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Flight-Deck Interval Management in Near-Term Arrival Operations

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***Abstract*—A simulation investigated NASA Air Traffic Management Technology Demonstration #1 (ATD-1) procedures and prototype technologies, including the Traffic Management Advisor for Terminal Metering, Controller-Managed Spacing tools, and Flight Deck Interval Management (FIM) equipment. The ATD-1 procedures and technologies comprise an integrated solution for managing high-density arrivals that NASA is developing and transferring to government and industry stakeholders for NextGen. During each of eighteen simulation trials, experienced controllers managed approximately two hundred departures and over-flights together with seventy-five arrivals to Phoenix Sky Harbor International Airport in a realistic near-term environment. Eight of the arrivals were desktop-based flight simulators flown by airline pilots, which were equipped with prototype FIM equipment in two-thirds of the trials. The simulation provided system-level measures of performance of the ATD-1 integrated arrival solution, demonstrating high conformance with Performance-Based Navigation procedures and a low rate of FIM interruptions. FIM operations provided benefits under specific conditions when FIM aircraft flew connected routes to the runway. This paper focuses on the integration of FIM with the ATD-1 ground-based technologies, discusses outstanding issues, and describes avenues for further research.**

Keywords-flight-deck interval management; terminal sequencing and spacing; performance-based navigation; controller-managed spacing

I. INTRODUCTION

The highest priority identified in the 2013 ICAO Global Air Navigation Plan for increasing capacity, improving efficiency, and harmonizing the global air traffic management (ATM) system is the continued development and implementation of Performance-Based Navigation (PBN) procedures [1]. Continuous Descent Operations (CDOs) along Area Navigation (RNAV)/Required Navigation Performance (RNP) routes are already yielding benefits at many major airports. Realizing benefits during sustained periods of high throughput requires advanced ATM tools and techniques for efficiently managing orderly traffic flows through the terminal area to the runway while meeting required separation minima with minimal added buffers. The US Next Generation Air Transportation System (NextGen) initiative [2] is therefore pursuing time-based scheduling combined with advanced ground-based and airborne spacing technologies that rely primarily on speed control to smoothly absorb delay and merge arrivals without resorting to vectoring and 'step-down' control techniques that interrupt efficient PBN procedures.

The NASA ATM Technology Demonstration #1 (ATD-1) commenced in 2011, with the aims of achieving increased use of PBN arrival procedures, demonstrating an airborne spacing application enabled by Automatic Dependent Surveillance-Broadcast (ADS-B)-In, and accelerating the transfer of NASA scheduling and spacing technologies for operational deployment [3]. The ATD-1 concept integrates scheduling capabilities provided by the Traffic Management Advisor for Terminal Metering (TMA-TM) with Controller-Managed Spacing (CMS) tools and Flight-Deck Interval Management (FIM) avionics. The TMA-TM extends the FAA's Time-Based Flow Management (TBFM) system by explicitly modeling PBN procedures inside the terminal area and generating de-conflicted schedules at meter fixes, terminal meter points, and runways [4]. The CMS tools present temporal and spatial schedule information to aid Terminal Radar Approach Control (TRACON) controllers in issuing speed instructions to maintain the schedule [5]. The TMA-TM and CMS technologies have been transferred to the FAA for use in the FAA's Terminal Sequencing and Spacing (TSS) program. The FIM application, called Airborne Spacing for Terminal Arrival Routes (ASTAR) [6], provides flight crews of equipped aircraft with speed commands to achieve their scheduled in-trail spacing, potentially providing additional spacing precision and reducing controller workload [7]. ATD-1 seeks to develop operational prototypes of these technologies for field demonstration and transfer the technologies to the FAA and industry stakeholders.

A system-level ATD-1 simulation conducted in Airspace Operations Laboratory (AOL) [8] at NASA Ames Research Center during April 2014 investigated full ATD-1 operations for arrivals to Phoenix Sky Harbor International Airport (PHX) using realistic traffic and winds, former controllers from Albuquerque (ZAB) Air Route Traffic Control Center (ARTCC) and Phoenix TRACON (P50), and the latest ATD-1 prototype technologies. Simulated arrival-flows included eight medium-fidelity single-pilot glass-cockpit desktop simulators developed at NASA Langley Research Center, called ASTORs ('Aircraft Simulation for Traffic Operations Research'). These RNAV-equipped ASTORs were flown by airline pilots, and equipped for FIM operations during two-thirds of the simulation trials. This paper describes the April 2014 simulation with an emphasis on ATD-1 FIM operations, complementing prior publications about ATD-1 simulations [9, 10]. The paper first provides background on ATD-1 FIM operations and their integration with the ground-side technologies and operations. Section III describes the simulation and Section IV presents results about FIM operations and air-ground integration issues. The paper concludes following a discussion of the results and future work.

II. BACKGROUND

ATD-1 began with the development of a concept of operations and the identification of integration steps toward fielding operational prototypes of the air and ground technologies in the expected four-to-five year timeframe. During its development at NASA Langley Research Center [11], FIM has evolved from a simple tactical system for spacing behind a lead aircraft, to an ADS-B-supported system, to a system tailored for achieving precise inter-arrival spacing during CDOs. Recent implementations of FIM research have shared intent information for a 'target' aircraft via data communication. A series of simulations and flight trials demonstrated controller workload reductions and improvements in efficiency and throughput, as well as applicability for specialized operations such as very-closely-spaced dependent parallel approaches. However, this prior work largely assumed universal FIM equipage and data-communication capabilities, making it suitable for later-term deployment. The NASA-developed TMA-TM and CMS tools, on the other hand, were well positioned for nearer-term integration due to the prevalence of RNAV/RNP-equipped aircraft and proliferation of PBN procedures.

