NASA's ATM Technology Demonstration-1: Moving NextGen Arrival Concepts from the Laboratory to the Operational NAS

Harry Swenson, John E. Robinson III, Aerospace Engineers, NASA Ames Research Center
Steve Winter, Engineering Fellow, Raytheon Technical Services Company

Introduction

This paper describes NASA's approach for transitioning NASA's Air Traffic Management Technology Demonstration – 1 (ATD-1) NextGen arrival concepts and technologies from laboratory simulations to operational evaluations in the US National Airspace System (NAS). The ATD-1 tools are an integrated and interoperable set of ground and airborne technologies that have demonstrated simultaneous increases in airport throughput and use of fuel-efficient descents from cruise to touchdown in high-fidelity simulations of congested traffic conditions. This article's focus is on the overall approach and design trades used to facilitate the integration of the ATD-1 ground-based technologies into the NAS. This includes enhancing the FAA's Time-Based Flow Management (TBFM) scheduling system, known as the Traffic Management Advisor (TMA), as well as the Standard Terminal Automation Replacement System (STARS) platform. The ATD-1 software-based technologies will be prototyped within TBFM and STARS systems, and the integration validated within high-fidelity human-in-the-loop simulations at NASA and FAA laboratories. This represents the completion of the concept exploration phase and the functional requirements definition phase for the ATD-1 technologies. It also provides the FAA with sufficient information to fully evaluate the impact of the ATD-1 technologies on its automation platforms to enable operational evaluation and accelerated transition of the technologies to the NAS. Although the concept and technologies are being developed for US airspace, it is expected that they would offer substantial benefits internationally.

NextGen and Terminal Arrival Operations

The US future Next Generation Air Transportation System (or NextGen), includes goals for expanding the capacity of high-demand airports, while increasing the fuel efficiency of arriving aircraft.[1] Today, arrivals into high-density airports during high throughput time periods often experience significant inefficiencies resulting from use of static miles-in-trail procedures, step-down descents, and significant vectoring close to the airport. These contribute to reduced airport capacity, increased controller workload, increased arrival delay, as well as increased fuel burn, emissions and noise[2]. NASA has proposed to demonstrate capabilities to alleviate these inefficienceies while still maintaining high throughput by integrating a set of three ground and airborne research technologies into a project called Air Traffic Management

Technology Demonstration – 1 (ATD-1)[3]. ATD-1 has a primary goal to demonstrate these technologies in an operational evaluation in the NAS to validate the benefits demonstrated in high-fidelity simulations.

The challenges of sucessfully transitioning and evaluating automation technologies in the NAS are many. In the early 1990's, the FAA worked with NASA and the Mitre/Center for Advance Aviation System Development to successfully evaluate prototype technologies that were 'off-board' of the primary safety-critical air traffic automation plaforms. These technologies, called the Traffic Management Advisor (TMA)[4] and the User Request Evaluation Tool (URET)[5],then took nearly a decade to be implemented throughout the NAS, even though their benefits had been well-established in operational evaluations. Much of this delay was associated with the full integration of these technologies into safety-critical FAA automation platfoms. More recently both the FAA and Eurocontrol have conducted field evaluations of arrival metering using airborne technologies that included the Required Time of Arrival (RTA) capabilites of modern Flight Management Systems (FMS)[6,7]. The results have demonstrated that while there are potential benefits of the airborne techologies supporting fuel-efficient descent procedures but there is also a requirement for significant advances in ground-based air traffic automation platforms to make them operationally viable.

The ATD-1 project addresses the two-fold challenge of simultaneously 1) advancing new technologies for benefits validation through operational evaluations in the NAS, and 2) accelerating the transition to broad operational use. This article highlights the key challenges of transitioning the ATD-1 concepts and technologies from laboratory prototypes to modified versions of the TBFM and STARS automation platforms, suitable for an initial operational field evaluation. This approach provides the highest potential that the FAA will be successful at introducing the ATD-1 concepts and technologies into full operation at the earliest opportunity.

ATM Technology Demonstration-1 (ATD-1)

The ATD-1 Concept[3] leverages three NASA research efforts to create a single, integrated arrival solution, as shown in Figure 1:

- **TMA-TM**: Traffic Management Advisor with Terminal Metering (TMA-TM) for precise time-based schedules to the runway and meter points within terminal airspace[8];
- **CMS**: Controller-Managed Spacing (CMS) decision support tools for TRACON controllers to manage aircraft delay better using speed control[9];
- **FIM**: Flight-deck Interval Management (FIM) aircraft avionics and flight crew procedures to conduct arrival-to-arrival airborne spacing operations[10].

