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Enabling Performance-Based Navigation Arrivals:

Development and Simulation Testing of the Terminal Sequencing and Spacing System

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***Abstract*—NASA has developed an advanced arrival management capability for terminal controllers, known as Terminal Sequencing and Spacing (TSS). TSS increases use of performance-based navigation (PBN) arrival procedures during periods of high traffic demand. It enhances two Federal Aviation Administration operational systems with terminal metering and controller spacing tools. Sixteen high-fidelity human-in-the-loop simulations, involving more than five hundred hours of evaluation time, were conducted to mature TSS from proof-of-concept design to fully functional prototype. These simulations modeled arrival procedures at several U.S. airports, incorporated a broad range of traffic demand profiles and wind conditions, and used controllers with extensive operational experience. Two metrics are evaluated for these simulations: PBN Success Rate and Inter-Arrival Spacing Error. The PBN Success Rate shows a definitive trend when TSS is used. It increases from 42% for today's operations to 68% for terminal metering only and 92% for terminal metering with controller-managed spacing tools. Meanwhile, the Inter-Arrival Spacing Error improves 25–35% when TSS is used compared to not used. The TSS technology was transferred to the FAA, and it is targeted for deployment to several busy airports in the United States starting in 2018.**

Keywords-terminal sequencing and spacing; performance-based navigation; terminal metering; controller-managed spacing;

I. INTRODUCTION

The Next Generation Air Transportation System (NextGen) in the United States, as well as the Single European Sky ATM Research (SESAR) in Europe, propose advanced air traffic management (ATM) technologies and procedures to safely, efficiently, and reliably accommodate the forecasted increase in traffic demand [1][2]. As a result of volatile fuel costs, industry pressure to leverage prior airline investments, and a worldwide desire to reduce greenhouse gas emissions, a major emphasis of NextGen and SESAR is the development of efficient performance-based navigation (PBN) arrival procedures using Area Navigation (RNAV) and Required Navigational Performance (RNP). Today, the vast majority of commercial jet aircraft are RNAV-equipped and many are RNP-equipped. While the Federal Aviation Administration (FAA) continues developing new PBN arrival procedures for airports in the United States, the existing RNAV arrival procedures remain significantly under-utilized in periods of high traffic demand, and the more advanced RNP arrival procedures are unutilized altogether.

The use of PBN arrival procedures during periods of traffic congestion is not consistent with the controllers' typical strategy of vectoring to achieve spacing and matching speeds to maintain spacing. Without new spacing tools, terminal controllers are unable to consistently achieve the desired in-trail spacing using only speed adjustments. Therefore, NextGen and SESAR envision arrival scheduling combined with ground-based and airborne spacing technologies. Time-based arrival scheduling will progressively meter the traffic flows to ensure that aircraft merge smoothly from different directions and avoid downstream congestion that would otherwise prevent them from flying efficient flight paths. Meanwhile, controllers will predominantly use speed adjustments to control aircraft along their routes and infrequently use vectoring to absorb additional delay due to excess demand or avoid separation violations. The most highly equipped aircraft will also have airborne spacing capabilities.

In 2011, the National Aeronautics and Space Administration (NASA) initiated its Air Traffic Management Technology Demonstration #1 (ATD-1) activity as an extension of its earlier ATM research [3]. ATD-1 integrates time-based scheduling across the entire arrival phase of flight with ground-based tools for terminal controllers and an airborne spacing capability for highly equipped aircraft. The time-based scheduling element, called Traffic Management Advisor for Terminal Metering (TMA-TM), extends the FAA's Time-Based Flow Management (TBFM) system by performing detailed modeling and scheduling of the terminal portions of the PBN arrival procedures. The ground-based spacing tools, called Controller-Managed Spacing (CMS) tools, enhance the FAA's Standard Terminal Automation Replacement System (STARS) with textual and graphical representations of the arrival schedule as well as speed advisories. The airborne spacing capability, called Flight Deck Interval Management (FIM), is an Automatic Dependent Surveillance–Broadcast (ADS-B) 'In' application that provides speed commands to the flight crew in lieu of speed instructions from the controller.

The primary ATD-1 objectives are (1) to develop fully functional operational prototypes of the ground and airborne spacing technologies, (2) to demonstrate the integrated ATD-1 concept in a series of operational evaluations, and (3) to transfer the mature technologies to the FAA and industry stakeholders. Fully functional prototypes of the ground components (i.e., TMA-TM and CMS) have been developed and recently transferred to the FAA. The FAA refers to this capability as Terminal Sequencing and Spacing, or TSS. The airborne component (i.e., FIM) continues to be refined and will be transferred to the FAA and stakeholder community by 2018.

This paper focuses on the simulation testing of TSS. Whereas previous papers evaluated the results of individual simulations (see Table 1), this paper describes the evolution of the TSS simulations and looks broadly at a subset of their results that evaluate the efficacy of these tools. The remainder of the paper is organized as follows: Section II reviews previous work related to TSS; Section III describes the sixteen high-fidelity, human-in-the-loop (HITL) simulations used to evaluate TSS; Section IV presents results for PBN success rate and final approach fix schedule conformance. Finally, Section V summarizes key findings and discusses the next steps related to TSS deployment.

II. BACKGROUND

In the United States, research and development of terminal spacing tools has been ongoing for more than 30 years. Early tools focused on increasing runway throughput using complex models of controller behavior. For example, [4] adjusted an aircraft's nominal speed profile and provided a heading correction in order to maintain a fuel-efficient descent and meet a desired arrival time. A more sophisticated tool developed by NASA balanced runway loading, optimized arrival sequences, and calculated dynamic turn and speed advisories to maximize runway throughput and maintain required separation [5]. It eventually reached sufficient maturity to be field-tested [6].

With the advance of RNAV arrival procedures, later tools focused on using speed control along a published lateral path. This paradigm avoided the complexity of dynamic paths and vertical profiles that hindered earlier efforts. In the late '90s, tools were developed that adjusted the published speed profiles to maintain the schedule in the terminal area [7]. While integration with advanced arrival management functions was proposed, the FAA was only beginning to deploy time-based metering functions to the en route domain. As a result, [8] adopted a simpler design that presented the projected positions of aircraft on merging RNAV routes as if they were in-trail in order to not require an arrival schedule.

