Status of Transferring NASA's Terminal Sequencing and Spacing Technologies to the FAA

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Introduction

Safely and efficiently sequencing and spacing aircraft arrivals in a dense terminal radar approach control (TRACON) airspace is a challenging multi-constraint control problem. Arrivals must enter the TRACON at a prescribed altitude and speed and continue reducing altitude and speed and eventually merge with other arrivals at key waypoints, and finally land at the assigned runway with the appropriate wake vortex separation. Weather uncertainty, the use of multiple arrival runways across multiple airport configurations, and interactions with other aircraft within the TRACON airspace, all contribute to the complexity of safely and efficiently managing aircraft arrivals. The addition of performance-based navigation (PBN) procedures, including disparate user investment in PBN capabilities, adds to this complexity. Managing the arrivals with these additional constraints has become increasingly more difficult as the FAA continues to add PBN procedures requested by the airline community. The effect is workload increases, runway throughput decreases, and TRACON controllers (hereafter referred to as terminal controllers) typically issue radar vectors to absorb delay that results in additional fuel consumption.

For the last several years, NASA, in collaboration with the FAA and industry partners, has developed technologies focused on improving TRACON operations as part of the FAA's Next Generation Air Transportation System (NextGen) [1]. The NextGen architecture includes transformational technologies and procedures such as optimized profile descents (OPDs) and PBN procedures leveraging user investments in area navigation (RNAV) and required navigation performance (RNP) capabilities. Operationally, air route traffic control center (ARTCC) controllers (hereafter referred to as center controllers) issue 'Descend via' clearances for those aircraft equipped with flight management systems (FMS) capable of full performance vertical navigation in order to execute OPDs. The pilot can use the FMS to determine the top-of-descent (TOD) point and airspeed schedule. Near TOD, the aircraft's autopilot adjusts the airspeed and flight path angle to begin executing the OPD. Eventually, the aircraft enters TRACON airspace on a standard terminal arrival/RNAV route. If established, RNP approach routes, including curved radius-to-fix (RNP-RF) legs, are possible for those aircraft that have an RNP-certified FMS with advanced performance navigation monitoring and alerting.

In the US, a few airports have already established RNAV OPD procedures, including Phoenix Sky Harbor International Airport (PHX), Denver International Airport (DEN), and Atlanta Hartsfield International Airport (ATL). Some airports, such as PHX, make use of modernized FAA TRACON and ARTCC automation. Established PBN routes and modernized automation systems were key reasons PHX was identified for a NASA project known as the Air Traffic Management Technology Demonstration -1 (ATD-1) [2]. ATD-1 is a technology maturation project that will allow for an operational demonstration of a subset of the ATD-1 prototype automation, in partnership with the FAA at the FAA's William J. Hughes Technical Center (WJHTC), planned for early 2015.

ATD-1 expects to improve efficiency in the TRACON with newly developed ground and airborne automation. The ATD-1 portfolio is comprised of two ground automation technologies and one airborne technology. The ground automation technologies are referred to as Terminal Sequencing and Spacing (TSS), and is described in this paper.

Through numerous human-in-the-loop (HITL) simulations conducted by NASA and the FAA, TSS has demonstrated better conformance to PBN procedures, decreased controller workload, and increased throughput by trading radar vector clearances for speed clearances as the primary delay absorption strategy [3-10]. These previous HITL simulations used general-purpose workstations, collectively referred to as the Multi-Aircraft Control System (MACS) simulation platform, to study air transportation technologies [11]. MACS performs various functions such as simulating surveillance radar and emulating ARTCC and TRACON radar displays/workstations. MACS is cost-effective for laboratory testing because it performs the functions of various specialized hardware and software components used in real operations. However, for deployment into the National Airspace System (NAS), TSS must be integrated with operational hardware and software, such as the FAA's Standard Terminal Automation Replacement System (STARS), and Time-Based Flow Management (TBFM) platforms.

