Evaluation of Flight Deck-Based Interval Management Crew Procedure Feasibility

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Air traffic demand is predicted to increase over the next 20 years, creating a need for new technologies and procedures to support this growth in a safe and efficient manner. The National Aeronautics and Space Administration's (NASA) Air Traffic Management Technology Demonstration – 1 (ATD-1) will operationally demonstrate the feasibility of efficient arrival operations combining ground-based and airborne NASA technologies. The integration of these technologies will increase throughput, reduce delay, conserve fuel, and minimize environmental impacts. The ground-based tools include Traffic Management Advisor with Terminal Metering for precise time-based scheduling and Controller Managed Spacing decision support tools for better managing aircraft delay with speed control. The core airborne technology in ATD-1 is Flight deck-based Interval Management (FIM). FIM tools provide pilots with speed commands calculated using information from Automatic Dependent Surveillance – Broadcast. The precise merging and spacing enabled by FIM avionics and flight crew procedures will reduce excess spacing buffers and result in higher terminal throughput. This paper describes a human-in-the-loop experiment designed to assess the acceptability and feasibility of the ATD-1 procedures used in a voice communications environment. This experiment utilized the ATD-1 integrated system of ground-based and airborne technologies. Pilot participants flew a high-fidelity fixed base simulator equipped with an airborne spacing algorithm and a FIM crew interface. Experiment scenarios involved multiple air traffic flows into the Dallas-Fort Worth Terminal Radar Control airspace. Results indicate that the proposed procedures were feasible for use by flight crews in a voice communications environment. The delivery accuracy at the achieve-by point was within +/- five seconds and the delivery precision was less than five seconds. Furthermore, FIM speed commands occurred at a rate of less than one per minute, and pilots found the frequency of the speed commands to be acceptable at all times throughout the experiment scenarios.

Nomenclature

ADS-B = Automatic Display Surveillance – Broadcast
ASTAR = Airborne Spacing for Terminal Area Routes
ASTOR = Aircraft Simulation for Traffic Operations Research

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ATC	=	Air Traffic Control
ATD-1	=	Air Traffic Management Technology Demonstration – 1
ATOL	=	Air Traffic Operations Laboratory
CMS	=	Controller Managed Spacing
EFB	=	Electronic Flight Bag
FAF	=	Final Approach Fix
FDB	=	Full Data Block
FIM	=	Flight deck-based Interval Management
IFD	=	Integration Flight Deck
IM	=	Interval Management
N	=	number of observations
NextGen	=	Next Generation Air Transportation System
OPD	=	Optimized Profile Descent
PF	=	pilot flying
PM	=	pilot monitoring
RNAV	=	Area Navigation
SD	=	standard deviation
TMA-TM	=	Traffic Management Advisor with Terminal Metering
TOD	=	top-of-descent
TRACON	=	Terminal Radar Approach Control

I. Introduction

Air traffic demand is predicted to increase by 2 to 3% per year over the next 20 years, with the number of revenue passenger miles nearly doubling by 2032.[1] If the current air transportation system is left unmodified, this projected growth will lead to increased delays, fuel costs, noise pollution, and greenhouse gas emissions. The Federal Aviation Administration's (FAA) Next Generation Air Transportation System (NextGen) concept envisions a comprehensive transformation of the National Airspace System to support this continued growth in a safe, reliable, and efficient manner.[2] The National Aeronautics and Space Administration (NASA) is collaborating with the FAA and other industry partners to develop advanced technologies and automation tools necessary for NextGen.

Improving the efficiency of terminal area arrival operations is an especially complex task. Conditions in busy terminal areas today often result in inefficient arrival paths involving frequent changes in speed, heading, and altitude to maintain safe separation between aircraft and absorb large amounts of delay. These inefficiencies lead to increased fuel burn and noise pollution, as well as higher controller workload and traffic congestion. Furthermore, greater uncertainty in the current system causes controllers to add separation buffers between aircraft, thus reducing throughput and increasing delays. Although more efficient arrivals are available, current technology limits their use to periods of light to moderate traffic conditions. New concepts and technologies are needed to make efficient arrival procedures feasible during heavy traffic.

NASA's Air Traffic Management Technology Demonstration – 1 (ATD-1) will operationally demonstrate the feasibility of efficient arrival operations combining ground-based and airborne NASA technologies.[3,4] The ATD-1 integrated system consists of the following three core components.

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

The Traffic Management Advisor (TMA) was originally developed at NASA Ames Research Center (ARC) and is currently used at Air Route Traffic Control Centers nationwide to determine an appropriate arrival schedule.[5] TMA-TM is an enhanced form of TMA that includes terminal area metering and enables the use of more efficient arrival procedures. CMS decision support tools were also developed at NASA ARC. They provide controllers with the information necessary to achieve arrival schedule conformance using speed commands, thus reducing the use of tactical vectoring.[6,7] The use of TMA-TM in conjunction with CMS tools has been assessed, and results indicate an increase in airport throughput.[8-11]

Interval Management (IM) is an airborne spacing concept in which the flight crew is responsible for flying their aircraft at a speed that achieves their assigned time-based spacing interval behind a target aircraft, while Air Traffic Control (ATC) remains responsible for ensuring that all aircraft maintain safe separation. Typically, ATC designates a spacing buffer in addition to the separation requirement to ensure that separation is always maintained. The goal of airborne spacing is to decrease this spacing buffer by decreasing the variability of the time error associated with an aircraft's arrival at a specific point along its arrival route. The precise merging and spacing enabled by FIM avionics and flight crew procedures reduces excess spacing buffers and results in higher terminal throughput. Studies by MITRE,[12-14] EUROCONTROL,[15-18] and NASA Langley Research Center (LaRC)[19-21] have demonstrated an increase in efficiency through the use of FIM operations.