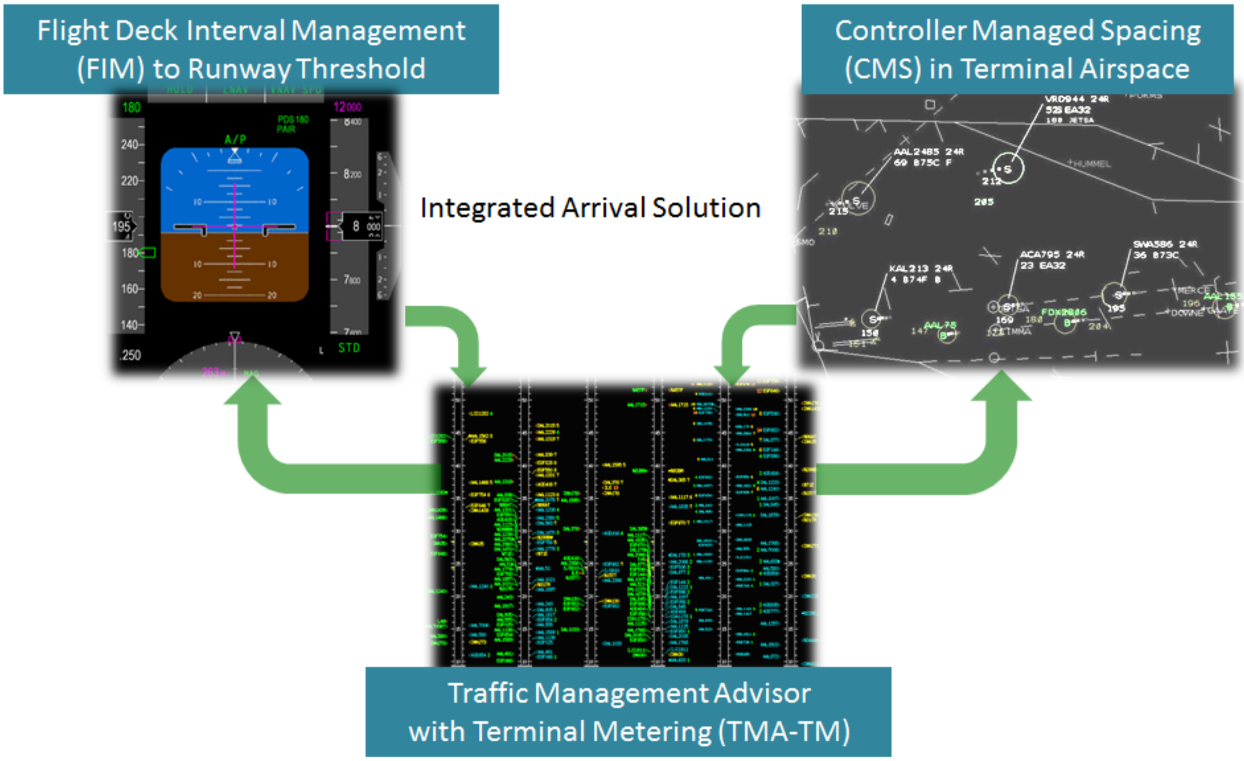

Figure 1 ATD-1 Technology Components

Building on emerging Performance-Based Navigation (PBN) infrastructure, the ATD-1 technologies integrate into a single concept for arrival scheduling, sequencing and spacing[11],. Figure 2 illustrates the flow of a number of arriving flights transitioning from cruise to landing following the ATD-1 operational concept and aided by its technologies shown in figure 1.

- Starting at approximately 200 NM from the airport for jet transports, and somewhat closer for slower aircraft, the arrival sequence and time-based schedule are calculated for aircraft to a metering fix ("the TRACON Gate") to provide an efficient arrival sequence for each runway. This time-based schedule is based on calculated 4-D trajectories that adhere to all required separation constraints at flow merge points throughout the terminal area (outlined in gray).
- From about 100-160 NM from the meter fix, depending on aircraft type, the arrival sequence is frozen and displayed to En Route controllers providing a time to achieve the scheduled entry to the terminal airspace.
- En Route controllers direct the arriving aircraft to meet the meter-fix scheduling and spacing goals, the same as today with the TBFM system.
- FIM-equipped aircraft are issued voice clearances with scheduling information to engage their interval management automation, and begin maneuvering to achieve the required spacing behind a designated leading aircraft.
- The aircraft are handed off to the TRACON prior to transitioning the metering fix.
- Appropriately-equipped aircraft use their FMS to fly an Optimized Profile Descent (OPD) through the terminal area (FIM-equipped aircraft do this while trailing their leading aircraft).

- Guided by the CMS decision support tools, TRACON Controllers issue speed-control corrections to adjust residual spacing errors (and other disturbances) at interim metering and merge fixes for non-FIM equipped aircraft.
- The aircraft arrive at the runway threshold in an efficiently-spaced sequence.