NASA and Raytheon have collaborated to develop a TSS-enhanced prototype of STARS. In parallel, NASA has developed a TSS-enhanced prototype of TBFM. Through a NASA and FAA partnership, the TSS-enhanced STARS and TBFM prototypes will be tested at the FAA's WJHTC in early 2015. This test is known as the Operational Integration Assessment (OIA), and will require a seamless integration of several WJHTC laboratories, such as En Route Automation Modernization (ERAM), TBFM, STARS, and the Target Generation Facility (TGF). The OIA is a risk-mitigation activity using NASA's TSS prototype prior to the eventual, routinely performed, Operational Test and Evaluation (OT&E) that will utilize operational software.

This paper, a follow-on to [12], describes the ATD-1 technologies, focusing on the ground automation components, and discusses the current status of integrating these technologies with operational systems, including STARS and TBFM. These system integrations are critical prerequisites for the OIA at the WJHTC.

The remainder of this paper is organized as follows: an overview of ATD-1 technologies is described in the next section, followed by a description of the prototype STARS used at the NASA Ames Research Center (NASA Ames). Lastly, the paper concludes with a discussion of relevant deployment issues and challenges and the interoperability of the TSS-enhanced STARS and TBFM with ERAM.

ATM Technology Demonstration-1 (ATD-1)

The ATD-1 portfolio includes three distinct technologies that provide an integrated arrival concept for scheduling, sequencing, and spacing and is required to interface with the FAA's ERAM, STARS, and TBFM [13]. The first technology leverages TBFM, the successor to the Traffic Management Advisor (TMA) and extends it to include terminal metering (TMA-

TM) for conflict-free schedules to the runway and metering points through the TRACON [14,15]. The second technology, controller-managed spacing (CMS), provides a set of decision support tools for terminal controllers to better manage aircraft delay using speed control from the TRACON entrance to the runway threshold [16]. Airborne spacing is complimentary for highly equipped aircraft, and is achieved with the third ATD-1 technology, flight-deck interval management (FIM) [17,18].

The integration of these three technologies enables an integrated arrival and spacing system with the following concept of operations. Beginning in ARTCC airspace, prior to an aircraft's TOD and about 200 nautical miles (NM) from the runway, TMA-TM four dimensional (4-D) trajectory predictions determine the aircraft's arrival sequence and conflict-free scheduled times-of-arrival (STA) at the TRACON boundary (usually the meter fix), meter points within the TRACON and the runway threshold. The arrival sequence and STAs are frozen at about 130 NM from the meter fix and displayed to the center controllers. The center controllers employ various tactical control strategies (e.g. speed and path assignments) to deliver the aircraft to the meter fix at or near its meter fix STA. The soon-to-be operational ground-based interval management for spacing (GIM-S) is expected to improve the accuracy of preconditioning arrivals to the meter fix. Research has indicated that the required meter fix STA delivery accuracy should be less than one minute [15]. Aircraft equipped with FIM avionics are issued a FIM clearance by the center controllers prior to TOD, and begin automatically spacing (via speed control) behind a designated lead aircraft. Center controllers hand-off aircraft to the terminal controllers prior to the meter fix. Terminal controllers make use of the CMS advisories and issue speed clearances to non-FIM equipped aircraft as required to adjust for any minor perturbations.
TMA-TM and CMS are ground-based automation tools, and when integrated as a system is referred to as TSS. Figure 1 shows the benefits of TSS by comparing the ground tracks for traffic composed of 80% standard and 20% RNP authorization required (RNP-AR) arrivals, from a recent PHX west-flow HITL simulation with and without TSS available to the terminal controllers. Immediately apparent is the reduction in path distance flown due to the reduction of radar vectors that is enabled by TSS. The baseline on the left, without TSS, achieved a 74% PBN conformance rate. The TSS-enhanced system on the right side of Figure 1 enabled a 98% PBN conformance rate without any loss of runway throughput.