In addition to utilizing these advanced technologies, aircraft will fly new, more direct Area Navigation (RNAV) routes that extend from en route airspace to the runway. Optimized Profile Descent (OPD) procedures will also be implemented to provide a fuel-efficient continuous descent approach rather than the step-down descents used today. The Automatic Dependent Surveillance – Broadcast (ADS-B) infrastructure currently being implemented by the FAA will also be leveraged. The FIM tools will calculate speed commands using information provided by ADS-B, which is more accurate than traditional radar. The ability of flight crews to make more precise speed adjustments will enable a reduction in spacing buffers resulting in higher terminal throughput.

These technology components and procedures have been evaluated independently, and each has demonstrated benefits. As an integrated system, these technologies will increase throughput, reduce delay, and minimize environmental impacts. Initial studies at NASA ARC to demonstrate the ATD-1 concept and validate operational feasibility indicate that the concept is viable and operations are acceptable.[22-24]

As part of the preparations for the ATD-1 flight demonstration, a human-in-the-loop experiment was conducted at NASA LaRC in 2012. The objective of this experiment was to assess if the procedures outlined in the ATD-1 Concept of Operations,[25] when used with the integrated ATD-1 technologies, were acceptable to and feasible for use by flight crews in a voice communications environment. This paper describes the experiment's methodology and the results of the evaluation of the feasibility of the flight crew procedures. Additional details regarding the results associated with the pilot acceptability and workload ratings are presented in a companion paper.[26]

II. Methodology

A. Experiment and Scenario Design

The focus of this human-in-the-loop experiment was to evaluate the acceptability and feasibility of the proposed air/ground procedures when used with a prototype flight deck control-display interface in a voice communications environment. The airspace environment was modeled on the Dallas-Fort Worth (DFW) Terminal Radar Approach Control (TRACON) area. Each experiment scenario consisted of multiple air traffic flows involving 25 arrival aircraft flying into DFW airport and landing on runways 17C and 18R. All aircraft flew OPDs to the Instrument Landing System (ILS) intercept to the runway threshold. Some aircraft initialized in level cruise and flew the full arrival and approach to the runway, while others initialized in descent and flew only a portion of the arrival before flying the approach. One of the arrival aircraft employed a full-scale, high fidelity fixed base simulator with subject pilots operating as a two-person crew. This simulator was equipped with the latest version of NASA LaRC's airborne spacing algorithm, Airborne Spacing for Terminal Area Routes (ASTAR),[27] and a prototype flight deck control-display interface. The remaining 24 arrival aircraft were flown by two researcher pseudo-pilots using medium fidelity simulators. To provide a realistic traffic environment, each scenario also included 25 departure aircraft. Recently retired DFW air traffic controllers served as confederate Center, Feeder, Final, and Tower controllers issuing speed commands, vectors, and IM clearances.

Subject aircraft performing FIM operations were expected to use the ASTAR-provided speed guidance whenever possible. This speed guidance is designed such that the spacing aircraft will achieve the assigned spacing goal behind the target aircraft at the achieve-by point while remaining within 10% of the optimized profile airspeed. In this experiment, the achieve-by point was the final approach fix (FAF). The FIM prototype flight deck control-display interface shown in Fig. 1 consisted of two side-mounted electronic flight bags (EFB) for data entry and conformance monitoring, and ADS-B guidance displays mounted under the glare shield in the pilot's forward field of view for airspeed commands.

Previous research on FIM conducted by NASA LaRC has utilized datalink to transfer information from ATC to the flight crew. However, the ground infrastructure necessary to support datalink will not be available for the ATD-1 flight demonstration. Instead voice communications must be used to transfer the information necessary for FIM operations. In this experiment, confederate controllers issued IM clearances to the flight crews, who then entered the

information into the EFBs, and activated the FIM avionics. The IM procedure required the flight crew to enter the following pieces of information included in the IM clearance into the EFBs.

- IM achieve-by point (i.e., FAF)
- Scheduled Time of Arrival at the IM achieve-by point
- Target aircraft callsign
- Assigned spacing goal (spacing interval required at the IM achieve-by point)
- Target aircraft flight path (arrival and transition)

FIM interface consisting of the IM application running on side-mount electronic flight bags. Target and error speed values are shown on ADS-B guidance displays mounted in the forward field of view.

Figure 1. Prototype flight deck control display interface

Five flight scenarios were defined using the 1x5 experiment matrix shown in Fig. 2 to allow an examination of five flight crew procedures.

1. The Nominal scenario consisted of an IM clearance issued by ATC prior to top-of-descent (TOD). After achieving the spacing goal, the subject aircraft maintained nominal FIM operations until reaching the achieve-by point.
2. During the Amend scenario, the initial IM clearance was issued shortly after TOD. Approximately two minutes after the spacing goal was achieved, ATC issued an amended clearance to increase spacing by 20 seconds.
3. In the Terminate scenario, the initial IM clearance was issued shortly after TOD. Once both the subject and target aircrafts were inside the DFW TRACON, ATC cancelled the IM clearance and vectored the target aircraft for landing on runway 13R. ATC then issued a new IM clearance with a new target for the subject aircraft.
4. The Suspend/Resume scenario consisted of an IM clearance issued by ATC prior to TOD. After the assigned spacing goal was achieved, ATC suspended the IM clearance and issued a speed change of 20 knots for the subject aircraft. Approximately two minutes later, ATC cleared the subject aircraft to resume IM spacing.