In the ATD-1 concept of operations [12], the TMA-TM first computes estimated times-of-arrival (ETAs) and uses them to produce scheduled times-of-arrival (STAs) for each arriving aircraft that satisfy separation constraints imposed along its assigned arrival route to the runway. Buffers are added to account for uncertainties without excessively limiting throughput. Controllers then begin metering aircraft, ensuring that they are close enough to their assigned STAs to avoid separation problems due to flow compression during descent that could lead controllers to interrupt efficient PBN procedures. These initial steps apply to all scheduled arrivals; thereafter, TRACON controllers use the CMS tools to continue metering by issuing a limited number of speed instructions to keep non-FIM-equipped aircraft on schedule and ensure safe separation on final approach.

ATD-1 integrates FIM operations by adapting the trajectory-based ASTAR FIM application for near-term operation. The FIM application is not fully integrated with the aircraft avionics, but instead resides on an Electronic Flight Bag (EFB) in a representative retrofit configuration. Commanded speeds and fast-slow indications are shown on auxiliary Configurable Glass Displays (CGDs) positioned in pilot's forward field of view. The ATD-1 concept of operations specifies that controllers issue FIM clearances by voice, using information from the arrival schedule presented on ARTCC controller workstations. Controllers remain responsible for ensuring safe separation.

ARTCC controllers issue FIM clearances for FIM-equipped aircraft. An achieve-by-then-maintain FIM clearance type is used [13], for which ASTAR requires information about the target aircraft, its planned trajectory, the time-based assigned spacing goal (ASG), the assigned achieve-by point (ABP) at which the ASG should be acquired, and the planned termination point (PTP) until which the ASG should be maintained. ASTAR generates trajectory predictions for the ownship and target aircraft using representations of the assigned PBN arrival routes, forecast wind information, and target state information provided via ADS-B. To simplify the clearance for ATD-1, the ABP and PTP are both defined as the final approach fix (FAF) of the TMA-TM-assigned arrival runway, so that these elements need not be communicated (Fig. 1). The selection of the FAF as the ABP also enables the TMA-TM to compute the ASG given the desired separation at the ABP without requiring ASTAR to explicitly model the target aircraft's approach speed profile. Upon engagement, ASTAR immediately begins to command speeds to achieve the ASG while remaining within 15% of the published speed along each segment of the procedure. The schedule is expected to be formulated to allow the ASG to be achieved earlier than the ABP without violating required separation constraints along the way.

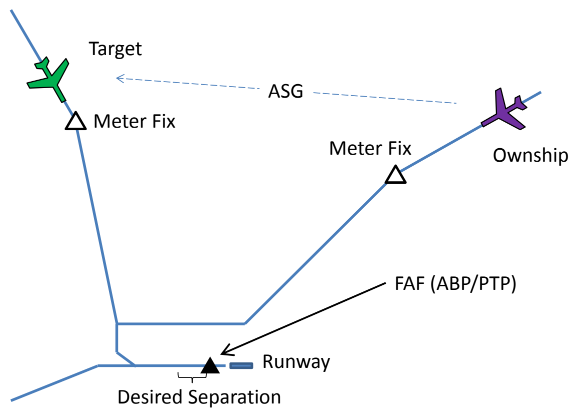

Figure 1. Elements of ATD-1 FIM operation.

After reading back the FIM-clearance elements, a pilot enters them into the EFB FIM application. Once ADS-B state information for the specified target aircraft is available and ASTAR begins displaying commanded airspeeds, the pilot flies the PBN procedure while following the commanded speeds to the PTP unless otherwise instructed by a controller. The following section provides an overview of the system-level simulation, including descriptions of the procedures, clearance phraseology, and cockpit and controller displays used to test the ATD-1 concept of operations.

III. Simulation Description

The ATD-1 simulation (referred to as 'CA-5.3'in [9]) was the third in a series of large-scale human-in-the-loop simulations intended to facilitate system-level comparisons of current day, TSS operations, and mixed TSS/FIM operations for managing PHX peak-period arrival flows under the most realistic conditions possible. The controller positions, airspace, routes, and voice-only communications remained the same throughout the series of simulations, but due to improvements to the prototype ATD-1 system prior to this simulation, it was cast as an integral study with the objective of comparing ATD-1 operations with and without FIM. Operations that do not involve FIM are referred to as 'TSS' operations.

The simulation investigated east- and west-flow PHX configurations with TMA-TM runway balancing using realistic simulated winds and traffic that included turbojet, turboprop, and piston arrivals to PHX, as well as satellite arrivals, departures, and over-flights. RNAV-equipped PHX arrivals 'descended via' published PHX RNAV Standard Arrival Routes (STARS); other arrivals flew published non-RNAV STARS. The simulation used standard radar separation minima with a 0.3 nmi scheduling buffer. Reduced separation (2.5 nmi) was permissible on the final approach course within 10 nmi of the runway for appropriate wake-category aircraft. PHX has three parallel runways; the two outboard runways were used for arrivals in both east- and west-flow operations. All arrivals flew ILS approaches to their assigned runways.

A. Airspace and Routes

ARTCC controllers staffed four high-altitude sectors and four low-altitude arrival sectors (Fig. 2). At the time of the study, published PHX STARS crossed four meter fixes distributed around the P50 boundary. Two 'Feeder' controllers and two 'Final' controllers managed traffic in the TRACON. The RNAV STARS with downwind segments required the Final controllers to issue base-turn vectors to the final approach. Similarly, aircraft scheduled as 'crossovers' required vectors to the landing runway on the other side of the airport. Fig. 3 shows the TMA-TM-adapted RNAV routings for west-flow operations; depictions of the east-flow and non-RNAV STAR adaptations are provided in [9].