TSS is a ground-based automation that will be used by air traffic control (ATC), but its affect on piloting has also been examined. A recent study has shown that existing pilot training and automation is sufficient to conduct TSS [19]. The two ground-based ATD-1 technologies will now be briefly described.

Traffic Management Advisor with Terminal Metering (TMA-TM)

TMA-TM is a first-come first-served scheduler with best-equipped best-served functionality for those PBN-capable aircraft. TMA-TM extends TBFM to include terminal metering (TM) for conflict-free schedules (STAs) to the runway and intermediate TRACON meter points. TBFM is currently a scheduling tool used at ARTCCs whereas TMA-TM is an advanced prototype based upon an earlier TBFM release 3.12 (July 2011). For each aircraft, TMA-TM generates an estimated time-of-arrival (ETA) and a STA at all metering points, including the TRACON meter points. The ETA is the time that the aircraft would arrive at a certain location (e.g. meter fix, TRACON meter point, or runway) without considering separation requirements of other arrivals. The STA is the conflict-free arrival time at a certain location. The time offset between ETA and STA is referred to as delay. The terminal metering enhancements include: (1) accurately representing RNAV and RNP routes by including additional custom waypoints and turn radius parameters (for RNP-RF) that are tailored to the TRACON and arrival route structure. These PBN routes connect the runway to the published standard terminal arrival route resulting in single, continuous trajectory from ARTCC airspace to the runway threshold; (2) ensuring the 4-D trajectory predictions make use of the published and standard operating procedure altitude and speed restrictions along the routes in the TRACON and adding operationally feasible altitude and speed constraints where required; and (3) a delay allocation strategy that first de-conflicts aircraft at the runway threshold, then TRACON meter points, followed by meter fixes using speed-control only. This delay allocation strategy assures that the STAs can be met with speed reductions. Depending on the airspace topology and aircraft type, aircraft can absorb up to about two minutes of delay using speed-control; any remaining delay will need to be absorbed by the ARTCC.

Controller-Managed Spacing (CMS) Advisory Tools

CMS advisory tools use the arrival schedule generated by TMA-TM to provide visual cues to the terminal controllers to enable efficient metering in the TRACON. These tools are displayed in Figure 2. The CMS tools consist of runway assignments, arrival sequence number, slot marker circles, slot marker indicated airspeed (IAS), aircraft IAS, speed advisories, early/late indicators, and timelines. The slot marker circles provide a visual representation of the STA trajectory generated by TMA-TM by showing the planned position along the scheduled trajectory at the current time. The relative distance between the aircraft and the slot marker circle is delay that the controller needs to manage. If the delay can be absorbed with speed-control, speed advisories are displayed, otherwise early/late indicators are provided. Timelines provide the controllers a way of determining the arrival sequence and overall arrival demand.

Standard Terminal Automation Replacement System (STARS)

Raytheon-developed STARS replaces older, outdated, hardware/software in the TRACON facilities. It has been deployed to many small and medium TRACON facilities, and is currently being deployed at large TRACONs through the FAA's Terminal Automation Modernization and Replacement (TAMR) program. Controllers interface with STARS through the terminal controller workstations (TCWs). STARS offers several enhancements over the older systems: a key one being the improved capability to receive and fuse tracks from multiple short- and long-range radars, and automatic dependent surveillance-broadcast, into a single, smooth one-second aircraft track update that is displayed to the terminal controllers. STARS, also known as Full Service STARS (FS STARS), has two variants tailored to the size of the facility. A Local Integrated Terminal Equipment system (STARS-LITE) is intended for control towers without a TRACON. The second variant, Enhanced LITE (STARS-ELITE), is planned to be installed at small and medium sized TRACON facilities. STARS-ELITE offers much of the same functionality and associated software as FS STARS, but with a smaller hardware footprint.