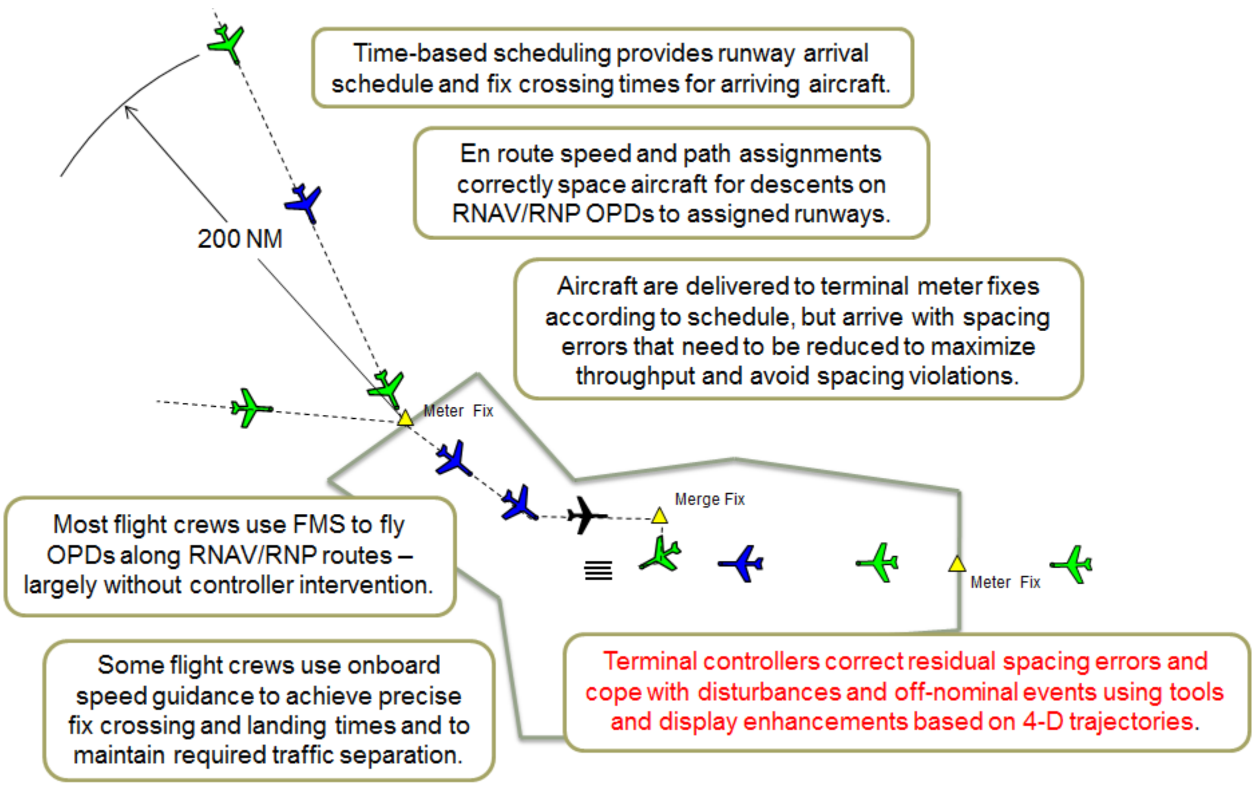

Figure 2 ATD-1 Integrated Arrival Scheduling and Spacing Concept

TMA-TM

TMA-TM is an advance prototype version of the FAA TBFM time-based scheduling tool, currently in use at the En Route ARTCC facilities throughout the NAS. TBFM assists air traffic controllers and traffic managers in matching arrival demand with airport arrival constraints such as required separations and Airport Arrival Rate (AAR). It achieves this by providing recommended sequencing, scheduling and spacing information for arriving aircraft to the TRACON Gate through the generation of scheduled times of arrival (STA) at the meter fix, merge fix and runway.

TMA-TM extends the basic TBFM scheduling capability by including merge fixes inside TRACON airspace. Its terminal delay model is enhanced to more-accurately represent PBN based trajectories, and enforcing separation constraints of flow merges within the terminal area. In addition, the TMA-TM scheduling system provides information to render, TBFM system, timeline displays on the terminal automation (*i.e.*, STARS) for the terminal merge points for the TRACON controllers (Figure 3).

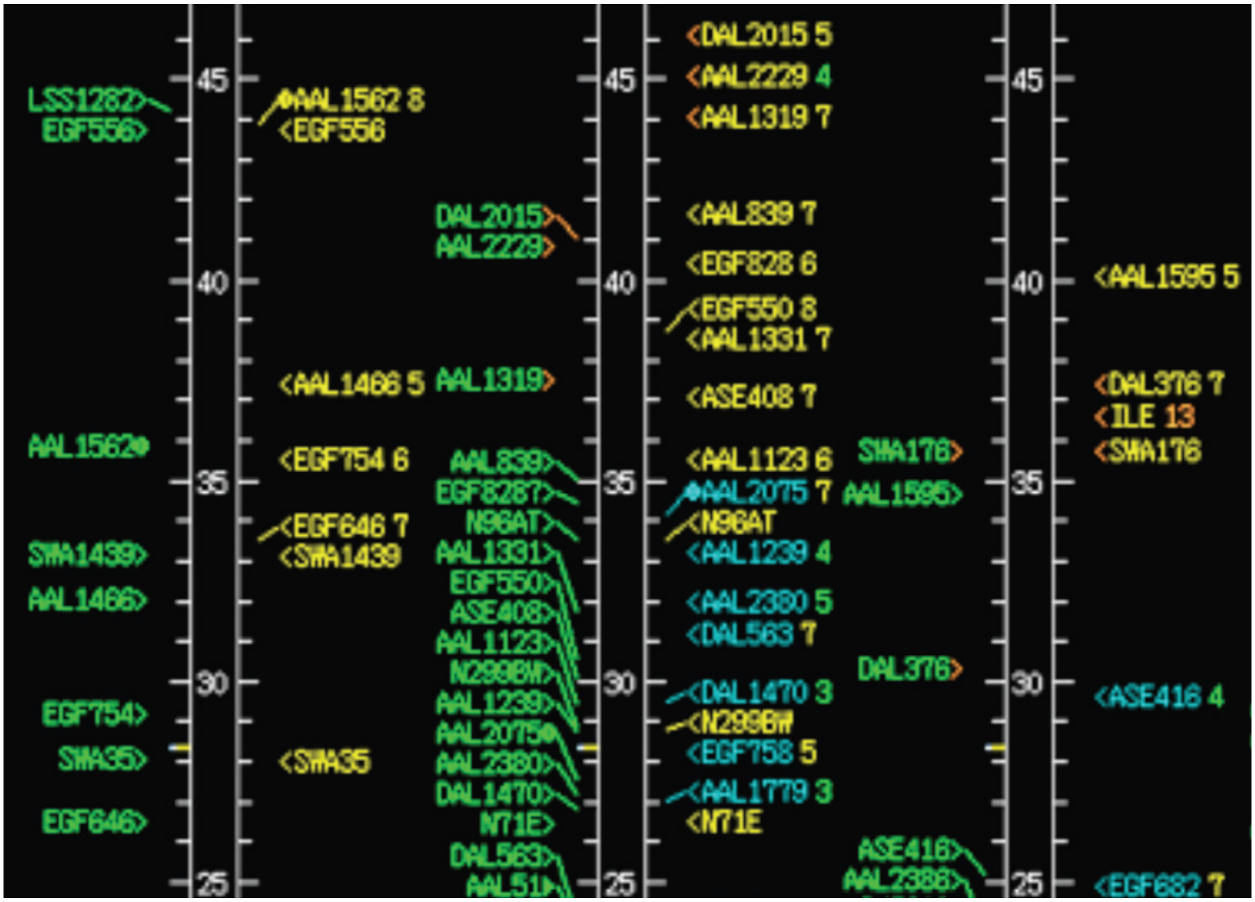

Figure 3 TMA-TM Timeline Display. Estimated Times of Arrival (ETA) are shown to the left of the timeline, Scheduled Times of Arrival (STA) are shown to the right of the timeline, with time increasing up the display.