B. Traffic Scenarios and Winds

One east-flow and one west-flow traffic scenario were developed based on actual PHX traffic samples drawn from peak arrival periods in 2011. The scenarios reflect morning and evening arrival rushes, respectively. The east-flow scenario has approximately 5% non-RNAV-equipped arrivals, while the west-flow scenario has approximately 19%. Departures and

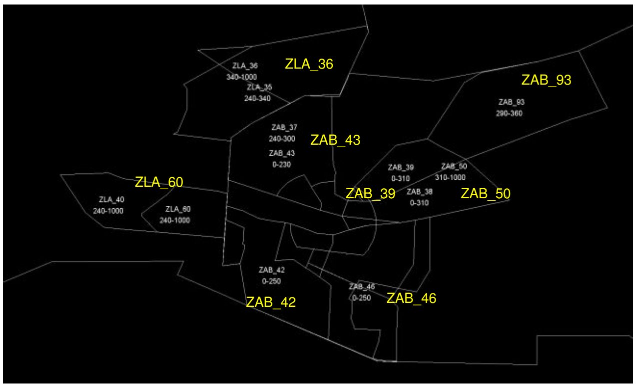

Figure 2. En-route sectors.

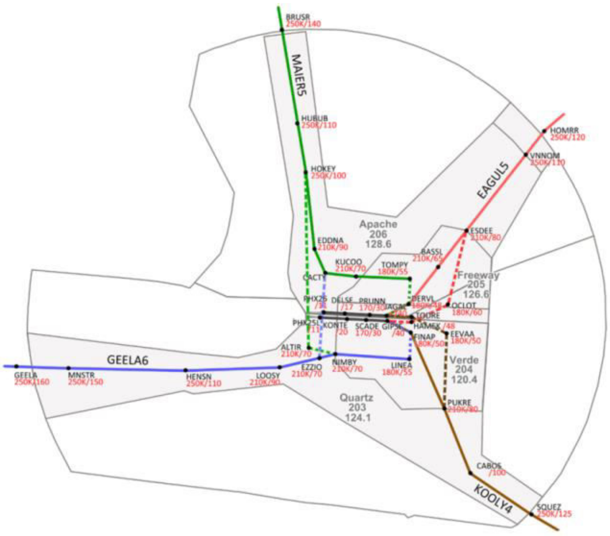

Figure 3. TMA-TM west-flow RNAV route adaptation. Dashed lines indicate vectoring paths represented in the adaptation.

over-flights were adjusted to ensure any impacts to the test sectors were delayed until the traffic flows were well established following initialization. Each traffic scenario was paired with three different sets of 2011 gridded winds with different characteristics representing prevalent PHX wind patterns. Forecast winds were selected to yield a wind-forecast error of approximately 10 kts rms for use in the ground-system computations.

The scenarios lasted approximately 60 minutes and the average peak arrival rate was 90 to 96 aircraft per hour. The resulting TMA-TM schedules required aircraft to absorb an average of approximately three minutes of en-route delay. ASGs computed as the difference between the TMA-TM-calculated STAs for the FIM and target aircraft typically ranged from 71 s to 77 s. TMA-TM runway balancing resulted in between one and five crossover aircraft in each scenario, with more crossovers occurring in the west-flow scenarios. The majority of aircraft were controlled via Multi Aircraft Control System (MACS) [8] pseudo-pilot stations. When identifying aircraft for replacement with one of the eight ASTOR simulators, special attention was paid to potential FIM pairings. Table 1 lists, for each scenario-wind combination, the number of ASTORs that were scheduled behind a target aircraft flying a different RNAV STAR and the length of 'strings' of

TABLE I. ASTOR-ASSIGNMENT CHARACTERISTICS IN EACH TRAFFIC SCENARIO-WIND COMBINATION.

Scenario/Wind	Number of Target Aircraft on Different STARS	FIM Aircraft String Lengths
E1	6	1,1,3, 3
E2	7	1, 1, 2, 4
E3	4	1, 1, 1, 2, 3
W1	5	1, 1, 2, 4
W2	6	1, 1, 2, 2, 2
W3	6	1, 2, 3, 2

ASTORs (including strings of length 1) arriving on the same runway.

C. Controller Interfaces

ARTCC controllers used high-fidelity MACS En-Route Automation Modernization (ERAM) workstation emulations. FIM information appeared in the meter list for FIM-equipped aircraft (Fig. 4). FIM status was indicated above the data-block callsign; controllers made entries to toggle the FIM-status indication when they issued FIM clearances to equipped aircraft, and when pilots reported that they were performing FIM operations (Fig. 5). Fig. 5 also shows the Delay Countdown Timer (DCT) that supplies delay information to support metering. The DCT shows the difference between an aircraft's current ETA and STA, rounded to the nearest 10 s; a positive DCT value indicates the aircraft needs to be delayed. ARTCC controllers also had existing operational tools available for use, including speed and altitude fly-out menus, trend vectors, and J-rings. In addition, a ZAB Traffic Management Coordinator (TMC) and a P50 TMC/Arrival Coordinator used TMA-TM timelines along with Traffic Situation Displays and plan-view controller displays [9] emulated in MACS. Under limited circumstances the TMCs could use these displays to manage controller requests for sequence swaps and reschedules.

TRACON controllers used high-fidelity MACS emulations of Standard Terminal Automation Replacement System (STARS) workstations outfitted with CMS tools. Fig. 6 shows the STARS data-block. The top portion of Fig. 6 shows the aircraft ahead of the slot marker with its current indicated airspeed. The TMA-TM-computed airspeed is shown next to the target symbol. The third line of the data-block shows the assigned runway, then a back-slash, then the sequence number of the aircraft. For crossover aircraft, the assigned runway and sequence number appears in yellow, as in Fig. 6. The last third-line value is the CMS speed advisory. The lower portion of Fig. 6 illustrates how scratchpad information about the assigned RNAV arrival and the aircraft type and equipage is time-shared with the current altitude and groundspeed indication. It also illustrates how the speed advisory is replaced with an early/late indication (1 s early, in this case), once the aircraft has slowed to the advised speed. Spacing cones are among the existing operational tools that were also available in the STARS emulation; the CMS timeline that shows the TMA-TM schedule also appears (see [9]).

