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Simulations of Continuous Descent Operations with Arrival-Management Automation and mixed Flight-Deck Interval Management Equipage

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***Abstract*—Air traffic management simulations conducted in the Airspace Operations Laboratory at NASA Ames Research Center have addressed the integration of trajectory-based arrival-management automation, controller tools, and Flight-Deck Interval Management avionics to enable Continuous Descent Operations (CDOs) during periods of sustained high traffic demand. The simulations are devoted to maturing the integrated system for field demonstration, and refining the controller tools, clearance phraseology, and procedures specified in the associated concept of operations. The results indicate a variety of factors impact the concept's safety and viability from a controller's perspective, including en-route preconditioning of arrival flows, useable clearance phraseology, and the characteristics of airspace, routes, and traffic-management methods in use at a particular site. Clear understanding of automation behavior and required shifts in roles and responsibilities is important for controller acceptance and realizing potential benefits. This paper discusses the simulations, drawing parallels with results from related European efforts. The most recent study found en-route controllers can effectively precondition arrival flows, which significantly improved route conformance during CDOs. Controllers found the tools acceptable, in line with previous studies.**

Keywords- arrival management; continuous descent operations; controller tools; flight-deck interval management

I. INTRODUCTION

New air traffic management (ATM) technologies and procedures required for addressing projected future air-traffic demand, and economic and environmental concerns, have been the focus of research and development by the US Next Generation Air Transportation System (NextGen) initiative [1] and the Single European Sky ATM Research program (SESAR) [2]. Both efforts have identified promising concepts and technologies for transforming today's ATM system and have detailed implementation plans in place [3, 4]. However, because the deployment of advanced ATM technologies requires considerable investments on the part of Air Navigation Service Providers (ANSPs) and industry stakeholders, it is critical to continue to encourage industry involvement and provide sound data to support further infrastructure and avionics investment decisions.

In 2011 NASA launched ATM Technology Demonstration-1 (ATD-1) to demonstrate increased, more consistent use of Performance-Based Navigation (PBN), demonstrate an ADS-B-In spacing application, and accelerate the transfer of NASA scheduling and spacing technologies for operational deployment. ATD-1 is a multi-year collaborative effort between researchers at NASA Ames and Langley Research Centers, the FAA, and industry partners to integrate, mature, and operationally demonstrate NASA-developed technologies that reflect the NextGen emphasis on PBN approaches to streamlining arrival management [5]. The ATD-1 technologies are a ground-based arrival-management system that includes trajectory-based controller tools and Flight-Deck Interval Management (FIM) avionics enabled by Automatic Dependent Surveillance-Broadcast (ADS-B). Together these technologies are intended to promote Continuous Descent Operations (CDOs) along Area Navigation (RNAV) Optimized Profile Descents (OPDs) [6] when high traffic levels would otherwise prevent them. As the proportion of FIM-equipped aircraft increases, improved arrival precision is expected to further increase throughput and the proportion of uninterrupted CDOs [7, 8]. Assessing these benefits in an operational setting is a key objective of ATD-1.

ATD-1 is devoted to developing the prototype ground-based and airborne software, procedures, and phraseology toward an integrated package suitable for field testing. The Airspace Operations Laboratory (AOL) at NASA Ames is one of three primary ATD-1 laboratories at NASA. Researchers in the AOL have conducted a series of four human-in-the-loop simulations focused on iteratively developing and integrating the laboratory prototype, and refining the controller tools, procedures, and phraseology specified by the ATD-1 Concept of Operations (ConOps) [9]. The simulations have afforded the opportunity to investigate the evolving ATD-1 technologies and ConOps from both en-route and terminal-area controller

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perspectives in two different airspaces using controller teams with different levels of airspace and automation familiarity. These efforts, and the insights they have provided, mirror European experiences with related concepts in many respects (e.g., [10]).

This paper first highlights previous research on concepts for integrating arrival-management automation with airborne-spacing applications, then introduces the ATD-1 component technologies and ConOps. Next, it describes the AOL simulations—with a focus on the most recent—and presents salient results. The paper concludes with a discussion of implications and future work.

II. BACKGROUND

SESAR and NextGen research has pursued airborne-spacing applications and arrival-management systems (AMANs) for some time. EUROCONTROL researchers investigating airborne spacing in the terminal area reported reduced controller workload, better anticipation in constructing sequences without resorting to late vectoring, and more consistent inter-arrival spacing—and cited AMAN integration as an important next step [11]. An AOL study that incorporated runway-scheduling functionality found inter-arrival spacing improvements were possible without increased controller workload under mixed-airborne-spacing equipage [12]; another that included runway scheduling, en-route flow conditioning, and data communications also showed a positive effect on throughput when airborne spacing was used in conjunction with CDOs [13]. This research concluded before key enabling technologies were fully developed. With full ADS-B deployment nearing completion in the US [3] and significant ANSP investments in RNAV OPDs [14], projects like ATD-1 are especially pertinent.

The ATD-1 integrated arrival-management solution is called the Interval Management Terminal-Area Precision Scheduling System (IM-TAPSS) [5]. This section first describes the IM-TAPSS scheduling automation, controller tools, and FIM capabilities, and discusses related European developments. It then presents a ground-centric introduction to the ATD-1 ConOps, which specifies how IM-TAPSS is to be used in a voice-communications environment.

Figure 1. TMA-TM graphical timeline interface.

A. *ATD-1 Component Technologies*

In IM-TAPSS, the Traffic Management Advisor for Terminal Metering (TMA-TM) (Fig. 1) provides arrival-management functions similar to European AMAN functionality, in line with the AMAN principles summarized in [15]. The TMA-TM extends the Traffic Management Advisor originally developed at NASA Ames and currently deployed in US en-route traffic control centers [16]. The fielded system produces schedules at meter fixes on terminal-area boundaries according to airport-acceptance rates, and provides traffic managers with timeline interfaces that support manual schedule adjustments and provide delay information (i.e., Time-to-Lose (TTL)/Time-to-Gain (TTG)). TMA-TM leverages adapted representations of RNAV OPDs to more accurately predict trajectories for aircraft conducting CDOs, and uses these predictions to construct de-conflicted arrival schedules at terminal-area metering points and runways. TMA-TM also includes functionality to balance runway utilization and efficiently distribute required delays so that aircraft absorb large delays at higher altitudes, which is typically more efficient [17].