5. During the ADS-B Loss scenario, ATC issued the initial IM clearance prior to TOD. After the assigned spacing goal was achieved and both the subject and target aircraft were inside the TRACON, the target aircraft experienced a loss of ADS-B capability. The subject crew notified ATC that they were IM Unable due to ADS-B loss by the target, and ATC then cancelled the initial IM clearance and issued a new clearance with a new target.

During all five scenarios, the closest aircraft in the arrival stream for the same runway as the subject aircraft was designated as the initial target aircraft. If a new target was designated later in the scenario, it was always the next closest aircraft in the arrival stream. For both the Terminate and ADS-B Loss scenarios, the second clearance was issued in the TRACON at an altitude below 10,000 feet (ft).

Flight Crew Procedure	Nominal	Amend	Terminate	Suspend/Resume	ADS-B Loss

Figure 2.   Experiment design matrix

Every crew flew each scenario twice – once with the captain as the pilot flying (PF) and the first officer as the pilot monitoring (PM), and once with the first officer as the PF and the captain as the PM. Therefore, each crew flew a total of ten experiment runs. The run order of the scenarios was partially counterbalanced, and within each crew the pilots switched PF and PM responsibilities between runs.

The pilot participants received training material and access to computer based training prior to arriving at NASA. They also received four hours of classroom and hands-on training after arrival, including flying three training scenarios prior to commencing data collection. Each two-person crew participated in a two-day experiment session. The first day began with training, and then data collection flights were conducted, each lasting 25 minutes. The second day consisted of the remaining data collection flights, followed by a post-experiment questionnaire and debrief session.

B. Pilot Participants

Participants consisted of ten two-person crews of current, qualified 757/767 pilots employed by major U.S. air carriers (i.e., a total of 20 commercial airline pilots). All pilots were male and ranged from 40 to 62 years in age. On average, the pilots had 23 years of airline experience and over 13,000 hours of commercial airline flight time. To minimize potential effects associated with different airline operating procedures, all two-person crews were paired from the same airline, and the pilots flew in their current operational position (Captain or First Officer) using their company's standard operating procedures modified to include IM operations.

C. Scheduling and Spacing Technologies

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

1. Traffic Management Advisor with Terminal Metering (TMA-TM)

TMA-TM is an extension of the operational TMA that determines an arrival schedule based on airport conditions, airport capacity, required spacing, and weather conditions. This scheduling tool calculates the Estimated Time of Arrival and corresponding Scheduled Time of Arrival at various meter and merge points along the aircraft flight path. The TMA-TM data is broadcast to the en route and TRACON controller positions for use by the CMS tools to assist the controllers in maintaining optimum flow rates to the runways.

2. Controller Managed Spacing (CMS)

Three CMS tools were used in this experiment to provide controllers with the information needed to meet the TMA-TM generated schedule: early/late indicators, slot markers, and speed advisories. Early/Late indicators in the aircraft Full Data Blocks (FDB) enabled controllers to quickly assess the schedule-conformance information for that aircraft. Slot marker circles were used to indicate where an aircraft should be located at a given time if it were to fly the RNAV OPD, meeting all published speed and altitude restrictions. The relative position of the aircraft symbol and the slot marker provides a quick visual indication of how the aircraft is positioned relative to its scheduled time of arrival. Speed advisories in the aircraft's FDB helped controllers formulate speed clearances for aircraft not

performing FIM operations. The speed advisory is a recommended Calibrated Airspeed (CAS) which is predicted to place the aircraft back on schedule before reaching the scheduling fix.

3. Flight deck-based Interval Management (FIM)

The FIM tools provide onboard speed guidance to the flight crew to achieve a precise spacing interval behind a target aircraft and meet the schedule set by TMA-TM. In order to perform FIM operations in this experiment, the simulator flown by the subject pilots was equipped with NASA's ASTAR algorithm and a prototype FIM crew interface (see Fig. 1). The ASTAR airborne spacing algorithm produces speed guidance by determining time-to-go until an aircraft and its target reach an achieve-by point along a 4-D trajectory.

D. Facilities and Equipment

1. Air Traffic Operations Laboratory (ATOL)

This experiment used the ATOL, which contains a network of hundreds of real-time, medium-fidelity aircraft simulators. The simulation platform, known as the Airspace and Traffic Operations Simulation (ATOS), can be used for both batch and real-time human-in-the-loop experiments. Each aircraft simulator is referred to as an Aircraft Simulation for Traffic Operations Research (ASTOR).[28] The ASTOR components include: a six degrees of freedom aircraft model, Primary Flight Display (PFD), Multi-Function Display (MFD), autopilot and auto-throttle systems, Flight Management Computer (FMC), Multi-function Control Display Unit (MCDU), Mode Control Panel (MCP), and ADS-B.

This experiment required the addition of pseudo-pilot stations, which were developed to allow a single operator to control the basic functions of multiple ASTORs. Two researchers used the pseudo-pilot stations to control 24 ASTOR arrival aircraft that provided multiple air traffic flows into DFW. ATC controller stations using the Multi Aircraft Control System (MACS),[29] developed at NASA ARC, were also integrated into the ATOL to enable confederate air traffic controllers to provide a realistic air traffic control environment. All controller positions used standard Display System Replacement (DSR) or Standard Terminal Automation Replacement System (STARS) displays augmented with CMS tools. Four recently retired DFW air traffic controllers served as confederate Center, Feeder, Final, and Tower controllers.

