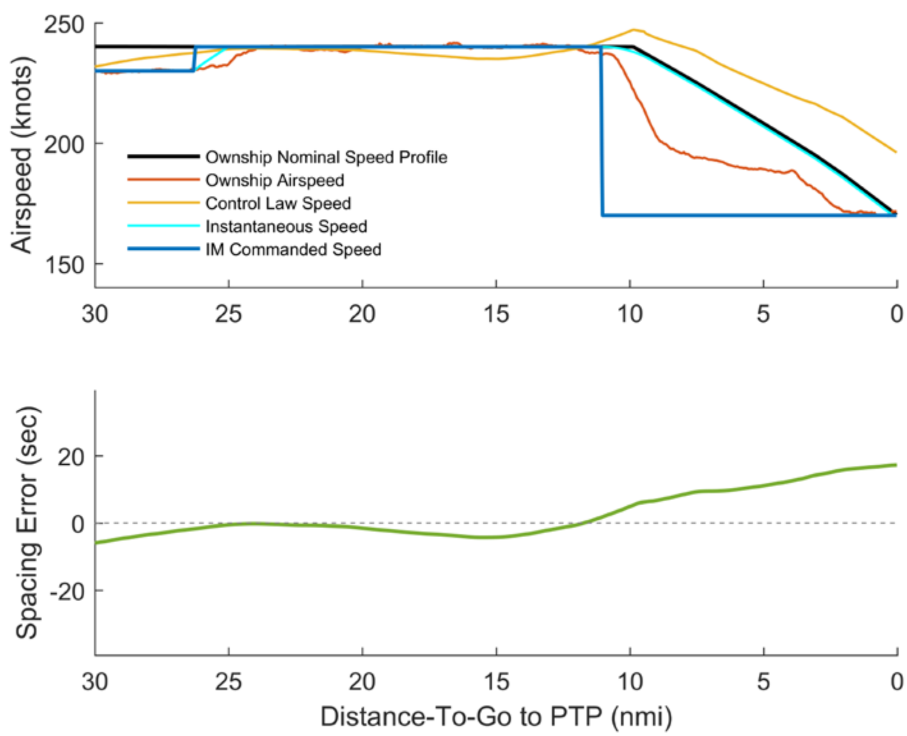


Figure 36. Pilot technique not incorporating the FSI.

7.9.4 Operational Uncertainty

This section contains two case studies that provide more detail about the impact of operational uncertainty, such as the impact of different-than-expected altitudes and the resulting different headwind components experienced by the Ownship and Target aircraft, the difference between the forecast and the sensed wind, and the variation in Target aircraft speed. These case studies also describe the impact of the uncertainties on the speed control laws, especially the CTD control law, and the pilot's ability to consistently and safely execute the IM operation.

7.9.4.1 High Speed Command Rate of the CTD Control Law

One of the negative pilot critiques was that the speed command rate was higher than desired. Analysis of the IM speed command rate indicated that the Maintain operations (CTD control law) had the highest speed command rate. This case study is a Maintain operation that had 25 speed commands, including the initial speed command, during the 22-minute operation.

Figure 37 illustrates how changes in either the spacing error or the Target aircraft's time-history airspeed can cause IM commanded speed changes. Factors that can also contribute to these changes are variations in the Target aircraft's airspeed or deviations from the lateral path by either the Target or Ownship (not factors in this case study), or differences between the altitude and headwind experienced by the Ownship and Target aircraft at the same along-path position (factors in this case study, and shown in Figure 38).

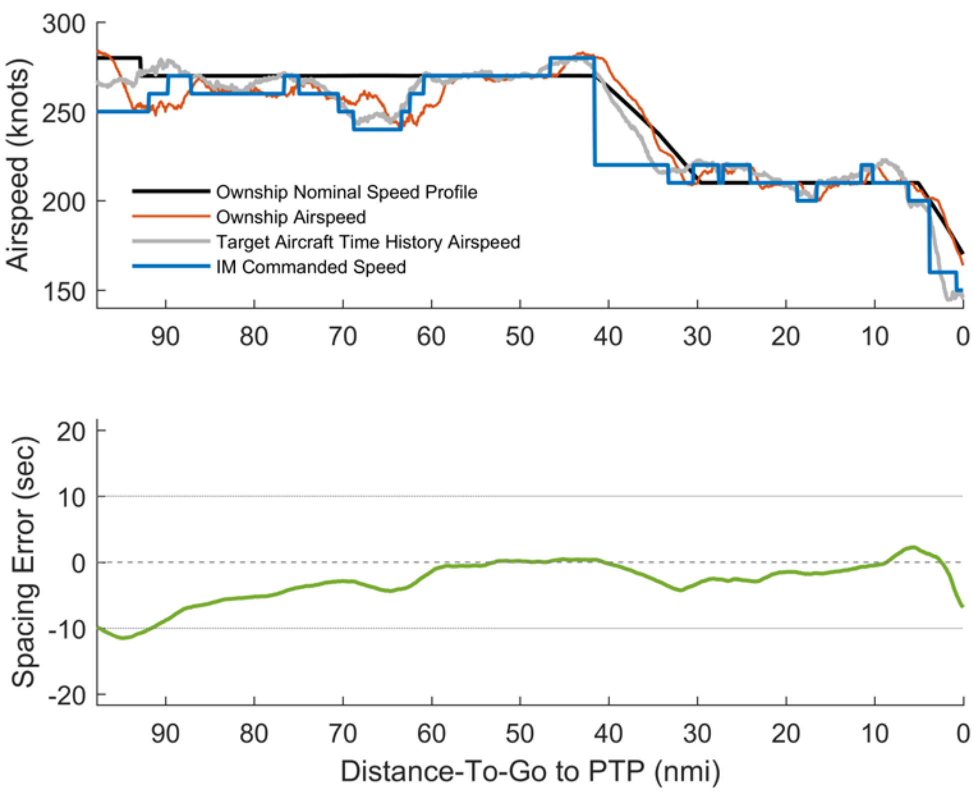


Figure 37. High rate of IM commanded speeds.

In this particular example, the two speed changes that were commanded between 100 and 90 nmi from the PTP were given as the spacing error was reduced from -10 seconds to 0 seconds. The initial IM commanded speed of 250 knots was given to generate a ground speed difference between the Ownship and Target aircraft to reduce the spacing error. Once the spacing error was at zero, the ground speed of the Ownship and Target aircraft must be similar to prevent the spacing error from increasing. That is, the IM commanded speed and the Target aircraft's time history speed must match. Therefore, the commanded speed increased from 250 knots to 270 knots as the spacing error was reduced.

The speed changes that occurred between 78 and 60 nmi from the PTP were caused by differences between the headwind experienced by the Ownship and the Target aircraft, which were the result of a difference in altitude between the two aircraft when they crossed the same along-path position (Figure 38). The IM speed changes that occurred from 35–10 nmi to the PTP were attributable to changes in the Target aircraft's ground speed, caused by small variations in the Target aircraft's altitude, headwind, and airspeed. Some of the commanded speed changes are probably necessary to meet the spacing success criterion; however, it may be possible to decrease some of the small 10 knot speed reversals by improving the filtering applied to the Target aircraft's time history speed.

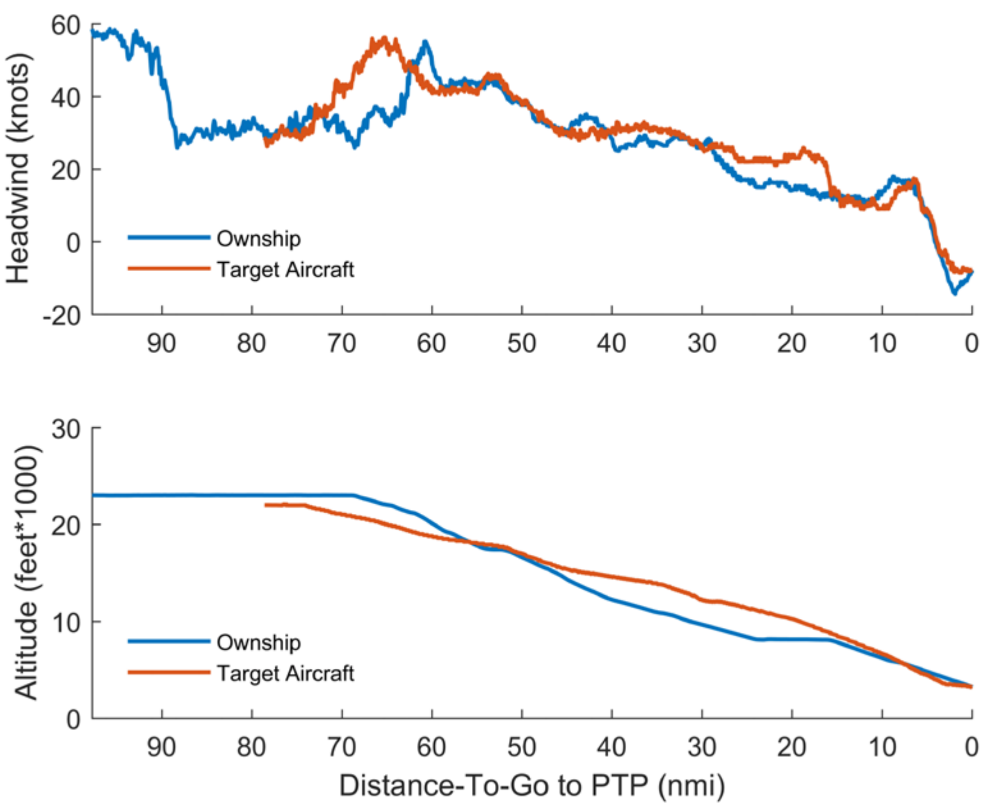


Figure 38. Difference in headwind due to altitude difference.

7.9.4.2 Speed Increases and High Speed on Final Due to Headwind

This case study illustrates one cause of the speed increases observed during arrival operations. Figure 39 shows an example where there were three consecutive 10 knot speed decreases followed by two consecutive speed increases within 30 nmi of the PTP. In this case, the speed changes were caused by a difference between the Ownship's headwind and the Target aircraft's headwind when they were at the same geographical location (i.e., the same DTG to the PTP).

During this scenario, the F-900 Target aircraft was on the JELVO.SUBDY1 simulating a high-delay profile by flying the procedure 10 to 20 knots slower than the published speeds. The B-757 Ownship was also on the JELVO.SUBDY1. The time-based Maintain operation (CTD control law) was initiated with the Target just prior to SUBDY, and the aircraft remained in trail until the PTP at ZAVYO. For Maintain operations like the one used in this case study, the CTD speed control law follows the Target aircraft's time history airspeed if there is no spacing error and uses a proportional speed control law to command deviations from that airspeed to correct any spacing error. The spacing error is maintained if the Ownship's along-path ground speed is the same as the Target aircraft's along-path time history ground speed (i.e., the ground speed the Target aircraft flew when it was at the Ownship's position).

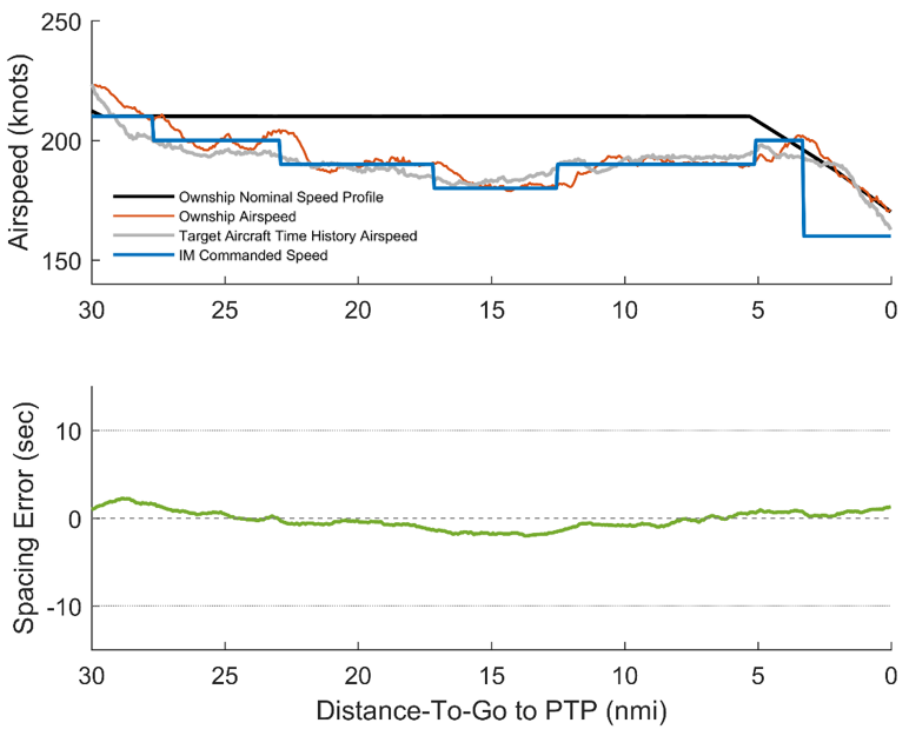


Figure 39. Maintain operation with many speed changes and reversals.

While both aircraft met the altitude constraints of the arrival and approach, the Target flew the procedure higher than the Ownship (Figure 40, bottom panel). This altitude difference resulted in the aircraft being subjected to different headwinds when crossing the same point, with at times as much as a 17 knot difference between headwinds of the two aircraft (Figure 40, top panel). These different headwinds combined with the Target aircraft's slower than nominal airspeed resulted in speed changes that were needed to match the Target aircraft's time history ground speed and to maintain the spacing interval.

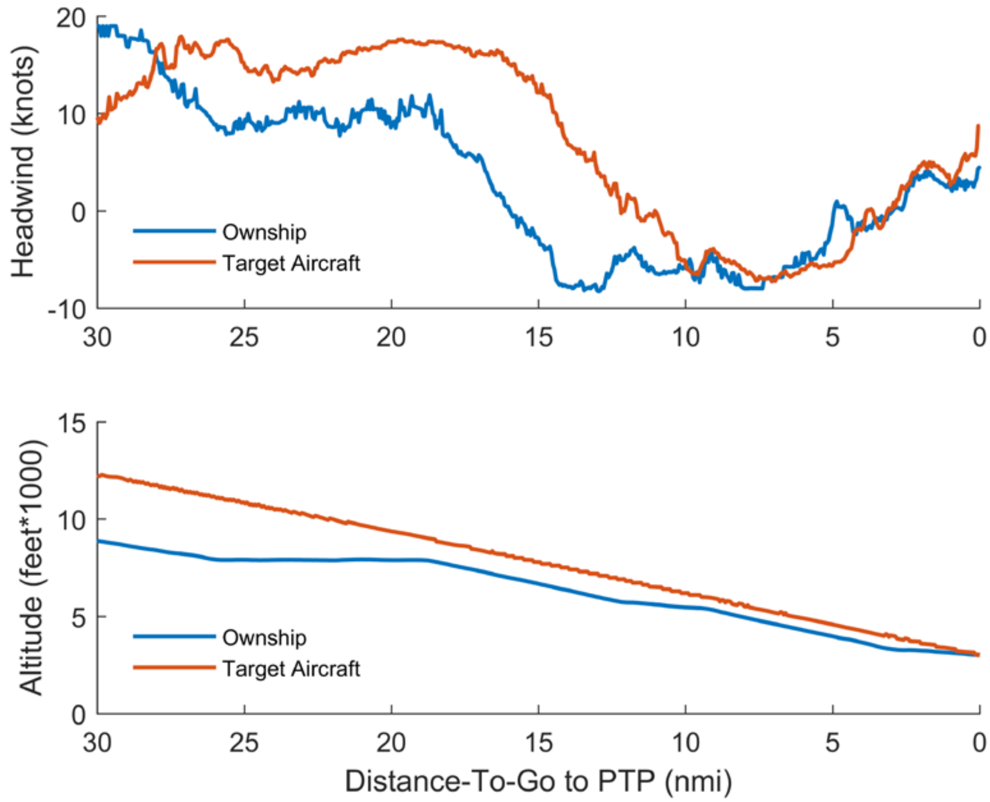


Figure 40. Difference in headwind due to altitude difference.