Advanced AMAN functionality, including integration with departure-management automation and flexible scheduling, is implemented in commercially available AMANs that have been deployed by several European ANSPs [18]. Most provide a core set of capabilities similar to TMA-TM; several also provide route-allocation functionality, wake-category-based schedule optimization, collaborative flow-management to enable airlines to specify flight priorities, and planning features to support recovery from off-nominal situations (cf. [19, 20]). Advanced advisories at individual en-route and terminal-area controller positions, including data-block display of speed and route advisories for absorbing delay, are also under development [21].

IM-TAPSS uses the Controller-Managed Spacing (CMS) tools to assist terminal-area controllers (Fig 2) [22]. CMS tools include schedule timelines, TTL/TTG values (referred to as early/late, or E/L, indicators), and speed advisories. The timeline shows the TMA-TM estimated times-of-arrival (ETAs) on the left side and scheduled times-of-arrival (STAs) on the right for all aircraft at the scheduling point. Weight-class indicators are shown next to each aircraft identifier; the identifiers change color when the associated aircraft's STA is frozen. Advised speeds are computed to put the aircraft back on schedule. If an advisory cannot be computed because the required speed is outside the available speed control margin, an E/L indicator appears instead of a speed advisory.

The CMS tools also include slot markers (or 'slot-marker circles')—unique trajectory-based tools that were developed in the AOL to translate temporal schedule information into spatial targets. The slot markers use trajectory predictions along each aircraft's assigned nominal RNAV OPD through the forecast wind field to show where each aircraft should be now if it were to fly the nominal speed profile and arrive on schedule (cf. [23]). The current indicated airspeed of each slot marker is displayed next to it. Dwelling on an aircraft's data block

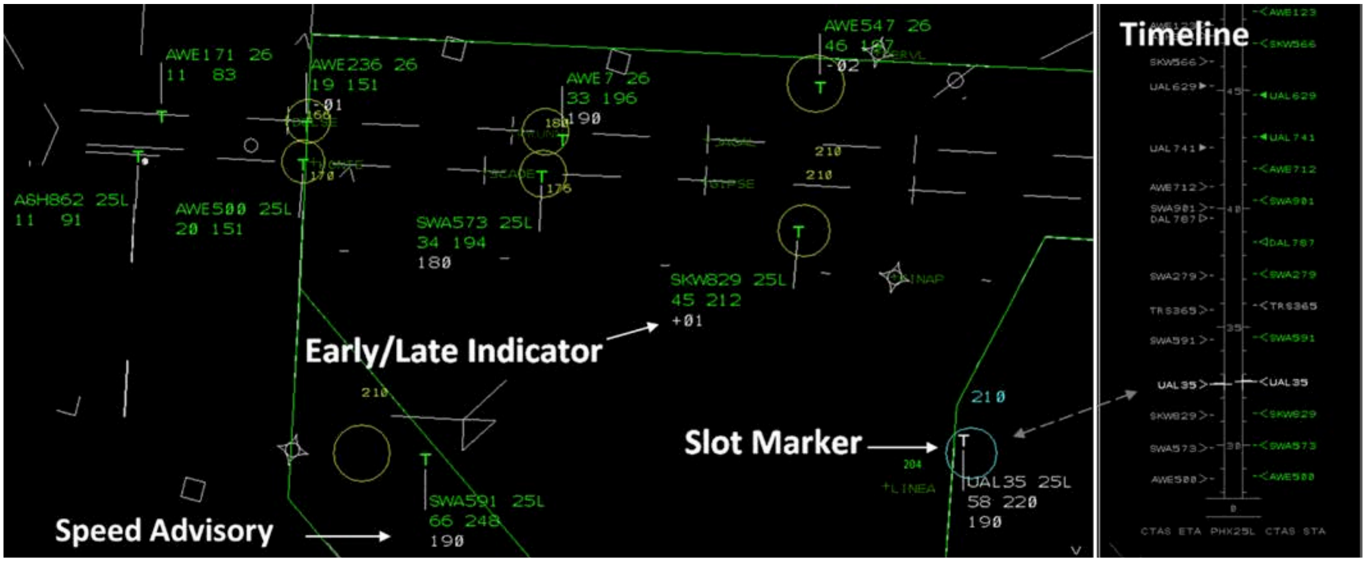


Figure 2. Controller-Managed Spacing (CMS) tools, illustrating synchronous highlighting of data block, slot marker, and timeline entries.

Figure 3. Example ASTAR Electronic Flight Bag (EFB) implementation with ADS-B Guidance Display (AGD).

highlights its slot marker and timeline entries, as shown in Fig. 2.

The Airborne Spacing for Terminal Arrival Routes (ASTAR) algorithm developed at NASA Langley provides FIM capabilities in IM-TAPSS [24]. ASTAR uses ADS-B data to provide flight crews with speed commands during CDOs, enabling aircraft to precisely achieve an assigned spacing interval at a specified 'achieve-by' point. Thus, ASTAR allows controllers to issue a single strategic clearance which delegates the task of providing speed instructions to the aircraft avionics. Fig. 3 depicts one possible flight-deck integration scheme; others are discussed in [8]. Unlike other airborne spacing applications (e.g., [25]), ASTAR's trajectory orientation supports FIM initiation in en-route airspace, and enables aircraft to achieve the TMA-TM-computed time-spacing interval behind a lead aircraft (or 'target') arriving via a different RNAV OPD; this mode is called 'paired-spacing' mode. ASTAR also includes a mode in which it commands speeds to achieve a specified STA at the achieve-by point until the lead aircraft enters ADS-B range, when 'paired-spacing' mode can engage. Two important aspects of ASTAR are that it requires both the own-ship and target to remain within specified lateral and vertical tolerances of reference trajectories that correspond to the assigned RNAV OPD(s) and, similarly, that the speeds it commands are limited to be within specified tolerances around the reference speed profile.