2. Integration Flight Deck (IFD)

The IFD is a full-scale simulator representative of a large commercial transport category aircraft and is driven by an appropriate aircraft dynamics mathematical model.[30] The cockpit includes standard ship's instruments representative of a line operations aircraft, and the cockpit's visual system is a panorama system that provides 200° horizontal by 40° vertical field-of-view. For this experiment, all pilot participants flew the IFD and the visual scene used was the DFW terminal environment in a daytime setting. This simulator was also equipped with the ASTAR algorithm and the prototype FIM crew interface to enable the flight crews to perform FIM operations.

E. Dependent Measures

To assess the feasibility of the procedures, quantitative data were collected during each run, including spacing error at the FAF and the number and rate of speed commands issued by the airborne spacing algorithm. Although the achieve-by point was the FAF, the spacing error at the runway threshold was an additional metric of interest. To assess the acceptability of the proposed flight crew procedures, pilot acceptability and workload ratings were collected via electronic questionnaires and a post-experiment group debrief session.

III.   Results and Discussion

The results of the evaluation of the feasibility of the flight crew procedures are presented in this paper. Additional details regarding the results associated with the pilot acceptability and workload ratings are described in a companion paper.[26] For the following analyses and results, a sample size of 20 observations was anticipated for each scenario. However, data from one run of the ADS-B Loss scenario were excluded from the analyses due to simulation error.

A. Rate of Speed Commands

Much of the pilot workload for airborne spacing comes from implementing the commanded IM speeds. Pilots were instructed to maintain their speed within ±10 knots of the commanded speed and their altitude within ±400 ft of the vertical path. For each run, data were collected on the number and rate of IM speed commands. Table 1 presents the mean rate of speed commands over the entire flight, as well as for each segment of flight: from Flight

Level (FL) 240 to FL180, FL180 to 11,000 ft, 11,000 ft to 6,000 ft, and 6,000 ft to the FAF. In the ADS-B Loss scenario, the initial IM clearance was issued around FL240. During both the Terminate and ADS-B Loss scenarios, the initial IM clearance was cancelled and a new clearance was issued between 11,000 ft and 6,000 ft. Therefore, the subject aircraft was conducting FIM operations less than 75% of the time during these flight segments, and so the rate of speed commands is not given in these three cases. Previous work by EUROCONTROL found two speed changes per minute was acceptable to the flight crew when performing spacing operations.[16,17] In this experiment, the frequency of speed changes was highest from 6,000 ft to the FAF, but was still less than one per minute in all scenarios. Statistical analysis was performed using the one-sample Poisson rate test, a hypothesis test appropriate for analyzing the number of occurrences of an event in a given length of time. For all five scenarios, the mean rate of speed commands was acceptable, i.e., less than two per minute for each flight segment ($p < 0.0005$).

Table 1. Mean rate of speed commands (number of speed commands per min) for each segment of flight. Note that mean rate = 'n/a' indicates aircraft was conducting FIM operations less than 75% of the time.

Scenario	N	FL240 to FL180	FL180 to 11,000	11,000 to 6,000	6,000 to FAF	Total
Nominal	20	0.22	0.44	0.35	0.76	0.49
Amend	20	0.09	0.65	0.53	0.67	0.54
Terminate	20	0.12	0.50	n/a	0.67	0.53
Suspend/Resume	20	0.13	0.40	0.35	0.61	0.43
ADS-B Loss	19	n/a	0.43	n/a	0.72	0.61

In order to further evaluate the acceptability of the IM speed commands, data were also collected via post-run electronic questionnaires. Using a scale of "1" (Completely Disagree) to "7" (Completely Agree), pilots were asked if "the IM commanded speeds were operationally acceptable and appropriate" and if "the frequency of the IM speed commands was acceptable at all times throughout the scenario." Descriptive statistics associated with the pilot acceptability ratings are shown in Tables 2 and 3. For each question, pilots responded positively (rating of "5" or higher) 96% of the time, and the median rating was "7" in all cases. Only two of the 20 pilots provided ratings of "3" (Slightly Disagree) or less during the experiment scenarios. One pilot commented that the issuance of a new clearance below 10,000 ft during the ADS-B Loss scenario resulted in too much heads-down time by the PM. Comments from the other pilot indicated that two speed commands occurred in less than five seconds (sec) during two of the scenarios. Statistical analysis was performed using the Wilcoxon signed rank test, a nonparametric test appropriate for analyzing ordinal data. There were no statistically significant differences between the mean responses from the PF and PM in any scenario ($p \geq 0.205$). For all five scenarios, pilots reported the IM commanded speeds were operationally acceptable and appropriate, i.e., mean acceptability rating greater than 4.5 ($p \leq 0.001$). The pilots also found the frequency of the IM speed commands to be acceptable in all scenarios ($p \leq 0.001$).

Table 2. Descriptive statistics for pilot ratings of operational acceptability and appropriateness of IM commanded speeds

Scenario	N	Pilot Flying					Pilot Monitoring				
		Mean	SD	Min	Median	Max	Mean	SD	Min	Median	Max
Nominal	20	6.3	1.3	2	7	7	6.8	0.4	6	7	7
Amend	20	6.9	0.4	6	7	7	6.7	0.6	5	7	7
Terminate	20	6.6	0.8	4	7	7	6.5	1.4	1	7	7
Suspend/Resume	20	6.5	0.9	4	7	7	6.8	0.4	6	7	7
ADS-B Loss	19	6.3	1.5	1	7	7	6.4	1.3	2	7	7

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Table 3.   Descriptive statistics for pilot ratings of acceptability of the frequency of the IM speed commands

Scenario	N	Pilot Flying					Pilot Monitoring				
		Mean	SD	Min	Median	Max	Mean	SD	Min	Median	Max
Nominal	20	6.6	0.6	5	7	7	6.7	0.5	6	7	7
Amend	20	6.6	0.8	5	7	7	6.5	0.9	4	7	7
Terminate	20	6.5	0.8	4	7	7	6.2	1.4	1	7	7
Suspend/Resume	20	6.6	0.8	4	7	7	6.6	0.8	4	7	7
ADS-B Loss	19	6.4	1.5	1	7	7	6.5	1.1	3	7	7

B. Spacing Error at the Final Approach Fix

The primary measure of the FIM tool's performance is the ability to accurately and precisely deliver aircraft to the achieve-by point, which was the FAF in this study. The distribution of the time error associated with an aircraft's arrival at the FAF is shown in Fig. 3 for all five scenarios, and descriptive statistics are given in Table 4. Values of the spacing error less than zero indicate that the subject aircraft arrived earlier than its assigned spacing goal, and values greater than zero indicate the aircraft arrived late.