FIM-status information entered by ARTCC controllers is transferred to the STARS display in a different format, which replaces the CMS speed-advisory/early-late indication in the

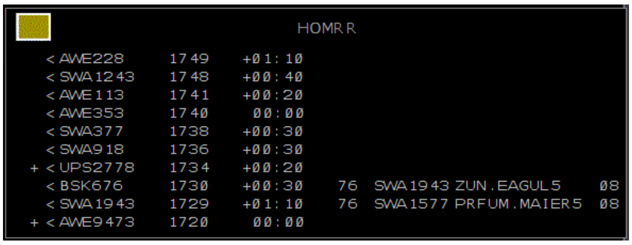

Figure 4. ERAM meter list showing ASG, target aircraft callsign, target aircraft route, and assigned runway information for FIM clearances.

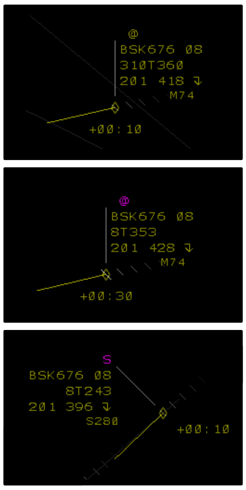

Figure 5. ERAM data-blocks with DCTs below aircraft target symbol. '@' symbol above the callsign indicates FIM-equipage; controllers toggle symbol pink when issuing a FIM clearance, and change it to an 'S' when an aircraft reports FIM engagement.

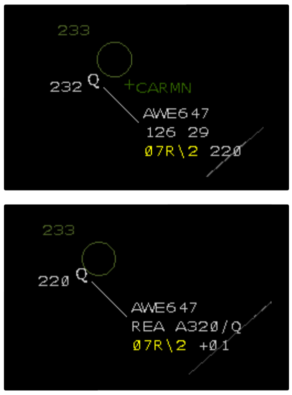

Figure 6. STARS data-blocks with time-shared information in line 2 and crossover runway\sequence number highlighted yellow.

third line of the data-block for FIM-equipped aircraft. Fig. 7 shows a STARS depiction of three aircraft in the area of the P50 boundary. The first aircraft (ASH2045) is either not FIM-equipped or did not receive a FIM clearance in en-route airspace. The second (AWE116) has been identified to be actively performing FIM operations, and the third (AWE189) has been issued a FIM clearance and either did not initiate FIM operations or the operation has been suspended.

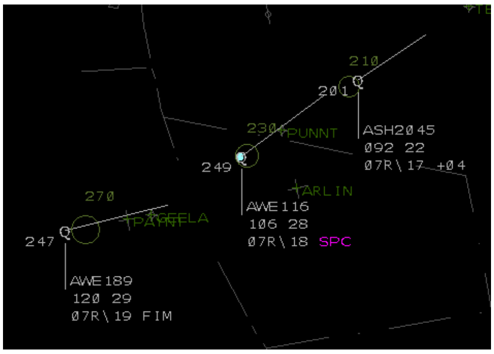

Figure 7. Sequence of arrivals in STARS with TRACON FIM-status indicators.

D. Flight-Deck Interfaces

The ASTOR simulators provide B757-type aircraft performance, mouse-based controls, and a full suite of Boeing-

Figure 8. ASTOR glass-cockpit displays.

777-style glass-cockpit displays spanning two computer monitors, as shown in Fig 8. For the simulation, an auxiliary FIM CGD is positioned on the left, next to the Primary Flight Display; on the right is the EFB that hosts the FIM application.

The EFB is designed to be implemented as a touch-screen-based device with bezel hard-keys. The main EFB FIM application page is shown in Fig. 9. On the left are buttons for entering ownship information and forecast descent winds, along with a field that shows the next waypoint the aircraft will cross; on the right are buttons for entering the FIM clearance. The topmost button on the right enables the pilot to enter the ASG, the second button the target aircraft, and the third button the target aircraft's route. The latter buttons access pages with a keypad for entering text, and menus for selecting known routes and callsigns identified via ADS-B.

The top of the display (Fig. 9) has areas that show the FIM-commanded airspeed and the deviation between the actual and commanded speeds. Below them is a status box that shows the current status of the FIM application (e.g., CALCULATING, IM SPACING <TARGET CALLSIGN>, SUSPENDED). Below that is an alerting box that displays caution and advisory messages when the FIM application is not operating nominally. For example, IM TGT OFF PATH is displayed when the target is not within specified tolerances of its specified trajectory; IM SPD LIMITED indicates the commanded speed is limited by the requirement to be within 15% of the published speed on the current procedure segment.

Fig. 10 depicts the CGD. On the top right is a box that displays the FIM-commanded airspeed. The speed value is highlighted for 10 s when it changes; if the pilot does not set the commanded speed on the Mode Control Panel within 10 s, the commanded speed blinks until set. Below the commanded speed is the FIM status indication. When FIM operations are active, the status area mirrors the indications shown in the EFB status area. When the FIM application is receiving ADS-B information the CGD shows the target call-sign below the status indication. On the left side of the CGD is a fast/slow indication; at the bottom is a display area for system caution and information messages (e.g., DRAG REQD).

Figure 9. EFB-based ASTAR FIM application.

Figure 10. Configurable Glass Display (CGD) for FIM.

E. Procedures and Phraseology

FIM-equipped aircraft initialize at cruise altitude, with the planned route preprogrammed in the ASTOR's Flight Management System (FMS). Pilots first enter the ownship-route information in the EFB FIM application. A 'company' uplink provides forecast descent wind information.