In this case study, the pilot flying also reported the energy level on final was not acceptable. Figure 39 indicates the aircraft was at 190 knots with no spacing error from 12 nmi to 5 nmi prior to the PTP, then IM prototype commanded a speed increase to 200 knots from 5 nmi to 4 nmi to compensate for the bump in the Ownship's headwind component at 5 nmi. While the increase in commanded speed kept the spacing error close to zero, the energy required to accelerate 10 knots and then immediately decelerate to final approach speed was not efficient, and in this particular case, the pilot reported the energy level was too high to assure that the stabilized approach criteria would be achieved on a routine basis.

7.10 Other Comments and Observations

7.10.1 Design of Arrival and Approach Procedures

The PBN arrival and approach procedures used in this flight test were designed in accordance with FAA guidelines (ref. 30), and were intended to allow the aircraft to fly from en route altitudes to the runway with the minimal use of throttles and speed brakes. Testing of the routes was accomplished in full-scale simulators at both NASA LaRC and United Airlines, as well as in-flight validation at KMWH by one of the flight test aircraft. However, in some locations the procedures were too steep or too fast to fly the aircraft at a near-idle descent without the use of speed brakes, and one waypoint had a speed constraint that was too slow (210 knots at SUBDY).

Furthermore, the 70 knot speed changes in the procedure that were intended to minimize the number of speed changes were reported by the pilots as operationally undesirable and were challenging to implement. The impact of these large procedural speed changes was amplified by the differences between the deceleration rate expected by the IM avionics and the aircraft's actual deceleration rate. This interaction was a primary contributing factor to the poor spacing accuracy at the ABP for the Cross-FAF operations, and to those IM operations where the spacing errors were outside the 10-second IM tolerance for the maintain stage of the Maintain, Capture, and Cross-Merge operations.

7.10.2 Aircraft Systems

7.10.2.1 Vertical Navigation Speed Mode

The IM procedures used by the pilots required them to control speed by opening the MCP speed window, similar to when a controller issues a speed instruction during an arrival procedure. This places the FMS into the VNAV "speed" mode for most of the descent. This mode removes some of the altitude protection provided by the "path" mode, thereby requiring greater diligence by the pilot to monitor and correct the vertical flight path using thrust and drag while simultaneously achieving the IM commanded speed. The VNAV "speed" mode also did not appear to provide consistent performance, in particular when changing pitch to decelerate the aircraft. The change in pitch was sometimes faster than expected, while at other times the change in pitch was slower than expected. A precise description of the behavior could not be written, nor could any documentation of the operating logic be found to explain the variance in behavior.

The pilots in this flight test and in previous experiments (refs. 16, 17, 19, and 20) stated that using the VNAV speed mode increased workload slightly, but managing vertical path while achieving the IM speed was still relatively easy. Nevertheless, an integrated avionics system that allowed pilots to command the IM speed with the behavior and protection of the VNAV "path" mode would be of considerable benefit.

7.10.2.2 Auto-Throttles

Close adherence of the aircraft's speed to the IM commanded speed is assumed and of benefit for IM operations; however, the auto-throttle systems of the B-757 and B-737 did not exhibit rapid and consistent control to the airspeed set in the MCP. The systems in both aircraft responded very slowly to deviations of less than ±12 knots (the difference between the aircraft's airspeed and the airspeed set in the MCP speed window). Furthermore, the auto-throttles seemed to respond in an inconsistent manner–sometimes reducing power and decelerating the aircraft more quickly than expected, while at other times causing a much more gradual deceleration. These performance characteristics caused the aircraft's airspeed to deviate from the expected speed, contributing to differences between the actual acceleration and deceleration of the Ownship and the acceleration and deceleration used in the IM avionics prototype calculations. These differences caused additional commanded speed changes to resolve the spacing error. If the Target aircraft also has an auto-throttle system with these characteristics, it should be expected that the change to the spacing error caused by variations in the Target's airspeed, and the resulting increase in speed changes to compensate for it, would occur more often or be more pronounced.

To produce system behavior that was more optimized for an IM operation, the pilots adopted two mitigation strategies. One was to manually override the auto-throttle system by placing the throttle levers in a position that would control the acceleration or deceleration to match the FSI. A second strategy was to intentionally set a larger than required speed change value in the MCP speed window in order to trigger throttle changes. For example, if the IM commanded speed changed by 10 knots, the auto-throttle system sometimes did not respond to the new speed. The pilots would intentionally set a 15 knot speed difference to activate the auto-throttles and then immediately set the commanded speed once the throttles had started to move. In many cases, the pilots took specific additional actions to compensate for the auto-throttle system behavior which slightly increased their workload to conduct an IM operation.

7.10.2.3 Interaction of Altimeter Setting and an Altitude Constraint

The descent gradient on the SUBDY1 arrival after NALTE did not meet the design goal of a near-idle thrust descent. The 17,000 foot altitude restriction at NALTE, where the two transitions on the SUBDY1 arrival merge (see Figure 6), created a unique problem when the altimeter setting was changed. The NALTE altitude restriction on the SUBDY1 arrival occurred immediately after the 18,000-foot transition level, where pilots change the altimeter setting from standard pressure to local pressure. When the altimeter setting is changed, the vertical path changes in direct proportion to the difference between the two altimeter settings. With the higher than standard altimeter settings prevalent throughout this flight test, changing to the local altimeter setting when passing through 18,000-feet caused the aircraft to immediately transition high on vertical path. This required the pilot to extend the speed brakes to increase the aircraft's descent rate to meet the 17,000-feet altitude restriction at NALTE.

The flight segment immediately after NALTE was shallower, and required some power to meet the next altitude constraint. In the VNAV "path" mode normally used during PBN arrivals, the FMS compensates by increasing power to fly a short level segment prior to continuing the descent to the next altitude constraint. In the VNAV "speed" mode used by the pilots to conduct the IM operation, the descent commenced immediately since the throttles were at idle to resolve the issue caused by the change to the altimeter setting. This resulted in the aircraft momentarily going below the desired vertical path until the pilot increased power and retracted the speed brakes to return to the vertical path. This was aerodynamically inefficient, and the pilots said it increased their workload and would be an undesirable operation to conduct routinely.

8 Secondary Test and Results

8.1 Secondary Test Matrix

The two goals of this secondary test matrix were to (1) characterize the impact to IM operations of using arrival and approach procedures suited for the use of speed as the control method, and (2) characterize the impact of specific aircraft type on the performance of the IM operations. Three arrival scenarios (B03, B04, and B05) from the primary test matrix in Table 2 were adapted to create the secondary test matrix shown in Table 10. These twelve scenarios were designed to evaluate the following two independent variables:

- Arrival and Approach Procedure
- Aircraft Type

The special STAR procedures created for this flight test met the design criteria specified in the FAA's Standard Terminal Arrival Program and Procedure document (ref. 30), and were flight tested by certified crews in two simulation facilities. Despite this, it quickly became apparent during the flight test that the arrival and approach procedures were several hundred feet too high or too low at certain waypoints, and 10 to 20 knots too fast or too slow at some waypoints to use speed as the primary control mechanism to achieve the desired spacing interval. Therefore, minor modifications to the altitude and speed constraints on the arrival and approach procedures in the IM avionics were made to assess the change in performance when using well-designed procedures. The specific changes to the altitude and speed constraints on the arrival and approach procedures are detailed in Appendix D. These altitude and speed changes were applied only to the procedures in the IM avionics prototype hosted on the EFB, while the certified procedures in the FMS were not modified.

The IM clearance type and initial spacing error were also controlled for, in order to support direct-comparison case studies. A software anomaly resulted in one missing data point for the B-757 aircraft in scenario B03_25. The observed initial spacing error shown in Figure 41 ranged between 27 seconds early to 66 seconds late, and the distance to the PTP when the IM operations were initiated ranged between 106 to 39 nmi.

In order to achieve the first goal of the secondary matrix, individual direct-comparison case studies were conducted to assess the difference in performance when altitude and speeds were changed with all other variables held constant. For the second goal of characterizing the impact of aircraft type, individual direct-comparison case studies were conducted to assess the difference in performance when the aircraft type was changed with all other variables held constant. The metrics analyzed included delivery accuracy at the PTP and rate of IM speed changes.

Table 10. Secondary test matrix.

Scenario	Data base	Lead a/c Delay	IM1 Aircraft	IM1 Clearance Type	IM1 T/D	IM1 Spacing Error	IM1 ABP	IM1 PTP	IM2 Aircraft	IM2 Clearance Type	IM2 T/D	IM2 Spacing Error	IM2 ABP	IM2 PTP
B03_13	1	None	B-737	CROSS	Time	+60 sec	FAF	FAF	B-757	CROSS	Time	+30 sec	FAF	FAF
B03_23	2	None	B-737	CROSS	Time	+60 sec	FAF	FAF	B-757	CROSS	Time	+30 sec	FAF	FAF
B03_15	1	None	B-757	CAPTURE	Time	+60 sec	n/a	FAF	B-737	CROSS	Time	+30 sec	FAF	FAF
B03_25	2	None	B-757	CAPTURE	Time	+60 sec	n/a	FAF	B-737	CROSS	Time	+30 sec	FAF	FAF
B04_13	1	None	B-737	CAPTURE	Time	-60 sec	n/a	FAF	B-757	CAPTURE	Time	0 sec	n/a	FAF
B04_23	2	None	B-737	CAPTURE	Time	-60 sec	n/a	FAF	B-757	CAPTURE	Time	0 sec	n/a	FAF
B04_15	1	None	B-757	CAPTURE	Time	-60 sec	n/a	FAF	B-737	CAPTURE	Time	0 sec	n/a	FAF
B04_25	2	None	B-757	CAPTURE	Time	-60 sec	n/a	FAF	B-737	CAPTURE	Time	0 sec	n/a	FAF
B05_13	1	None	B-737	CAPTURE	Time	+60 sec	n/a	FAF	B-757	CROSS	Time	+30 sec	FAF	FAF
B05_23	2	None	B-737	CAPTURE	Time	+60 sec	n/a	FAF	B-757	CROSS	Time	+30 sec	FAF	FAF
B05_15	1	None	B-757	CAPTURE	Time	+60 sec	n/a	FAF	B-737	CROSS	Time	+30 sec	FAF	FAF
B05_25	2	None	B-757	CAPTURE	Time	+60 sec	n/a	FAF	B-737	CROSS	Time	+30 sec	FAF	FAF

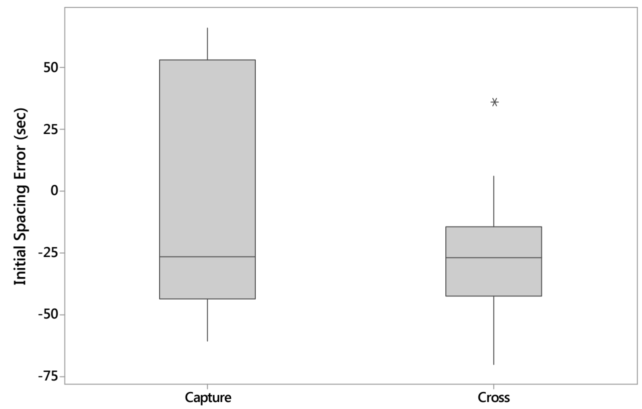


Figure 41. Initial spacing error for scenarios in secondary test matrix.

8.2 Results from Secondary Test

Table 11 groups the secondary test results to allow for the comparison of data with only the arrival and approach procedure database in the IM avionics varied as the independent variable. One of the runs in case study R.11 was not valid; therefore R.11 has been removed from this analysis.

When changing from database 1 (the baseline arrival and approach procedures) to database 2 (modification of speed and altitude constraints in the procedures as described in Appendix D), eight of the eleven case studies exhibited a negligible change in the spacing error at the PTP (less than 1.5 seconds), with the three remaining cases exhibiting an improvement in spacing accuracy. On average, the number of speed commands increased by approximately three, which was expected since three new speed constraints were added to each combination of arrival and approach procedures. The magnitudes of the speed commands were reduced, and there was no overall clear trend in the number of IM speed reversals.

Table 11. Secondary test results for change to route constraints.

Case #	Scenario	Data base	Ownship	Clearance Type	Target Id	PTP Spacing Error (sec)	# Speed Commands	# Speed Reversals
R.01	B04	1	N757HW	CAPTURE	N889H	0.51	10	4
	B04	2	N757HW	CAPTURE	N889H	0.34	12	2
R.02	B04	1	UAL2197	CAPTURE	N757HW	2.57	14	5
	B04	2	UAL2197	CAPTURE	N757HW	–3.75	16	3
R.03	B04	1	UAL2197	CAPTURE	N889H	–0.83	7	0
	B04	2	UAL2197	CAPTURE	N889H	0.73	12	4
R.04	B04	1	N757HW	CAPTURE	UAL2197	0.16	10	3
	B04	2	N757HW	CAPTURE	UAL2197	–1.02	14	3
R.05	B03	1	UAL2197	CROSS	N889H	4.51	6	4
	B03	2	UAL2197	CROSS	N889H	2.38	6	1
R.06	B03	1	N757HW	CROSS	UAL2197	9.53	5	2
	B03	2	N757HW	CROSS	UAL2197	0.11	11	4
R.07	B05	1	UAL2197	CAPTURE	N889H	–0.93	8	1
	B05	2	UAL2197	CAPTURE	N889H	–1.05	11	4
R.08	B05	1	N757HW	CROSS	UAL2197	7.39	6	2
	B05	2	N757HW	CROSS	UAL2197	–0.09	8	4
R.09	B05	1	N757HW	CAPTURE	N889H	0.33	7	1
	B05	2	N757HW	CAPTURE	N889H	0.13	11	5
R.10	B05	1	UAL2197	CROSS	N757HW	2.16	8	3
	B05	2	UAL2197	CROSS	N757HW	1.37	12	3
R.12	B03	1	UAL2197	CROSS	N757HW	0.23	9	5
	B03	2	UAL2197	CROSS	N757HW	1.41	11	4

Pilot comments were overwhelmingly favorable with the changes made to the altitude and speed constraints on the arrival and approach procedures in database 2 compared to database 1, in particular the slower speed during the turn on the RNP AR approach (HIXOS to ZETEK) and the reduction in the magnitude of the IM commanded speed changes. Two examples are given below to illustrate the impact the design of the procedures had on IM behavior.

Figure 42 contains two sequential Capture operations (CTD control law) flown by the B-757 behind the F-900 (case number R.01). The panels on the left show IM behavior using database 1 (the original procedures shown in Appendix D), and the panels on the right using database 2 (altitude and speed constraints modified for the IM avionics). The IM spacing performance throughout the operation and at the PTP was not significantly different between the two databases; however, the maximum magnitude of the speed changes was reduced and there were two fewer speed reversals when using the modified database.

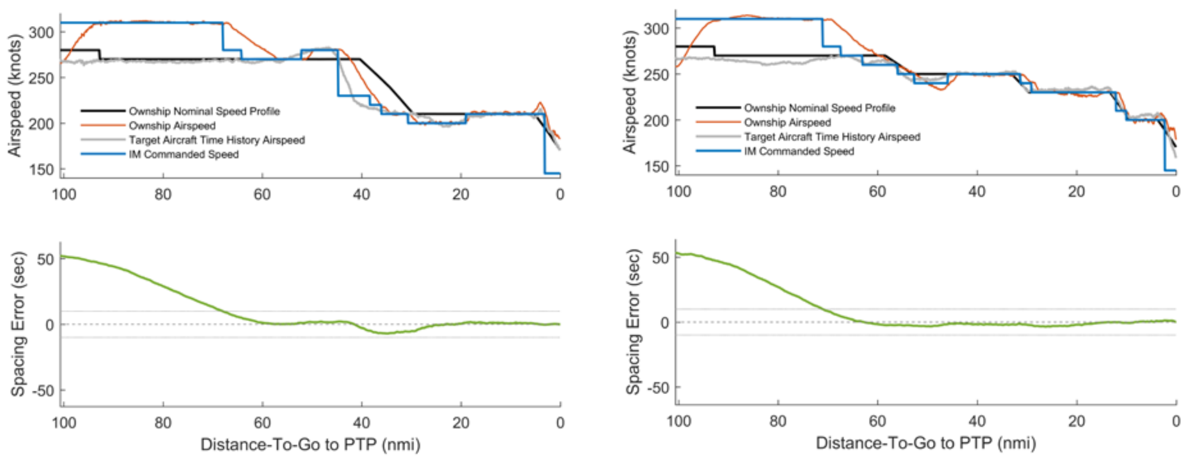


Figure 42. CTD control law using original (left) and modified (right) procedures.