For this experiment, the a priori success criteria was determined to be a mean spacing error within ±5 sec with a standard deviation of less than 5 sec. From Fig. 3 and Table 4 it can be seen that the spacing error was within ±5 sec in 98 of the 99 flights. The largest spacing error occurred during the Amend scenario when the aircraft was 5.3 sec early. Statistical analysis was performed using the one-sample t-test and one-sample variance test to test the mean and standard deviation, respectively. For all five scenarios, the spacing error at the FAF had a mean within ±5 sec ($p < 0.0005$) and a standard deviation significantly less than 5 sec ($p < 0.0005$). Confidence intervals on the mean spacing error shown in Table 4 indicate that the delivery accuracy is within ±2.5 sec with at least 95% confidence in all scenarios. This clearly demonstrates the effectiveness of the ASTAR algorithm for the proposed flight crew procedures.

Table 4.   Descriptive statistics and confidence intervals for spacing error at the FAF (sec)

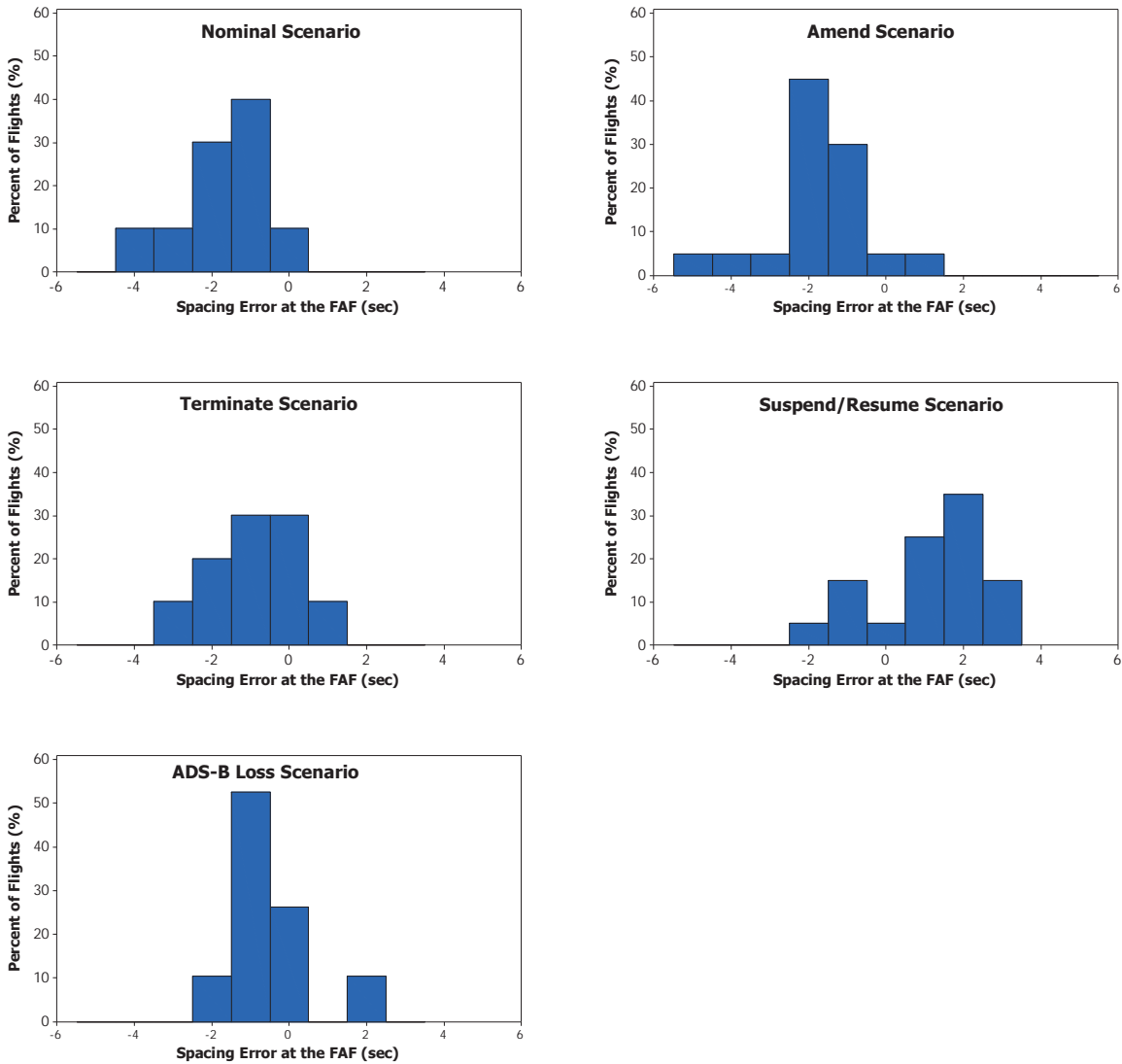| Scenario	N	Mean	SD	Min	Median	Max	95% CI on Mean
Nominal	20	-1.7	1.0	-4.1	-1.5	-0.1	(-2.1, -1.3)
Amend	20	-1.8	1.3	-5.3	-1.6	0.5	(-2.4, -1.3)
Terminate	20	-0.8	1.1	-3.4	-0.9	0.9	(-1.3, -0.4)
Suspend/Resume	20	1.2	1.5	-1.7	1.5	3.4	(0.4, 1.9)
ADS-B Loss	19	-0.5	0.9	-1.6	-0.7	1.7	(-0.8, -0.1)