NASA Ames Research Center's Prototype Enhanced LITE STARS (STARS-ELITE)

Beginning in 2012, engineers at NASA Ames and Raytheon began collaborating on extending the STARS-ELITE capabilities to display the CMS advisory tools on the TCWs. Early basic prototypes were designed and tested at

Raytheon's Mt. Laurel, New Jersey facility. In the spring of 2013, the ATC laboratory at NASA Ames acquired a STARS-ELITE that consisted of three TCWs and the development environment for STARS-ELITE software and adaptation. To facilitate HITL simulations in the ATC laboratory all of the relevant systems were integrated: TMA-TM (scheduling and spacing), CMS (advisory tools for terminal controllers), three STARS-ELITE TCWs (displays CMS tools), and MACS (radar simulator, additional controller/pilot display emulators and traffic generator). Several system functional tests culminated in a week of HITL simulations.

Validation of the Integration of TSS and STARS-ELITE

The ATC laboratory at NASA Ames was configured to model Albuquerque Center (ZAB) and Phoenix TRACON (P50) arrival airspace by combining high and low altitude sectors into four sectors of airspace each for ZAB and P50—two sectors for the south and two for the north. Simulation results in the form of performance data (e.g., throughput, PBN conformance, etc.) and controller workload and acceptability ratings from questionnaires validated the performance and acceptability of the TSS-enhanced STARS-ELITE prototype to display CMS advisories [20]. Figures 3 and 4 display the CMS advisories as rendered and used on the STARS-ELITE TCW in the recent NASA Ames HITL simulations at a feeder and final position, respectively. In Figure 4, a controller can immediately identify that COA1459 (lower right corner) is ahead of schedule because it is ahead of its slot marker (recall that the slot marker visually represents the planned position along the scheduled trajectory at the current time). The slot marker's IAS is 230 knots, whereas COA1459's IAS is 250 knots, displayed as a two-digit speed above the aircraft symbol. The CMS algorithm is advising a speed of 210 knots, shown on the 3rd line of the flight data block (FDB), to meet the STA.

Terminal proximately alert (TPA) cones are shown for the two aircraft nearest to the runway threshold. TPA is a current capability in all the operational variants of STARS. TSS is expected to compliment the advanced terminal controller automation tool used to monitor compression on final approach, automated TPA (ATPA), by increasing delivery accuracy to the final terminal controllers.

Future Plans

Researchers at NASA Ames received a beta version of TBFM release 4.2 in the spring of 2014. This version of TBFM includes the GIM-S functionality and additional scheduling capabilities not present in release 3.12. Over a six-month period, the TSS algorithms will be re-implemented in TBFM release 4.2, while preserving the current capabilities. In the fall of 2014, HITL simulations will be used to validate a TSS-enhanced prototype TBFM release 4.2. The TSS-enhanced TBFM and STARS-ELITE prototypes will then be transferred to the WJHTC for the OIA, beginning in early 2015.

Operational Considerations

Several challenges remain in transitioning TSS from the laboratory to the operational environment [12]. In addition to those challenges identified in [12], an important challenge for executing TSS simulations at the WJHTC is that it requires the integration of the ERAM, STARS, TBFM, and the TGF platforms. These platforms are seldom integrated to conduct an OT&E; therefore, the OIA provides an opportunity to accomplish this multi-platform integration, and to develop traffic scenarios that make use of atmospheric forecasts and PBN procedures. The experience gained from conducting the OIA would be leveraged for the OT&E. Other operational considerations are highlighted below.

Interfacing with ERAM

In the NASA laboratory environment, ARTCC flight plan messages were sent with MACS using a model of the current ERAM interface. At the WJHTC, the OIA will require the TSS-enhanced TBFM to interface with ERAM. The current TBFM system being modified by NASA requires the PBN eligibility information that exists in the Internal Civil Aviation Organization flight plan. TBFM will need to be modified at the interface level to accept the additional PBN eligibility information available from ERAM.

For the OPD procedures to be most effective, the center controllers would be required to issue expected runways for the procedure derived from TSS. The current ERAM is not expected to communicate runway assignments with TBFM; therefore, expected runway assignments will not be displayed to center controllers, and subsequently will not be issued.