Figure 43 contains two sequential Cross-FAF operations (TBO control law) flown by the B-737 behind the F-900 (case number R.05). The left and right panels represent operations flown with the original and modified procedures. Similar to the CTD speed control law, the results showed a reduction in the maximum speed change magnitude and the number of speed reversals.

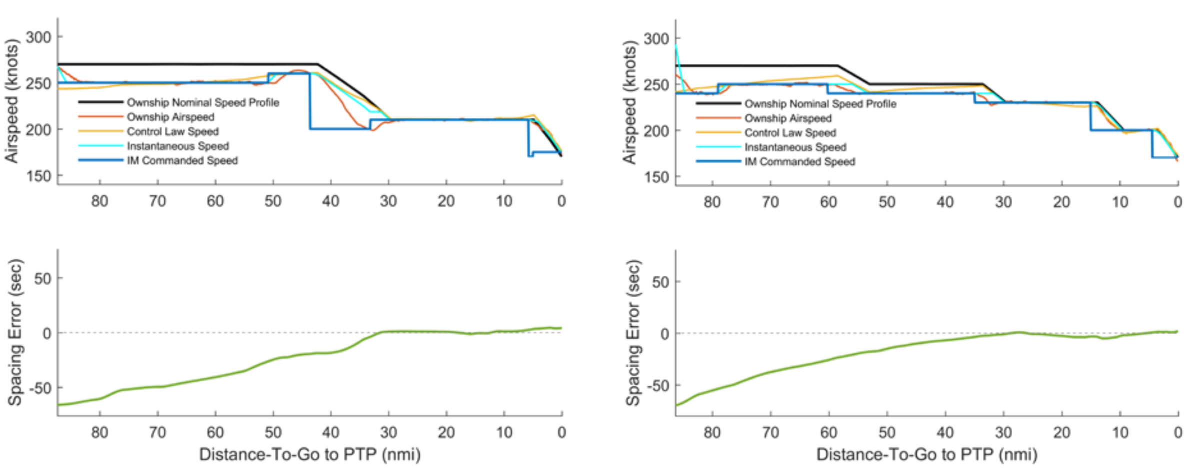


Figure 43. TBO control law using original (left) and modified (right) procedures.

Table 12 groups the secondary test results to allow for the comparison of data when aircraft type was the independent variable. One of the runs in case study A.07 was not valid (the same run as R.11), and another run in case study A.05 was a different IM clearance type, therefore both have been removed from this analysis. No clear trends were evident when the aircraft type was switched in terms of spacing accuracy, number of speed commands, or number of speed increases. While this limited data is not conclusive, it does seem to indicate that the spacing algorithm was robust for the aircraft types flown in this flight test, and aligns with previous research (refs. 49 and 50).

Table 12. Secondary test results for change to aircraft type.

Case #	Scenario	Data Base	Ownship	Clearance Type	Target Id	PTP Spacing Error (sec)	# Speed Commands	# Speed Reversals
A.01	B04	1	N757HW	CAPTURE	N889H	0.51	10	4
	B04	1	UAL2197	CAPTURE	N889H	–0.83	7	0
A.02	B04	1	UAL2197	CAPTURE	N757HW	2.57	14	5
	B04	1	N757HW	CAPTURE	UAL2197	0.16	10	3
A.03	B04	2	N757HW	CAPTURE	N889H	0.34	12	2
	B04	2	UAL2197	CAPTURE	N889H	0.73	12	4
A.04	B04	2	UAL2197	CAPTURE	N757HW	–3.75	16	3
	B04	2	N757HW	CAPTURE	UAL2197	–1.02	14	3
A.06	B03	1	N757HW	CROSS	UAL2197	9.53	5	2
	B03	1	UAL2197	CROSS	N757HW	0.23	9	5
A.08	B03	2	N757HW	CROSS	UAL2197	0.11	11	4
	B03	2	UAL2197	CROSS	N757HW	1.41	11	4
A.09	B05	1	UAL2197	CAPTURE	N889H	–0.93	8	1
	B05	1	N757HW	CAPTURE	N889H	0.33	7	1
A.10	B05	1	N757HW	CROSS	UAL2197	7.39	6	2
	B05	1	UAL2197	CROSS	N757HW	2.16	8	3
A.11	B05	2	UAL2197	CAPTURE	N889H	–1.05	11	4
	B05	2	N757HW	CAPTURE	N889H	0.13	11	5
A.12	B05	2	N757HW	CROSS	UAL2197	–0.09	8	4
	B05	2	UAL2197	CROSS	N757HW	1.37	12	3

In summary, the results from the secondary flight test indicate that modifying the altitude and speed constraints on the arrival and approach procedures did produce desirable results from the pilots' perspective of acceptability. In addition, results indicate that aircraft type does not appear to be a factor in the spacing performance or behavior of the algorithm.

9 Discussion

This section integrates the analyzed data, pilot ratings and comments, and observations from the research team. The two primary categories are the performance and behavior of the IM spacing algorithm (section 9.1), and the IM procedure used by the pilots to conduct the IM operation (section 9.2). Two additional categories in this section are the IM interfaces and displays (9.3), and the impact of the arrival and approach procedure design (9.4). While development of the IM interfaces and displays was outside the scope of the flight test, these areas impacted the results and generated comments from the pilots to warrant including the results here.

Recommendations outside the research scope of this flight test and without sufficient data to present here are listed in Appendix H, "Observations and Areas for Future Research." This appendix includes comments and suggestions about the ATD-1 ConOps, the design of the spacing algorithm, and how the flight crews execute the IM procedure.

9.1 Spacing Algorithm

As previously described, two different speed control laws were used in the IM avionics prototype: a CTD speed control law and a TBO speed control law. The CTD speed control law was used during the maintain stage, which is defined as the portion of the Cross operation after the ABP, the entire Capture operation, and the entire Maintain operation. The TBO speed control law was used during the achieve stage, which is defined as the portion of the Cross operation prior to the ABP and the entire Final Approach Spacing operation. The spacing accuracy and speed control behavior results pertaining to each of these speed control laws are discussed.

The results of this flight test indicate that the CTD speed control law was able to achieve the desired spacing performance; however, comments from the pilots and researcher observations indicated that certain speed control behaviors were undesirable. One spacing accuracy criterion used to evaluate the CTD speed control law was a spacing accuracy within 10 seconds at the PTP, or the distance-based equivalent, at least 95 percent of the time. Across the 88 en route and arrival operations that used the CTD speed control law, there was only one operation that had a spacing error greater than either the 10-second threshold or the equivalent distance (see sections 7.4.1 and 7.5.1.2). This indicates the ability of the CTD speed control law to meet the desired spacing precision at the PTP. A second performance criterion was used to evaluate how well the ASG was maintained after it was captured or achieved. The criterion was to maintain the spacing error within 10 seconds, or the distance-based equivalent, for at least 95 percent of the time after the ASG was captured after the Ownship crossed the ABP for time-based Cross operations, or after the Target aircraft crossed the ABP for distance-based Cross operations. All of the en route operations met this criterion (section 7.4.1); however, 13 out of the 77 applicable arrival operations did not (section 7.5.1.3). Approximately half of the 13 cases did not meet the criterion because of differences between how the Ownship and Target aircraft flew the 270 to 210 knot procedural deceleration segment on the SUBDY1 arrival. Most of the other cases that did not meet the criterion were caused by spacing errors greater than 10 seconds at the ABP, which caused the spacing error to be out of tolerance at the beginning of the maintain stage. Reducing the size of the procedural deceleration segments would have likely resulted in improved spacing accuracy throughout the maintain stage.

Even though the CTD speed control law met the spacing accuracy IM tolerance criterion, there were cases where pilot comments indicated that the speed behavior should be improved. In general, they found two types of speed behaviors to be undesirable: many speed changes within a short period of time and speed reversals. The data for time-based arrivals in section 7.5.2 supported the pilot comments, indicating that approximately half of the IM speed changes were speed reversals and that the Maintain operation had a relatively high average speed command rate of 0.80 speed commands per minute, or approximately 16 speed changes per arrival. Several important findings were identified from the examination of case studies (see sections 7.9.2.1, 7.9.4.1, and 7.9.4.2). The first finding was that the speed commands were correct control actions in reaction to the spacing error, winds, or the Target aircraft's ground speed. A second key finding was that altitude deviations and corresponding headwind deviations between the Ownship and Target aircraft can cause undesirable speed reversals and speed increases (see sections 7.9.4.1 and 7.9.4.2). Lastly, speed reversals and increases can occur when the Ownship deviates from The Target aircraft's speed to correct the spacing error and then returns to the Target aircraft's speed as the spacing error is corrected (see section 7.9.2.1). One disadvantage of the CTD speed control law is that these speed behaviors can propagate through a string of aircraft that are using the CTD speed control law, since the IM commanded speed is a combination of the speed flown by the Target aircraft and the speed control required to resolve the spacing error. Some of the undesirable speed behaviors caused by small perturbations could possibly to be reduced through additional filtering or other speed control law enhancements; however, the benefit of these approaches will be limited by the spacing accuracy criterion, the uncertainty of the Ownship's and Target aircraft's altitudes and headwinds, and errors in the estimation of the Target's airspeed from its ground speed data.

The TBO speed control law achieved the desired spacing accuracy for all of the Final Approach Spacing operations and was very close to achieving the desired spacing accuracy at the ABP for the Cross-Merge operations when operationally unrealistic runs were not included in the analysis (sections 7.7.1 and 7.5.1.1). However, both the time- and distance-based Cross-FAF operations, which had the ABP and PTP co-located at the FAF, did not achieve the desired spacing accuracy. The investigation of several case studies found two primary factors that contributed to larger than desired spacing errors at the ABP. The first factor is the difference between the speeds commanded by the TBO speed control law and the speeds flown by the Ownship (see sections 7.9.2.2, 7.9.3.2, and 7.9.3.3). The effect of these differences was amplified by the large 70 knot procedural speed change on the UPBOB1 arrival. The second contributing factor was a software implementation error that prevented trajectory updates that should have occurred due to differences between the sensed winds and the wind forecast, resulting in cases where the Ownship had significantly larger headwind deviations than it would have had if the wind blending functionality worked properly (see section 7.9.2.3).

Data in section 7.4.2 indicate that the Cross-FAF operation, which only used the TBO speed control law, had a lower speed command rate than the Capture and Maintain operations, which only used the CTD speed control law. Nevertheless, the TBO speed control law commanded speed increases and speed reversals that the pilots found undesirable. An analysis of case studies identified one behavior that was particularly problematic. The case study in section 7.9.2.1 is an example where the spacing error changed during the procedural deceleration to the FAF, causing the TBO speed control law to command a series of speed increases when the pilots were configuring their aircraft for landing.

The size of the procedural speed changes along with how they were implemented by the TBO speed control law contributed to poor spacing accuracy at the ABP for the Cross-FAF arrival operations. The first method that could be used to solve these issues is to limit the size of procedural speed changes to 40 knots or smaller, reducing the impact of variability during procedural speed changes on the spacing error (see section 9.4). Additionally, the use of assumed aircraft configuration information and a dynamic model of the Ownship could reduce differences between the deceleration of the Ownship and the nominal speed profile. Other potential solutions involve modifications to the TBO speed control law. One solution may be to break large procedural speed changes into multiple IM speed commands. This approach would enable the Ownship to correct for changes to the spacing error in the middle of a large deceleration segment; however, it would likely result in additional IM speed commands that the flight crew would need to respond to. It may also be possible to use techniques, such as Model Predictive Control, to predict how the spacing error will change throughout the deceleration segment instead of commanding a speed based on the current state of the spacing error (ref. 48).

9.2 Procedure and Flight Crew Technique to Conduct the IM Operation

The flight crews' IM procedure was divided into two phases: programming the IM application and conducting the IM operation (section 4.4). Comments and observations about the programming phase are given in section 9.3. Overall, the flight crews rated conducting the IM operation as very acceptable, with three specific issues identified below.

First, entering the IM commanded speed into the MCP speed window places the FMS into the VNAV "speed" mode for most of the descent, removing some of the altitude protection provided by the "path" mode (section 7.10.2.1). In particular, pilots reported cases where speed decreases occurred immediately prior to an altitude constrained waypoint as challenging and operationally undesirable. Furthermore, the VNAV "speed" mode also did not appear to provide consistent performance in changing pitch to decelerate the aircraft. While the VNAV "speed" mode is used but not preferred in current operations, this mode does require greater attention by the pilot to monitor and correct to the vertical flight path while achieving the IM commanded speed.

Second, the auto-throttle systems did not always exhibit rapid and consistent control to the airspeed set into the MCP speed window (section 7.10.2.2). There were instances where the auto-throttle switched to idle mode and did not activate until the difference between the speed set in the MCP and the Ownship's speed was greater than 10 knots. To compensate for the "dead-band" in the Ownship's auto-throttle system, the flight crews occasionally set a different speed in the MCP than the displayed IM commanded speed or manually over-rode the auto-throttle system to force the engines to a more appropriate power setting.

Third, the flight crews reported what appeared to be conflicting guidance between the FSI and the speed conformance monitoring function. In particular, there were instances where the FSI was centered while the IM commanded speed was flashing, indicating that the speed conformance monitoring function assessed the aircraft's airspeed as out of conformance. The FSI was generally correct; however, the design of the display and the logic of the instantaneous speed calculations, which drives the FSI display, were not intuitive to the pilots which made it difficult to follow the FSI (section 7.9.2.2). The frequent flashing of the IM commanded speed symbology was due to the speed conformance monitor assuming a generic rate of deceleration that did not always align with the IM instantaneous speed when the spacing error changed during a procedural deceleration.

As a result, throughout the flight test, some pilots began to realize that the following the FSI enabled them to achieve the desired spacing accuracy and began to rely on it, often trying to keep the FSI as close to zero as possible. While closely monitoring the and following FSI display led to increased spacing accuracy at the conclusion of the IM operation (section 7.9.3.3), it also increased the pilot workload throughout the IM operation to a level that some pilots reported as not operationally acceptable (section 7.8.2.5).

9.3 IM Interface and Displays

The development of the human-machine interface for the IM displays was outside of the scope of the ATD-1 Avionics Phase 2 contract. Therefore, although some effort was invested in creating the IM displays to meet as many requirements defined in reference 8 as possible, neither time nor resources were available for a formal human factors analysis as there would be for a certified IM avionic system.

The workload to enter the forecast wind, Ownship data, and the IM clearance data required for the IM operation into the IM avionics prototype was considered by many pilots as very high for typical airline operations (section 7.8.2.5). This was substantiated by cockpit video evidence showing that there were instances where over 150 button pushes on the EFB were required to fully program the IM application prior the start of an IM operation. Methods to mitigate this data entry issue include a more intuitive data entry design, software that is robust to data entry errors, standardization of button location and functionality, and simplification of button labels (“BACK”, “DONE”, and “RETURN” were frequently confusing to pilots). The eventual use of data communication to upload the IM information was frequently cited by the pilots as an important and effective method to reduce workload and data entry error.

Pilots reported having the IM clearance information automatically deleted when the IM operation was terminated automatically by the software (i.e., when the aircraft crossed the PTP), but being retained when the IM operation was terminated manually (i.e., by the flight crew), was confusing. The recommendation was the IM avionics should treat the IM clearance information uniformly, whether terminated automatically or manually.