Figure 3. Spacing error at the FAF (sec) for each of the five scenarios

C. Spacing Error at the Runway Threshold

Although the achieve-by point in this study was the FAF, the delivery accuracy and precision of the FIM tools to the runway threshold was also a measure of interest. The distribution of the spacing error for the five scenarios is shown in Fig. 4 and descriptive statistics are given in Table 5. It can be seen that for all five scenarios, the observed mean spacing error at the runway threshold was within ±2 sec and the observed standard deviation was less than 3 sec. The spacing error was within ±5 sec in 94% of the flights (93 of the 99 flights), and the largest error occurred during the Amend scenario when the aircraft reached the runway threshold 8.5 sec early. Confidence intervals shown in Table 5 indicate that the mean delivery accuracy to the runway threshold is within ±2.6 sec with at least 95% confidence for all scenarios. Even though the achieve-by point was the FAF, the ASTAR algorithm still delivered the aircraft to the runway threshold with reasonable accuracy and precision.

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Table 5.   Descriptive statistics and confidence intervals for spacing error (sec) at the runway threshold

Scenario	N	Mean	SD	Min	Median	Max	95% CI on Mean
Nominal	20	-0.7	2.2	-4.1	-0.6	3.8	(-1.7, 0.4)
Amend	20	-0.5	2.9	-8.5	-0.2	5.0	(-1.8, 0.9)
Terminate	20	-1.6	2.3	-6.3	-1.7	1.9	(-2.6, -0.6)
Suspend/Resume	20	0.4	2.9	-5.8	0.8	5.3	(-1.0, 1.8)
ADS-B Loss	19	-1.3	2.5	-5.1	-1.8	5.1	(-2.5, -0.2)
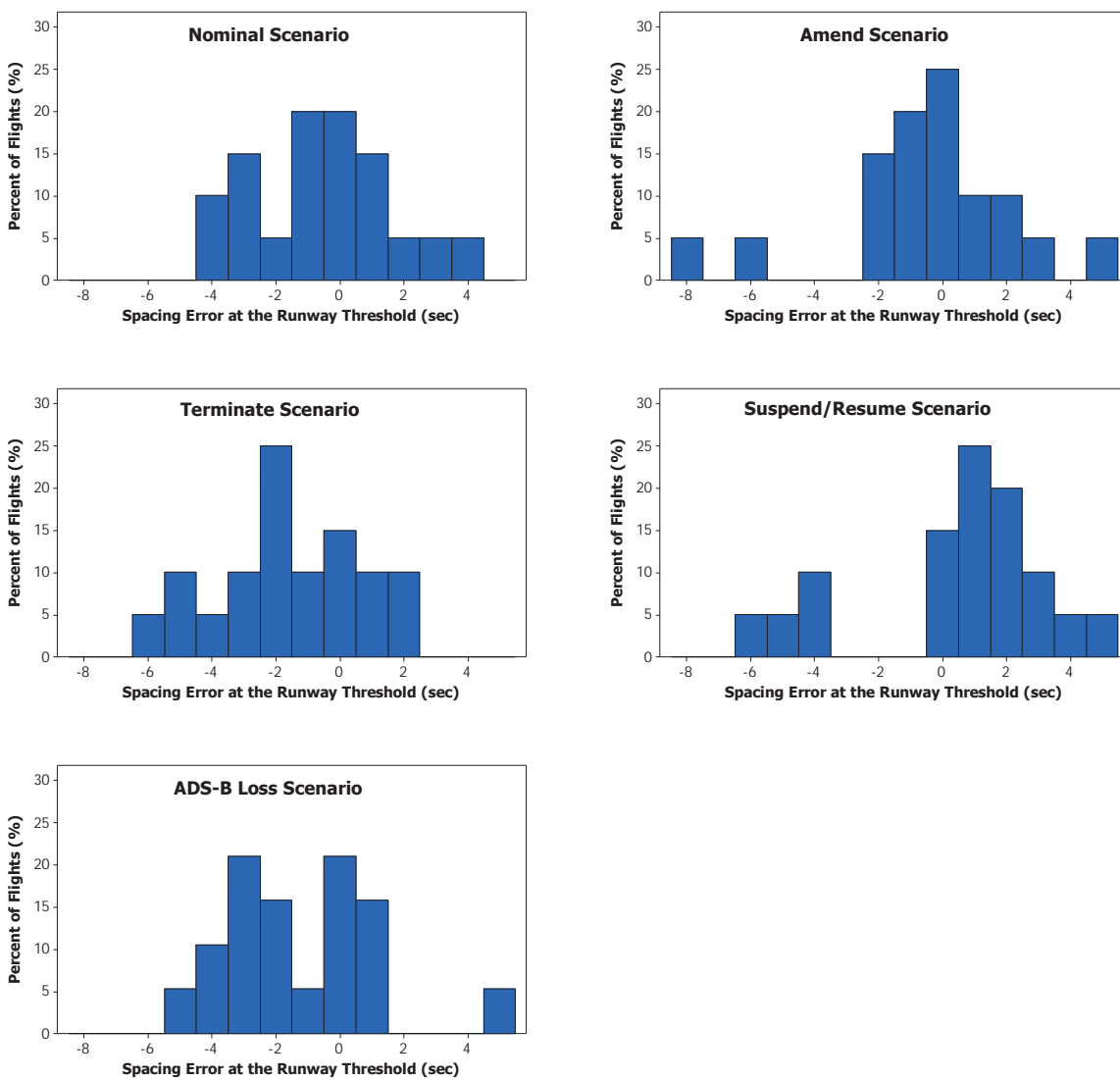
Figure 4.   Spacing error at the runway threshold (sec) for each of the five scenarios