CMS

The CMS tools enable sustained use of PBN procedures by terminal controllers and maximize throughput for capacity-constrained runways by giving them strategic and tactical visibility of the recommended sequencing and spacing from TMA-TM. The display of timelines (Figure 3) provides a strategic view that includes time-based information of the total arrival flow situation. Figure 4 shows the other CMS display features: **Slot Marker Circles**, displayed as map symbology, represent the current spatial position of the schedule on the aircraft's planned 4-D trajectory enabling controllers to instantaneously know how close an aircraft is to meeting scheduling objectives at terminal merge fixes and runway; and **Speed Advisories,** displayed in the data-block, which recommend aircraft speed clearances controllers should use to achieve the scheduling goals.

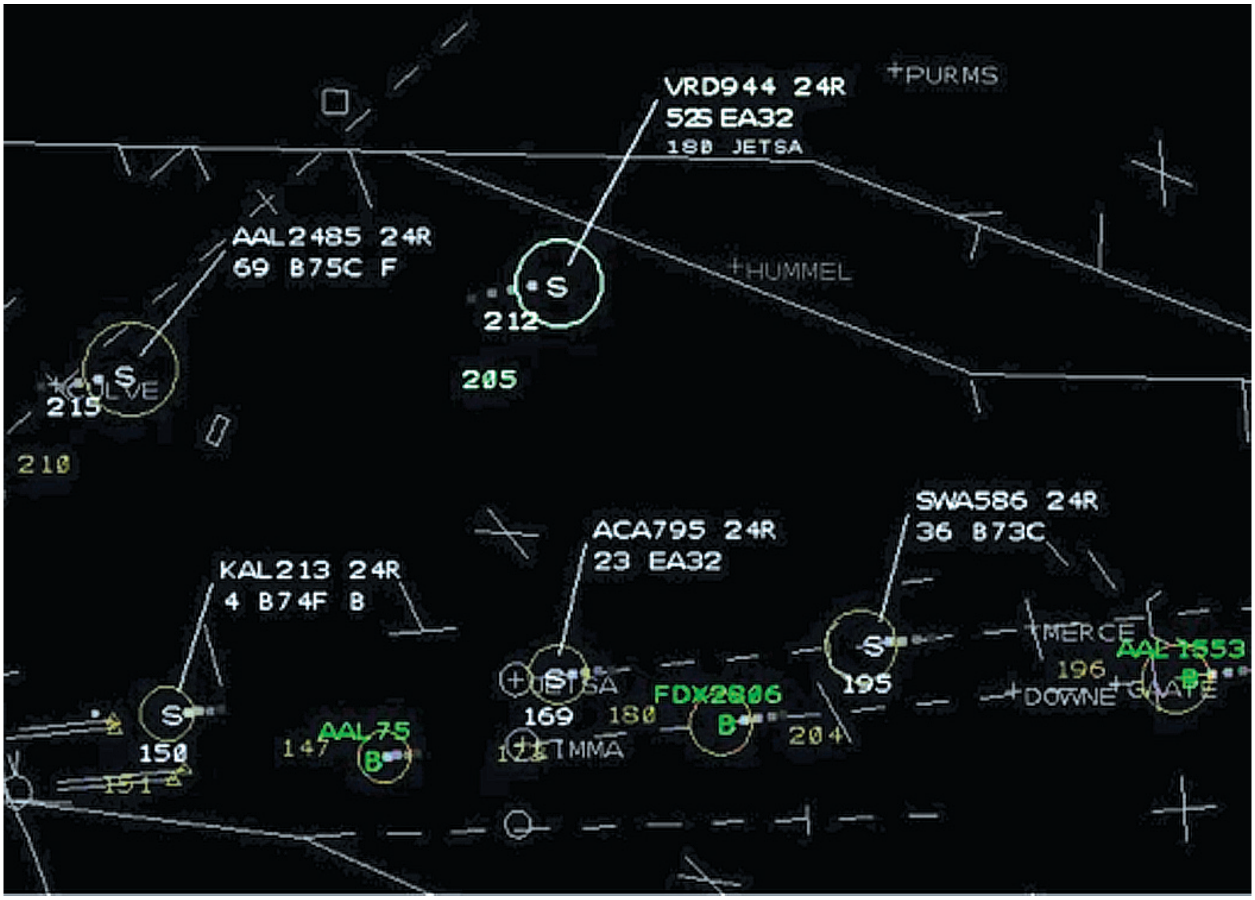

Figure 4 Controller Display with integrated CMS Decision Support Tools

FIM

FIM is an advanced avionics capability that enables an aircraft using Automatic Dependent Surveillance – Broadcast (ADS-B) data to fly efficient descents while achieving and maintaining a precise interval behind a lead aircraft, without controller intervention. FIM requires two components. The on-board avionics component is represented by displays to enable the flight crew to enter sequencing and interval information received from air traffic controllers. The other requirement is ADS-B "In" information to achieve the required interval behind a designated lead aircraft. A complementary ground component provides an ARTCC and TRACON display capability presenting air traffic controllers with sequence and spacing interval information from TMA-TM, for transmission to the aircraft, as well as indications of the FIM capability and status of aircraft (*e.g.*, that a FIM-equipped aircraft is in-trail).

