Flight Demonstration of the Tailored Arrival Manager

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A flight demonstration of arrival traffic management automation was conducted in partnership between NASA, FAA and Boeing as an element of the latter's ecoDemonstrator 2020 flight program. For the demonstration, NASA's prototype Tailored Arrival Manager (TAM) was used to compute efficient trajectory-based solutions to traffic management problems representing those encountered during time-based metering operations today. TAM solutions involving route modifications were uplinked to a Boeing 787 airplane using Controller Pilot Data Link Communications and seamlessly loaded into the airplane's Flight Management System (FMS). The paper describes the concept and technology behind TAM along with the data exchanges and procedures involved with the demonstration. All TAM solutions were delivered in a timely manner and successfully integrated with the airplane's FMS, thereby demonstrating the basic feasibility of trajectory-based arrival management using currently available data communications and avionics equipage. Although TAM solutions were not executed during this initial demonstration, a limited study of trajectory prediction accuracy was possible given that the airplane flew uninterrupted, automated descents with known route and speed intent. Analysis revealed that TAM meter-fix arrival time predictions were accurate to within ± 30 seconds for time horizons of 30 minutes or less, which matched closely with FMS predictions acquired through real-time data exchange. Top-of-descent predictions over similar time horizons were found accurate to within ± 5 nautical miles.

I. Introduction

Flight operations that minimize energy consumption, emissions, and noise are an important element of global initiatives to reduce aviation's impact on the environment [1]. Key to operational improvements is the accommodation of energy-efficient trajectories during busy and complex traffic conditions. During such conditions today, air traffic control actions needed to ensure separation and manage traffic flows often prevent the planning and execution of continuous trajectories that could minimize environmental impact. Nowhere is the problem more challenging than in the arrival domain where flights are converging towards capacity-constrained terminal airspace and airports. Without automation to significantly extend human capabilities, efficient arrival trajectories will become increasingly unmanageable as operations grow beyond pre-pandemic levels.

The problem of enabling continuous descents has received considerable attention in recent years. Over the past decade – stemming from initial flight research at Louisville [2] – the FAA has implemented Optimized Profile Descent (OPD) procedures for many airports across the U.S. National Airspace System (NAS). While enabling vertical profiles that reduce noise and fuel consumption, an OPD is a static, *one-size-fits-all* route structure with speed and altitude constraints that is published as a specialized Standard Terminal Arrival Route (STAR). As such, OPDs are not tailored to individual aircraft performance, traffic situations, or weather conditions. In addition, OPD's by themselves do not prevent traffic conflicts or ensure that capacity constraints are met. Without such tailoring, the environmental benefits of optimized profiles are potentially lost due to disruptive control actions.

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Several technologies have emerged in recent years that expand on the OPD concept with more dynamic and tailored flight management. For example, Tailored Arrivals, stemming from initial trials at the Oakland Air Route Traffic Control Center (ARTCC) [3], have been implemented by the FAA for oceanic arrivals to SFO, LAX, and MIA. While tailored for individual aircraft performance and communicated using digital data communications, Tailored Arrivals, in their current implementation, rely on tactical control actions to manage conflicts and capacity constraints; such actions can impede an otherwise continuous and efficient descent. Other technologies, such as those developed under NASA's Airspace Technology Demonstration 1 activity, have expanded on the OPD concept by coupling ground-based and airborne spacing capabilities with scheduling automation to manage traffic constraints [4]. While effective, such techniques are limited primarily to speed control, depend on corrective actions by controllers and pilots, and do not result in closed-form trajectory solutions that can be shared between airborne and ground automation. Other efforts have addressed traffic constraints by adding path dynamics to the final descent stages by selecting from route options defined by an array of pre-defined points in terminal airspace [5]. NASA's Efficient Descent Advisor (EDA) [6] generates closed-form trajectory solutions in enroute airspace that condition flights for continuous descent in the presence of scheduling constraints and traffic conflicts. EDA, however, resolves conflicts only at the time of initial advisory generation. Moreover, EDA relies on voice-based clearances, which require multiple transmissions to convey full trajectory solutions to the flight deck and are subject to communication errors.

To address the limitations described above, NASA has developed prototype automation known as the Tailored Arrival Manager (TAM). TAM computes energy-efficient trajectory solutions tailored to any traffic condition. Unlike static OPDs, TAM solutions are not limited to fixed airspace structures and are tailored to individual aircraft performance. Resulting solutions are conflict-free and designed to maximize throughput in the presence of capacity constraints. Furthermore, TAM solutions are based on closed-form trajectories that can be shared among stakeholders and their supporting automation systems. Once computed by ground automation, a TAM solution involving speed and route intent is uplinked using digital data communications and integrated with the aircraft's Flight Management System (FMS). As such, TAM solutions potentially minimize environmental impact while addressing traffic and weather constraints with manageable controller and pilot workload.