B. ATD-1 Concept of Operations Overview

Although ATD-1 has a distinct terminal-area focus, operations begin when the TMA-TM acquires each aircraft while it is still in cruise. TMA-TM assigns aircraft a runway, and computes ETAs at the meter fix, runway, and at intervening metering points (e.g., terminal-area fixes where RNAV OPDs merge). It then uses the ETAs together with desired spacing information to assign STAs at each scheduling point. When an aircraft reaches a 'freeze horizon' specified at a site-specific distance (e.g., 200 nmi) from the terminal area, the TMA-TM locks in its STA to provide a stable control target. En-route controllers now begin working to 'precondition' the aircraft using vectoring or other techniques as necessary to reduce the delay required to keep the aircraft within the speed control margin. Ongoing FAA en-route modernization efforts are expected to include Ground-based Interval Management (GIM) speed advisories to assist controllers in preconditioning aircraft efficiently [7].

Following preconditioning, en-route controllers reestablish aircraft on RNAV OPDs (e.g., by clearing aircraft direct to the meter fix), and clear aircraft for CDOs using phraseology shown in Table 1. Once a FIM-equipped aircraft has been preconditioned and established on an RNAV OPD, the controller alerts the crew that a FIM clearance is available, and issues it when the crew is ready (Table 1). After the crew enters the required parameters, ASTAR begins commanding speeds

TABLE I. EXAMPLE ATD-1 CLEARANCE PHRASEOLOGY.

Clearance Type	Phraseology
CDO Initiation with Runway Assignment	<CALLSIGN>, DESCEND VIA THE MAIER THREE ARRIVAL, BOULDER CITY TRANSITION, TO RUNWAY TWO-SIX.
FIM Clearance Availability	<CALLSIGN>, INTERVAL SPACING AVAILABLE, ADVISE WHEN READY TO COPY.
FIM Initiation	<CALLSIGN>, FOR INTERVAL SPACING, CROSS JIFFY AT 1432:30Z. WHEN ABLE, SPACE NINE-ZERO SECONDS BEHIND DELTA EIGHT-SEVEN-SEVEN ON THE BONHAM FIVE ARRIVAL, FORT SMITH TRANSITION.
CDO Speed Adjustment	<CALLSIGN>, DESCEND VIA THE MAIER THREE ARRIVAL, EXCEPT MAINTAIN TWO-ZERO-ZERO KNOTS.
CDO Termination	<CALLSIGN>, DESCENT CLEARANCE CANCELLED, FLY HEADING TWO-ZERO-ZERO, MAINTAIN SEVEN THOUSAND FEET
FIM Suspension	<CALLSIGN>, SUSPEND INTERVAL SPACING, SLOW TO TWO-THREE-ZERO KNOTS.

toward an STA at the achieve-by point until the target enters ADS-B range, when it transitions to paired-spacing mode.

Terminal-area controllers are expected to use the CMS tools to issue speeds to ensure proper inter-arrival spacing for non-FIM aircraft while maintaining CDOs (Table 1); crews of FIM aircraft should follow the ASTAR-commanded speeds. Under nominal conditions, aircraft should cross the meter fix within their speed control margin for correcting residual schedule errors and adjusting for disturbances due to winds or other factors inside the terminal area. Because controllers retain separation responsibility, they may find it necessary to interrupt CDOs or suspend FIM operations if they deem small adjustments from the nominal speed profile insufficient to maintain safe separation (Table 1).

The ATD-1 ConOps, with its focus on extended CDOs and FIM operations starting at high altitudes, seeks to maximize the potential benefits of IM-TAPSS. It also focuses on leveraging RNAV-OPD infrastructure investments, as opposed to requiring airspace or route modifications (cf. [11]). The next section describes human-in-the-loop simulations intended to mature IM-TAPSS and investigate ConOps-related issues.

III. SIMULATION STUDIES

The AOL has served as the principal IM-TAPSS integration laboratory responsible for establishing and testing technical and procedural interoperability between the latest TMA-TM prototype, ASTAR-equipped Aircraft Simulator for Traffic Operations Research (ASTOR) simulators from NASA Langley, and the AOL's CMS tools and Multi-Aircraft Control System (MACS) controller workstation emulations and pseudo-pilot stations [26]. 'CMS ATD-1' simulations in January, April, and June 2012—referred to as 'CA-1,' 'CA-2,' and 'CA-3,' respectively—have allowed researchers to iteratively refine required functionality and collect data using the latest IM-TAPSS system before the integrated software is used by the other laboratories conducting ATD-1 research at NASA Ames and Langley. The 'CA-4' simulation, conducted in December 2012, continued this process. This section first briefly describes the preceding simulations before describing CA-4 in detail.

A. CA-1, CA-2, and CA-3 Simulations

CA-1, CA-2, and CA-3 [27] simulated arrivals to Dallas/Fort Worth International Airport (DFW) along RNAV OPDs developed at NASA Langley to support prior FIM research. CA-1 and CA-2 introduced controller participants experienced with CMS operations in the AOL to mixed-FIM-equipage arrival operations, gained initial controller acceptance, and examined a variety of controller-tool configurations (e.g., no controller tools, tools only available for non-FIM aircraft). These simulations illustrated that effective preconditioning using precise meter-list STAs made the terminal-area controllers' task more manageable and increased the effectiveness of the CMS tools by ensuring aircraft needed only small adjustments possible with speed control. They also identified a need for FIM-related information (i.e., which FIM-equipped aircraft have been issued FIM clearances, which are paired with their assigned target, etc.), leading to the development of prototype FIM-status designators on controller displays.