A very common pilot comment was that the FSI, the secondary speed cue provided to help the flight crew fly the desired speed during speed changes, was not always intuitive. Much of this lack of understanding was due to the difference between the deceleration expected by the control law compared to the aircraft’s actual deceleration (see section 7.9.3.2), which frequently drove the FSI "triangle" from the center to the top of the FSI when the pilots decelerated the aircraft by setting the throttles to IDLE.

The Early/Late Indicator showed the pilots their current spacing error, and was intended as a method for pilots to monitor the progress of the IM operation. To be consistent with reference 8, the Early/Late Indicator was shown when the Ownship was within 30 nmi of the ABP for Cross and Final Approach Spacing operations, and throughout the entire arrival for Capture and Maintain operations. Pilots had three comments on how the Early/Late Indicator could be improved. First, pilots reported that the displaying of the Early/Late Indicator for only a portion of the Cross operation was inconsistent, and that it should also always be shown in the “Available” and “Paired” states. Second, the pilots expected the upper and lower bounds of the indicator to indicate the feasibility of the IM operation, and when the bounds were reached, the flight crew procedure associated with the flight crew suspending the IM operation should be triggered. The pilots stated in this situation, a textual indication should also be displayed to the flight crew that the operation is no longer predicted to be feasible. Third, some pilots believed the “Early” indication included separation criteria. Although not part of the ATD-1 ConOps, separation criteria were clearly an overriding concern of the pilots, and many of them expected the Indicator to incorporate that criterion.

A final pilot comment was that the similar design and close proximity of the FSI and the Early/Late Indicator to each other occasionally made it difficult to interpret the information. If both indicators are retained in future implementations, distinctly different symbology should be considered.

9.4 Impact of Arrival and Approach Procedure Design

One factor that contributed to the undesirable spacing behavior during the flight test was the magnitude of the procedural speed changes in the arrival and approach procedures (section 7.10.1). Examples include the large procedural speed changes from 240 to 170 knots on the UPBOB1 arrival and from 270 to 210 knots on the SUBDY1 arrival, which amplified the impact caused by the difference between the deceleration expected by the IM avionics prototype compared to the aircraft’s actual deceleration. This design choice was a contributing factor to the poor spacing accuracy at the ABP for the Cross-FAF operations, and also to the spacing errors that were outside of the 10 second maintain stage IM tolerance during Maintain, Capture, and Cross-Merge operations. Results from the secondary test (section 8.2) support designing the arrivals and approaches with smaller procedural speed changes, perhaps 40 knots or less on arrival and 20 knots or less on approach, improved the behavior of the spacing algorithm.

A second factor in the design of the procedures was the descent angle and speed constraints on the segment from NALTE to SUBDY, which typically required the pilots to use speed brakes, and resulted in a relatively slow speed of 210 knots while still 35 nmi from the airport. The modified database used in the secondary flight test created an altitude window at NALTE and raised the speed constraint at SUBDY from 210 knots to 230 knots. The pilots rated operations conducted with the modified database consistently better than with the original database. This aligns with an earlier flight test that explored precise spacing by flying the airspeed generated by onboard avionics which noted that using speed control on approaches designed for idle descent will result in frequent use of speed brakes to maintain the vertical path and the desired airspeed (ref. 39).

The third factor in the design of the procedures was that the speeds associated with the waypoints immediately prior to the FAF resulted in the pilots rating some of those operations as having too much energy (too fast) on final to assure the ability to achieve a stabilized approach. The modified database lowered the speed constraint of the initial waypoints on the approach (HIXOS and IWKID) from 210 knots to 200 knots which slightly reduced the number of speed reversals that occurred within the final 20 nmi of the operations. None of the operations conducted with the modified database were rated by the pilots as having too much energy on final.

Unrelated to the two previous issues, the 17,000-foot altitude restriction at NALTE, which was within close proximity to the 18,000-foot altimeter change to local pressure setting, caused additional workload for the pilots (section 7.10.2.3). Either changing the constraint to an altitude window or using an altitude constraint at least 2000 feet below the 18,000-foot changeover would mitigate the additional use of throttle and speed brake at this point on the arrival.

10 Conclusions

NASA's ATD-1 subproject successfully completed a 21-month effort to develop an IM avionics prototype that culminated in a 19-day flight test. Under NASA contract with Boeing Research and Technology, an IM avionics prototype was built based on NASA guidance and developing international IM standards, integrated into two test aircraft, and then flown in real-world conditions to determine if the subproject goal of increasing throughput at busy airports while increasing the efficiency of aircraft arrival operations could be met. Overall the primary goals of the ATD-1 flight test were met, which were to develop avionics software to conduct IM operations, to integrate those avionics into two aircraft, and to conduct a flight test of the IM operations.

The IM avionics prototype developed as part of the ATD-1 contract and flown in the flight test generally met the performance success criteria (ref. 8) across different phases of flight. Despite the challenges of conducting the flight test without the two ATD-1 ground components, the IM operation demonstrated significant promise in fulfilling its role in the ATD-1 ConOps (ref. 1) to produce precise spacing intervals between aircraft. However, for the IM avionics prototype as flown in this flight test, the rate of commanded speed changes and speed command reversals during IM operations was undesirably high, and based on questionnaire responses, the pilot workload to conduct IM operations was also high. Rationale for the results are summarized and grouped below in terms of the spacing algorithm, the flight crew technique to conduct IM operations, the IM interfaces and displays, and the impact of the arrival and approach procedures.

From the spacing algorithm perspective, of the four IM operation types tested in the flight test, the CTD control law generally achieved the desired IM tolerance criterion. The TBO control law did meet the spacing accuracy for the Final Approach Spacing operations and was very close to meeting the spacing goal for the Cross-Merge operations. However, the spacing accuracy criterion for the Cross-FAF operations, both time- and distance-based, was not met. The two primary issues identified for the Cross-FAF operation were the difference between the speeds expected by the control law and the speeds actually flown by the aircraft, and a software implementation error where the trajectory was not correctly updated when the sensed winds were different than the forecast winds. Pilot comments throughout the flight test indicated that the acceptability of the IM operation could be improved if the frequent speed changes and the number of speed reversals were reduced. Some of this behavior could, and should, be improved through additional filtering or other control law enhancements; however, care must be taken to not negatively impact the spacing accuracy provided by the IM operation. However, it is noted that this approach does not address the uncertainty in the data used to calculate the trajectories of the Ownship and Target aircraft, which was another source to the higher than desired speed change rate.

From the perspective of the flight crews conducting the IM operation, while they frequently reported the IM operation as acceptable, there were three issues identified that may require further development prior to final implementation. First, using the VNAV "speed" mode removed some of the protection available in the VNAV "path" to meet altitude constraints, and required greater attention by the pilot to achieve the vertical path while maintaining the IM commanded speed. Second, the auto-throttle system of both IM equipped aircraft did not exhibit rapid and consistent control to the speed set in the MCP speed window, and both systems required the pilots to manually over-ride the throttles or modify the speed in the MCP to overcome the "dead-band." Third, the use of the FSI typically enabled accurate spacing when there were large procedural speed changes, but increased pilot workload to an undesirable level as reported by some of the subject pilots.

Although some effort was invested in refining the IM interfaces, a full development cycle was outside of the scope of the ATD-1 contract. Flight crew comments about the data entry process included the complexity and significant amount of time needed to enter the data, the need to standardize terminology and the location of the buttons, and that the inconsistent deletion of the IM clearance information was confusing. For the IM displays, the FSI was frequently cited as not intuitive, and some comments recommended that the upper and lower bounds of the Early/Late Indicator represent when the IM operation is no longer deemed feasible. Other comments about the Early/Late Indicator noted that if the bounds represent an infeasible IM operation, then there should be an accompanying message indicating that the IM operation should be suspended. Some pilots reported a strong desire for separation criteria to be included in the calculation of the "early" bound.

Finally, the arrival and approach procedures were intended to be generally representative of PBN procedures in place today; however, the choice of airspeed constraints created large speed changes, which was the primary factor contributing to the poor spacing accuracy of the Cross-FAF operations and to those operations where the spacing error was not within 10 seconds for 95 percent of the time during the maintain stage. The choice of speed constraints for the approach waypoints was also the primary cause for pilots reporting the aircraft was too fast on final approach. As shown when using database 2 with the modified altitudes and speed constraints on the arrival procedure, pilots reported an improvement in the operation, in particular the slower speeds on approach.

In summary, the flight test demonstrated that the IM avionics prototype met the spacing accuracy design goals for the majority of the IM operations flown, and that the capabilities demonstrated by the IM avionics prototype have shown significant promise in contributing to the goals of improving aircraft efficiency and airport throughput. The poor spacing accuracy of the Cross-FAF operation, the high IM speed command rate, and the number of speed reversals observed in this flight test require consideration in future designs of IM avionic systems.

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Appendix A. Increased Throughput from Greater Precision

Increasing runway throughput or reducing arrival delays can be achieved through greater precision of the aircraft inter-arrival times (ref. 43). The relationship of airport demand, potential throughput increase, and arrival delay reduction may be described through the following example. Figure 44 illustrates a nominal distribution of the error in the inter-arrival times between aircraft crossing the runway or FAF as the solid line. For many ATC facilities, this distribution would be approximately 20 seconds for operations under instrument meteorological conditions (ref. 44). To maintain an acceptably small number of go-around operations caused by inadequate separation or runway occupancy problems, a spacing buffer must be added to the nominal spacing interval. This buffer is the time interval between the go-around boundary and the nominal, no-error point on the distribution. The use of precision airborne spacing techniques enables this error distribution to be reduced, as shown in Figure 44 by the dotted line curve shifting to the left. By reducing the distribution of the error, the spacing buffer may then be reduced while maintaining the same acceptable number of go-around operations and the same separation standards.

MITRE conducted a comparable analysis with a similar approach to increasing runway throughput by greater delivery precision, with potential increases of 10 arrival operations per hour in certain metrological and traffic conditions (ref. 46).

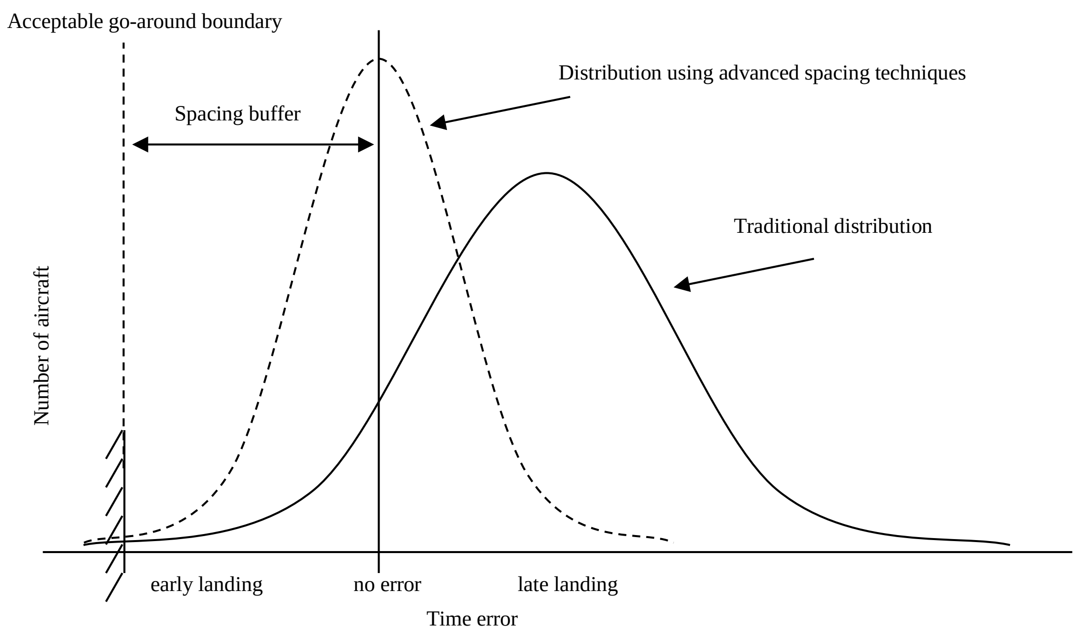


Figure 44. Distribution of landing time error.

While a small reduction in this spacing buffer may seem insignificant, from an airport capacity and arrival delay standpoint this small improvement can result in a large, system-wide benefit. Using the IM spacing operation, it is feasible to reduce the spacing buffer from 15-20 seconds to 5–7 seconds, which results in a 5 percent increase in runway throughput. This assumes a range of final approach speeds between 130 to 150 knots and 3 nmi separation between aircraft (ref. 44). The demand graph in Figure 45 shows this 5 percent increase in throughput yields a 29 percent reduction in arrival delays (ref. 45).

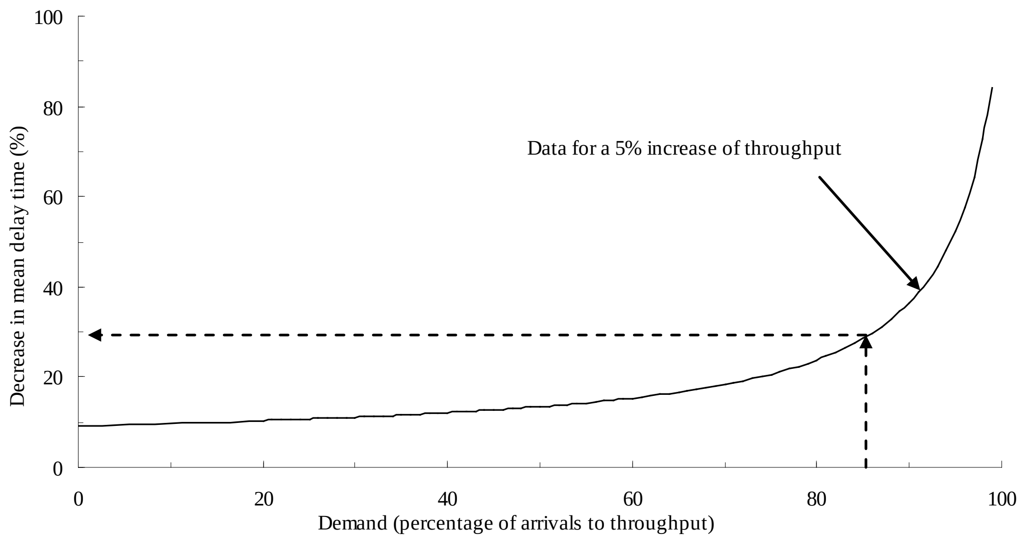


Figure 45. Demand versus throughput graph.

Appendix B. Speed Control Law Algorithm

This appendix provides details on the speed control algorithm used in this flight test. As previously noted, this spacing algorithm uses both TBO and CTD speed control laws. The TBO speed control law was used for the achieve stage of the Cross IM operation, i.e., the portion of the operation before the ABP, and the Final Approach Spacing IM operation. The CTD speed control law was used for the maintain stage of the Cross operation, i.e., the portion of the operation after the ABP, the Capture operation, and the Maintain operation. In general, both control laws calculated a spacing error, a speed correction based on the spacing error, and the speed command as the sum of some nominal speed and the speed correction. While not explicitly noted in the following sections, the speed correction, nominal speed, and speed command values were calculated in calibrated airspeed (CAS), with any required internal conversions from ground speeds not shown. More information about the NASA spacing algorithm used during the NASA simulations and facilities is given in reference 24, and information about the Honeywell spacing algorithm used by the IM avionics prototype in the flight test is in reference 25.

B.1 Four-Dimensional Path Generation

For both speed control laws, the trajectory generator (TG) produced four-dimensional trajectories for both the Ownship and the Target aircraft. Input to the TG for trajectory calculation included relevant path descriptors, aircraft state data, planned cruise and descent performance data for the Ownship, and both forecast and sensed wind data. Path descriptors could include the names of waypoints, STARs, approaches, and runways. For Final Approach Spacing IM operations, only the runway name was required for the path description. Path altitudes and speeds for the path construction were taken from the relevant procedure, e.g., STARs and approaches; input performance data for the Ownship including cruise altitude, cruise speed, and descent speed; observed performance from the aircraft state data prior to and after the top of descent; and altitude and speed requirements from the IM MOPS (ref. 8). Because cruise altitude and cruise speed were not explicitly available for the Target aircraft, a “discovery algorithm” based on the Target’s ADS-B state data was used to estimate these data. Additionally, generic descent and deceleration performance parameters were used for path calculation of both aircraft.