The purpose of this paper is to describe an initial flight demonstration intended to accelerate the development of TAM and show that digital data exchanges could be accomplished in a real-world environment. The concept behind TAM is first described, both as an end-state capability and as a simplified capability specific to the fight demonstration. The systems and procedures behind the demonstration are then described. Findings are then presented that include a case study of solution uplink and pilot-response times along with an assessment of trajectory prediction accuracy between ground-based and airborne automation systems.

II. Concept Overview

A. End-State

In its end-state concept vision, TAM computes trajectory solutions that enable continuous, energy-efficient descents while simultaneously ensuring safe separation and optimized arrival throughput. This computation relies on NASA's AutoResolver technology [7–9] to predict trajectories, detect conflicts involving traffic and weather, and resolve any conflicts with trajectory solutions that meet all scheduling constraints and crossing conditions. As such, AutoResolver – a full description of which is beyond the scope of this paper – is the core prediction and decision-making component of TAM. Resulting trajectory solutions are parameterized into speed, altitude, and route intent components that can be sent as a single digital data transmission to the flight deck. Such solutions are designed for automated integration with avionics to allow precision guidance and control along the intended trajectory with little or no pilot input required. Digital solution delivery with air-ground system integration is designed to minimize controller and pilot workload, reduce communication errors, and allow for a greater variety and complexity of trajectory modifications with a single data transmission.

Figure 1 illustrates a vision of TAM as a decision-support capability for air traffic controllers in an FAA ARTCC. Here, TAM is shown as having been integrated with today's Time-Based Flow Management (TBFM) automation, which prescribes a Scheduled Time of Arrival (STA) for each arriving flight to cross a meter fix, located at the boundary of terminal airspace. TAM computes conflict-free trajectory solutions that meet these STAs while minimizing energy consumption and emissions. After a solution is delivered, TAM continues to monitor the progression of the flight for conflicts and schedule conformance and uplinks trajectory modifications if needed. Although TAM can rely on a STAR that is specified in a flight plan for nominal route intent, it does not strictly require such structure. With precision delivery of flights into terminal airspace in accordance with flow-management schedules, aircraft can potentially proceed with a continuous descent to the runway with fewer tactical interruptions than would otherwise be required. In the further term, using the same underlying technology, TAM could uplink comprehensive digital trajectory solutions from cruise flight to landing. In the still further term, TAM can support increasingly autonomous operations in which trajectory solutions are uplinked and flown with human actions required on a *control-by-exception* basis only to manage unusual circumstances.