IV. Conclusions

NASA has developed a set of ground-based and airborne arrival management technologies, including TMA-TM, CMS decision support tools, and FIM avionics and procedures. The integration of these technologies will increase throughput, reduce delay, and minimize environmental impacts. ATD-1 will operationally demonstrate the efficient arrival operations provided by this integrated system of NextGen technologies.

The human-in-the-loop experiment described in this paper was conducted as part of initial preparations for the ATD-1 flight demonstration. It was designed to assess the acceptability and feasibility of the proposed air/ground procedures in a voice communications environment. Five flight scenarios were defined to allow flight crews to fully exercise the procedures during different flight phases and operational events. These scenarios consisted of a nominal IM clearance flown to landing, an amended IM clearance on arrival, a terminated IM clearance with a reissue of a new clearance, a suspension and resumption of the IM clearance, and a system error causing a flight crew termination of IM (ADS-B loss) with a subsequent new clearance issued at low altitude (below 10,000 ft).

Overall, the procedures were deemed feasible for use by the flight crew in all scenarios and phases of flight flown in the experiment. FIM speed commands occurred at a rate of less than one per minute, and pilots found the frequency of the speed commands to be acceptable at all times throughout the experiment scenarios. Pilots also reported that the IM commanded speeds were operationally acceptable and appropriate during all scenarios. In addition, the delivery accuracy at both the FAF and the runway threshold was within ±5 sec and the delivery precision was less than 5 sec. The results of this experiment demonstrate the effectiveness of the airborne spacing algorithm and the air/ground procedures investigated. The empirical data and pilot feedback also suggest ways in which the algorithm and procedures may be improved. Future research is planned to investigate the effects of winds, weather, and turbulence on the acceptability and feasibility of the ATD-1 air/ground procedures.

References

[1]Federal Aviation Administration, "FAA Aerospace Forecast, Fiscal Years 2012-2032," URL: http://www.faa.gov/about/office_org/headquarters_offices/apl/aviation_forecasts/aerospace_forecasts/2012-2032/ [cited 12 June 2013].

[2]Federal Aviation Administration, "NextGen Implementation Plan March 2012," URL: http://www.faa.gov/nextgen/implementation/media/NextGen_Implementation_Plan_2012.pdf [cited 12 June 2013].

[3]Prevot, T., Baxley, B. T., Callantine, T. J., Johnson, W. C., Quon, L. K., Robinson, J. E., Swenson, H. N., "NASA's ATM Technology Demonstration-1: Transitioning Fuel Efficient, High Throughput Arrival Operations from Simulation to Reality," International Conference on Human-Computer Interaction in Aerospace (HCI-Aero), Brussels, Belgium, September 2012.

[4]Baxley, B. T., Swenson, H. N., Prevot, T., Callantine, T. J., "NASA's ATM Technology Demonstration-1: Integrated Concept of Arrival Operations," 31st Digital Avionics Systems Conference (DASC), Williamsburg, VA, October 2012.

[5]Swenson, H. N., Hoang, T., Engelland, S., Vincent, D., Sanders, T., Sanford, B., and Heere, K., "Design and Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center," First USA/Europe Air Traffic Management Research and Development Seminar (ATM1997), Saclay, France, June 1997.

[6]Kupfer, M., Callantine, T., Martin, L., Mercer, J., and Palmer, E., "Controller Support Tools for Schedule-Based Terminal-Area Operations," Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), Berlin, Germany, June 2011.

[7]Martin, L., Kupfer, M., Palmer, E., Mercer, J., Callantine, T., and Prevot, T., "Acceptability and Effects of Tools to Assist with Controller Managed Spacing in the Terminal Area," *Proceedings of the 9th International Conference on Engineering Psychology and Cognitive Ergonomics*, edited by D. Harris, Springer-Verlag, Berlin, Heidelberg, 2011, pp. 432-441.

[8]Swenson, H. N., Thipphavong, J., Sadovsky, A., Chen, L., Sullivan, C., and Martin, L., "Design and Evaluation of the Terminal Area Precision Scheduling and Spacing System," Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), Berlin, Germany, June 2011.

[9]Thipphavong, J., Swenson, H., Lin, P., Seo, A. Y., and Bagasol, L. N., "Efficiency Benefits Using the Terminal Area Precision Scheduling and Spacing System," 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, AIAA Paper 2011-6971, Virginia Beach, VA, September 2011.

[10]Martin, L., Swenson, H., Sadovsky, A., Thipphavong, J., Chen, L., and Seo, A. Y., "Effects of Scheduling and Spacing Tools on Controllers' Performance and Perceptions of Their Workload," 30th Digital Avionics Systems Conference (DASC), Seattle, WA. October 2011.

[11]Thipphavong, J., Martin, L., Swenson, H., Lin, P., and Nguyen, J., "Evaluation of the Terminal Area Precision Scheduling and Spacing System for Near-Term NAS Application," International Conference on Applied Human Factors and Ergonomics (AHFE), San Francisco, CA, July 2012.