Each of these prior terminal spacing tools demonstrated some degree of operational benefit, but none of them gained sufficient technical maturity to be deployed operationally. Meanwhile, industry reports continued to assert that advanced sequencing and spacing tools for terminal controllers is necessary to achieve high PBN utilization. References [9], [10], and [11] reaffirm the urgency for terminal spacing tools to consistently achieve the desired in-trail spacing, spacing tool integration with arrival management functions, and automation support to facilitate mixed equipage operations. In addition, the underutilization of existing aircraft equipage is cited by the airline industry as a reason for their reluctance to invest in the additional equipment necessary for NextGen and SESAR.

As a result of the continued capability shortfall, NASA developed the predecessor to TSS called Terminal Area Precision Scheduling and Spacing (TAPSS) [12]. TAPSS extended the FAA's en route time-based metering capabilities into the terminal area, enabled utilization of PBN arrival procedures from cruise to landing, and provided CMS tools to help terminal controllers maintain schedule conformance. Its time-based scheduling paradigm for multiple meter points is similar to the concept proposed in [13]. The resulting time-based operations reflect a combination of the upstream traffic conditioning achieved by [14] and the fine-tuned spacing along final approach provided by [15].

III. CONCEPT OF OPERATIONS

TSS is an advanced traffic management function for terminal controllers and traffic managers. It is composed of two decision support elements—strategic TMA-TM and tactical CMS tools—to enable use of PBN arrival procedures in heavy traffic conditions. This section describes those tools and explains how they support increased PBN utilization.

A. *Decision Support Technologies*

The FAA's TBFM system [16] is similar to European AMAN systems [17]. TBFM generates an arrival schedule and provides advisories for en route controllers to maintain schedule conformance. TBFM uses 4-D trajectory predictions to determine runway assignments, arrival sequences, and scheduled times-of-arrival (STAs). Runway assignments are selected to minimize total arrival delay. Arrival sequences and STAs are computed for meter fixes located near the terminal boundary and the runway threshold. Today, TBFM information is not available to terminal controllers, so they manually assign runways, sequence the aircraft for landing, and ensure separation primarily using vectors and fuel-inefficient step-down descents without knowledge of the TBFM schedule.

TMA-TM, shown in Fig. 1, is an extension of TBFM. It includes more sophisticated scheduling in the terminal area not present in TBFM, and provides advisories for terminal controllers to maintain schedule conformance. Arrival sequences and STAs are computed for additional terminal

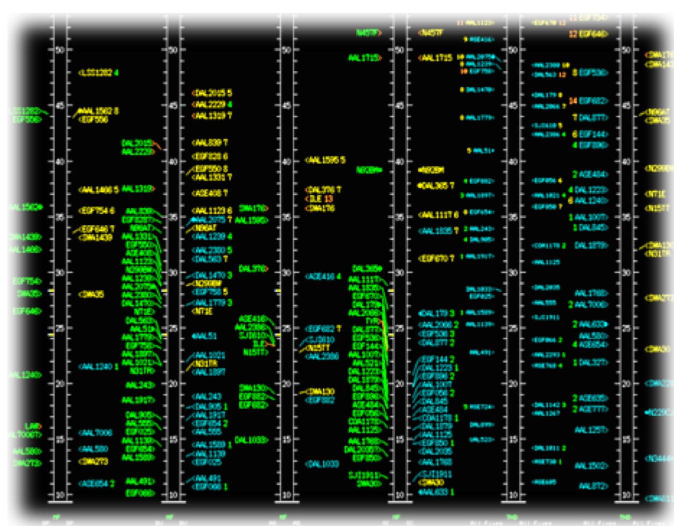

Figure 1. TMA-TM traffic management timeline display.

meter points where traffic flows merge. At these points, the STAs are computed to allow aircraft to remain on their assigned PBN arrival procedures. In particular, the delay allocated along each route segment is based upon the TBFM 4-D trajectory and limited to an amount that can be absorbed by speed control alone. Typically, high-side arrivals can absorb 40–60 seconds in the terminal area, low-side arrivals only 20–40 seconds, and straight-in arrivals less than 15 seconds.

The CMS tools are display aids to help terminal controllers sequence and space aircraft along their arrival routes (both PBN and traditional). Fig. 2 shows the different CMS tools that can be displayed on the terminal controller workstation. They include a slot marker and its airspeed, the aircraft's estimated airspeed, the scheduled runway and landing sequence, a speed advisory, and an early/late (E/L) indicator. The circular slot marker provides a spatial representation of the schedule. More precisely, the slot marker travels along the aircraft's scheduled trajectory, and it is where the system expects the aircraft to be at the present time. To follow the slot marker (i.e., maintain schedule conformance), a speed advisory to the next terminal meter point can be given. When a speed change is not sufficient to meet the aircraft's STA, an E/L indicator is displayed instead. Timelines (shown on the right) are available for the controller to quickly monitor arrival sequences, traffic demand, and delay values. Display clutter can be mitigated by not displaying these tools along final approach.

B. *High-Level Concept*

Although TSS addresses inefficiencies in the terminal area, a TSS operation begins several hundred miles from the airport in en route airspace. While the aircraft is still in cruise, TMA-TM begins calculating estimated times-of-arrival (ETAs) at the meter fix, terminal meter points, and runway threshold. These ETAs, in conjunction with required separation, are used to assign a runway and generate an arrival schedule. Prior to top-of-descent, TMA-TM freezes the aircraft's scheduled runway and STAs. Controllers and traffic managers are able to manually change the scheduled runway and STAs, if necessary. En route controllers use TBFM tools to meet the aircraft's meter fix schedule. Once schedule conformance can be managed by speed adjustments alone, the en route controller issues a 'Descend Via' clearance for the PBN arrival procedure to the TMA-TM scheduled runways. The en route controller continues using TBFM tools to maintain schedule conformance. The en route controller hands off the aircraft to a terminal feeder controller near the terminal boundary with a schedule conformance error less than 30–40 seconds.

After accepting a handoff, the terminal feeder controller assigns the TMA-TM scheduled runway. The aircraft continues descending via its PBN arrival procedure. The feeder controller monitors schedule conformance using the slot marker circles and E/L indicators. The feeder controller uses the combination of speed advisory, slot marker airspeed, and aircraft airspeed information to mitigate residual schedule errors. At 15–20 NM from landing, the feeder controller hands off the aircraft to a terminal final controller in preparation for merging onto the final approach course.