CA-3 expanded operations to two independent runways at DFW, and added emulations of GIM speed advisories to the MACS en-route controller workstations. It also refined how FIM-clearance information appeared in the en-route controllers' meter lists when the TMA-TM froze a FIM-equipped aircraft's STA. The FIM achieve-by point was relocated from the runway threshold to the Final Approach Fix (FAF) to obviate difficulties related to trajectory-prediction accuracy in the region between the FAF and the runway. Finally, simple winds-at-altitude and forecast wind errors were implemented within IM-TAPSS. Perhaps the biggest change from the CA-1 and CA-2 studies, however, was that CA-3 controller participants were recently retired with an average of nearly thirty years of experience with DFW operations—but no familiarity with the CMS tools, FIM operations, or the MACS simulation platform. This led to the development of a training process and afforded the opportunity to examine its efficacy.

CA-3 showed that controllers found workload low and operations acceptable, seldom vectored aircraft off the RNAV lateral routes, rated the CMS tools consistently with prior studies, and rated the training highly. However, at critical junctures controller performance was observed to suffer from misunderstandings about scheduling functionality, FIM aircraft behavior, and speed-control techniques. Some controllers commented specifically on their desire to better understand not only their roles, but also the roles of other actors in the system. Overall, CA-3 indicated a greater familiarity with the system is needed to yield consistent benefits. The results were probably quite similar to those that might be obtained if an IM-TAPSS system at a comparable level of maturity were introduced in the field with limited controller orientation [27]. These findings are strikingly similar to those from a similar EUROCONTROL AMAN simulation [10].

B. CA-4 Simulation

CA-4 sought to continue investigations of issues identified in the prior studies, while addressing a number of new aspects of IM-TAPSS integration. Specifically, CA-4 attempted to quantify the effect of preconditioning the arrival flows, compare operations with only slot markers and timelines to the full CMS tool set, and continue to examine FIM operations. At the same time, it sought to validate new adaptation information for published RNAV OPDs into Phoenix Sky Harbor International Airport (PHX) and integrate realistic winds with the updated IM-TAPSS laboratory prototype. It also sought to evaluate three-character E/L indicators and speed advisories in the third line of the data blocks in preparation for integrating the CMS tools into existing terminal-area controller workstations, along with the updated display formats for FIM-status designators. In addition, CA-4 added the capability for the FAA Level-D-certified Boeing 747-400 (B744) simulator housed in the Crew Vehicle Systems Research Facility at NASA Ames to participate in AOL simulations as a non-FIM-equipped arrival. The following subsections present the approach used in CA-4.

1) Routes, Airspace, and Traffic Scenarios

CA-4 simulated west-flow arrivals to runways 25L and 26 at PHX. PHX was chosen because it shares characteristics of likely ATD-1 demonstration sites, including established RNAV OPDs. Fig. 4 depicts the route and airspace layout, including four low-altitude test sectors. Subject controllers who staffed these sectors were also required to work aircraft in outlying high-altitude sectors as required to precondition the arrivals and issue clearances to aircraft in cruise. Fig. 4 also shows high-altitude crossing restrictions defined along the published arrival transitions in order to impart consistent descent behavior.

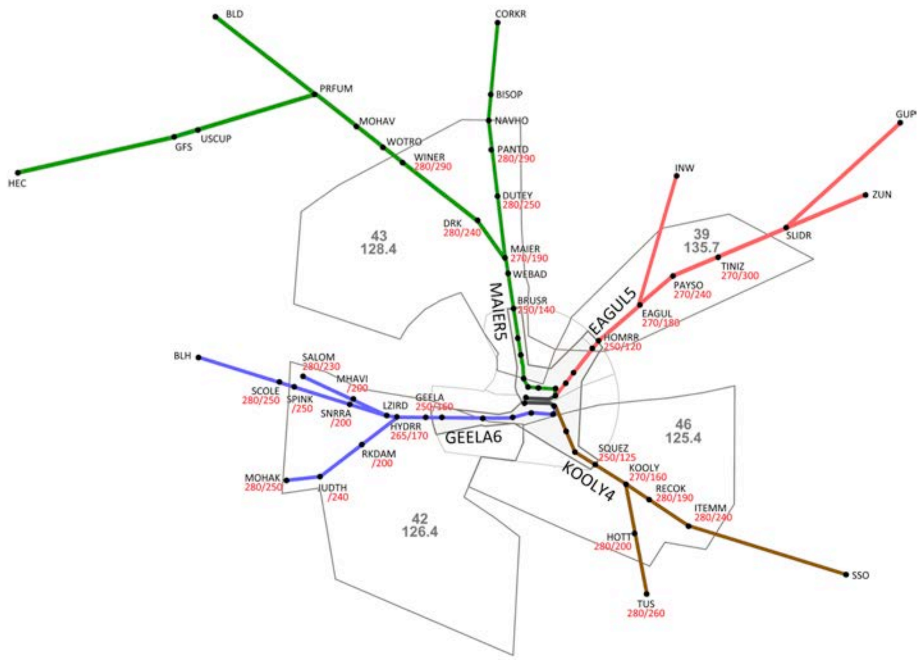


Figure 4. PHX west-flow RNAV OPDs and arrival transitions through low-altitude en-route sectors.