The original specification called for automatic updating of both aircraft trajectories when the sensed winds differed significantly from an internal wind model which blended the Ownship’s sensed winds and the wind forecast. However, this functionality did not work properly due to a software implementation error. The aircraft’s actual vertical position was used to automatically update the aircraft’s trajectory when there was a large difference between the aircraft’s actual vertical position and the predicted vertical path from the trajectory.

B.2 Trajectory-Based Speed Control

The TBO speed control law calculated a spacing error based on both aircraft path positions, the operation’s ASG, a speed correction, and the speed command as the sum of some nominal speed and the speed correction. Reference 8 requires the ASG to be defined in either time or distance. For a time-based ASG, the spacing error was calculated based on the following rules:

- If the Target is not past the ABP,
    - *Spacing error = Ownship’s time to the ABP - (Target’s time to the ABP + ASG),*

- Otherwise,
    - *Spacing error = Ownship's time to the ABP - (Target's clock time passing the ABP + ASG - current clock time).*

For a distance-based ASG, the spacing error was calculated in time, with this time based on the ASG distance. The spacing error was calculated based on the following rules:

- If the Target is not past the ABP,
    - *Spacing error = Ownship's time to a distance equal to the ASG before the ABP - Target's time to the ABP,*
- Otherwise, if the Target is not past the PTP,
    - *the algorithm switches to the CTD algorithm for a maintain operation,*
- Otherwise, if the Target is past the PTP,
    - *pair-wise spacing is not valid and a speed command is calculated to match the Target's ground speed at the PTP.*

The basic speed correction value was calculated as the spacing error multiplied by a proportional gain, with the proportional gain value increasing as the Ownship's distance to the ABP decreases. Additionally, a ground speed compensation value was used in the TBO control law as a way to limit the Ownship from closing too quickly on the Target aircraft when both are relatively far from the ABP. This compensation value was based on the difference between the Target's current ground speed and the Target's trajectory ground speed at the Target's current position, multiplied by a proportional gain, with this gain value decreasing as the Target's distance to the ABP decreases. Ground speed compensation in this implementation was designed to only compensate for slower than nominal speeds by the Target aircraft in order to compensate for the accepted ATC tendency to slow aircraft below the nominal arrival speeds when they are farther from the ABP. The total speed correction value became the sum of the basic speed correction value and the ground speed compensation.

To calculate the speed command, a nominal speed was required, which was based on the speed at the end of the current Ownship trajectory speed segment. This current speed segment was relative to the Ownship's position on its path and ended at a point ahead of this position either where a change in the speed profile occurs or at the end of the path. For example, in Figure 46 there are three speed segments: a constant 210 knot speed segment; a 210 to 170 knot deceleration segment; and a constant 170 knot speed segment. If the aircraft was on the constant 210 knot speed segment, then the nominal speed would be 210 knots. If the aircraft was on either the deceleration segment or the constant 170 knot speed segment, then the nominal speed would be 170 knots. The basic TBO command speed was then the sum of this nominal speed and the speed correction value.

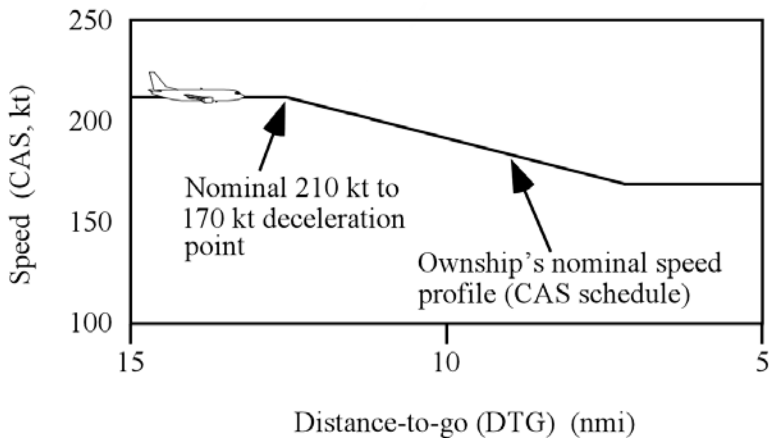


Figure 46. Example of a TBO nominal profile.

B.3 State-Based CTD Control

A time-history data set, generated from the previous 10 minutes of ADS-B data from the Target aircraft and recorded at approximately 1 Hz, was the basis of the "trajectory" used by the state-based, CTD speed control law. In this regard, the Target's ground speed, ground track, and altitude data, along with the Ownship's forecast and sensed wind data, were used to synthesize a CAS profile and determine speed change points for the Target aircraft. Unlike the TG data, however, the time-history data were constantly updated with the Target aircraft ADS-B data. Because of this updating, the pseudo-trajectory from the time-history data set was reassessed on a continuing basis. This time-history data set was also used to estimate various spacing parameters. For example, to determine the Target's time history at the Ownship's current position, the Ownship's current latitude and longitude were compared against the time-history data. The two points closest to the Ownship's position were determined and an interpolation against the Ownship's position was then used to obtain an accuracy of better than 1 Hz.

For a time-based ASG, the spacing error was calculated as:

- *Spacing error = current clock time - Target's history time at the Ownship's position - ASG,*

where the Target's history time at the Ownship's position was estimated from the time-history data set, noting that the Ownship and the Target aircraft must be on a common horizontal path for a time-based operation to be valid. For a distance-based ASG, similar to the TBO control law, the spacing error was calculated in time based on the ASG distance. The spacing error was calculated as:

- *Spacing error = time behind Target at the ASG - time behind Target along TG path to Ownship,*

where the time behind Target at the ASG was calculated as:

- *Time behind Target at the ASG = current clock time - Target's history time at a distance behind the Target equal to the ASG,* and the time behind the Target along the TG path to the Ownship was calculated, using the four-dimensional trajectory time to the Planned Termination Point (PTP), as:

- *Time behind the Target along the TG path to Ownship = Ownship's time to the PTP - Target's time to the PTP.*

This technique of using the four-dimensional trajectory time in the calculation was required for the special case where the Target is past the ABP, the Ownship is on a merging path with the Target, and the Ownship was not past the ABP.

Similar to the trajectory-based speed control law, the CTD speed correction value was calculated simply as the spacing error multiplied by a proportional gain, with the proportional gain schedule value increasing as the Ownship's distance to the PTP decreases.

The nominal speed for a time-based ASG was based on the speed at the end of the current speed segment, noting that the speed segment data were from the time-history pseudo-trajectory data, not the TG trajectory. Because the pseudo-trajectory was being continuously updated, a long deceleration segment could produce a continuously changing current speed segment, i.e., the current segment was a deceleration, the deceleration ends at the Target's current position, and the Target was still decelerating. An example of this situation is shown in Figure 47 and Figure 48. In Figure 47 at time t = 0, the Target aircraft has decelerated from 250 knots to 160 knots. In Figure 48 at time t = n, the Target has continued to decelerate to 145 knots. To preclude numerous speed command changes based on a changing nominal speed value, logic was developed to inhibit the updating of the nominal speed until the Ownship was near the pseudo-trajectory point used to determine the nominal speed value. For example, assume that at time t = 0, the Ownship is at 30 nmi DTG and the nominal speed is 160 knots. The pseudo-trajectory point used for the inhibited nominal speed value in this case would be 20 nmi. If at time t = n (Figure 48) the Ownship is at 25 nmi DTG, then the nominal speed value would still be 160 knots, even though the Target has slowed to 145 knots, because the Ownship is not sufficiently near the pseudo-trajectory point.

For a distance-based ASG operation, the nominal speed was simply the Target's current speed. The basic CTD speed command was then the sum of this nominal speed and the speed correction value.

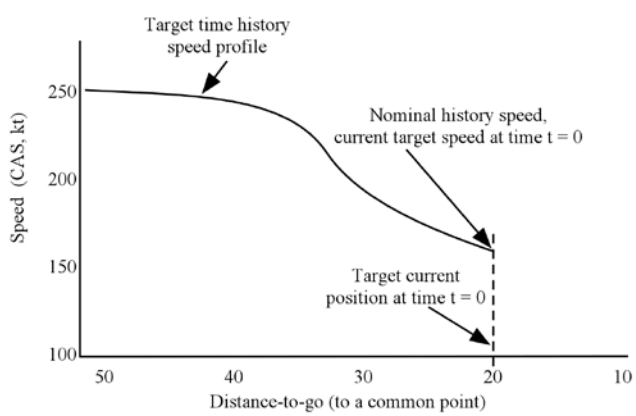


Figure 47. Example of deceleration of the Target aircraft.

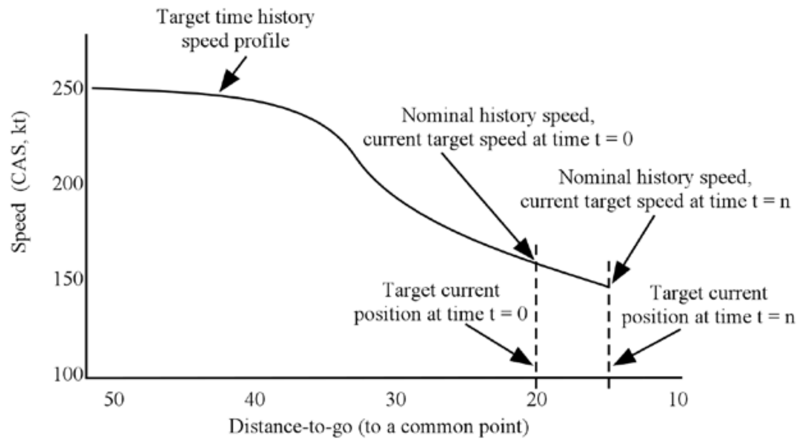


Figure 48. Example of continuing deceleration of the Target aircraft.

B.4 Speed Limiting

The previous simplistic descriptions of the TBO and CTD control laws do not account for both the operational and IM MOPS (ref. 8) requirements for speed command limiting in certain situations. For the maximum speed command value that could be output by the trajectory-based control law, the smallest value from the following list would be used as the maximum speed limit:

- Vmo
- Pilot-entered maximum speed limit
- 15 percent above the Ownship's TG trajectory speed at the end of the current speed segment
- Route imposed speed limit, e.g., RNAV speed limit

For the minimum speed command value that could be output by the TBO control law, the largest value from the following list would be used as the minimum speed limit:

- Minimum final approach speed
- Pilot-entered minimum speed limit
- 15 percent below the Ownship's TG trajectory speed at the end of the current speed segment

For the CTD control law, in addition to operational limits, a limit on the speed correction value was imposed so that a very large spacing error would not overwhelm the nominal speed value, thus eliminating unacceptable speed commands under this situation. The speed correction value was limited to ±33 percent of the nominal speed. For the maximum speed command value that could be output by the CTD control law, the smallest value from the following list would be used as the maximum speed limit:

- Vmo
- Pilot-entered speed limit
- If the ASG was time-based and the pseudo-trajectory was not in a deceleration segment, 15 percent above the Ownship's current TG trajectory speed

- If the ASG was time-based and the pseudo-trajectory was in a deceleration segment, 15 percent above the Ownship's TG trajectory speed at a point used for the inhibited nominal speed value
- If the ASG was distance-based, 15 percent above the Ownship's TG trajectory speed at the Target's position
- Route imposed speed limit, e.g., RNAV speed limit

For the minimum speed command value that could be output by the CTD control law, the largest value from the following list would be used as the minimum speed limit.

- minimum final approach speed
- pilot-entered minimum speed limit
- if the ASG was time-based and the pseudo-trajectory was not in a deceleration segment, 15 percent below the Ownship's current TG trajectory speed
- if the ASG was time-based and the pseudo-trajectory was in a deceleration segment, 15 percent below the Ownship's TG trajectory speed at a point used for the inhibited nominal speed value
- if the ASG was distance-based, 15 percent below the Ownship's TG trajectory speed at the Target's position

B.5 Speed Quantization

To reduce the number of speed changes displayed to the pilot, speed quantization and hysteresis techniques were used. For the speed quantization, the speed commands were output in either 5- or 10 knot increments, with the default value being 10 knots. For the trajectory-based control, a 5 knot speed quantization was used if the Ownship was within 5 nmi of the PTP and if the absolute value of the spacing error was less than 9 seconds. For the CTD control, a 5 knot speed quantization was used if the Ownship was within 60 seconds of the PTP and if the absolute value of the spacing error was less than 3 seconds. Hysteresis was included in the quantization logic to reduce dithering of the output speed command when the command speed was near the breakpoint for the quantization value.

B.6 Mach/CAS Transition

Because the operation could be conducted at high altitude, where the speed control is typically in Mach, the trajectory generator and the control laws needed to determine the cruise and initial descent conditions and when the use of Mach versus CAS was appropriate. For the Ownship, cruise altitude, cruise speed, and descent speed were obtained from data entered by the pilots into the IM avionics. For the Target aircraft, the cruise altitude and cruise speed were calculated by a "discovery algorithm" based on the Target's ADS-B state data. For this test, the Target aircraft's planned CAS used for the calculation of the Mach-to-CAS transition altitude was assumed to be 280 knots. Mach values and both aircraft Mach-to-CAS transition altitudes were then calculated using these data and the Ownship's barometric pressure adjustment and temperature.

Based on the calculated Ownship's Mach-to-CAS transition altitude, for the condition where the Ownship was above the transition altitude, an indication was set in the output data that the speed command should be displayed in Mach.

B.7 Fast/Slow Indicator

While the speed command presented the speed value which the pilots were expected to enter into the auto-throttle system, a FSI was provided to the pilots to assist in modulating the aircraft's thrust and drag during a speed change. This FSI depicted the Ownship's speed relative to a speed command trend value provided by the speed control algorithm. By closely tracking this indicator during a speed change, the aircraft was more likely to match the planned trajectory during a trajectory speed change and was less likely to produce what was known as a self-induced spacing error. For both control laws, this speed command trend value was calculated in a manner similar to the basic speed command calculation for that control law, except a nominal speed trend value was used in lieu of the nominal speed value in this calculation.

For the TBO control law, the nominal speed trend value was the Ownship's trajectory speed at the Ownship's position (Figure 49). The resulting speed command trend was speed limited using the same technique as the basic speed command. Logic was also applied such that the speed command trend matched the value of the output speed command at the end of each speed change.

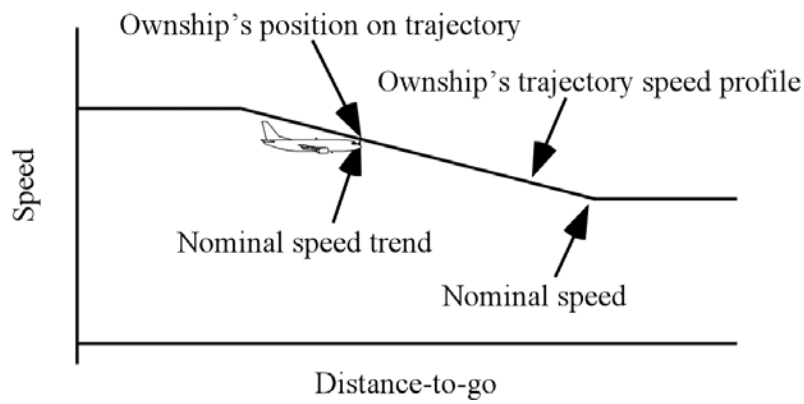


Figure 49. Example of the nominal speed trend relative to the speed trajectory.