After accepting a handoff, the terminal final controller makes any last minute adjustments needed to ensure safe separation. The final controller monitors spacing conformance using the slot marker circles. When appropriate, the final controller clears the aircraft for the assigned runway. The final controller issues vectors to the final approach course for arrival procedures not connected to the approach procedure. Otherwise, the aircraft continues descending via its PBN arrival procedure until reaching the initial approach fix. Near the final approach fix, the final controller hands off the aircraft to the tower controller.

IV. Simulation Method

From 2012 through 2014, sixteen high-fidelity HITL simulations were conducted by NASA to mature TSS from Technology Readiness Level (TRL) 4 (i.e., proof-of-concept) to TRL 6 (i.e., fully functional) [18]. These simulations included arrival procedures at several airports in the United

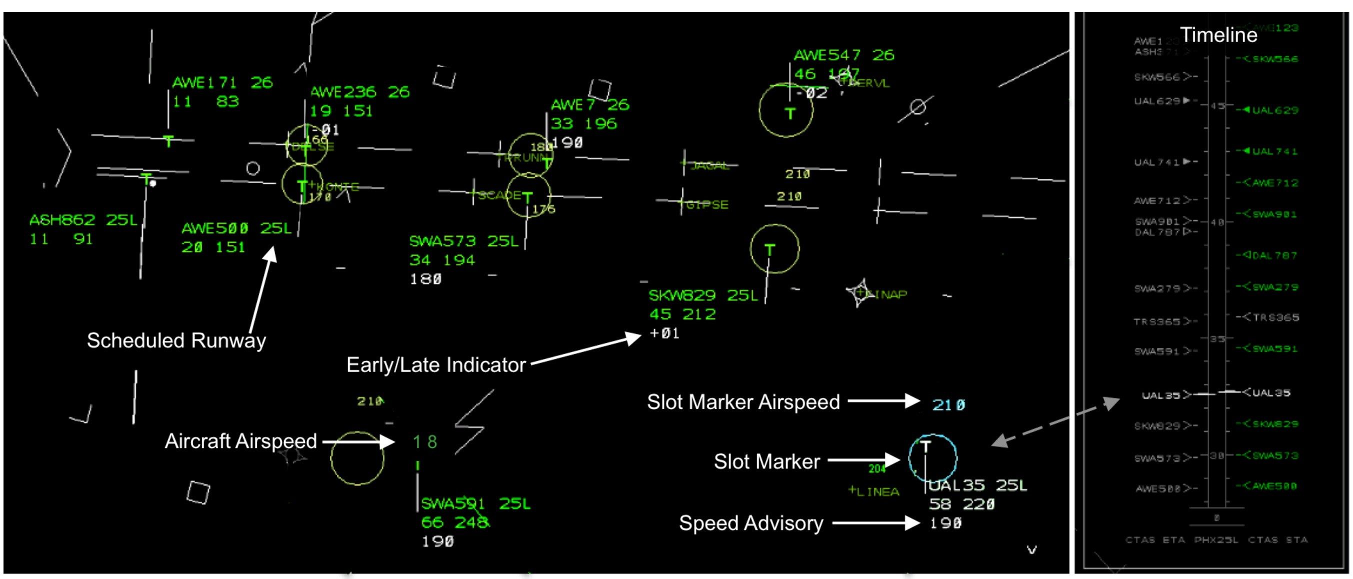

Figure 2. Controller-Managed Spacing tools illustrating datablock, slot marker, and timeline elements.

States for a broad range of traffic demand profiles and wind conditions, using controllers with extensive operational experience. Table 1 summarizes the key aspects of these simulations. For brevity, all references to the simulations are by acronym identifier (e.g., REACT) instead of full name (e.g., RNP-Enabled by ATD-1 Controller Tools). Detailed descriptions of these simulations can be found in the references listed in the table's right-most column.

A. Simulation Runs

The TSS technology maturation process involved more than five hundred hours of real-time, high-fidelity HITL simulation evaluation. Each TSS simulation consisted of shakedown runs to verify test readiness followed by data collection runs to conduct the experiment or test. The number of data collection runs, each lasting approximately one hour, is shown in the *Runs* column of Table 1. Human factors personnel debriefed the controllers and pilots; they administered questionnaires at the end of every simulation run as well as the end of the simulation. In addition, approximately forty researchers, software engineers, and simulation support staff at NASA Ames Research Center and NASA Langley Research Center performed verification and validation testing of TSS prior to evaluation by operational personnel.

B. Simulation Phases

The four phases of TSS simulation testing—integration (I), concept refinement (C), performance evaluation (P), and operational integration (O)—are shown in the *Phases* column of Table 1. The initial simulations focused on the integration of the various TSS components. Later simulations refined the TSS concept of operations in response to controller feedback. The final simulations evaluated the performance, controller acceptability, and operational integration of a fully functional TSS prototype.

1) Integration Activities

TAPSS was an extension to NASA's Traffic Management Advisor (TMA) and tested using a custom real-time simulation environment called the Multi-Aircraft Control System (MACS) [30][31]. The integration activities improved several areas of the TAPSS proof-of-concept design. First, TAPSS was re-implemented in recent versions of the FAA's TBFM and STARS software that would be associated with full-scale deployment of TSS. Next, the MACS medium-fidelity emulations of the controller workstations were updated to have the same look-and-feel and standard tools as the FAA's automation platforms. Lastly, the MACS simulation environment was modified to use the same software architecture and subsystem interfaces as the operational FAA systems. These improvements were chosen to reduce the risk of operational implementation and allow TSS to be seamlessly transitioned between NASA's simulation environment and the FAA's testing environment.