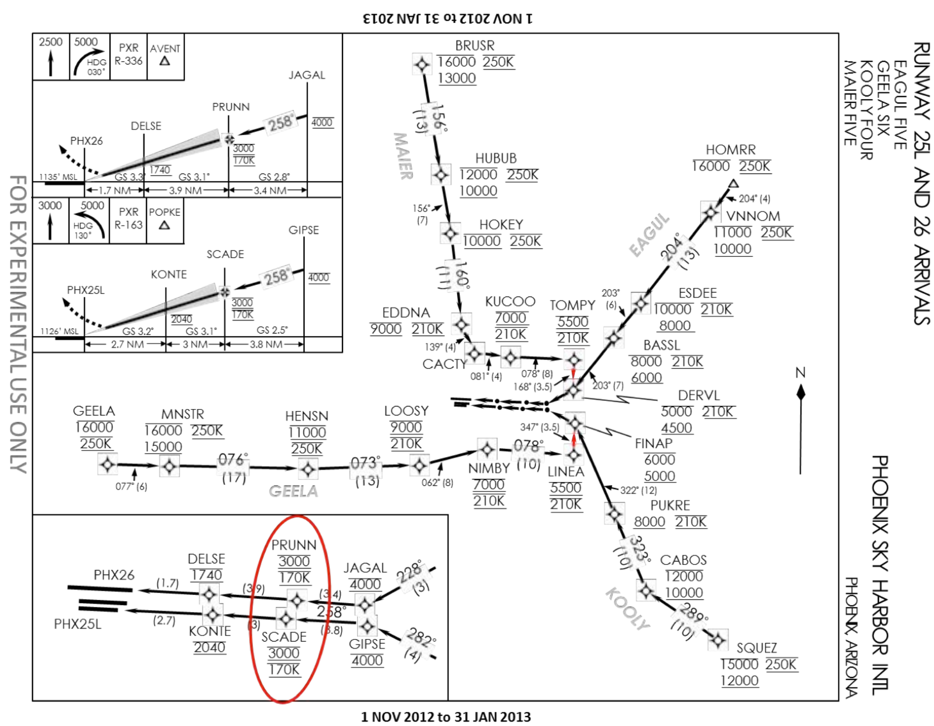


Figure 5. Experimental chart depicting PHX terminal-area RNAV OPDs, with final-approach fixes circled and artificial base legs in red.

The terminal-area portions of the routes are illustrated via the terminal-area chart simulator pilots used during CA-4 (Fig. 5). During west-flow operations published RNAV OPDs from the east connect to the runway 25L and 26 approach procedures. Published downwind arrival segments from the west are unconnected, but artificial base-leg segments, shown in red in Fig. 5, were defined for consistency across air and ground systems in CA-4.

Two ‘Feeder’ controllers and two ‘Final’ controllers staffed four terminal area sectors. The north Feeder transferred control of aircraft arriving via the MAIER or EAGUL routes to the runway-26 Final near the EDDNA or ESDEE waypoints, respectively; the south Feeder transferred control of aircraft on the GEELA or KOOLY routes to the runway-25L Final after LOOSY or near PUKRE.

AOL researchers constructed traffic scenarios by distributing recorded PHX arrival traffic to the RNAV routes so that the various sectors experienced comparable traffic loads; all aircraft in the simulation were assumed to be RNAV-equipped. Eight FIM-equipped ASTOR simulators were assigned to the published EAGUL and KOOLY arrivals that connect to the approach procedures. The B744 simulator was initialized to arrive either on the MAIER or the EAGUL arrival to runway 26, which can accommodate heavy jets. Three different traffic scenarios were finalized after ensuring the TMA-TM—configured with a 0.3 nmi spacing buffer and standard 3/4/5 nmi wake-vortex spacing requirements—yielded reasonable schedules with an arrival rate of 42-44 aircraft per hour for each runway during any given fifteen-minute period.

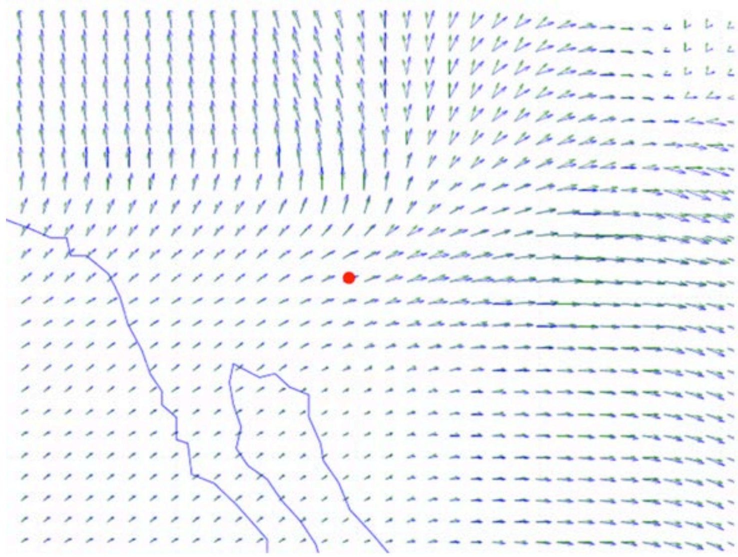


Figure 6. CA-4 gridded winds at ~10,000 ft, with approximate location of PHX.

2) Winds

CA-4 extended the simple wind representations used in CA-3 to gridded winds based on PHX archival data. Test winds from data two hours apart, with an approximately ten-knot RMS error, were converted to formats required by the IM-TAPSS laboratory-prototype components (Fig. 6). The winds were intended to provide realism, as well as variation in the traffic scenarios through the use of one set as the actual winds and the other as the forecast winds in different simulation trials.

3) Controller Tools

Fig. 2 above depicts the modified CMS E/L indicators and speed advisories developed for CA-4. The three-character E/L indicators display the required delay with one-second precision (e.g., -15 indicates an aircraft is fifteen seconds late), and switch to one-minute precision if the absolute delay exceeds 99 s (e.g., +2M indicates an aircraft is approximately two minutes early).

FIM-clearance parameters for equipped aircraft are provided by TMA-TM and added to meter lists similar to those en-route controllers currently use. Fig. 7 illustrates how the FIM-clearance information is organized in the order required by the FIM-clearance phraseology in Table 1. For example, the FIM clearance for DAL808 is: DELTA 808, FOR INTERVAL SPACING, CROSS SCADE AT 1915:24Z. WHEN ABLE, SPACE ONE-THREE-ZERO SECONDS BEHIND UNITED SEVEN-FOUR-ONE ON THE GEELA SIX ARRIVAL, BLYTHE TRANSITION.

En-route controllers in the simulation also had prototype GIM speed advisories and redesigned FIM-status designators available (Fig. 8). Fig. 8(a) illustrates the 'I' portal that appears when a speed advisory like that in (b) is available. Fig. 8(a) also shows the '@' symbol that indicates an aircraft is FIM-equipped. Fig. 8(c) illustrates how the '@' turns magenta following a controller entry signaling that a FIM clearance has been issued to the aircraft. Controllers could change the FIM-status designator to 'R' or 'S' to signify that a flight crew has reported following ASTAR-commanded speeds to meet the achieve-by-point STA or execute paired spacing, illustrated by (d) and (e) in Fig. 8. Fig. 8 also shows delay-countdown information adjacent to an aircraft's target symbol on the en-route displays.