ARTCC controllers perform metering and issue clearances for RNAV-equipped arrivals to descend via an RNAV STAR. ARTCC controllers attempt to meter non-FIM-equipped aircraft to arrive within 30 s of their STA at the meter fix and clear aircraft to resume normal speeds prior to transferring control to the TRACON unless otherwise coordinated. For FIM-equipped aircraft, ARTCC controllers absorb delay in excess of 1 min and issue the 'descend via' clearance. They then issue the FIM clearance as their workload permits.

FIM clearance phraseology is given in Table 2. To mitigate potential read-back errors, controllers first alert pilots to the forthcoming clearance. The phraseology includes "when able" in case the target aircraft is not currently within the ownship's ADS-B range, or either aircraft is not currently within specified tolerances of its trajectory. The phraseology also provides for amendments and conditional engagement. The examples in Table 2 illustrate how clearance information is listed in the controller's meter list (Fig. 4) in the order required by the phraseology. "Report paired" is included to instruct the pilot to notify the controller when the FIM operation begins. The fifth entry in Table 2 is an example of a clearance a controller could issue if deemed necessary to ensure separation in the interim before FIM engagement, while leaving the FIM clearance in force.

TABLE II. FIM CLEARANCE PHRASEOLOGY.

ID	Controller	Pilot
1	SWA1943, clearance available, advise when ready to copy.	SWA1943 ready to copy.
2	SWA1943, when able, space SEVENTY SIX seconds behind SWA1577 on the MAIER FIVE arrival, PRFUM transition. Report paired.	When able, space SEVENTY SIX seconds behind SWA1577 on the MAIER FIVE arrival, PRFUM transition. Report paired, SWA1943.
3	SWA1943, amend clearance, when able, space NINETY THREE seconds behind SWA1577 on MAIER FIVE arrival, PRFUM transition. Report paired.	Amend clearance, when able, space NINETY THREE seconds behind SWA1577 on the MAIER FIVE arrival, PRFUM transition. Report paired, SWA1943.
4	SWA1943, after EAGUL, when able, space ONE HUNDRED THIRTEEN seconds behind SWA1577 on the MAIER FIVE arrival, PRFUM transition. Report paired.	After EAGUL, when able, space ONE HUNDRED THIRTEEN seconds behind SWA1577 on the MAIER FIVE arrival, PRFUM transition. Report paired, SWA1943.
5	SWA1943, maintain TWO SEVEN ZERO knots until paired.	SWA1943 Roger, maintain TWO SEVEN ZERO knots until paired.

Table 3 lists phraseology pilots use to notify controllers about the status of their FIM operation. The first entry is the nominal phraseology a pilot uses to notify the controller that they have begun following the ASTAR-computed FIM airspeeds. Reporting 'paired behind' supersedes prior controller-assigned or published speeds. Pilots include their commanded airspeed when they report paired, so that controllers expect the impending speed change. The second and third entries show phraseology used to check-in with a TRACON controller; a pilot who is actively conducting FIM uses the second entry, while a pilot whose FIM operation was never initiated or has been suspended uses the third entry.

TABLE III. FIM PILOT-NOTIFICATION PHRASEOLOGY.

ID	Pilot	Controller
1	Albuquerque Center, SWA1943 paired behind SWA1577, speed TWO SIX ZERO.	SWA1943 roger.
2	SWA1943 leaving ONE FIVE THOUSAND with INFORMATION HOTEL, DESCENDING VIA the EAGUL FIVE arrival, PAIRED BEHIND SWA1577	Roger, SWA1943.
3	SWA1943 leaving ONE FIVE THOUSAND with INFORMATION HOTEL, DESCENDING VIA the EAGUL FIVE arrival, with SPACING CLEARANCE BEHIND SWA1577	Roger, SWA1943.
4	SWA1943, unable interval spacing due to <reason>.	<New clearance>

Pilots use the fourth entry in Table 3 to report problems; in this case, the controller is expected to provide an alternative clearance.

Controllers are expected to suspend FIM operations if they deem it necessary to ensure separation. Table 4 shows phraseology controllers can use to verify the status of the FIM operation, or to suspend or cancel it. The first and last entries illustrate how a controller can inquire about the FIM clearance or operation. Without the exchange of trajectory information among the systems, 'unconnected' route segments require FIM cancellation, as vectoring either aircraft can lead to trajectory-prediction errors that prevent ASTAR from achieving the ASG. Controllers use entries 2 and 3 to suspend or cancel the FIM operation, respectively. In the simulation, issuing an alternative speed or heading vector was also considered to suspend FIM.

TABLE IV. FIM VERIFICATION, SUSPENSION, AND CANCELLATION PHRASEOLOGY

ID	Controller	Pilot
1	SWA1943, verify paired behind SWA1577 *or* SWA1577, verify interval spacing clearance.	Affirmative, SWA1943 *or* Spacing clearance is SEVENTY SIX seconds behind SWA1577, SWA1943.
2	SWA1943, suspend interval spacing, <new clearance>.	Suspend interval spacing, <new clearance read-back>.
3	SWA1943, cancel interval spacing, <new clearance>.	Cancel interval spacing, <new clearance read-back>.
4	SWA1943, say speed.	Maintaining / Slowing to / Increasing to XXX knots, SWA1943.

If FIM is not initiated or is suspended in en-route airspace, ARTCC controllers meter the aircraft to within 30 s of their meter-fix STA prior to transferring control to the TRACON. Feeder controllers use the CMS tools to meet aircraft STAs while allowing FIM aircraft to follow their commanded speeds to the extent possible. Final controllers merge aircraft according to the schedule, using the CMS tools to issue speeds as appropriate. In the simulation, Final controllers were instructed to cancel FIM on the unconnected downwind segments and provide altitude and vector instructions to intercept the ILS. Controllers were also encouraged to ensure the FIM-status indicators were correctly updated.