2) Concept Refinement

Prior TAPSS research defined an initial set of operational procedures, scheduling algorithms, and spacing tool presentations [12]. The concept refinement simulations were used to finalize the TSS concept of operations. Final adjustments to the terminal metering algorithms and CMS tools were made; specific controller/pilot phraseology was defined; and training materials were developed. For example, FIAT-1 investigated different terminal delay distribution schemes, and FIAT-2 evaluated the performance impact of using a limited set of CMS tools rather than the full set. In general, the concept refinement simulations included combined high-altitude and low-altitude en route arrival controllers, two terminal feeder controllers and two terminal final controllers. The en route controllers delivered aircraft into the terminal area using the FAA's current en route metering tools. The terminal controllers used TSS to assist merging and spacing of arrival aircraft. Further underscoring the ATD-1 objective of accelerating the deployment of its matured technologies, NASA and the FAA conducted the REACT, TSS-1, and TSS-2 simulations jointly.

3) Performance Evaluations

Following the integration activities and concept refinement simulations, a series of performance evaluations were conducted to measure the benefits of the fully functional TSS prototype. The CA-5.x simulations evaluated TSS across a wide range of traffic and wind conditions. During CA-5.1, terminal controllers handled arrival operations without TSS available to assist them; During CA-5.2 and CA-5.3, terminal

TABLE I. SUMMARY OF NASA'S HIGH-FIDELITY HUMAN-IN-THE-LOOP TSS SIMULATIONS

ID	Date	Phase[a]	Arrival Scenario	Arrival Procedures[b]	Wind Model	Wind Error Model	Wind Scenarios	Traffic Scenarios	Runs	Ref.
CA-1	Jan 2012	I	DFW South	R,F	Parametric	Parametric	1	3	19	[19]
REACT	Mar 2012	C	DAL South	N,R,P	None	None	-	2	10	[20]
CA-2	Apr 2012	I	DFW South	R,F	Parametric	Parametric	1	3	18	-
CA-3	Jun 2012	I	DFW South	R,F	Parametric	Parametric	1	4	24	[21]
TSS-1	Sep 2012	C	LAX West	N,R,P	Gridded	Statistical	1	4	10	[22]
FIAT-1	Oct 2012	C	LAX West	N,R,F	Gridded	None	1	1	16	[23]
CA-4	Dec 2012	I	PHX West	R,F	Gridded	Statistical	1	4	16	[24]
CA-4.1	Mar 2013	C	PHX West	R,F	Gridded	Statistical	1	4	8	-
FIAT-2	Mar 2013	C	PHX West	N,R,P,F	Gridded	Statistical	1	1	17	[25]
TSS-2	Apr 2013	C	PHX West	N,R,P,F	Gridded	Statistical	1	1	15	[26]
CA-5.1	Jul 2013	P	PHX East/West	N,R	Gridded	Statistical	8	4	19	[27]
FIAT-3	Aug 2013	I	PHX East	N,R	Gridded	Statistical	4	2	19	[28]
CA-5.2	Sep 2013	P	PHX East/West	N,R	Gridded	Statistical	8	4	19	[27]
FIAT-4	Feb 2014	P	PHX East	R,F	Gridded	Statistical	4	2	31	-
CA-5.3	Apr 2014	P	PHX East/West	N,R,F	Gridded	Statistical	8	4	19	[27]
FIAT-5	Nov 2014	O	PHX West	N,R,P	Gridded	Statistical	1	3	38	[29]

a. (I) Integration; (C) Concept Refinement; (P) Performance; (O) Operational Integration Assessment

b. (N) non-RNAV; (R) RNAV; (P) RNP-AR; (F) FIM controllers handled those same operations using TSS. All other elements of these simulations were the same. The physical realism of the performance evaluations was significantly higher than earlier TSS simulations. The CA-5.x simulations included separate high-altitude and low-altitude en route arrival controllers, two terminal feeder controllers, and two terminal final controllers as well as two traffic managers. The en route arrival controllers used the FAA's current time-based arrival metering tools to deliver aircraft into the terminal area. The terminal controllers used TSS to assist merging and spacing of the arrival aircraft. The en route and terminal traffic managers monitored (and occasionally made adjustments to) the TMA-TM system. Additional confederate controllers managed non-arrival traffic to increase the simulations' realism.

4) Operational Integration Assessment

The final phase of TSS simulation testing is an upcoming fourth joint FAA/NASA HITL simulation called the Operational Integration Assessment (OIA). It will be conducted at the FAA's William J. Hughes Technical Center in mid-2015. The OIA will examine the interoperation of TSS with the latest en route ground interval management tools, and evaluate procedures for handling off-nominal events like missed approaches and pop-up flights. The OIA will simulate Phoenix arrival operations with a larger geographic scope than earlier TSS simulations. Controllers will staff positions in Denver and Albuquerque Air Route Traffic Control Centers (ARTCCs) as well as Phoenix Terminal Radar Approach Control (TRACON). The OIA will use prototype versions of the FAA's TBFM system (version 4.2.3) and STARS ELITE terminal automation system (build R2D7) modified to include the TSS capabilities in conjunction with the FAA's operational ERAM en route automation system (version EAD2000).

C. Arrival Procedures

TSS is designed to assist terminal controllers with merging and spacing aircraft along PBN arrival procedures in a busy mixed-equipage environment. The TSS simulations modeled a comprehensive set of PBN implementations indicated in the *Arrival Scenario* and *Arrival Procedures* columns of Table 1. REACT evaluated TSS in the context of proposed RNP-AR procedures for Dallas-Love Field. FIAT-1 and TSS-1 used the current conventional arrival procedures and proposed PBN arrival procedures, respectively, for Los Angeles International Airport. Meanwhile, CA-1, CA-2, and CA-3 constructed RNAV overlays of conventional arrivals to Dallas/Fort Worth International Airport.

The remaining simulations used published RNAV arrival procedures with custom RNP-AR procedures to Phoenix Sky Harbor International Airport (PHX). These procedures are representative of the latest PBN procedure designs at airports in the United States. Fig. 3 shows the PHX West Flow RNAV arrival procedures to Runways 25L and 26; Fig. 4 shows the PHX East Flow RNAV arrival procedures to Runways 07R and 08. RNAV arrivals to offload runways end with vectors to the final approach courses (shown by the dashed lines). RNAV arrival procedures from the low-side to the default runway connect to ILS approach procedures (shown by the solid grey lines); RNAV arrival procedures from the high-side to the default runway either end on downwind with vectors to the final approach course (shown by the solid arrows) or connect to RNP-AR approach procedures (shown by the purple radius-to-fix arcs). Approximately 90–95% of the simulated traffic was RNAV- or RNP-AR-equipped and assigned to these arrival procedures. The remaining regional jet and turboprop traffic was assigned to conventional arrival procedures, and a few piston aircraft flew direct routes to the airport. Many of these simulations also incorporated fully integrated FIM operations for 10–20% of the simulated traffic.