As aircraft transition to terminal-area airspace, FIM-status designators entered upstream transfer automatically to the terminal-area controller workstations, enabling them to cross-check FIM status with that reported in check-in communications. Terminal-area controllers could also make entries to change the displayed FIM status. In CA-4 the terminal-area designators were redesigned to replace the CMS E/L indicators or speed advisories in the three-character field on the third line of aircraft data blocks. Fig. 9 illustrates the appearance of the FIM-status designators on the terminal-area workstation for (a) 'FIM clearance issued,' (b) 'following speed commands to meet STA,' and (c) 'following speed commands in paired-spacing mode.' Other tools expected to be available on terminal-area controller workstations during the

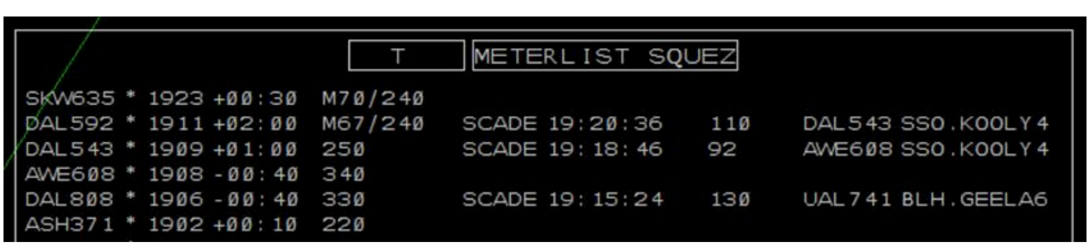
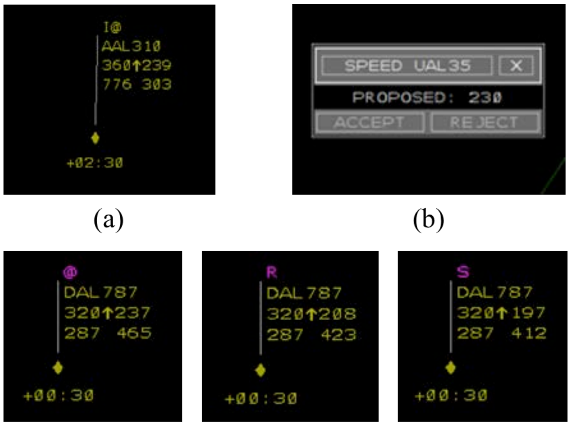


Figure 7. Meter list display on en-route controller workstation, showing FIM-clearance parameters for FIM-equipped aircraft; from left to right, the parameters are achieve-by point, STA at achieve-by-point, required spacing interval, lead aircraft, and lead aircraft's assigned RNAV OPD.



(a) (b)

(c) (d) (e)

Figure 8. En-route speed advisories and FIM-status designators.

(a) (b) (c)

Figure 9. Terminal-area FIM-status designators.

ATD-1 demonstration timeframe, such as Terminal Proximity Alert (TPA) 'spacing cones' and J-rings, were also available in CA-4.

4) Participants

Controllers with AOL experience (including, with three exceptions, experience from CA-1 and CA-2) participated in CA-4; however, none were familiar with PHX operations. Boeing glass-cockpit type-rated pilots, many of whom had participated in CA-3, were recruited as ASTOR pilots. As in previous simulations, general aviation pilots and students staffed the MACS pseudo-pilot stations. Participants were organized into a Center control room, a terminal-area control room, an ASTOR cluster, and a pseudo-pilot area in a portion of the AOL (Fig. 10). Terminal-area controllers were stationed relative to one another like actual controllers in PHX. Controllers staffed the same control positions for the duration of CA-4.

5) Training and Procedures

As in CA-3, controllers received three days of training during the week prior to data-collection. Training began with a general briefing about the study, followed by separate briefings for pilots, en-route controllers, and terminal-area controllers. The next two-and-one-half days were devoted to traffic simulations intended to familiarize controllers with the PHX airspace and the latest controller tools, during which integration work on the CA-4 IM-TAPSS laboratory prototype continued in parallel. Controllers began with light-traffic training runs while the ASTOR pilots practiced separately. The training progressed to include ASTORs conducting FIM operations in heavier traffic. En-route controllers practiced preconditioning

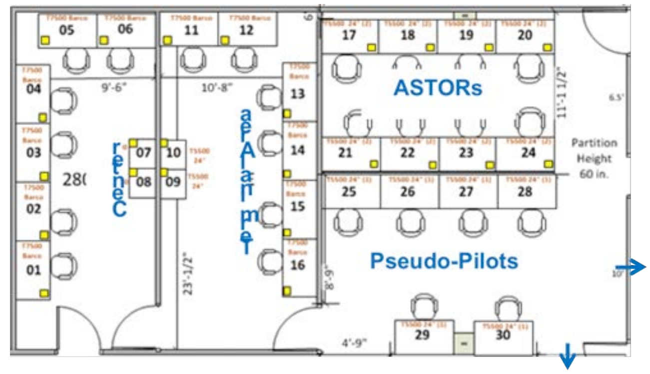


Figure 10. AOL laboratory layout for CA-4.

the arrival flows. Delivering aircraft on time or slightly early was characterized as ideal, as prior research indicates slowing aircraft to absorb delay in the terminal area is easier for both pilots and controllers than making up time. The CA-4 training period concluded with a review briefing.

6) Data-Collection Schedule

Problems with how certain traffic scenarios played out in specific winds, along with other inconsistent system behaviors, led to an unbalanced experimental matrix. In the end, CA-4 compared operations across available scenario-plus-winds combinations for two levels of preconditioning: one in which en-route controllers were instructed to precondition arrivals to less than one minute of meter-fix delay or better ("precise" preconditioning), and one in which less than two minutes of meter-fix delay was considered acceptable ('imprecise' preconditioning). It also compared conditions with only CMS timelines and slot markers available to conditions when the 'third-line' tools were available in addition to the timelines and slot markers.