B.8 Measured Spacing Interval (MSI) Calculation

The Measured Spacing Interval (MSI) is the spacing along the horizontal path between the Ownship's and the Traffic's along-path positions. This parameter was used by the pilot for the scenario setup of a Maintain or Capture operation. The definition of the MSI is dependent on whether the clearance is time-based or distance-based. The MSI is only valid when the Ownship and the Traffic are on a common path. The MSI is calculated as

- for a time-based MSI,
  - *MSI = current clock time - Target's history time at the Ownship's position.*
- for a distance-based MSI,
  - *MSI = Ownship's DTG to the PTP - Target's DTG to the PTP,*

where these distances are from the TBO data.

B.9 Predicted Spacing Interval (PSI) Calculation

The Predicted Spacing Interval (PSI) is the predicted spacing at the ABP. This parameter was used by the pilot for the scenario setup of a Cross or Final Approach Spacing operation. The definition of the PSI is dependent on whether the clearance is time-based or distance-based. The PSI is defined whenever there is an Achieve Stage in the IM Operation. The PSI is calculated as

- for a time-based MSI,
  - *PSI = Ownship's estimated time of arrival to the ABP - Target's estimated time of arrival to the ABP*,
- until the Target passes the ABP, then
  - *PSI = Ownship's estimated time of arrival to the ABP - Target's actual time of arrival at the ABP*.

For a distance-based PSI, the PSI is the predicted along-path distance of the Ownship to the ABP at the time when the Traffic is predicted to cross the ABP.

Appendix C. IM Commands for Procedural Speed Changes

In order to decrease the number of speed commands presented to pilots, the IM avionics prototype provided procedural speed changes as a single speed command. It was found that the size of the procedural speed changes combined with providing these changes as a single speed command contributed to undesirable spacing performance during the Cross-FAF operations.

The implementation of this functionality was different for the TBO and CTD speed control laws. For the TBO speed control law, the IM commanded speed was the sum of the nominal speed profile at the end of a procedural speed change and the speed control required to resolve the spacing error. Since the CTD speed control law did not use the nominal speed profile when calculating the IM commanded speed, a heuristic was used to estimate the Target aircraft's airspeed at the end of a deceleration. This heuristic was based on the Target aircraft's recorded time-history data beginning at the Ownship's position, whether or not the Target aircraft's time-history airspeed was constant or decreasing, and then estimated the Target aircraft's speed at the end of that deceleration segment. Similar to the TBO control law, the IM commanded speed for the CTD control law was calculated as the summation of that end speed estimation and the amount of speed control required to resolve the spacing error. This CTD end speed heuristic was only used for time-based operations, because the CTD control law for distance-based operations only used the Target aircraft's current speed. That is, for CTD distance-based operations, there was no look-ahead along the Target's time history data to predict the end of a deceleration because the Target's current speed was used. In this regard, the CTD distance-based operation was similar to a station-keeping operation (ref. 43).

During this flight test, large procedural speed changes, such as the 240 to 170 knot speed change on the UPBOB1 arrival, contributed to poor spacing performance of the Cross-FAF operations. Because procedural speed changes were provided as a single speed command, increasing the magnitude of a procedural speed change amplified the differences between the Ownship's deceleration and the planned trajectory speed during a speed change (see Appendix B for an explanation of how the speeds were calculated). To resolve this issue, the prototype pilot interface provided the pilots with a secondary speed cue. This secondary speed cue, called the instantaneous speed, closely followed the control law speed and was displayed to pilots via the FSI. While the FSI provided the pilot with speed guidance that they could fly to achieve the spacing goal, the pilots either found it unintuitive and did not use it or relied almost exclusively on it after setting the IM commanded speed in the MCP. When the pilots heavily referenced the FSI to minimize spacing error, the additional intervention with throttle and speed brake increased the pilot workload to some degree compared to current operations (see case study in section 7.9.3.3).

During discussions after the flight test with the wider IM community, it was clarified that (ref. 8) intended for the IM commanded speed to be limited to within ±15 percent of the continuous nominal speed profile instead of the discrete final deceleration speed used by the IM prototype. If this approach had been used by the IM prototype, the large procedural speed changes would have been broken into multiple smaller speed commands, potentially solving some of the spacing performance issues observed during the Cross-FAF clearance and reducing the need for the FSI. However, splitting large changes to the procedural speed into multiple smaller speed changes will result in an increase in the number of speed commands that the flight crew would need to execute. Future IM software designs should carefully consider how to implement procedural speed changes while ensuring precise spacing and minimizing the number of speed commands.

Appendix D. Arrival and Approach Procedures

D.1 Primary Test Matrix (20 Jan – 16 Feb 2017; 16 days)

Figure 50 through Figure 53 are the arrival and approach procedures used during the first 16 days of the ATD-1 flight test. These special STAR procedures were designed in accordance with FAA guidance (ref. 30) and tested in full-scale simulators at both United Airlines and NASA Langley. During this testing it was determined that the curved segment after the FAF (LACIP) on the approach to runway 14L was not well-suited for IM operations, therefore all flight operations during the test were conducted to runway 32R, and the NALTE1 arrival procedure (Figure 52) was not used.

D.2 Secondary Test Matrix (20 Feb – 22 Feb 2017; 3 days)

As described in section 7.10.1, minor adjustments to some of the altitude and airspeed constraints on the arrival and approach procedures were made for the IM avionics (the procedure constraints loaded into the FMS were left unchanged). These changes were intended to remove what was believed to be a negative impact on the IM performance caused by less than ideal procedure design, and the results of this change are detailed in section 8.2.

The changes to the altitude and airspeed constraints on the arrival and approach procedures used by the IM avionics prototype during the final three days of testing were

- SUBDY1 STAR:
  - NALTE: change 17000AT to 19000B/17000A
  - NALTE: add 250 knots
  - SUBDY: change 210 knots to 230 knots
- UPBOB1 STAR:
  - UPBOB: add 210 knots
- RNAV RNP Z 32R:
  - HIXOS: add 200 knots
  - IWKID: add 200 knots

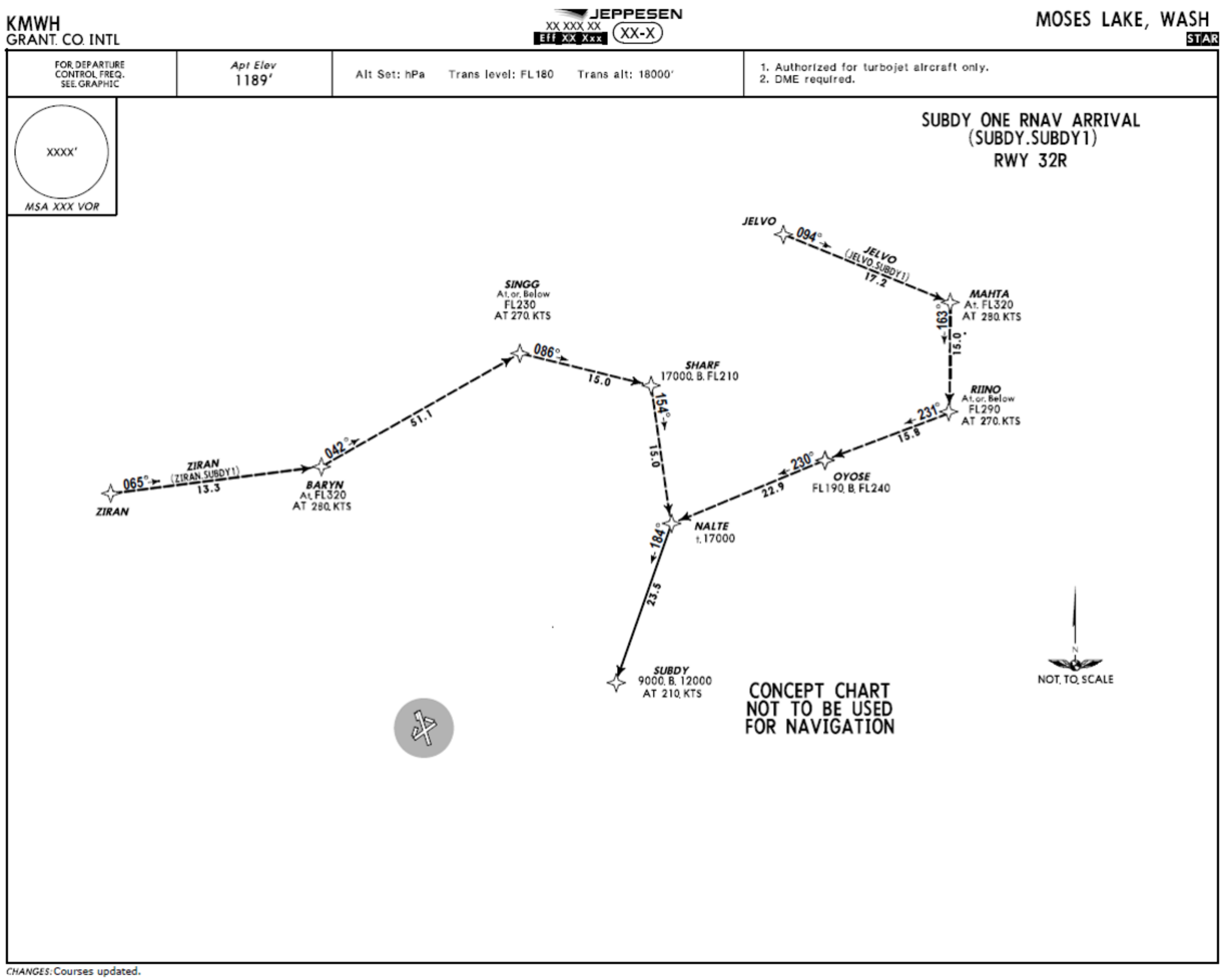


Figure 50. SUBDY1 RNAV STAR to runway 32R at KMWH.

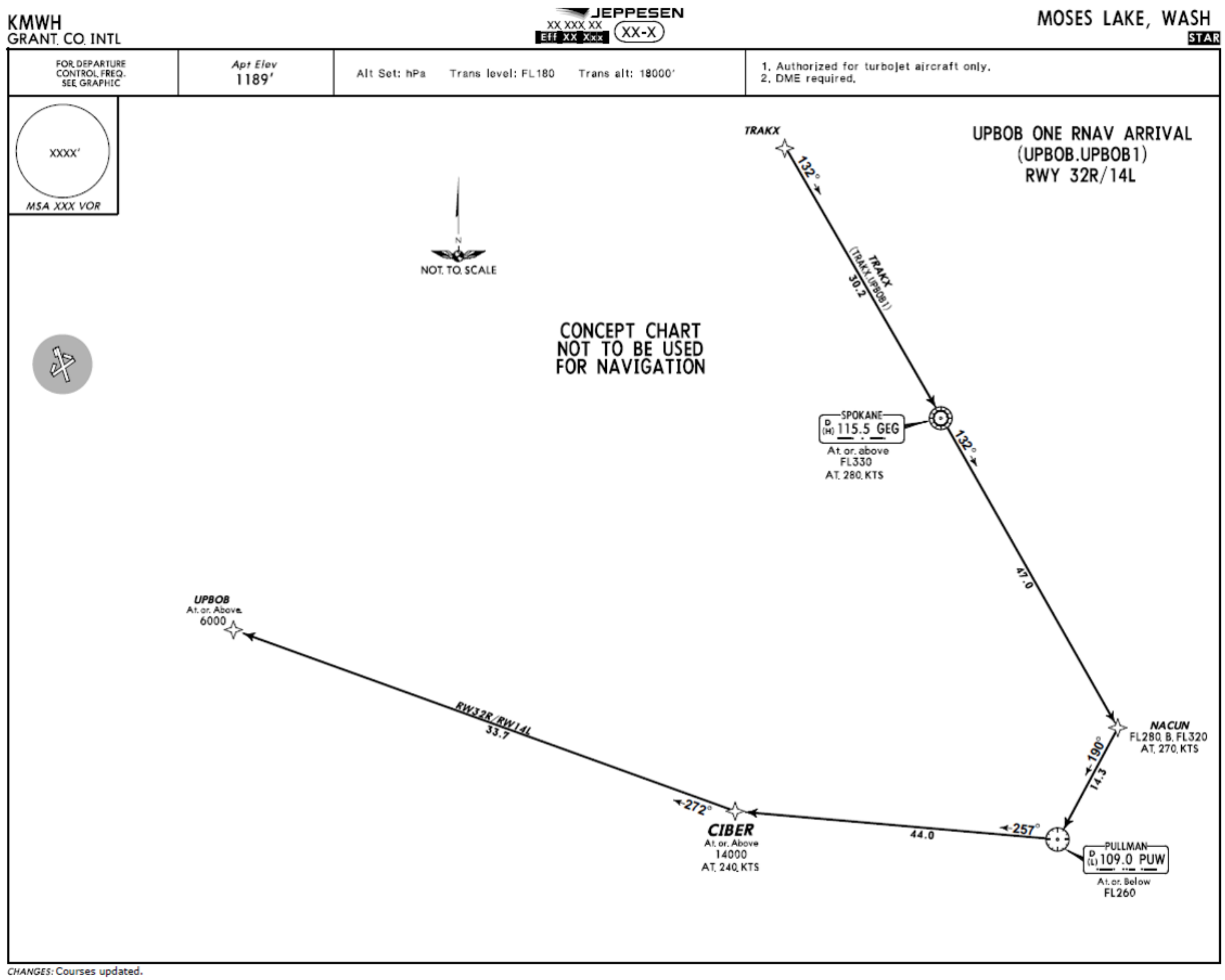


Figure 51. UPBOB1 RNAV STAR to runway 32R at KMWH.