D. Wind Scenarios

It is essential that the accuracy of the arrival schedule and controllers' schedule conformance not be adversely impacted by the expected winds and wind forecast errors. Therefore, twenty different wind scenarios were used during the TSS simulations (shown in Wind Scenarios column of Table 1). These wind scenarios were selected to have moderate to strong

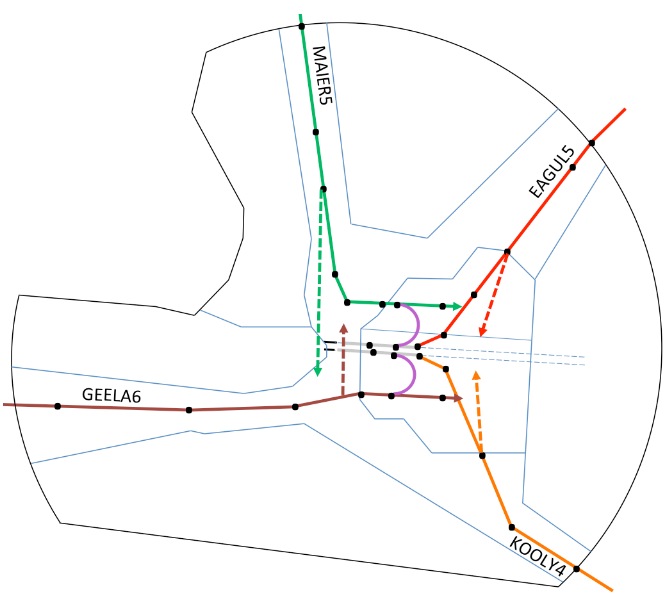

Figure 3. PHX West Flow RNAV/RNP-AR arrival procedures.

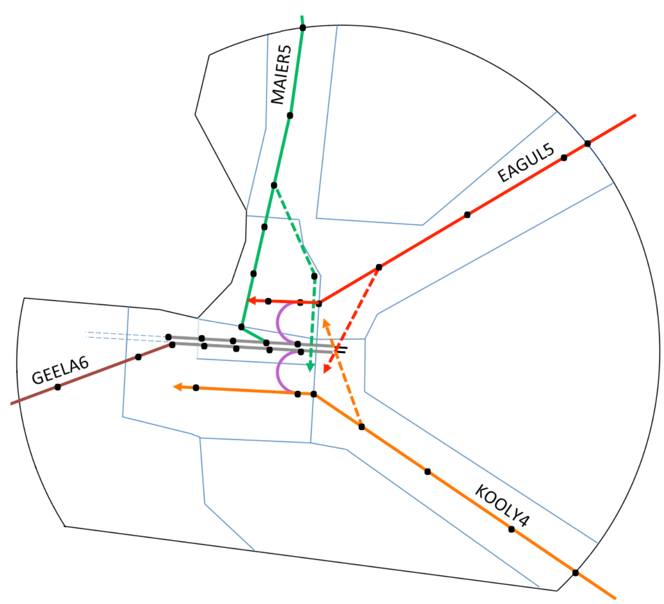

Figure 4. PHX East Flow RNAV/RNP-AR arrival procedures.

headwinds on final approach (to impact runway throughput) and substantial variation across the traffic flows (to impact merging and spacing complexity).

The simulated winds progressed from no winds, to parametric wind models, and finally to realistic gridded winds. For the parametric wind models, wind magnitude and direction varied with altitude. For the gridded winds, individual Rapid Update Cycle (RUC) forecasts were used [32]. Similarly, the simulated wind errors progressed from no error (i.e., matched winds), to parametric error models, and then to statistical errors consistent with observed forecast errors. For parametric wind error models, wind magnitude error varied with altitude. For the statistical wind errors, separate time-shifted RUC forecasts were used as the truth and predicted winds. An example of different truth and predicted gridded winds around PHX is shown in Fig. 5. The simulated aircraft flew through the truth winds while TSS used the predicted winds to compute its aircraft trajectories. The magnitude of the simulated wind error vector was approximately 10 knots rms to be consistent with historically observed forecast errors [33]. Overall, the controllers reported that the winds had little or no impact on the usability or acceptability of TSS.

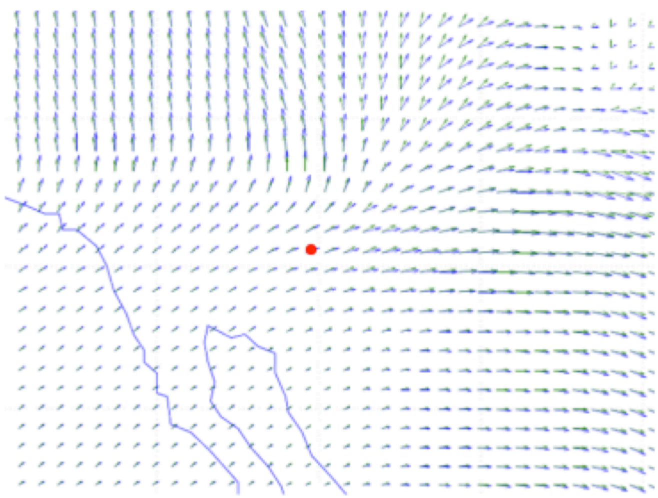

Figure 5. Example of truth and predicted gridded winds.

E. *Traffic Scenarios*

Fluctuating traffic demand and mixed aircraft capabilities combine with complex route geometries to reduce the unaided controller's ability to allow uninterrupted PBN arrival procedures. Detailed analyses of the simulated airports' arrival operations were performed to create an extensive set of traffic demand profiles. The number of traffic scenarios is shown in the *Traffic Scenarios* column of Table 1. Aircraft were distributed across the arrival routes with fleet mixes representing today's operations, as well as expected future operations. All of the simulated traffic scenarios were 45–60 minutes in duration and represented periods of high traffic demand (arrival delay approximately 3–5 minutes). Typically, the arrival demand was approximately 10–20% greater than historically observed peak levels. More than fifty separate traffic demand profiles were used during the TSS simulations. When considering the variation of the wind scenarios, more than one hundred traffic conditions were simulated.