Figure 5 shows a simulated Primary Flight Display with the speed bug on the left speed tape indicating a 180-knot speed advisory to conform to the required spacing behind the lead aircraft at the final approach fix. This represents a potential end-state implementation of the FIM cockpit interface operating directly through the primary flight control displays. For the ATD-1 demonstration, the speed advisory information and FIM status are being prototyped as an auxiliary guidance display presented in the forward field of view with guidance information derived from algorithms within an electronic flight bag[12].

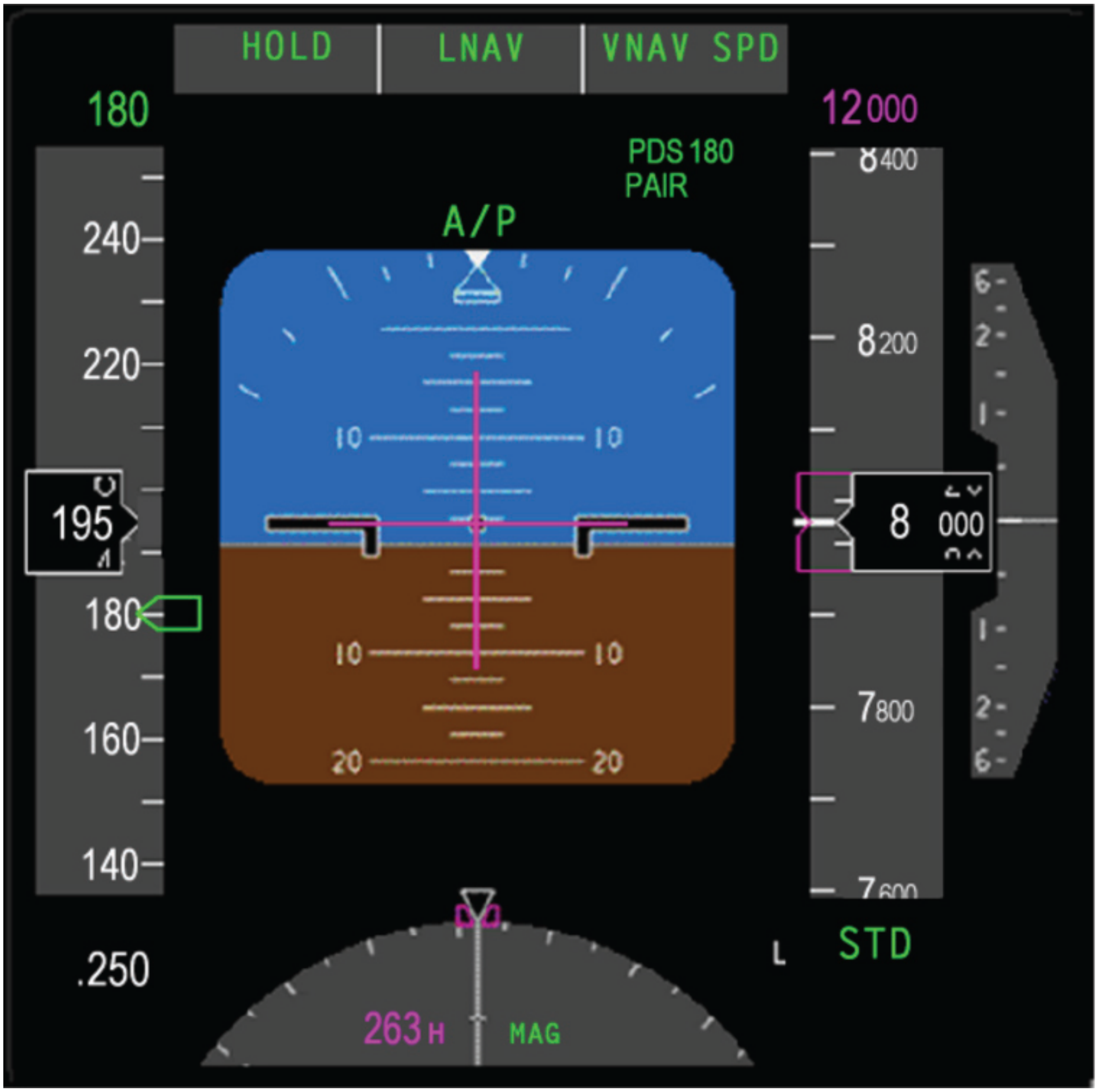

Figure 5 ASTOR Simulator Primary Flight Display with FIM Information

ATD-1 Implementation Approach into Current FAA Automation Platforms

The ATD-1 integration and development effort was started in 2011, bringing together technologies that had been the subjects of separate long-term research activities. Starting in January 2012, a number of Human In The Loop (HITL) simulations have been conducted at NASA's Ames and Langley Research Centers. These simulations have explored, at increasing levels of fidelity and maturity, the ATD-1 concepts using the laboratory prototypes including the NASA enhanced FAA TBFM system. The initial simulation results of these early fully integrated ATD-1 technologies confirmed similar levels of benefits from earlier, studies with complete aircraft FIM equipage, although the ATD-1 studies concentrated on mixed equipage operations, thereby validating the higher precision of spacing control provided by the airborne FIM technologies with a mixed (10% FIM and 90% standard) equipage operation.