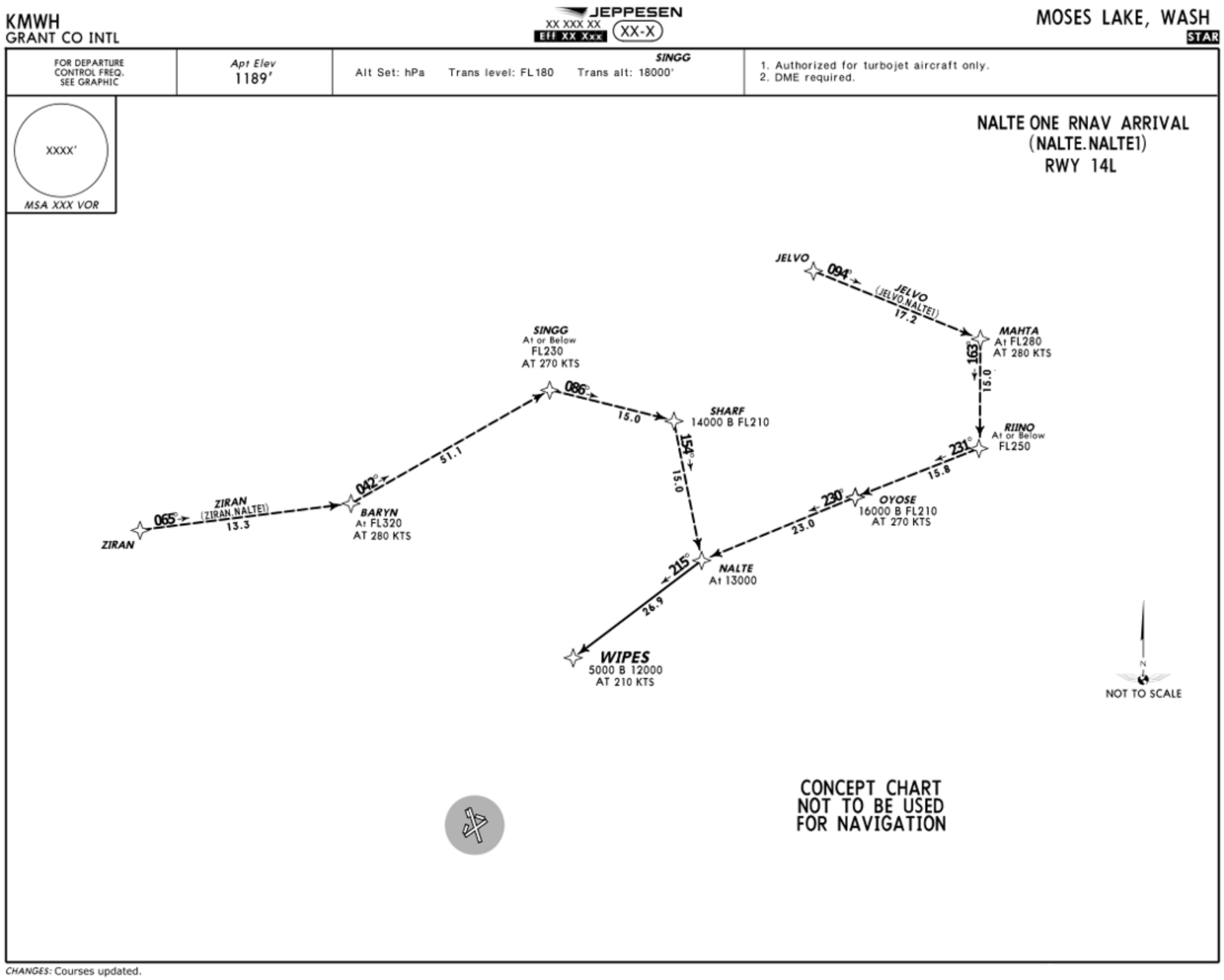
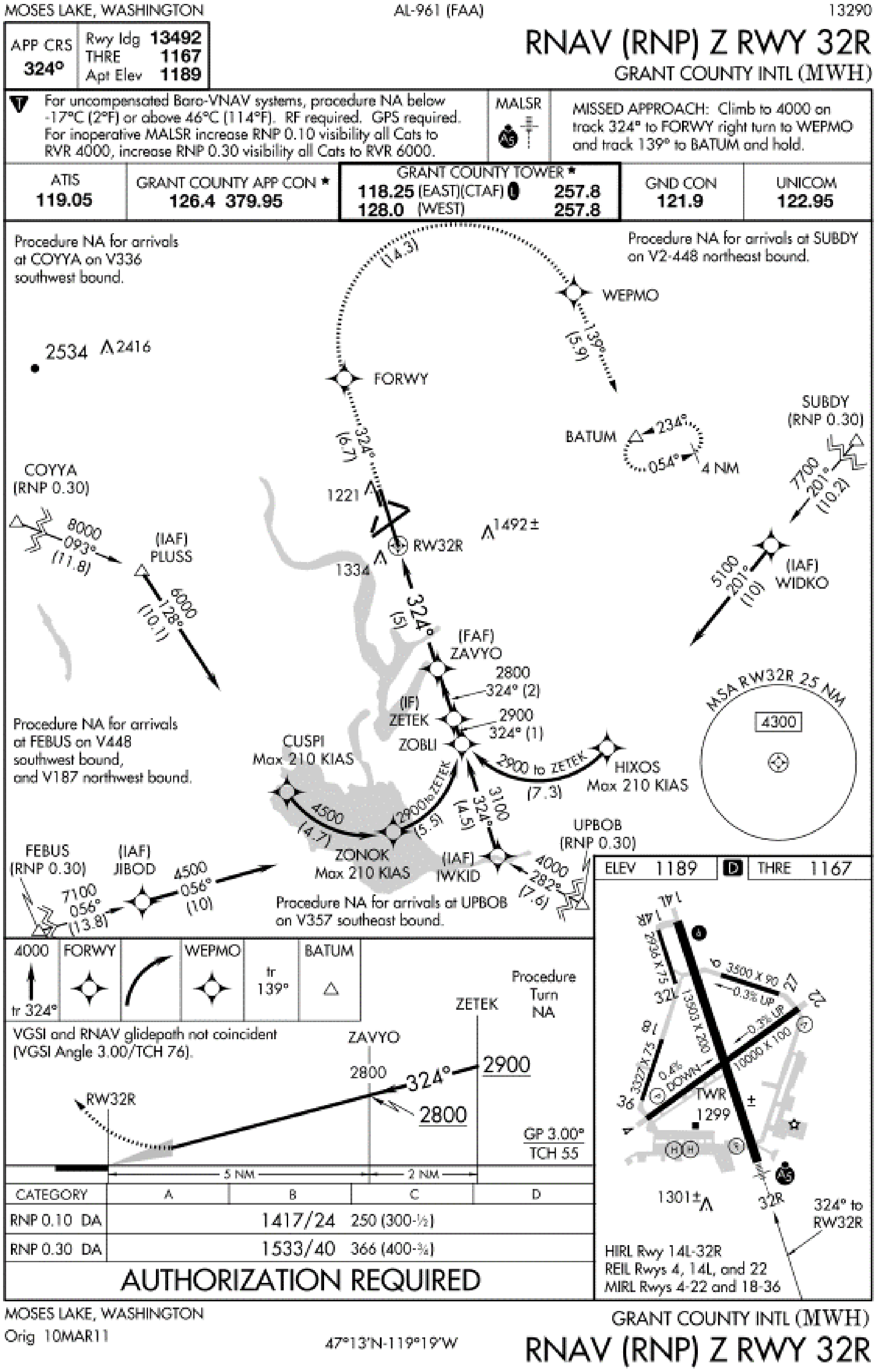


Figure 52. NALTE1 RNAV STAR to runway 14L at KMWH.



CATEGORY	A	B	C	D
RNP 0.10 DA	1417/24 250 (300-½)			
RNP 0.30 DA	1533/40 366 (400-¾)			

AUTHORIZATION REQUIRED

Figure 53. RNP AR approach to runway 32R at KMWH.

Appendix E. Test Card Examples

This appendix contains the five test card formats used during the flight test, with scenario B03 on February 21st as the example. Configuration control was critical, so the "date" field indicated the day the scenario would be flown, and the "published" field indicated the publication date and change number (if appropriate). For example, if a change had been made after the initial 2 p.m. distribution of the test cards, a complete set of new test cards would have been published as "2/16, change 1."

Figure 54 illustrates the format used by the controllers, which contained all of the scenarios for that day on one page. The letters "IP" indicate the "Initial Point" the aircraft was to head to after the previous IM operation was complete, and "LT" or "RT" indicated a "left turn" or "right turn" if holding was required.

ATD-1 Flight Plan **Date: 2/21/2017** **(KMWH 32R)** Published: 2/16

Scenario 1: A04 (first half of flight plan)

- N889H: Route: BFI..ZIRAN..BARYN..JELVO, FL230
- UAL2197: Route: SEA..ZIRAN..BARYN..JELVO, FL230
- N757HW: Route: BFI..ZIRAN..BARYN..JELVO, FL230

Scenario 2: B04 (second half of flight plan)

- N889H: IP: RIINO 343010, LT, FL220 Route: RIINO.SUBDY1.SUBDY.RRZ32R
- UAL2197: IP: MAHTA 274010, RT, FL230 Route: MAHTA.SUBDY1.SUBDY.RRZ32R
- N757HW: IP: JELVO 222010, RT, FL230 Route: JELVO.SUBDY1.SUBDY.RRZ32R

Scenario 3: B04

- N889H: IP: RIINO 343010, LT, FL220 Route: RIINO.SUBDY1.SUBDY.RRZ32R
- UAL2197: IP: MAHTA 274010, RT, FL230 Route: MAHTA.SUBDY1.SUBDY.RRZ32R
- N757HW: IP: JELVO 222010, RT, FL230 Route: JELVO.SUBDY1.SUBDY.RRZ32R

Scenario 4: B03

- N889H: IP: SINGG 222015, LT, FL220 Route: SINGG.SUBDY1.SUBDY.RRZ32R
- UAL2197: IP: MAHTA 274010, RT, FL230 Route: MAHTA.SUBDY1.SUBDY.RRZ32R
- N757HW: IP: NACUN 312010, LT, FL230 Route: NACUN.UPBOB1.UPBOB.RRZ32R

Scenario 5: B03

- N889H: IP: SINGG 222015, LT, FL220 Route: SINGG.SUBDY1.SUBDY.RRZ32R
- UAL2197: IP: MAHTA 274010, RT, FL230 Route: MAHTA.SUBDY1.SUBDY.RRZ32R
- N757HW: IP: NACUN 312010, LT, FL230 Route: NACUN.UPBOB1.UPBOB.RRZ32R

Scenario 6: B05

- N889H: IP: RIINO 343010, LT, FL220 Route: RIINO.SUBDY1.SUBDY.RRZ32R
- UAL2197: IP: MAHTA 274010, RT, FL230 Route: MAHTA.SUBDY1.SUBDY.RRZ32R
- N757HW: IP: NACUN 312010, LT, FL230 Route: NACUN.UPBOB1.UPBOB.RRZ32R

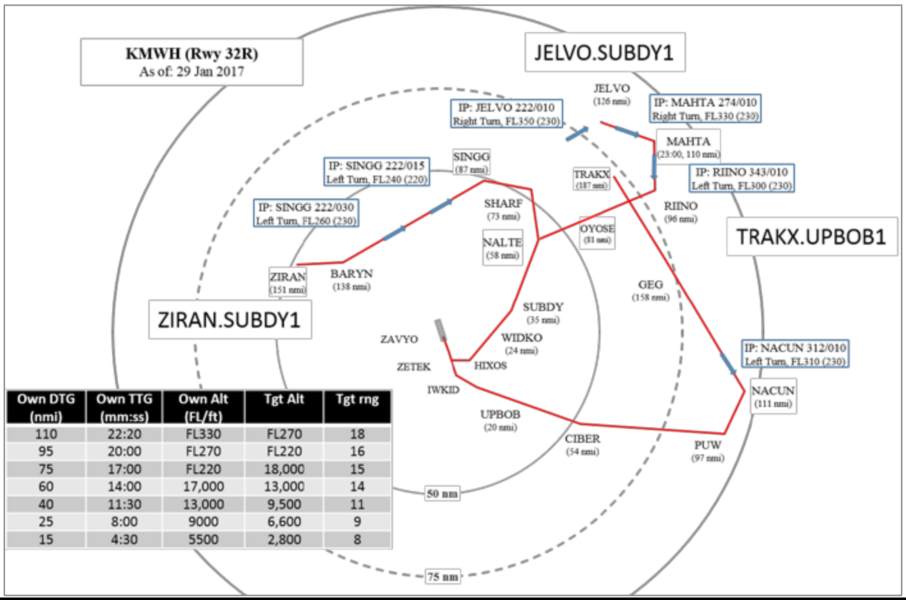
Scenario 7: B05

- N889H: IP: RIINO 343010, LT, FL220 Route: RIINO.SUBDY1.SUBDY.RRZ32R
- UAL2197: IP: MAHTA 274010, RT, FL230 Route: MAHTA.SUBDY1.SUBDY.RRZ32R
- N757HW: IP: NACUN 312010, LT, FL230 Route: NACUN.UPBOB1.UPBOB.RRZ32R

Figure 54. Flight test card for air traffic controllers.

The FTD formatted test card (Figure 55) contained one page per scenario. The top of the card displayed the date, sequence of scenario, scenario number, database, start/stop time, publication date, and change number. A schematic of the route structure was at the top portion of the card, and the bottom half of the page was a worksheet organized by aircraft arrival flow (left to right) and by tasks to be accomplished (top to bottom). The "*Diff from Long Pole*" indicated the difference in time the FTD had to add or subtract from the "long pole" aircraft to calculate the scheduled time of arrival for the other aircraft. The spacing error used the reverse convention where the "+" indicates the aircraft is early.

2/21/2017 Seq #: 5 Scenario: **B03** NDB: 1 Start/Stop time: Published: 2/16



Own DTG (nmi)	Own TTG (mm:ss)	Own Alt (FL/ft)	Tgt Alt	Tgt rng
110	22:20	FL330	FL270	18
95	20:00	FL270	FL220	16
75	17:00	FL220	18,000	15
60	14:00	17,000	13,000	14
40	11:30	13,000	9,500	11
25	8:00	9000	6,600	9
15	4:30	5500	2,800	8

Sequence / Call sign	#1 / **N889H**	#2 / **UAL2197**	#3 / **N757HW** (LP)
IP, Alt	SINGG 222/015, LT, FL220	MAHTA 274/010, RT, FL230	NACUN 312/010, LT, FL230
Route	SINGG.SUBDY1.RRZ32R	MAHTA.SUBDY1.RRZ32R	NACUN.UPBOB1.RRZ32R
Crew to FTD: ETA to:	ZAVYO:	ZAVYO:	ZAVYO:
Diff from Long Pole	-5	-3	
FTD to crew: STA to:			
(Delay) FIM Type	(None)	CROSS	CROSS
ABP		ZAVYO	ZAVYO
Desired PSI		90-150 sec	120-180 sec
Crew to FTD: PSI			
Desired Spacing Error		+60 sec	+30
FTD to crew: ASG			
ARM at:		RIINO	PUW

Notes: Target speed: no delay.

Figure 55. Flight test card for the Flight Test Director.

Aircraft-specific test cards were given to each pilot. Figure 56 illustrates the card for the first aircraft in the arrival stream (the F-900), which had specific airspeeds to fly in order to emulate the ground schedule response to an airport system delay (“no delay” in scenario B03). Scenarios with a delay had slower speeds assigned to each waypoint for the first aircraft.

N889H	**B03** (Rwy 32R)	# 5
Date: 2/21/2017	NDB: 1	Printed: 2/16

File To: SINGG 222015..SINGG

IP: SINGG 222/015, LT, FL220

ETA at ZAVYO (from FMS): __________

ZAVYO STA (from FTD): __________

Depart Initial Pt to achieve ZAVYO STA

Aircraft 1 Ownship Data:

- DESTINATION: **KMWH**
- Runway: **32R**
- Route / STAR: SUBDY1.SINGG (ZIRAN)
- Approach: RRZ32R.SUBDY
- Speed Profile: FL220 270 KT

Aircraft 1 Route: [FTD freq: 123.525]

- SINGG 270
- SHARF 270
- NALTE 270
- SUBDY 210
- WIDKO 210
- HIXOS 210
- ZETEK 190
- ZAVYO 170

AC #1: N889H, SINGG 222/015, FL220

AC #2: UAL2197, MAHTA 274/010, FL230

AC #3: N757HW, NACUN 312/010, FL230

Target speed: no delay.

Figure 56. Flight test card for the lead aircraft.

Figure 57 illustrates the test card for the second aircraft in the arrival stream (the United Airlines B-737). From top to bottom, it contained information to setup the scenario, Ownship data, IM data, and the arrival sequence and starting location of all three aircraft. The spacing error used the reverse convention where the "+" indicates the aircraft is early.

UAL2197	**B03** (Rwy 32R)	# 5
Date: 2/21/2017	NDB: 1	Printed: 2/16, ch1

File To: JELVO

IP: MAHTA 274/010, RT, FL230

ETA at ZAVYO (from FMS): _________

ZAVYO STA (from FTD): _________

Depart IP to achieve ZAVYO STA

<u>Aircraft 2 Ownship FIM Data</u>:

- DESTINATION: **KMWH**
- Runway: **32R**
- Route / STAR: SUBDY1.MAHTA (JELVO)
- Approach: RRZ32R.SUBDY (ENTER DONE)
- Cruise Descent: FL230 .78M 270 KT (DONE)
- CRUISE & DESCENT WINDS: entered

<u>Aircraft 2 FIM Data:</u> [FTD freq: 123.525]

Note: if required, clear FIM data (CANCEL IM) prior to data entry

- IM CLEARANCE: **CROSS**
- Test ASG (blue): **111 sec**
- TARGET ID: **N889H**
- TARGET ROUTE: ZIRAN.SUBDY1.SUBDY.RRZ32R
- ACHIEVE BY: **ZAVYO**
- TERMINATE: ZAVYO (ENTER ARM)

ARM at RIINO

- PSI desired: 90-150 sec Error: +60 sec [Goal: 150-210 sec]
- **PSI** (white, from algorithm): _________ ***PSI to FTD***
- **ASG** (blue, FTD assigned): _________ ***Execute FIM***

AC #1: N889H, SINGG 222/015, FL220

AC #2: UAL2197, MAHTA 274/010, FL230

AC #3: N757HW, NACUN 312/010, FL230

Target speed: no delay.

Figure 57. Flight test card for the second (first IM) aircraft.