F. *Controller Participants*

Forty-one different terminal controllers participated in testing and evaluation of TSS. Controller participants for the TSS simulations were selected from two distinct pools—active Certified Professional Controllers (CPCs) and retired former controllers. The National Air Traffic Controllers Association (NATCA) provided the active CPCs.

The REACT, TSS-1, TSS-2, and OIA simulations used eleven active CPCs from eight TRACONs—Boston, Chicago, Dallas/Fort Worth, Detroit, Miami, New York, Phoenix, and Southern California. These controllers typically had 10–15 years of ATC experience. One controller had participated in an earlier TSS simulation; the others did not have experience using the TSS tools. All had experience with RNAV arrival procedures but not the more advanced RNP-AR approach procedures. The OIA simulation will also include active CPCs as well as active traffic managers.

The remaining simulations used retired controllers from several TRACON facilities—Dallas/Fort Worth, Northern California, Phoenix, and Southern California. These controllers typically had 20–30 years of ATC experience. They had considerable experience with the types of operations being simulated (e.g., RNAV OPDs, high-density terminal operations, time-based metering, etc.). Many of these controllers had participated in earlier NASA simulations using the TSS tools.

G. *Additional Simulations*

In addition to the simulations listed in Table 1, NASA conducted several risk-mitigation simulations to validate various assumptions of the TSS concept. Another experiment investigated the en route controller's ability to meet the meter fix schedule conformance expected for TSS operations [34]. Two pilot-in-the-loop simulations were conducted in NASA's Advanced Concepts Flight Simulator and B747-400 full-mission flight simulators. These simulations used active commercial pilots to identify potential energy-management issues related to the speed profiles suggested by TSS [35][36].

Finally, the MITRE Corporation's Center for Advanced Aviation System Development (CAASD) conducted an additional five simulations using NASA's TSS operational prototypes and the same MACS simulation environment as the other simulations. These simulations had three main purposes: (1) determine which CMS tools were necessary and which were optional, (2) study the impact of meter fix delivery accuracy on TSS performance, and (3) determine strategies for accommodating off-nominal situations [37][38]. Some examples of these conditions included handling go-arounds, scheduling pop-up flights, and swapping aircraft sequences. NASA provided subject matter expertise for these simulations, but they were conducted wholly by MITRE with sponsorship from the FAA.

V. SIMULATION RESULTS

ATD-1 followed an Agile System Engineering process that defined a consistent testing approach for each simulation. One element of this framework was a common set of Measures of Performance (MOPs). The six TSS-related MOPs were:

- PBN success rate
- Number of controller-to-pilot instructions
- Excess in-trail separation at the runway threshold
- Inter-arrival spacing error at the final approach fix
- Controller acceptability in terms of the Controller Acceptance Rating Scale
- Controller workload in terms of the NASA TLX Scale

The remainder of this paper discusses results for two of these six MOPs: the PBN Success Rate (PSR) and the Inter-arrival Spacing Error (ISE) at the final approach fix. These metrics are evaluated for the seven most recent PHX simulations—TSS-2, FIAT-2, FIAT-3, FIAT-4, CA-5.1, CA-5.2, and CA-5.3 (results for FIAT-5 and the OIA are pending).

A. *Tool Conditions*

Four different tool conditions were simulated.

- *Baseline* included en route metering only (i.e., current metering operations), and terminal delay was not limited to speed control only.
- *None* included en route and terminal metering (i.e., TSS scheduling), but CMS information was not presented to terminal controllers.
- *Limited* included en route and terminal metering with the scheduled runway, landing sequence, and slot marker information available to terminal controllers.
- *Full* included en route and terminal metering with all CMS information available to terminal controllers.

When a simulation included runs with and without wind error (e.g., FIAT-2), only simulation runs with gridded wind errors were included in the statistics.

B. *PBN Success Rate*

PBN Success Rate (PSR) is the MOP that determines how frequently RNAV- and RNP-AR-equipped aircraft remained on their PBN arrival procedure without being vectored before reaching the end of the published lateral path. There are three normal points of termination associated with TSS operations: intercept of the final approach course to begin executing an approach procedure for the default runway (e.g., EAGUL arrivals to PHX Runway 26), vectors from the downwind segment to intercept final (e.g., MAIER arrivals to PHX Runway 26), and vectors to crossover to the offload runway (e.g., GEELA and KOOLY arrivals to PHX Runway 26). Earlier analyses are conservatively refined in two ways. First, the PBN operation is not considered successful if the aircraft was vectored from downwind to final further than 1 NM from the planned (i.e., nominal) location. Second, aircraft assigned to the offload runway are not included in the metric, since vectors to crossover routinely occurred before tactical vectors for merging and spacing occurred.

Fig. 6 shows the mean PSR of the four tool conditions. The PSR is averaged across each of the simulations' runs. The whiskers show the 95% confidence interval of the mean. The numbers at the base of each column indicate the number of simulation runs included in the statistics.

The PSR shows a clear trend with respect to tool condition. The mean PSR increases from 0.42 (i.e., 42% of PBN operations were uninterrupted) for the Baseline condition to approximately 0.68 for the None condition to approximately 0.92 for the Limited and Full conditions. A one-way ANOVA substantiates that the effect of the tool condition is significant