[12]Bone, R. S., and Penhallegon, W. J., "En-route Flight Deck-Based Merging and Spacing Impact on Flight Crew Operations," 26th Digital Avionics Systems Conference (DASC), Dallas, TX, October 2007.

[13]Bone, R. S., Penhallegon, W. J., and Stassen, H. P., "Flight Deck-Based Merging and Spacing during Continuous Descent Arrivals and Approach: Impact on Pilots," MITRE, MTR080208, July 2008.

[14]Penhallegon, W. J., and Bone, R. S., "Flight Deck-Based Merging and Spacing Impact on Flight Crew Operations During Continuous Descent Arrivals and Approaches," 27th Digital Avionics Systems Conference (DASC), St. Paul, MN, October 2008.

[15]Hebraud, C., Hoffman, E., Papin, A., Pene, N., Rognin, L., Sheehan, C., and Zeghal, K., "CoSpace 2002 Flight Deck Experiments Assessing the Impact of Spacing Instructions from Cruise to Initial Approach," Eurocontrol Experimental Centre, EEC Report No. 388 – Volume I, February 2004.

[16]Hebraud, C., Hoffman, E., Pene, N., Rognin, L., and Zeghal, K., "Assessing the Impact of a New Air Traffic Control Instruction on Flight Crew Activity," AIAA Guidance, Navigation, and Control Conference and Exhibit, AIAA Paper 2004-5104, Providence, RI, August 2004.

[17]Hoffman, E., Pene, N., Rognin, L., and Zeghal, K., "Introducing a New Spacing Instruction. Impact of Spacing Tolerance on Flight Crew Activity," Human Factors and Ergonomics Society Annual Meeting Proceedings, Vol.47, 2003, pp. 174-178.

[18]Hoffman, E., Martin, P., Putz, T., Trzmiel, A., and Zeghal, K., "Airborne Spacing: Flight Deck View of Compatibility with Continuous Descent Approach (CDA)," 7th AIAA Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2007-7742, Belfast, Northern Ireland, September 2007.

[19]Baxley, B. T., Barmore, B. E., Abbott, T. S., and Capron, W. R., "Operational Concept for Flight Crews to Participate in Merging and Spacing of Aircraft," 6th AIAA Aviation Technology, Integration and Operations (ATIO) Conference, AIAA Paper 2006-7722, Wichita, KS, September 2006.

[20]Murdoch, J. L., Barmore, B. E., Baxley, B. T., Abbott, T. S., and Capron, W. R., "Evaluation of an Airborne Spacing Concept to Support Continuous Descent Arrival Operations," Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009), Napa, CA, June – July, 2009.

[21]Swieringa, K., Murdoch, J. L., Baxley, B., and Hubbs, C., "Evaluation of an Airborne Spacing Concept, On-board Spacing Tool, and Pilot Interface," 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, AIAA Paper 2011-6902, Virginia Beach, VA, September 2011.

[22]Cabrall, C., Callantine, T., Kupfer, M., Martin, L., and Mercer, J., "Controller-Managed Spacing within Mixed-Equipage Arrival Operations Involving Flight-Deck Interval Management," International Conference on Applied Human Factors and Ergonomics (AHFE), San Francisco, CA, July 2012.

[23]Callantine, T. J., Cabrall, C. D., Kupfer, M., Omar, F. G., and Prevot, T., "Initial Investigations of Controller Tools and Procedures for Schedule-Based Arrival Operations with Mixed Flight-Deck Interval Management Equipage," 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, AIAA Paper 2012-5673, Indianapolis, IN, September 2012.

[24]Thipphavong, J., Jung, J., Swenson, H. V., Lin, M. I., Nguyen, J., Martin, L., Downs, M. B., and Smith, T. A., "Evaluation of the Controller-Managed Spacing Tools, Flight-deck Interval Management and Terminal Area Metering Capabilities for the ATM Technology Demonstration #1," Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013), Chicago, IL, June 2013.

[25]Baxley, B. T., Johnson, W. C., Swenson, H. N., Robinson, J. E., Prevot, T., Callantine, T. J., Scardina, J., and Greene, M., "Air Traffic Management Technology Demonstration–1 Concept of Operations (ATD-1 ConOps)," NASA/TM-2012-217585, July 2012.

[26]Murdoch, J. L., Wilson, S. R., Hubbs, C. E., Smail, J., and Swieringa, K. A., "Acceptability of Flight deck-based Interval Management Crew Procedures," AIAA Modeling and Simulation Technologies Conference and Exhibit, AIAA Paper, Boston, MA, August 2013.

[27]Abbott, T. S., "An Overview of a Trajectory-Based Solution for En Route and Terminal Area Self-Spacing: Third Revision," NASA/CR-2012-217786, November 2012.

[28]Peters, M. E., Ballin, M. G., and Sakosky, J. S., "A Multi-Operator Simulation for Investigation of Distributed Air Traffic Management Concepts," AIAA Modeling and Simulation Technologies Conference and Exhibit, AIAA Paper 2002-4596, Monterey, CA, August 2002.

[29]Prevot, T., Smith, N., Palmer, E., Mercer, J., Lee, P., Homola, J., and Callantine, T., "The Airspace Operations Laboratory (AOL) at NASA Ames Research Center," AIAA Modeling and Simulation Technologies Conference and Exhibit, AIAA Paper 2006-6112, Keystone, CO, August 2006.

[30]National Aeronautics and Space Administration, "NASA Langley Research Center: The Flight Simulation Facilities," URL: http://oim.hq.nasa.gov/oia/scap/docs/SCAP_FLIGHTSIM_112508_508.pdf [cited 12 June 2013].