STARS Hardware and Software Versions

As discussed previously, STARS-ELITE reduces the hardware footprint required in a facility relative to FS STARS, and is the key reason NASA developed the TSS-enhanced prototype on the STARS-ELITE. However, STARS-ELITE compatible software lacks some FS STARS capabilities useful for high-density TRACONs, such as the ATPA functionality, requiring an eventual merging of STARS software versions. CMS and ATPA add information to the FDB, requiring human factors and procedures development prior to integrating TSS into FS STARS.

Eventually, the OT&E will need to utilize an operational TSS-enhanced FS STARS at the WJHTC, whereas the OIA in early 2015 will make use of the TSS-enhanced prototype running on a STARS-ELITE string at the WJHTC.

Transitioning to the Operational TSS-Enhanced TBFM and STARS

Expecting a successful assessment of TSS at the WJHTC using a NASA-developed TSS-enhanced prototype TBFM release 4.2, the next step would be a future OT&E prior to deployment. However, the OT&E would require the operational versions of the TSS-enhanced TBFM and STARS.

Two different approaches were taken to develop the TSS-enhanced TBFM and STARS prototypes. In one approach, NASA developed the prototype TBFM using a recent, soon-to-be operational, release of TBFM. This approach was chosen for expediency due to NASA's extensive knowledge of the TBFM automation, because NASA originated it in the 1990s. In the second approach, NASA and Raytheon collaborated to develop the prototype STARS. NASA transferred the domain knowledge and provided insight into the TSS design philosophy, while Raytheon implemented the required software modifications, following their own, and FAA approved, internal software engineering processes, and engaging other Raytheon divisions responsible for operational STARS software development. The NASA-Raytheon collaboration approach expects to maximize software reuse when transitioning from prototype to operational software.

Transferring the TSS knowledge and insight to the TBFM contractor will be important as the software transitions from the prototype used during the OIA to the operational version. NASA has provided the modified TBFM software and documentation to accelerate the transition, and needs to continue its efforts once the FAA's contractors begin the development of the operational system.

Cultural Considerations and Training

Perhaps one of the most important considerations is that of the potential impact of TSS on the TRACON facility culture. TBFM will be used more frequently than it is in today's current operations. Terminal controllers will need to use it as a primary arrival decision support tool. Socialization of the TSS technologies has begun with the FAA's controller workforce, and the FAA intends to use current controller workforce members as active participants in the planned 2015 OIA simulations.

TSS training strategies will need to be developed and determined by the FAA. The training strategies need to include the terminal controller workforce and the TBFM current traffic management coordinator (TMC) users. Currently, the FAA and MITRE's Center for Advanced Aviation System Development are exploring the roles and responsibilities for the TMC users. A key element of the joint FAA-NASA OIA simulations at the FAA WJHTC will focus on potential training and deployment strategies in order to identify and capture training-related operational deployment issues. TSS training will need to include describing the strategy of use that spans the expected operational envelope. Terminal controllers will be expected to modify their strategic approach by proactively issuing speed commands. The use of recently retired controllers throughout the HITL simulations indicate that these training strategies are viable, but will require validation prior to implementation.

Summary

The implementation of NextGen technologies into the NAS is a highly complex endeavor. It requires the simultaneous integration of advanced procedures, aircraft fleet upgrades, and enhancements to multiple FAA automation platforms. To reduce risk of the implementation of the TSS technologies, NASA and the FAA have executed several strategies. Key risk reduction strategies conducted by NASA are: (1) to use versions of the FAA's automation platforms to prototype the technologies; (2) to conduct complex HITL simulations of expected operations including the variation in aircraft capabilities, and utilization of the TSS-enhanced FAA automation systems; and (3) to include, to the extent possible, FAA automation program organizations and controller workforce participants. These key steps will reduce the overall risk of the TSS technology implementation into the NAS.

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