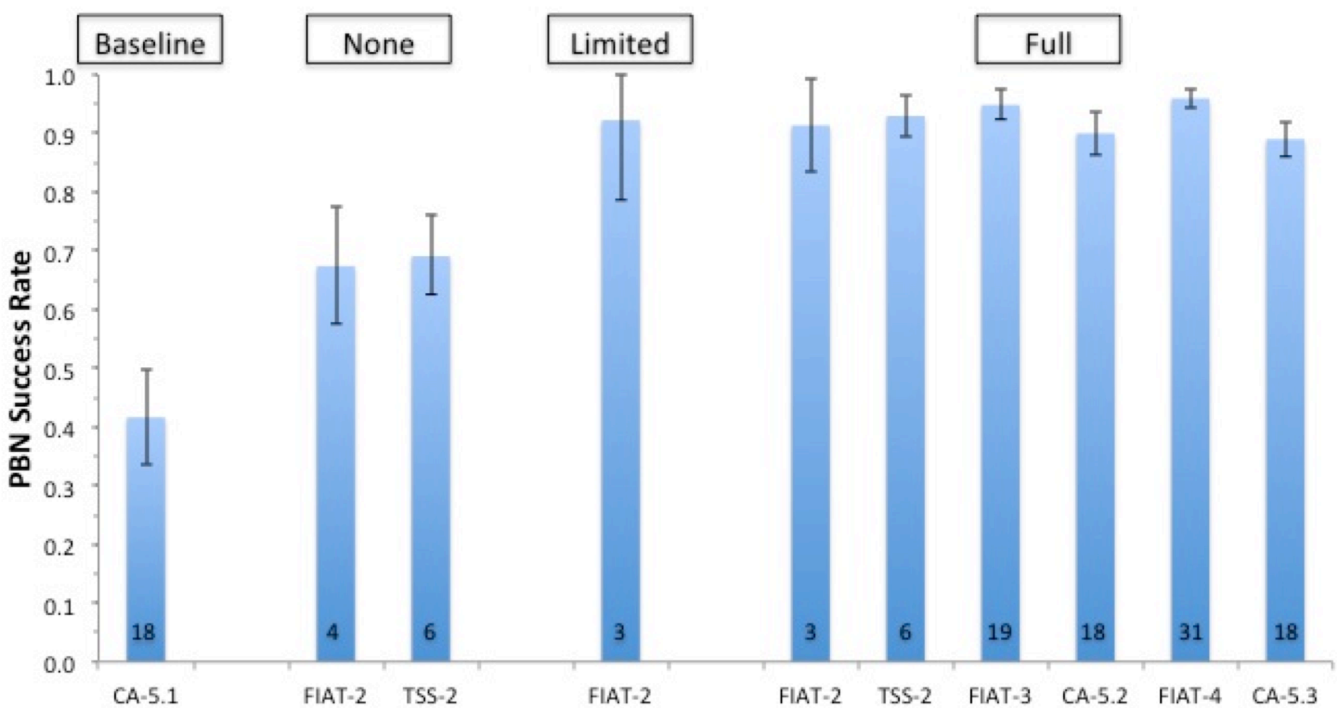

Figure 6. Variation of PBN Success Rate with tool condition.

[F(3,122)=204.76, p<0.0001]. Post hoc comparisons using the Tukey HSD test indicate that all of the inter-condition differences are significant at the p<0.0003 level with the exception of the difference between the Full and Limited conditions that is not significant. During all of the simulations, the controllers reported that the slot marker was the most useful CMS tool—in fact, more useful than existing automation functionality. The controllers also reported that their workload was acceptable and often reduced with TSS.

C. *Inter-Arrival Spacing Error*

Inter-Arrival Spacing Error (ISE) is the MOP that determines how precisely aircraft are spaced in time at the final approach fix. The ISE is defined as the difference between the desired and actual inter-arrival times. For the Baseline tool condition, the desired spacing is defined as the inter-arrival time associated with minimum separation at the runway threshold plus a separation buffer of 0.3 NM. For the None, Limited and Full tool conditions, the desired spacing is defined as the scheduled inter-arrival time at the runway threshold (which also included a 0.3 NM buffer). The actual inter-arrival spacing is measured at the final approach fix. In order to eliminate the effects of sporadic gaps in arrival demand, aircraft pairs whose undelayed inter-arrival times were modestly (approximately 10%) greater than the desired spacing are not included in any tool's statistics.

Fig. 7 shows the mean of the one-half 2.5% trimmed range of the ISE for all aircraft pairs. The 2.5% trimmed range is the difference between the 2.5 and 97.5 percentiles. This presentation of spacing error corresponds with the two-way spacing buffer necessary to have 95% of aircraft pairs conform to the desired spacing. The 2.5% trimmed range of the ISE is averaged across each of the simulations' runs. The whiskers show the 95% confidence intervals of the mean. The numbers at the base of each column indicate the number of simulation runs included in the statistics.

Unlike the PSR, the ISE does not readily show a trend with respect to tool condition. The inter-arrival spacing is more sensitive to the traffic demand and wind conditions associated with each simulation run as well as the particular controller participants. However, inspection of the ISE for individual simulations shows a clearer trend. For the CA-5.x simulations, the (one-half) 2.5% trimmed range of ISE was reduced from 31 seconds for the Baseline condition (CA-5.1) to 24 seconds for the Full tools condition (CA-5.2 and CA-5.3). Similarly, the FIAT-2 and TSS-2 simulations demonstrated reductions from 49 seconds to 32 seconds and from 33 seconds to 23 seconds, respectively. Separate Brown-Forsythe tests for unequal variances of the ISE found that the effect of the tool condition for each simulation was significant [CA-5.x F(1,1039)=443.74, p=0.0000; FIAT-2 F(1,219)=13.32, p=0.0003; TSS-2 F(1,487)=17.31, p=0.0000]. A smaller spacing buffer allows aircraft to be scheduled closer to minimum spacing and results in a higher throughput. Although increased throughput is not an explicit objective of TSS, these results demonstrate that the more effective upstream traffic management enabled by TSS increases PBN utilization and also naturally led to slightly higher runway throughput. The controllers reported that these higher throughputs were acceptable without increased workload.