Nineteen one-hour simulation trials were conducted during the CA-4 data-collection week, during which all MACS and ASTOR stations logged digital data, including flight state information, pilot and controller entries, and schedule information. TMA-TM also logged digital data. Controllers completed short questionnaires between trials, and a longer questionnaire at the end of the week. In addition, screen-capture movies that include recorded audio were collected from all MACS and ASTOR stations, and experts with extensive experience on TMA-TM and PHX operations served as observers. The next section presents salient results from CA-4.

IV. RESULTS

CA-4 was highly successful from a systems-integration and ConOps-refinement perspective. In its early stages, the study enabled researchers to make minor adjustments to the TMA-TM PHX site adaptation, establish the behavior of FIM-status designators, detect an outstanding wind-integration issue, and generally develop a more in-depth understanding of PHX operations. Although the wind-related issue rendered arrival-spacing accuracy metrics on final approach unusable, and negatively affected the success of FIM operations, controllers were observed to be largely successful in maintaining scheduled throughput levels. No statistically significant differences in any of the metrics can be attributed to the traffic

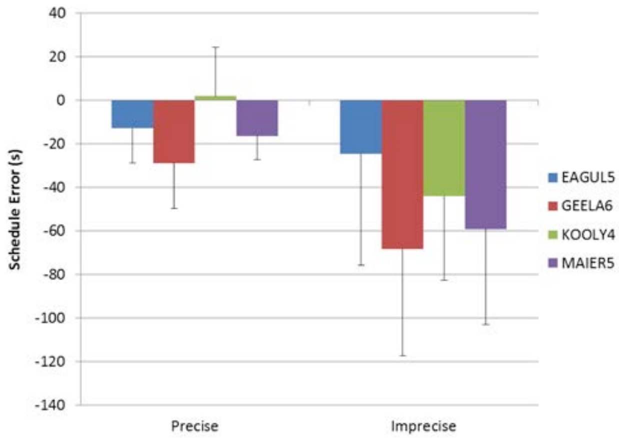


Figure 11. Meter-fix schedule conformance by preconditioning level and assigned RNAV OPD (negative values indicate aircraft arrived early).

scenario/wind combinations. This section presents salient results from CA-4.

A. TMA-TM and En-Route Controller Tools

The results indicate the TMA-TM and en-route controller tools provide the required support for ATD-1 operations. Controller questionnaire responses indicate the TMA-TM produced schedules that were largely achievable, stable, and accurate. The delay-countdown information, in particular, garnered the highest possible helpfulness and usability ratings. However, the en-route speed advisories were only 'moderately' accurate and stable—ratings that translated to indifferent assessments of helpfulness and usability. Ref. [10] also recognizes the importance of schedule stability.

B. Arrival-Flow Preconditioning Performance

The en-route controllers largely met the preconditioning goals set for them in CA-4. Fig. 11 shows the meter-fix-schedule errors observed when aircraft crossed the meter fixes along each RNAV OPD. Significant improvements in trials with preconditioning were observed for controllers working the GEELA and MAIER arrivals ($p < 0.01$); the KOOLY and EAGUL differences were not significant, but in those cases, 'imprecise' preconditioning was generally better than the approximately two minutes of schedule error requested. As in CA-3, controllers adopted individual strategies for preconditioning. Controllers working the KOOLY and MAIER arrival flows relied on vectoring more than the other two, who mainly used speed control.

C. RNAV OPD Conformance

Aircraft conformance with the published procedures in the terminal area verified the expected effects of preconditioning. For example, Fig. 12 compares aircraft lateral tracks and profiles from two simulation trials using the same scenario/wind combination and no third-line tools. In one trial (shown in blue), en-route controllers attempted to precondition arrivals to within one minute of their meter fix STAs; in the other (shown in red), controllers needed only to ensure aircraft arrived within two minutes of their meter-fix STAs. Fig. 12 demonstrates how the requirement to precondition aircraft more precisely redistributes workload to the en-route controllers and increases efficiency by moving delay-absorption maneuvers to higher altitudes; conversely, imprecise preconditioning leads to disorganized terminal-area traffic flows and (aside from one pilot non-compliance error) more interruptions in continuous low-altitude descent profiles.

These effects are confirmed for the CA-4 study on the whole. Fig. 13 plots the average number of aircraft observed to leave the lateral RNAV routes in en-route and terminal-area airspace under each level of preconditioning. In the terminal area, where speed control is preferable, significant differences were found between the two levels of preconditioning ($p < 0.01$). An analysis of the average number of level segments longer than 2 nmi flown in the terminal area also confirmed better results with precise preconditioning. While that difference is not significant, it does show an improvement of the sort that pilots who experience the operations frequently would likely notice.