F. Participants and Training

Experimental subjects were recently retired PHX and ZAB controllers with an average of 30 years of experience. Subject controllers were assigned to the sectors consistent with their professional experience. All but two participated in the previous two simulations. Other controllers with experience in the ATD-1 simulations served as confederates, staffing two sectors designed to surround the study airspace, as well as the tower and a departure sector. Eight glass-cockpit-qualified airline pilots flew the ASTOR single-pilot desktop simulators; in addition, eighteen regional jet pilots and aviation students staffed pseudo-pilot positions.

Four days of training began with a detailed briefing. The briefing was followed by hands-on training, beginning with a review of metering and the CMS tools for controllers, and PBN procedures for pilots, and progressing through a series of full-up training scenarios with FIM operations. Training materials included phraseology, airspace, and route reference sheets.

G. Data Collection

Data were collected over four days. Each scenario-wind pair was simulated three times in randomized order—once without FIM and twice with the ASTORs participating as FIM-equipped aircraft. All MACS stations, desktop flight simulators, and simulation data-communication hubs logged digital data. The data include flight state information, pilot and controller entries, and schedule information. The TMA-TM and ASTOR simulators also logged digital data. All participants completed short questionnaires between trials, and a longer questionnaire at the end of the simulation. In addition, screen-capture movies that include recorded audio were collected from all MACS and ASTOR stations, and AOL laboratory staff and a variety of subject-matter experts served as observers. Subjects were encouraged to alert observers to any events not typical of their experience piloting or working live traffic. A group-debrief discussion followed data collection.

IV. Results

The simulation produced results about TSS operations as well as operations that included FIM. Results limited to the ATD-1 ground-side technologies in this and prior AOL simulations are presented in [9]; this section summarizes pertinent findings for the present simulation and presents new results on TSS-FIM integration under the ATD-1 concept of operations.

A. PBN Success Rate

PBN success rate is an ATD-1 Measure of Performance (MOP) that addresses whether eligible aircraft maintain the published procedure's lateral path without being vectored unless required (i.e., to turn base or cross over to the other runway). As shown in Fig. 11, the PBN success rate was universally high with no consistent effect of FIM operations.

B. FIM Interruption Rate

The percentage of controller-interrupted FIM operations is a reflection of controller acceptability. Interruptions occur if controllers suspend FIM operations prior to the PTP, or before vectoring aircraft on downwind segments or crossover routes.

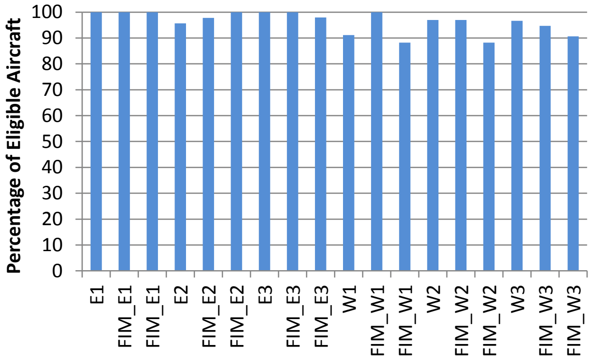

Figure 11. PBN success rate.

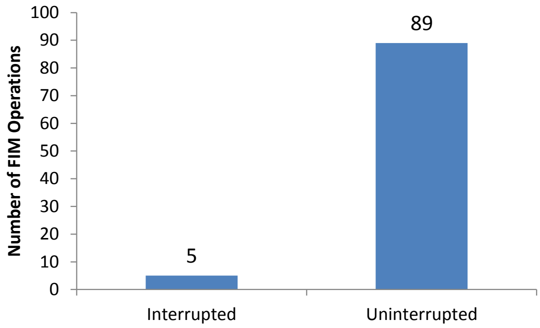

Figure 12. Interrupted vs. uninterrupted FIM operations.

Data reflecting when ASTAR was engaged overlaid on assigned procedures illustrates that, for the 94 out of 96 FIM-equipped aircraft in the simulation that received FIM clearances, only 5 of 94 (5.3%) of FIM operations were interrupted (three operations were suspended and later resumed) (Fig. 12).

C. Inter-Arrival Spacing

The ATD-1 FIM operation is expected to improve inter-arrival spacing. The ATD-1 MOP for inter-arrival spacing error for a pair of aircraft is defined as the difference in the scheduled in-trail time spacing and the actual in-trail time spacing measured when the FIM aircraft crosses the FAF. An inter-arrival time error (IAT) metric gives the central one-sigma range of the inter-arrival spacing error for all pairs in a given condition. The results presented here recognize that, for TSS operations, controllers need not accelerate aircraft that are behind schedule if a schedule-gap exists behind them; thus, it includes only those TSS pairs for which the trailing aircraft required TRACON delay and the required spacing met the following criterion:

$$STA_{trail} - STA_{lead} < 90\ s + \frac{required\ separation + 0.3\ nmi}{2.8\ nmi} \quad (1)$$

Fig. 13 shows the overall performance for TSS aircraft pairs vs. FIM pairs in the simulation. The blue dashed lines show the central 95th percentile range; the black dashed lines represent the central one-sigma range. Figs. 14 and 15 show the results for TSS pairs and FIM pairs, respectively, together with a decomposition of the results based on route geometries.

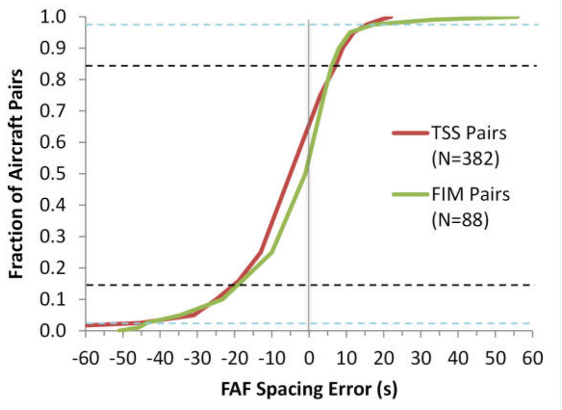

Figure 13. Cumulative distributions of inter-arrival spacing errors for TSS vs. FIM..