Figure 58 illustrates the test card for the third aircraft in the arrival stream (the Honeywell B-757). The spacing error used the reverse convention where the "+" indicates the aircraft is early.

N757HW	**B03** (Rwy 32R)	# 5
Date: 2/21/2017	NDB: 1	Printed: 2/16, ch1

File To: NACUN 312010

IP: NACUN 312/010, LT, FL230

ETA at ZAVYO (from FMS): __________ (LP)

ZAVYO STA (from FTD): __________

Depart Initial Pt to achieve ZAVYO STA

Aircraft 3 Ownship Data:

- DESTINATION: **KMWH**
- Runway: **32R**
- Route / STAR: UPBOB1.NACUN (TRAKX)
- Approach: RRZ32R.UPBOB (ENTER DONE)
- Cruise Descent: FL230 .78M 270 KT (DONE)
- CRUISE & DESCENT WINDS: entered

Aircraft 3 FIM Data: [FTD freq: 123.525]

Note: if required, clear FIM data (CANCEL IM) prior to data entry

- IM CLEARANCE: **CROSS**
- Test ASG (blue): **111 sec**
- TARGET ID: **UAL2197**
- TARGET ROUTE: JELVO.SUBDY1.SUBDY.RRZ32R
- ACHIEVE BY: **ZAVYO**
- TERMINATE: ZAVYO (ENTER ARM)

ARM at PUW

- PSI desired: 120-180 sec Error: +30 [Goal: 150-210 sec]
- **PSI** (white, from algorithm): __________ ***PSI to FTD***
- **ASG** (blue, FTD assigned): __________ ***Execute FIM***

AC #1: N889H, SINGG 222/015, FL220

AC #2: UAL2197, MAHTA 274/010, FL230

AC #3: N757HW, NACUN 312/010, FL230

Target speed: no delay.

Figure 58. Flight test card for the third (second IM) aircraft.

Appendix F. Forecast Winds and Forecast Wind Error by Day

An example of the forecast winds from NOAA given during the morning briefing are shown in Table 13 and that information was entered by the pilots of all three aircraft into their respective FMS and EFBs (if equipped). Winds forecast for FL340 were used and entered as FL350 for the en route operations. Since KMWH data were not available, the descent winds for KGEG and KYKM were interpolated (causing some wind direction forecasts to average between 10 degree increments). When surface winds were reported as ‘calm’, the pilots entered ‘359/01’. The criteria to update winds during the flight (i.e., a change to the landing runway) was never met, therefore the values entered prior to takeoff were used throughout the entire flight test. The wind levels entered into the equipment are listed below:

- FMS:
  - en route: FL350
  - descent: FL180, 12,000 feet, and 6000 feet
- EFB:
  - en route: FL350
  - descent: FL240, FL180, 12,000 feet, 6000 feet, and Surface

Table 13. Forecast winds by day.

Day	Date	FL340	FL240	FL180	12,000 ft.	6000 ft.	SFC
1	1/20/2017	210/30	230/23	200/18	170/21	170/23	360/08
2	1/24/2017	360/32	326/28	350/20	350/15	330/09	359/01
3	1/25/2017	030/41	360/28	015/25	350/15	280/06	359/01
4	1/26/2017	050/33	030/30	030/25	010/16	310/10	359/01
5	1/27/2047	340/59	310/27	300/25	290/20	260/10	050/05
6	2/01/2017	280/126	280/88	290/50	040/13	080/23	360/04
7	2/02/2017	290/69	280/66	290/42	320/10	060/17	010/10
8	2/03/2017	230/57	230/39	230/36	240/41	210/30	020/08
9	2/07/2017	260/82	260/60	255/39	250/22	130/12	340/11
10	2/08/2017	280/163	270/83	270/68	260/43	220/17	350/09
11	2/09/2017	240/126	240/87	225/57	240/55	220/52	220/04
12	2/10/2017	240/86	230/50	230/52	240/50	240/38	290/04
13	2/13/2017	030/23	240/12	330/23	340/15	020/05	360/05
14	2/14/2017	210/24	210/10	230/09	240/10	160/10	230/03
15	2/15/2017	240/43	240/39	230/46	240/39	220/27	110/04
16	2/16/2017	210/89	210/68	210/42	210/31	230/37	230/05
17	2/20/2017	240/78	220/28	220/30	230/48	210/30	350/06
18	2/21/2017	210/33	210/28	240/23	240/14	300/10	320/09
19	2/22/2017	220/20	220/20	230/18	270/15	330/08	030/04

For every valid IM operation, the root mean square error along the flight path between the NOAA descent wind forecast and the winds sensed by the Ownship and Target aircraft is shown in Figure 59 (ref. 26). Large error values indicate IM operations that were considered valid for analysis purposes where the difference between the forecast winds and actual sensed winds was fairly significant. As noted in section 7.9.2.3, a software error prevented trajectory updates due to differences between the sensed winds and the wind forecast, resulting in cases where the Ownship had significantly larger headwind deviations than if the wind blending functionality worked properly. In some of the Cross-FAF cases (for example, in section 7.9.2.3), these large headwind deviations degraded the spacing accuracy achieved at the ABP.

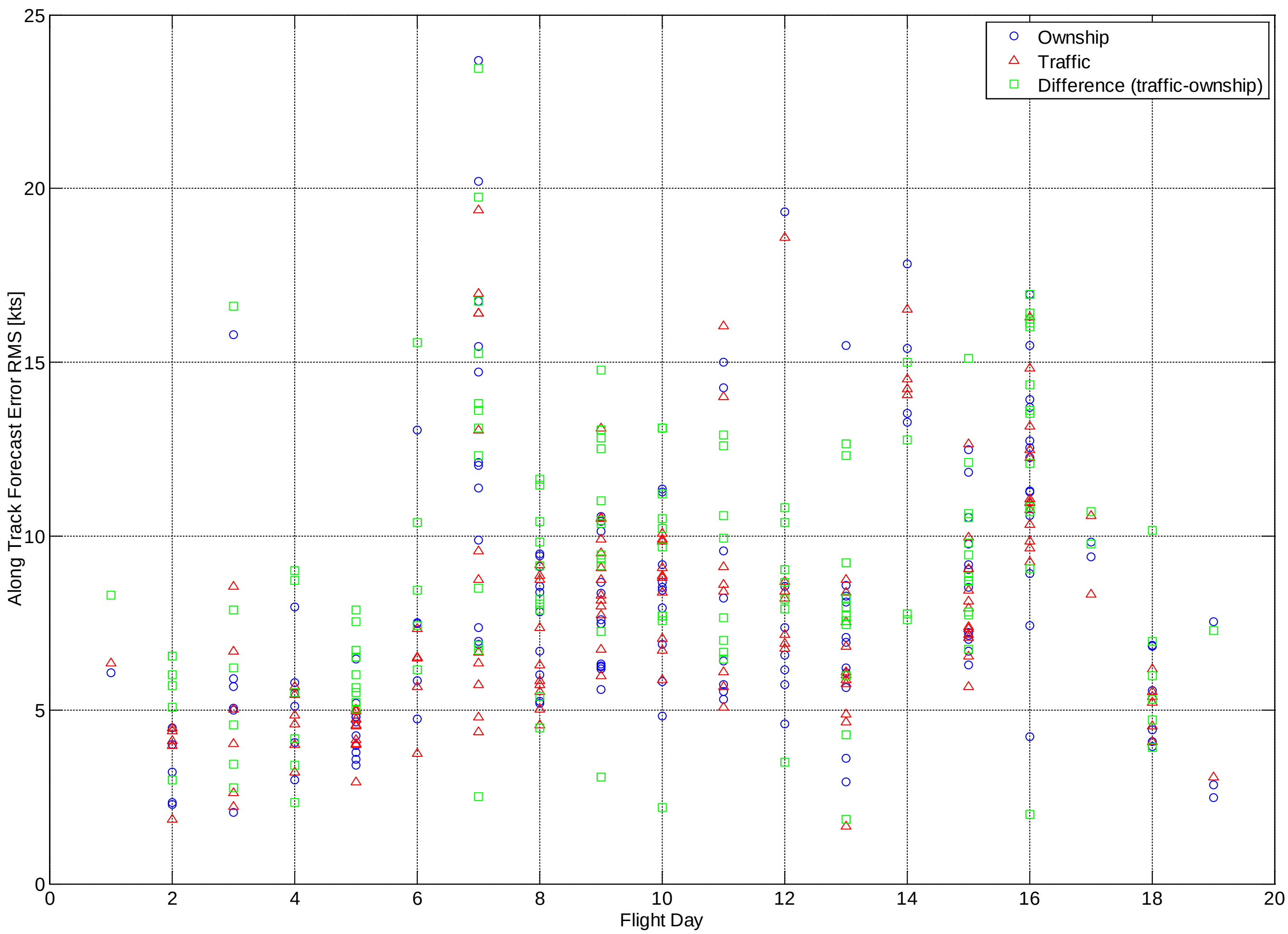


Figure 59. Root mean square error in knots of along-track forecast wind error by day.

Appendix G. Criteria for Valid Data

The following criteria were used to classify the data validity for each run:

1. Aircraft crossed the PTP while PAIRED in an IM operation
2. The IM operation had sufficient time producing valid data prior to crossing the ABP or PTP
   a) En route, TBO: 25 nmi prior to ABP
   b) En route, CTD: 25 nmi prior to PTP
   c) Arrival, TBO: 40 nmi prior to ABP
   d) Arrival, CTD: 40 nmi prior to PTP
   e) TRACON, TBO:10 nmi prior to default PTP
3. Interruption of the IM operation
   a) Prior to 40 nmi DTG for Ownship to the PTP:
      - Truncate data and begin IM operation at the end of the interruption
   b) Less than 40 nmi DTG for Ownship to the PTP:
      - Not long enough to cause a change to performance
         - Commanded IM speed at beginning is the same as after the interruption
         - MSI/PSI does not change more than 5 seconds or the corresponding distance
4. Changes to the IM operation due to incorrect PSI/MSI calculations will not be used
5. The ASG value at the beginning of the IM operation is the same as when crossing the PTP
6. The spacing error must be less than the “Feasibility Check” criteria, that is, 15 percent of the time to go to slow down, and 11 percent of the time to go to speed up (ref. 8, section 2.2.4.8.1). This check was only applied at the beginning of the valid data set.
7. There must be sufficient control authority for the Ownship to resolve the spacing error at the beginning of the valid data set.

Appendix H. Observations and Areas for Future Research

The information and questions presented in this appendix are potential areas for future research and development to enhance the performance and behavior of the IM operation in both an ATD-1 environment and a NextGen environment, e.g., trajectory-based operations, integrated avionics, and data comm. Some of these suggestions are already in the FAA's research and implementation plans, while others may represent a significant departure from the current IM concept.

H.1 Concept of Operations

The fully integrated ATD-1 ConOps was not exercised during the flight test due to not having the two ground elements, i.e., the schedule and the controller decision support tools, available for the flight test, therefore, the recommendations and areas for future research in this sub-section are based on previous simulation studies, as well as observations and comments from the pilots and researchers during the flight test.

- Since the aircraft will be at a spacing interval greater than the separation criteria when the IM clearance is issued, should the IM avionics have a requirement that the aircraft remain separated throughout the operation? Even in a NextGen environment where the controller retains separation responsibility, the next implementation of control laws should consider the minimum spacing and closure rate between aircraft, and in doing so, may decrease the number of times the controller intervenes during the IM operation. An implementation consideration of this proposal would be how the IM avionics would obtain the separation criteria relative to the aircraft types and current airspace location.
- The initial IM commanded speed generated by the IM avionics should not cause concern for the controller. One possible approach for resolving this issue would be for the pilot to inform the controller of the initial IM commanded speed prior to setting that speed in the MCP.
- Should there be a requirement for the ground software producing the IM clearance to ensure the time-based spacing interval for the FAF is not too small to meet separation criteria at higher altitudes due to certain wind conditions? Previous research has shown that an ASG calculated for the FAF may not be appropriate for upstream waypoints. In the analysis described in reference 42, the PBN arrival procedures at Phoenix Sky Harbor International Airport were used where the desired spacing at the FAF and an upstream meter point approximately 50 to 60 nmi prior to the FAF where compared to each other. 8,671 wind forecasts from 2011 were used to determine the rate at which the spacing interval at the FAF was insufficient when using a 6 nmi spacing interval at the upstream meter point. When using 3 nmi spacing at the FAF, the rate of insufficient spacing at the upstream meter point/fix was 0.03 percent, and this rate increased to 5 percent when using 2.5 nmi spacing at the FAF. This analysis demonstrates that a single ASG calculated for the FAF and used for the entire arrival and approach operation may provide inadequate separation at an upstream meter point, particularly if the ASG is for minimum or reduced separation criteria. Conversely, if the ASG is calculated for the upstream waypoint and then used for the entire arrival and approach operation, then the spacing at the FAF could cause a decrease in the efficiency of runway throughput.
- If the scheduled time of arrival to the first speed constrained waypoint for the Ownship was available to the flight crew prior to top of descent, that time could be used by the FMS to

calculate an appropriate Mach/CAS speed profile to most efficiently achieve the expected schedule time. This capability would be particularly useful if the IM operation commenced at the waypoint with the scheduled time of arrival.
- The Final Approach Spacing operation was not part of the ATD-1 ConOps, nor did the ATD-1 subproject conduct any human-in-the-loop experiments of the Final Approach Spacing operation. The flight test mirrored these operations as described in reference 8 as closely as possible, however, the operations as conducted in the flight test did not completely align with the procedures described in the standards. Human-in-the-loop experiments should be conducted to determine if the pilots will find conducting the Final Approach Spacing operations as defined in the standards as acceptable.

H.2 IM Avionics

- For the ATD-1 environment, changes to the IM avionics to reduce the number of speed commands and speed reversals should be considered. Possible changes could include:
  - improved filtering of the Target's groundspeed or time-history airspeed, the latter for the CTD speed control law;
  - improved model of the expected deceleration/acceleration rate for the Ownship aircraft based on altitude, airspeed, descent angle, and aircraft configuration; and
  - a more sophisticated method to trade-off spacing error with the rate of speed commands (see reference 47 as an example of research into this alternative), noting the potential impact of this change on string stability and the spacing error requirements defined in reference 8.
- For the ATD-1 environment, an evaluation of clearance data requirements and a formal redesign and evaluation of the IM displays should be conducted with a focus on reducing pilot workload.
- For the NextGen environment, the availability of intent information of the Target's trajectory could significantly reduce the number of speed commands and reduce the number of speed reversals.
- To achieve the desired spacing interval and tolerance envisioned by IM operations, either the IM avionics need to be directly tuned to and compensate for that aircraft's auto-throttle behavior or it would be desirable for the auto-throttle system to provide tighter accuracy to the commanded speed.

H.3 Flight Crew IM Procedure

- In an ATD-1 environment, the crew workload could be reduced and the protection of altitude constraints improved if alternatives were explored to increase the use of the FMS vertical path mode and auto-throttle system. Specifically, modify the aircraft system behavior to remain in vertical path mode when IM airspeeds are set in the MCP, or if not feasible, set the IM airspeed into the FMS instead of the MCP when above 10,000 feet.
- In a NextGen environment, the use of data comm to transmit the IM clearance information from the controller to the pilot, and to enable auto-loading of that information into the IM avionics, appears to promise a substantial decrease to pilot workload and data entry error.

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ATD-1 is sponsored by the National Aeronautics and Space Administration (NASA) Airspace Technology Demonstration (ATD) Project, part of NASA's Airspace Operations and Safety Program (AOSP) (formerly the Airspace System Program). The ATD-1 goal is to operationally demonstrate the capability of three integrated NASA research technologies, along with Automatic Dependent Surveillance – Broadcast (ADS-B) In technology, to achieve Trajectory-Based Operations (TBO) from cruise to the runway threshold while maintaining high throughput in busy terminal airspace. The expected benefits of improved safety, reduced fuel consumption, and improved schedule integrity are intended to address the forecasted increase in aircraft operations and flight delay, as well as stimulate aircraft equipage with ADS-B In.

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