This initial study validated that the ATD-1 technologies were at a high level of maturity when compared with the NASA Technology Readiness Level (TRL)[13] scale. The ATD-1 technologies are currently at a TRL-4-5 level, which is the level NASA typically concludes its aeronautics research unless compelling benefits or significant challenges warrant further study. Since the ATD-1 technologies represent a significant near-term step toward the NextGen goals, the decision was made further develop the concept and technologies up the TRL scale. Beyond the significant investment in resources, this involves advancing the technologies by moving them off laboratory platforms to the actual operational systems. Thus, initiating testing and evaluations in an operational environment for benefits validation is the logical next step in the TRL. These steps are critical, as without them either the concepts will remain in the simulation phase, or there may be significant risk of premature commitment to full-scale development and deployment . The actual implementation in key FAA automation platforms has become a critical next step in the transition of the ATD-1 ground-based technologies from laboratory prototypes to operational systems to reduce the investment risk of full-scale development in the TBFM and STARS automation platforms.

NASA's approach for TBFM is fairly straightforward. It heavily reuses the NASA TMA software developed for the field evaluations in the late 1990s. Many of the original TMA designers and software developers are still involved with the current enhancements described in references 4, 8, and 12, and much of the original architecture and code is intact. In addition, NASA worked closely with the FAA and its prime TBFM development contractors in a joint development process during the early transition stages to NAS-wide deployment. Finally, NASA recently worked with the FAA to integrate and evaluate a research precision departure release capability within a version of the TBFM operational software[14].

Thus, the challenge to "up-level" the FAA's current TMA with NASA's current TMA-TM features is considered relatively low-risk. Therefore, NASA acquired a current operational version of the FAA TBFM software, known as TBFM release 3.12, and began porting the TMA-TM features. Most of the software enhancements were constrained to three software modules of the TMA. The most significant changes were in the scheduling component, known as the "Dynamic Planner", which included the addition of scheduling constraints associated with terminal merge fixes. Another change included enhancing the "Route Analysis" function to more precisely consider RNAV and PBN routing and procedures through the terminal airspace. Finally, some changes were also made to the "Trajectory Synthesizer" component to support the 4-D calculation of the new trajectories defined by the Area Navigation (RNAV) and Performance Based Navigation (PBN) procedures. These changes comprised an addition of approximately 2500 lines of code to the TBFM software. A final design consideration for the up-leveling software was to ensure that the baseline TMA functionality could be run without the enhancements. This would enable both TMA-TM and the current operational TMA capability to be run within the same software, allowing quick reversions to the operational system.

The approach for the STARS automation platform was entirely different since the Raytheon Company has been its sole developer for the FAA since the late 1990s to the present. Thus, NASA had no insight into the feasibility or design implications of integrating the CMS component of the ATD-1 technologies into the platform. Therefore, in 2012, Raytheon was contracted by the FAA and NASA to complete the following tasks: 1) assess the feasibility of augmenting the current TRACON automation system, STARS, with the CMS and FIM capabilities, 2) conduct a design trade study to evaluate potential designs and required system interfaces, and 3) develop a STARS software prototype to demonstrate, in a laboratory setting, the key CMS functions. The Raytheon team was provided with an opportunity to conduct a thorough evaluation of the CMS tools implemented in the Multi-Aircraft Control System ($MACS^3$) simulation software, including observation and participation in NASA simulations. The Raytheon team then determined overall feasibility of porting the tools to the STARS platform.

The design and trade-study considered the following critical design constraints: 1) maintain the current FAA STARS architectural requirements, 2) produce and field a pre-production release within 3 years, and 3) maintain a minimal footprint within a FAA TRACON facility. The selected design included using STARS as the primary display with the partitioning of the CMS algorithms into trajectory-based computations that were allocated to TMA-TM and display presentation software within STARS. This required a significant addition to the existing TBFM-STARS interface including the development of a bi-directional data flow, but maintained the FAA architectural requirement of having trajectory-based computations within the TBFM automation. A final feasibility demonstration included the integration of the NASA enhanced version of the TBFM TMA 3.12 and a rapid prototyped CMS enhanced STARS running a simple SoCal TRACON adaptation driven by the embedded STARS ATCoach™ simulation environment at the Raytheon facilities.

The results of the study initiated a three-year contract to implement a full prototype of the ATD-1 tools within the STARS platform including the FIM related functionality, along with the creation of a pre-production release of STARS suitable for use in an initial field evaluation. In parallel, a NASA Team is transitioning the TMA-TM capabilities for the NASA research platform to the FAA TBFM system, as discussed previously, including the eventual up-leveling of the TMA-TM to the TBFM automation software consistent with an operational evaluation in the 2015-16 timeframe.

To manage the technical and organizational complexity of conducting an operational evaluation in the NAS, a joint FAA and NASA ATD-1 Research and Transition Team (RTT) has recently been established. The RTT leverages the knowledge of the NASA technology development with the direct oversight and input of the FAA eventual end-user of the ATD-1 technologies. This will ensure the highest potential return on NASA's investment.

ATD-1 Future Plans for the FAA Automation Platforms

One of first activities the RTT is will oversee is the transition of the ATD-1 TMA-TM and STARS CMS prototype technologies to the FAA William J. Hughes Technical Center, in Atlantic City, for Operational Test and Evaluation. Once that is complete, the next stage expected in 2015 is to test the technologies at a major US airport in a joint NASA-FAA field demonstration and evaluation. A series of operational evaluations will be performed, starting with a protracted period of shadowing operations and, as results permit, limited operational use. This approach is similar to the highly successful operational testing of the TMA conducted by the FAA and NASA in the late 1990s[15].