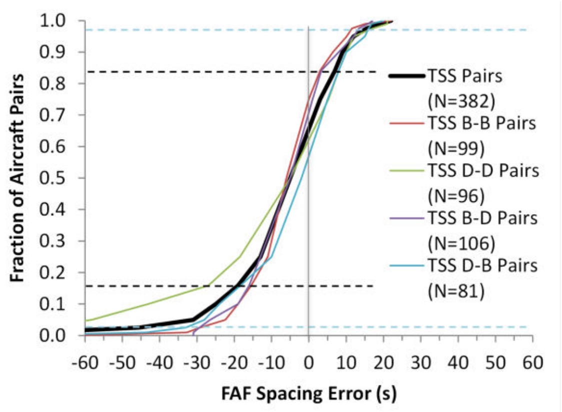

Figure 14. Cumulative distributions of inter-arrival spacing errors for TSS pairs for various route geometries.

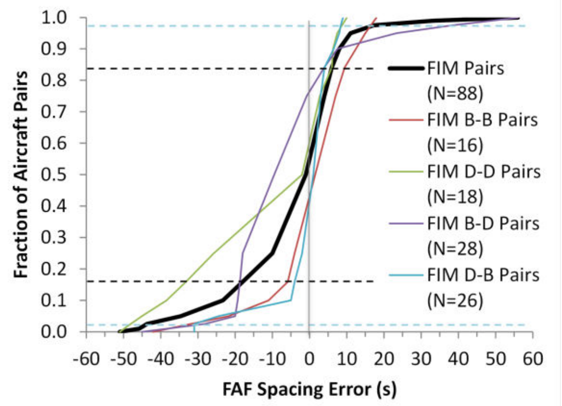

Figure 15. Cumulative distributions of inter-arrival spacing errors for FIM pairs for various route geometries.

Connected 'short-side' routes are referred to as base routes (B); unconnected 'long/high-side' routes are referred to as downwind routes (D). A 'B-D' pair, for example, has the target aircraft on a connected route to the PTP and the FIM aircraft on an unconnected route that required vectoring. TSS spacing results are more consistent across pairing types

Table V summarizes the one-standard-deviation inter-arrival-spacing-error ranges and IAT metrics. The overall results reflect a FIM IAT improvement of 1 s over TSS. For B-B pairs, FIM improves IAT by 1.5 s and yields a mean closer to zero, while the trailing aircraft in the TSS B-B pairs is usually late. When neither aircraft is on a connected route (D-D), trailing aircraft are consistently late under both conditions, and TSS yields a 2 s IAT reduction. The B-D condition also results in a 2 s IAT reduction under TSS, while FIM shows the greatest improvement (9s IAT) under the D-B condition. Errors for the FIM D-B condition are also distributed around zero. These results demonstrate improved FIM performance over TSS in the B-B and D-B conditions when the FIM aircraft's route connects to the PTP. The results for the 'unconnected' cases are likely influenced by the accuracy with which an aircraft's flight trajectory along vectors to the final approach matched the ASTAR trajectory prediction, as well as controller intervention after FIM was suspended on the downwind segment.

TABLE V. INTER-ARRIVAL SPACING ERROR SUMMARY.

Pair Type	1 σ Min (s)	1 σ Max (s)	IAT (s)
TSS All	-19	7	13
TSS B-B	-15	3	9
TSS D-D	-27	8	17.5
TSS B-D	-16	3	9.5
TSS D-B	-18	8	13
FIM All	-18	6	12
FIM B-B	-6	9	7.5
FIM D-D	-33	6	19.5
FIM B-D	-19	4	11.5
FIM D-B	-4	4	4

D. *Acceptability and Workload*

Real-time controller workload ratings collected using Workload Assessment Keypad (WAK) functionality integrated in the MACS controller workstations stayed low throughout the simulation; NASA TLX ratings obtained from questionnaire data show 'low' to 'moderate' average workload [9]. Questionnaire data indicate that the low-altitude ARTCC controllers felt the greatest impact of FIM on their attention-management abilities, probably due to their responsibility for issuing the FIM clearance while working to ensure aircraft met the TSS meter-fix delivery-accuracy requirement. Some reported high attentional demands and a negative effect on vigilance; TRACON controllers reported no such effects. During the debriefing, low-altitude Center controllers expressed doubt about issuing the FIM clearances in similar real-world situations. These results are also reflected in questionnaire responses about factors that increased complexity for controllers. Fig. 16 shows responses for low-altitude ARTCC controllers; Fig. 17 shows responses for TRACON controllers. In the TRACON, the effort required to manage non-jet and crossover aircraft outweighed FIM-related contributions to complexity.

Pilots reported a variety of workload-increasing occurrences during FIM operations including large speed changes, several speed changes in a short time span, and the need to retract flaps after extending them due to a commanded speed 'reversal.' Analysis of ASTAR behavior showed that pilots experienced an average of two speed reversals per FIM operations. Most were less than 10 kts, but some were 20 kts or

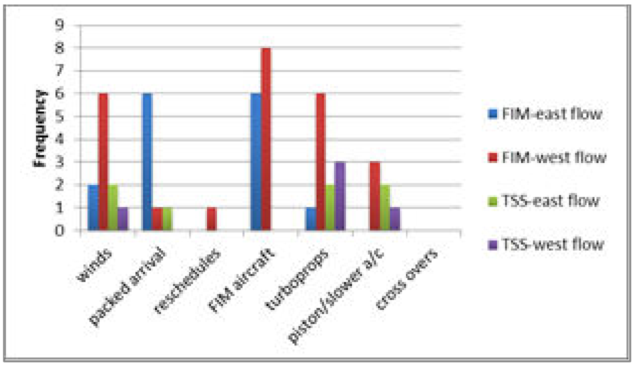

Figure 16.. Factors that increased complexity for low-altitude ARTCC controllers.