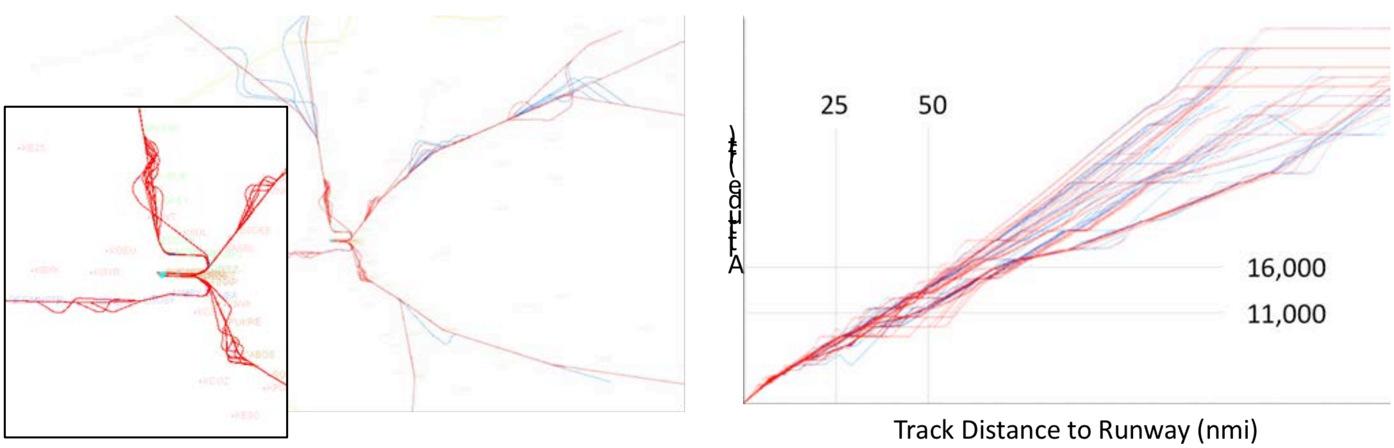


Figure 12. Comparison of lateral tracks and vertical profiles for one CA-4 trial with precise preconditioning (blue), and one without (red).

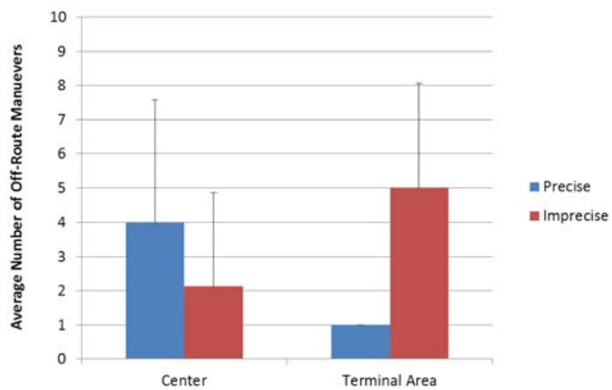


Figure 13. Preconditioning effects on lateral route conformance by control region.

D. CMS Tools

CA-4 investigated ATD-1 operations with two CMS-tool configurations: one with only timelines and slot markers, and one in which the third-line tools were also available. No significant differences were observed between the two, perhaps because controllers reported using the third-line indications (i.e., the E/L indicators and speed advisories) only half the time when they were available. Consistent with prior studies, all of the tools behaved acceptably, and controllers reported using slot markers the most. However, they were rated as less stable than the timelines in CA-4. This was likely integration-related, as both TMA-TM and MACS trajectory predictions affected their behavior in the CA-4 version of IM-TAPSS. Controllers again expressed a desire to flexibly control when slot markers are displayed for particular aircraft. Some of this functionality is already available in the IM-TAPSS prototype and will undergo further refinement for the next version of IM-TAPSS.

E. FIM-Clearance Phraseology

En-route controllers who issued FIM clearances rated them in a range between 'moderately manageable' and 'very manageable.' On the whole, the FIM-clearance phraseology worked well, and received high ratings for read-back clarity, accuracy, and timeliness. This contrasts with CA-3 results, and can be attributed to greater familiarity and better understanding of flight crew tasks. Controllers did, however, express the desire to split the FIM clearance into two parts if a particular situation warrants it. For example, if the target aircraft is off-route, or planned rescheduling will result in a new target, a controller could leverage ASTAR's capability to achieve an STA until the situation stabilizes. Issuing the clearance in two parts would also enable controllers to address other tasks in the interim.

F. FIM Operations and Status Indications

The wind-related issue is thought to have played a role in the large proportion of suspended FIM operations observed in CA-4; this issue is slated for immediate redress. However, both en-route and terminal-area controllers viewed the redesigned FIM-status designators favorably. The EAGUL and KOOLY en-route controllers who managed FIM-equipped ASTORs during CA-4 found the status-updating tasks 'very acceptable,' while the terminal-area controllers found them 'reasonably acceptable.' In line with preceding studies, CA-4 controllers reported on average that FIM operations 'increased task complexity,' but not excessively.

G. System Integration and Site-Adaptation

CA-4 fulfilled its objectives from a system-integration standpoint. It served as a successful test case for implementing IM-TAPSS in a new airspace and leveraging existing RNAV-OPD infrastructure. Creating the TMA-TM, MACS, and ASTOR route adaptations proved manageable and provided valuable experience for future work. Perhaps most importantly, PHX experts validated the compatibility of IM-TAPPS with PHX operations, as well as its operational need.

V. Conclusions

A series of ATM-focused simulations in the AOL at NASA Ames have provided valuable insights about operations that combine arrival management and trajectory-based controller tools with FIM avionics. The simulations have also made significant contributions to the integration of IM-TAPSS for the ATD-1 field demonstration. The most recent study, CA-4, demonstrated the importance of 'involving en-route controllers in arrival management' and clarifying how extra effort on their part contributes to 'orderly and expeditious arrival flows,' as earlier European research emphasized [10]. With practice, and a clear understanding of their role and those of others, controllers were shown capable of precise preconditioning which translated into more effective CDOs. CA-4 also confirmed the importance of familiarity with ATD-1 operations in increasing acceptance of the FIM operations and supporting phraseology, and framing expectations about training requirements for the ATD-1 field demonstration.

The work helps to identify important next steps in the IM-TAPSS development effort, beginning with correcting issues detected during CA-4. Both high- and low-altitude sector positions will have to be staffed and simulated to address workload distribution in the preconditioning process under normal arrival operations; follow-on work will investigate preconditioning with realistic en-route airspace configurations. Research will also continue to examine the FIM clearance phraseology and procedures to support FIM operations when RNAV arrival-to-approach connectivity is not available. Effects on Final controller strategies for meeting schedules constructed under assumptions about base-turn location will also be investigated.

Finally, as IM-TAPSS matures, increasing research effort will be placed on benefits assessment. A succeeding AOL simulation study, 'CA-5,' is planned to conduct a full-up comparison of ATD-1 operations with current PHX operations. CA-5 will simulate operations with a TMA-TM configured to operate like the deployed version, using actual PHX traffic and winds and experts in ATM at PHX. A second phase will then examine how IM-TAPSS performs under the same conditions. This work will help set the stage for planned technology-transfer activities and the ATD-1 demonstration.

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