Ultimately, following a succesful field evaluation the technologies will be transitioned to the corresponding FAA programs and scheduled for full development and release. An important goal for the NASA/Rayteon team is not to simply to achieve a single transition of concept and technology to the FAA, but to create a repeatable transition process that will enable other NextGen innovations to be realized in less time than previous projects. To this end, NASA and Raytheon, supported by the FAA, are developing a comprehensive Transition Plan, with associated processes, for taking the ATD-1 capabilities from the lab to the FAA environments.

Activities addressed in the Transition Plan and planned for the next three years include the following:

Completion of prototype development for NASA laboratory simulations

Now that the feasibility of creating the STARS CMS prototype software has been established, the prototype software must be completed. The prototype is designed to work in an integrated simulation environment.

Conduct of integrated human-in-the-loop (HITL) simulations

Before the prototype software can be used as the basis for a pre-production release, it must itself be evaluated and validated in HITL simulations at NASA Ames Research Center.

"Up-leveling" of the prototype to create a pre-production release, suitable for test and evaluation at the FAA Tech Center

Since the prototype software was developed for concept exploration for use in simulations using rapid prototyping techniques, the software will need to be "up-leveled" and matured to create a pre-production release using production software development techniques where all requirements are established, defined and feasible. This software can then be tested by the FAA and certified as being suitable for evaluation at an FAA TRACON. There will be four main types of activity to make the software better suited for this purpose: functional changes, software development process enhancements, software documentation, and software testing activities. These processes will be based on the production STARS software development, together with best practices learned from other prototyping activities. The goal is to ensure that the software meets all the non-functional requirements necessary for it to be suitable for testing and evaluation at the FAA Tech Center, and ready for evaluation at the Field Site.

Operational test and evaluation of the pre-production release at the FAA Tech Center

The pre-production release will be transferred to the William J. Hughes FAA Technical Center, where it will be subjected to systemic tests and evaluations to validate its suitability for further use for operational evaluations.

Release of the pre-production release to the designated FAA Field Site

Provided that the operational test and evaluation at the FAA Technical Center is satisfactory, and subject to availability and other considerations such as impending upgrades and/or airspace enhancement and air traffic controller acceptance for the designated FAA field site, the pre-production software will be released to the Field Site for evaluation on the facilities STARS training platform. This is a critical step and the role of controller acceptance at this stage is paramount. The approach for achieving the acceptance is so important that the authors felt that it could not be adequately described within scope of this article, and should be treated as a subject in its own right.

Operational evaluation of the pre-production release at the FAA field site, including shadow operations and limited operational use

It is planned that the system will undergo a number of operational evaluations at the field site. The evaluations will include offline testing in the STARS Training Laboratory, “shadow” operation in the STARS Training Laboratory, and, all being satisfactory, limited operation evaluation in live use during low-traffic periods, in conjunction with FIM-equipped test aircraft. This evaluation is expected to take place over several months.

Decommissioning and removal of the pre-production release from the FAA field site

It is important that once the field evaluation has been completed, the pre-production software should no longer be accessible for field use until FAA processes are completed for full-scale implementation. Therefore, an activity will be performed to ensure that this is the case by removing the software from the FAA field site.

A preliminary schedule for the activities is shown in Figure 6. The figure also shows the applicable NASA Technology Readiness Levels (TRLs) for the activities.

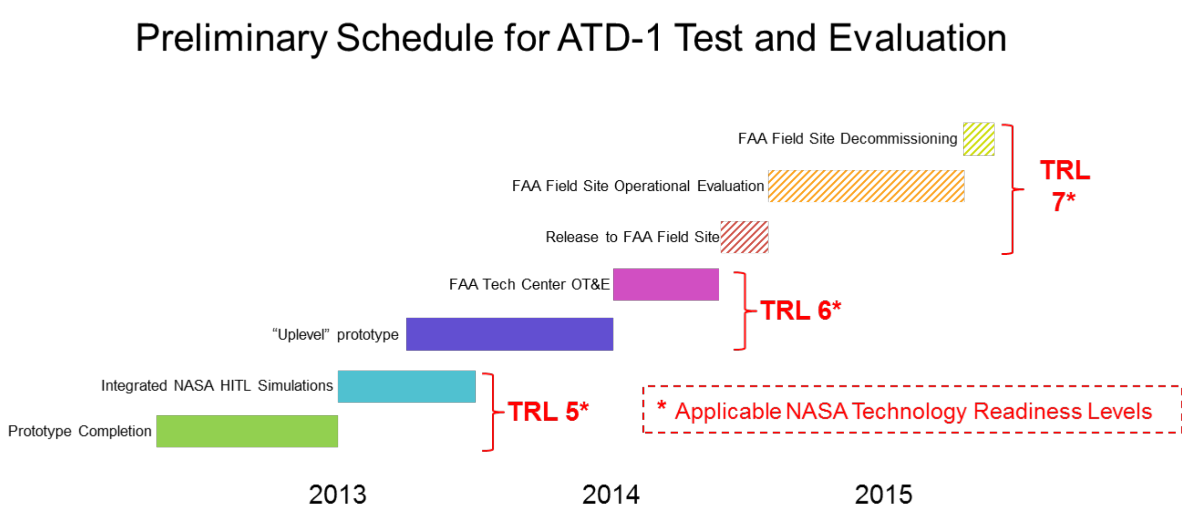

Figure 6 Preliminary Schedule for ATD-1 Test and Evaluation

ATD-1 Future Challenges

The future ATD-1 work faces a number of significant challenges. This section describes some of these and the how the team intends to address them.