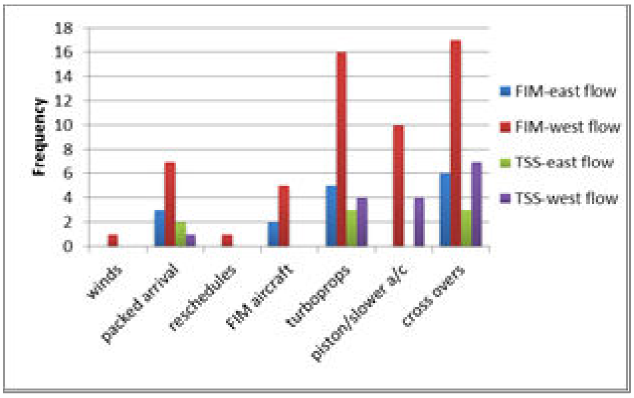

Figure 17.. Factors that increased complexity for TRACON controllers.

greater. Five of the eight ASTOR pilots reported they made more changes to their descent parameters in order to manage FIM operations; only one reported more changes due to controller intervention. Half said they had to change their scan. Pilots responded that the FIM workload was tolerable, and found the operation satisfactory approximately 90% of the time. Pilots commented that the FIM operation would likely become more manageable with a two-person crew.

V. Discussion

While FIM operations were seldom interrupted, performance improvements were only seen in cases where the FIM aircraft flew on an arrival with a connected route; however, connected routes are not prevalent for downwind arrivals in a near-term environment. Under certain conditions the simulation also exposed issues with the acceptability of FIM-commanded speeds.

Target aircraft trajectory-prediction difficulties in a near-term environment were recognized early in the ATD-1 integration process. Controllers absorb delay to meet the schedule by adjusting aircraft speeds differently than the published PBN speed profiles expected by ASTAR [14]. Delay-absorption techniques vary, so the contribution to trajectory-prediction error is not consistent across merging arrival flows. In extreme cases, controllers may also temporarily interrupt PBN vertical profiles to absorb delay. An environment such as Europe, where delay is managed more strategically due to the mix of airspace owners [15], might yield less trajectory-prediction uncertainty for mixed TSS-FIM arrival flows in a near-term environment. Forecast wind errors for a target aircraft arriving on a different route also contribute to trajectory uncertainties because the target aircraft's winds are not available to the FIM equipment. Finally, vectoring aircraft along unconnected routes leads to inaccuracies in the lateral route expected by ASTAR.

Controllers and pilots require predictable speed changes in order to manage PBN operations effectively. Trajectory-prediction issues can lead to large speed changes or speed reversals that surprise human operators and require extra work. Such problems may be magnified in high-traffic environments. Spacing behind a target aircraft on the same PBN procedure can be problematic if a controller slows the target aircraft and the FIM aircraft does not respond quickly enough; instructions issued to a target aircraft in a different arrival flow could cause the FIM aircraft to react in a way that is disruptive to surrounding traffic. Low-altitude controllers in the simulation were most likely to experience such problems when aircraft in a busy flow compress as they approach the meter fix.

Modifications to the ASTAR algorithm in [6] helped mitigate these issues, but using the TMA-TM schedule to derive an ASG at the FAF is also subject to the effects of winds along routes through multiple scheduling points. An analysis demonstrated that, in a small percentage of cases derived from historical data, along-route headwinds could lead to spacing intervals at the meter fix that could cause controllers to interrupt the FIM operation [16]. Suggested mitigations included using the most constraining interval as the ASG (reducing throughput if it is at an upstream constraint), waiting until after the meter fix to begin the FIM operation, assigning a smaller ASG after passing the constraining point, or only conducting FIM operations under favorable wind conditions.

Mixed operations must be feasible and cooperative for TSS and FIM to work together in an environment with relatively few FIM-equipped aircraft. TSS operations, in which Feeder controllers work toward a frozen TBFM schedule, and Final controllers revert to relative spacing, must integrate seamlessly with FIM operations that utilize relative spacing throughout. It is therefore expected that some schedule drift will occur whenever demand pressure is allowed to build without relief. [17]. Increased proportions of FIM-equipped aircraft make longer strings of FIM arrivals plausible. Thus, string stability [18] also needs to be evaluated for scalability to future growth in FIM operations. A batch simulation study is underway to assess the string stability of the latest ASTAR algorithm.

Increasing the availability of information to the FIM equipment via future capabilities such as data communications or expanded ADS-B message sets should also improve FIM integration. In particular, providing wind forecasts and trajectories for target aircraft merging downstream may reduce the speed uncertainties in low-altitude ARTCC airspace. Data-linked clearances would also reduce frequency congestion. It is reasonable to expect that alleviating problems with low-altitude ARTCC operations and always using connected routes would improve system-wide results. If these improvements can be made without data communications and expanded ADS-B message sets, then the integrated system may be closer to realization.

VI. CONCLUSION

A system-level simulation of ATD-1 integrated air-ground operations using the ATD-1 prototype technologies demonstrated consistent PBN-procedure conformance and FIM benefits under conditions when FIM aircraft flew connected routes to their assigned landing runways. The simulation also identified aspects of FIM operations that need improvement before FIM can reliably provide benefits in conjunction with TSS operations in a near-term environment. An ATD-1 study is planned to investigate alternative FIM clearance types [13] such as speed-matching capabilities that may allow for better FIM-TSS integration. Due to the apparent advantages of utilizing connected routes for FIM operations, the study plans to examine arrival operations at Denver International Airport (DEN), where newly published RNP approach procedures provide the required connectivity. The study will also afford a first look at RNP operations within an integrated TSS-FIM system. Results from this and future studies will inform government and industry stakeholders across the United States, Europe and Japan. Following this year's simulation efforts, validation flight tests are planned for 2016-2017.

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