VI. Outreach and Technology Transfer

A primary objective of ATD-1 was the transfer of the TSS capabilities to the FAA in order to validate their usefulness and accelerate their deployment. A deliberate outreach and technology transfer strategy to socialize the TSS concept and disseminate the TSS technologies was a necessary enabler of

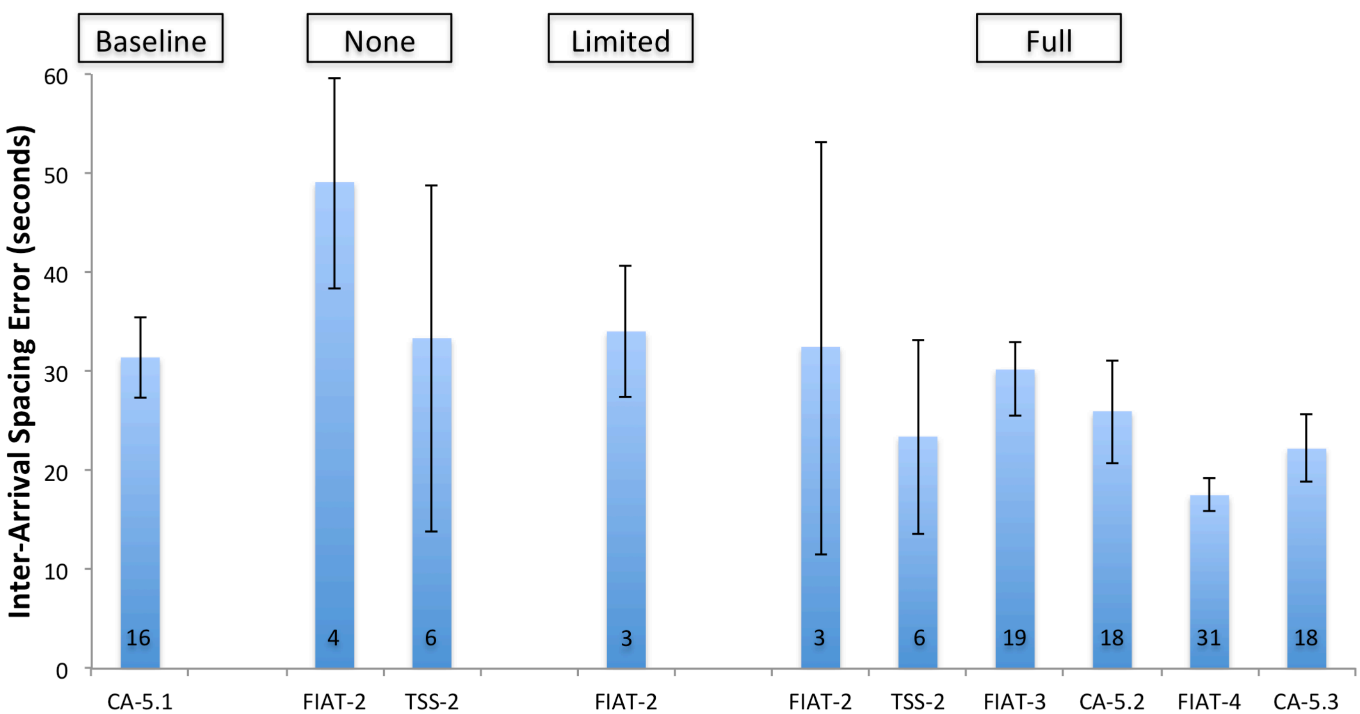

Figure 7. Variation of Inter-Arrival Spacing Error with tool condition.

this objective.

Socialization at the early stages of ATD-1 was essential to rapidly mature the TSS technologies. Busy en route and terminal air traffic control facilities were visited to observe their operations. NATCA was included in simulation testing as both observers and participants. Similarly, support was solicited from the airline trade organization, Airlines for America®, in particular its technical pilots subcommittee. Finally, technical representatives from the airframe manufacturers, avionics vendors, and system integrators were consulted to understand implementation issues.

Technology transfer of ATD-1 was equally comprehensive. Tech transfer packages—documenting the full breadth of ATD-1 results—have been delivered to the FAA every six to nine months since 2012 [39]. These packages include the updated concept of operations, technical publications, simulation reports, software functional descriptions, software interface descriptions, software source code for the operational prototypes, cost/benefit analyses, simulation training materials, and audio/visual materials. The final TSS tech transfer package is planned for June 2015. Tech transfer packages for the FIM capabilities will continue to 2018.

VII. CONCLUSIONS

NASA has developed an advanced arrival management capability, known as TSS, that increases PBN utilization during periods of high traffic demand. TSS extends the FAA's operational systems with terminal metering (called TMA-TM) and controller spacing tools (called CMS). Sixteen high-fidelity HITL simulations were conducted to integrate these capabilities into the FAA's TBFM and STARS platforms, refine the TSS concept of operations and procedures, and evaluate TSS performance. These simulations included a broad set of PBN arrival procedure implementations, more than fifty traffic demand profiles, and twenty wind scenarios reflecting realistic forecast errors. Eight additional simulations examined flight deck energy management, en route delivery accuracy, and procedures for handling off-nominal conditions like missed approaches and pop-up flights.

This paper evaluated two fundamental TSS metrics: PSR (PBN Success Rate) and ISE (Inter-Arrival Spacing Error) at the final approach fix. It examined these metrics broadly for the seven most recent PHX simulations. The PSR showed a definitive trend with respect to tool condition. The mean PSR increased from 0.42 for today's operations to 0.68 for terminal metering without CMS tools and 0.92 for terminal metering with CMS tools. The ISE also showed consistent improvement when analyzed across matching simulation runs. The mean one-half 2.5% trimmed range of ISE was reduced from 31 seconds to 24 seconds for CA-5.x, 49 seconds to 32 seconds for FIAT-2, and 33 seconds to 23 seconds for TSS-2. This increased spacing accuracy resulted in higher throughput at the runway threshold.

During all simulations, controllers reported the slot marker as the most useful CMS tool. Overall, controllers achieved the markedly increased PBN utilization and modestly improved spacing accuracy without increased workload. The controllers found use of TSS to be acceptable.

The extensive high-fidelity simulation testing of TSS, combined with a comprehensive technology transfer strategy, allowed TSS to progress from a proof-of-concept design in 2011 to a fully functional prototype in 2014. As demonstrated by these simulations, deployment and use of TSS will address the NextGen goal of consistent, widespread use of PBN arrival procedures during periods of high traffic demand.

VIII. NEXT STEPS

TSS is actively progressing through the FAA's investment cycle. In December 2013, the FAA completed the Investment Analysis Readiness Decision for its TBFM Program's Work Package 3. The Final Investment Decision is planned for April 2015. These milestones included developing the final program requirements for TSS in consultation with NASA subject matter experts. The FAA has stated that the breadth of TSS tech transfer is unprecedented and has significantly reduced the technical risk of implementation. The FAA is targeting deployment of TSS to several busy airports in the United States beginning in 2018. NASA will continue providing support as subject matter experts throughout the remaining phases of TSS deployment.

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