Proving ATD-1 operational concept and technology viability

At the early TRL levels (below 5), ATD-1 has validated the concept including detailed simulations focusing on the critical elements of the operational concept. These include complete definitions of computer human interfaces, concepts of use, and phraseology for controller and pilot interaction for both FIM and non-FIM equipped operations. ATD-1 has also established the general technological feasibility of integrated capabilities into the current FAA technology platforms. As ATD-1 technologies progress on the TRL scale, they will be able to be evaluated in increasingly realistic environments to allow the operational viability to be established and benefits to be verified. It is planned to include controllers from the designated FAA Field Site in the NASA simulations in order to give them the opportunity to provide facility-specific insights.

Ensuring that the "up-leveled" software has potential for field site evaluation

There are several aspects of this potential that include operational functional suitability as well as utility that need to be addressed to transition to the higher TRL levels:

- Functional suitability: i.e., is the ATD-1 functionality suitable for operational evaluation?
- Non-functional suitability: is the ATD-1 software of sufficient quality, does it have the necessary performance characteristics, and has it been adequately tested to permit its to be evaluated at the Field Site (including contingency and failure modes)?
- Usability: is the ATD-1 software and, in particular, the user interface usable by the operational controllers?
- Functional Compatibility: is the ATD-1 software functionally compatible with in-service releases of the FAA operational systems?

These issues will be addressed by a combination of incremental simulation, testing and evaluation, together with close collaboration with the FAA.

Maintaining and modifying the "up-leveled" software

It is inevitable that defects and potential improvements will be identified in the course of both the simulations and field evaluation. The Transition Plan will include detailed procedures and resources for managing and releasing changes to the pre-production software and adaptation in a controlled fashion that will permit new features and changes to be checked out as part of the ongoing evaluation.

Ensuring a smooth and safe transition at the field Site to and from the ATD-1 software

The modified software will be released to the Field Site in a similar way to production operational software releases. This will include adapting the processes used to transition between operational releases. These adapted processes are a key outcome of the RTT and will be thoroughly evaluated at the FAA Technical Center before performing them on the operational equipment at the site.

Coordinating evaluations across multiple systems and facilities

The ATD-1 evaluations will involve changes to multiple systems, including STARS, TMA/TBFM and test aircraft avionics at both the TRACON and its ARTCC. Tight coordination of the introduction of technologies will be required ensuring that changes at these facilities avoid any interruption of operational services.

Avoiding resource conflicts between the ATD-1 activities and FAA program activities

As the ATD-1 technologies are integrated into pre-production versions of the FAA platforms, the potential for conflict with FAA program activities, such as the Terminal Automation Modernization Replacement (TAMR) program, increases. To avoid this, Raytheon has set up a separate team for the STARS CMS development, based in Mount Laurel, NJ. In addition, NASA and Raytheon will include specific resource planning information in the Transition Plan that is under development. Furthermore, existing FAA processes and practices will be adapted to minimize the process impact of the ATD-1 evaluation.

Summary and Lessons Learned

NASA's approach and challenges for the transition of ground-based and flight deck automation technologies into the NAS that enable a NextGen vision of an integrated set of ground and airborne-based arrival technologies is described. These include significant enhancements to the FAA's TBFM and STARS automation platforms. The approach uses an innovative stepwise transition of research-proven laboratory technologies to operational evaluation in the NAS. The approach considers the unique and complex challenges for the introduction of substantial enhancements to current operational paradigms within the NAS and follows the NASA TRL scale to manage and judge progress. This will assist the complex interactions with NASA's and FAA's industry partners as well as NAS stakeholders to evaluate progress towards the goal of operational evaluations of the ATD-1 project. This is a success-driven approach that also enables the possibility of early adoption of some or all of the ATD-1 NextGen technologies within current FAA automation platforms.

A number of lessons learned and new approaches were defined to transition the ATD-1 technologies from laboratory concepts to pre-production prototypes with the potential for operational evaluation in the NAS. Key elements are summarized here, but could also be applied to other air-traffic management technologies attempting to implement the NextGen vision:

- **The value of an integrated Research and Development approach:** By bringing the complementary technologies (TMA-TM, CMS and FIM) that provide system benefits together, ATD-1 has been able to create a pathway to the systematic introduction of a complex yet complete operational and technical solutions to achieve fuel efficient, high throughput arrival operations..
- **The importance of early user engagement:** The early and continued involvement of controllers has not only built confidence in the ATD-1 concepts, but has refined the technologies and detailed operational requirements and provided quantitative benefits data and the capture of theorized system benefits.

- **The use of the NASA Technology Readiness Level (TRL) Model:** The TRL model is an effective framework for the incremental evolution of the ATD-1 concepts from the research labs to the real world.
- **The benefits of Human In The Loop (HITL) simulations:** The use of HITL in increasingly high-fidelity, representative simulations of actual terminal environments has enabled the early involvement of controllers and user evaluations. The controllers were able to offer real-world insights into the ATD-1 concepts and technologies.
- **Streamlining of the Transition Process for NextGen Technologies:** The creation of a standard transition approach, processes, and capabilities for NASA concepts and technologies should enable advanced capabilities to be delivered earlier, at lower cost, with less risk and improved outcomes for users.
- **Early Involvement of FAA system developers and suppliers:** The early involvement of engineers from FAA system developers has enabled up-front addressing of implementation issues, such as integration and interface development, allowed the engineers to offer insight into the research technologies to improve them, and ensured that operational system constraints (e.g., human-computer interface limitations) can be taken into account.
- **The importance of Comprehensive Transition Planning:** This is essential to ensure that all the processes, procedures, and resources required to safely evaluate the ATD-1 concepts and technologies, are identified and potential conflicts resolved early on.
- **The importance of open collaboration:** The NASA team uses an open, collaborative, approach, recognizing that for the ATD-1 concepts to be successful, all of the ATD-1 technologies must work effectively together.

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