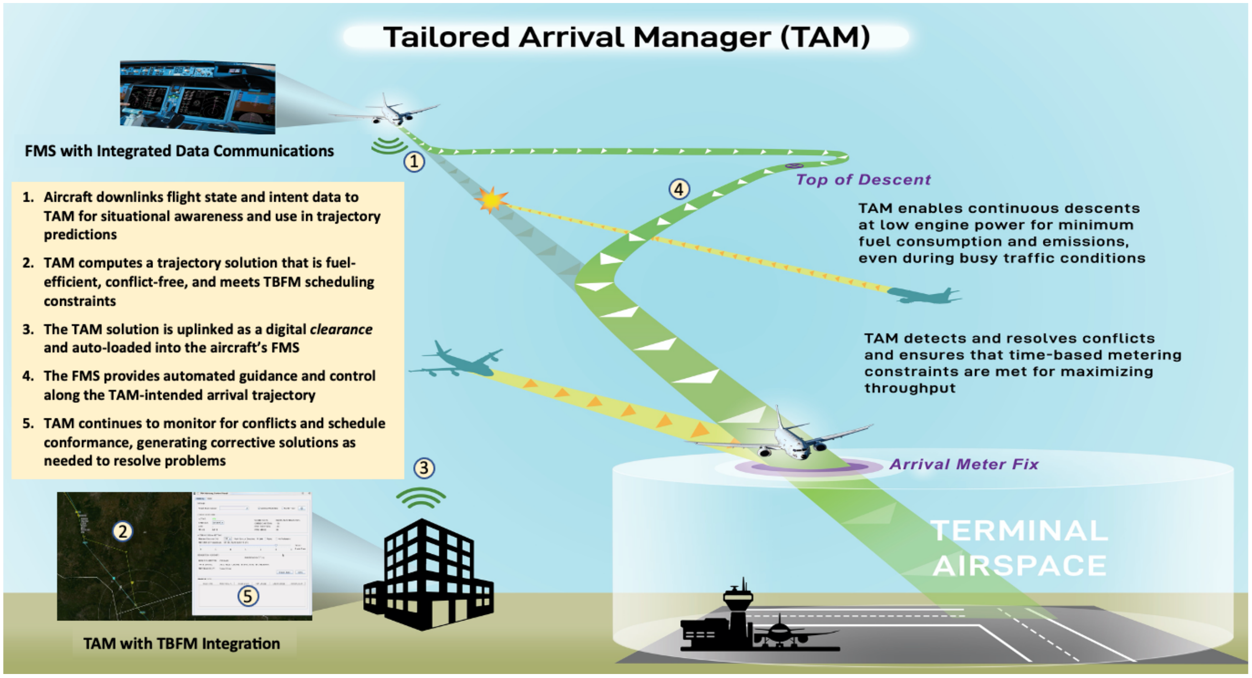


Fig. 1 TAM end-state concept vision

B. Flight Demonstration

The TAM flight demonstration was conducted as an element of Boeing's ecoDemonstrator (ecoD) flight program, which in 2020 involved a B787-10 aircraft equipped with Future Air Navigation System (FANS) 1/A avionics. Only a subset of the envisioned end-state TAM concept elements was selected for demonstration; most notably, conflict resolution and corrective advisory functions were suppressed. This was done to ensure that the primary objective of delivering solutions to the aircraft could be accomplished with minimal technical risk given limited flight opportunities. TAM capabilities focused on solutions that absorbed a specified amount of delay to a demonstration meter fix, emulating an arrival operation with TBFM scheduling providing STA targets.

Using AutoResolver and a supporting kinetic trajectory-prediction model for a B787, TAM computed solutions involving speed and path modification for delay absorption. Delay magnitude was set by the TAM system operator as an input to the advisory computation process; this delay setting acted as a surrogate for a STA computed by TBFM in the end-state operational concept previously described. While AutoResolver is fundamentally designed to predict and resolve traffic conflicts, those functions were suppressed for the flight demonstration in order to minimize technical risk and uncertainty. Furthermore, cruise speed adjustments – recognized as a necessary solution element for fuel efficient delay absorption in the end-state concept – were not included in the demonstration in order to simplify TAM computations and pilot procedures. As such, TAM solutions focused on path stretching for delay absorption together with a reduction in the airplane's intended descent speed. Path-stretch solutions that achieved a specified amount of delay were sent to the aircraft in cruise flight, a minimum of 10 minutes prior to Top-of-Descent (TOD) along the nominal flight route. Importantly, once received by the flight crew and loaded into the FMS, TAM solutions were not flown by the FMS for this initial demonstration; this was done to simplify test procedures that would have otherwise involved substantial coordination with FAA control facilities.

III. System Description and Test Procedures

An overview of the system used for the flight demonstration is shown in Fig. 2. The system architecture relied on NASA's TestBed ecosystem for traffic display and the management of data exchanges between TAM and external FAA and Boeing systems [10]. TestBed provided the software integration and network connectivity needed for the flight demonstration itself as well as the preparatory simulation exercises. TestBed provided an interface to the FAA laboratories used for the demonstration, which were located at the FAA William J. Hughes Technical Center.

The system is best described by following the procedural steps of the flight demonstration, described here and enumerated in Fig. 2. The sequence began with the acquisition of periodic data downlinked from the airplane over Automatic Dependent Surveillance (ADS). Both ADS-B and ADS-C data were received. ADS-B data were *broadcast* from the aircraft every second and processed by the FAA Target Generation Facility (TGF) into elements needed for TAM, specifically inertially-referenced position, altitude and velocity components (step 1 in Fig. 2). ADS-C data (step 2) were downlinked from the aircraft in accordance with a software *contract* specified by a ground station operated by Boeing, which called for downlink at the maximum available rate of every 64 seconds. ADS-C included the same inertially referenced data contained in ADS-B along with Mach number, wind velocity, and outside air temperature. ADS-C also included FMS intent data used by Boeing to derive TOD location and meter-fix Estimated Time of Arrival (ETA). As shown in Fig. 2, ADS-B and ADS-C data were pre-processed by the FAA TGF and the Boeing ground station, respectively, and connected to TAM through TestBed. TestBed also provided connectivity for receiving flight plans and atmospheric forecasts needed for TAM trajectory predictions (step 3).

Trajectory solutions were triggered by the TAM operator setting a required delay value for the aircraft to absorb prior to reaching the meter fix; this was a surrogate means of setting delay, for in the end-state concept required delay would be established by a TBFM scheduler aiming to balance traffic demand with airspace and airport capacity for maximum throughput. For additional control over solutions, the operator could select a preference for left-side or right-side path solutions, or select no preference and let the automation decide. This preference was invoked whenever the delay setting was high enough to require extension of the nominal route.

The TAM user interface developed for demonstration purposes is shown in Fig. 3, which included a control panel and geographic display. The control panel included the display of aircraft data, a slider-bar feature for setting meter fix delay, control over preferred path stretch direction, and display of the resulting TAM solution for absorbing the specified delay. For the demonstration, TAM solution components were limited to advised descent-speed and path modification; the latter was shown geographically on the plan-view traffic display, as depicted by the yellow path in Fig. 3. Also displayed on the traffic display was the TOD location corresponding to nominal (un-delayed) trajectory computed by TAM, the solution trajectory, and the nominal trajectory computed by the FMS.

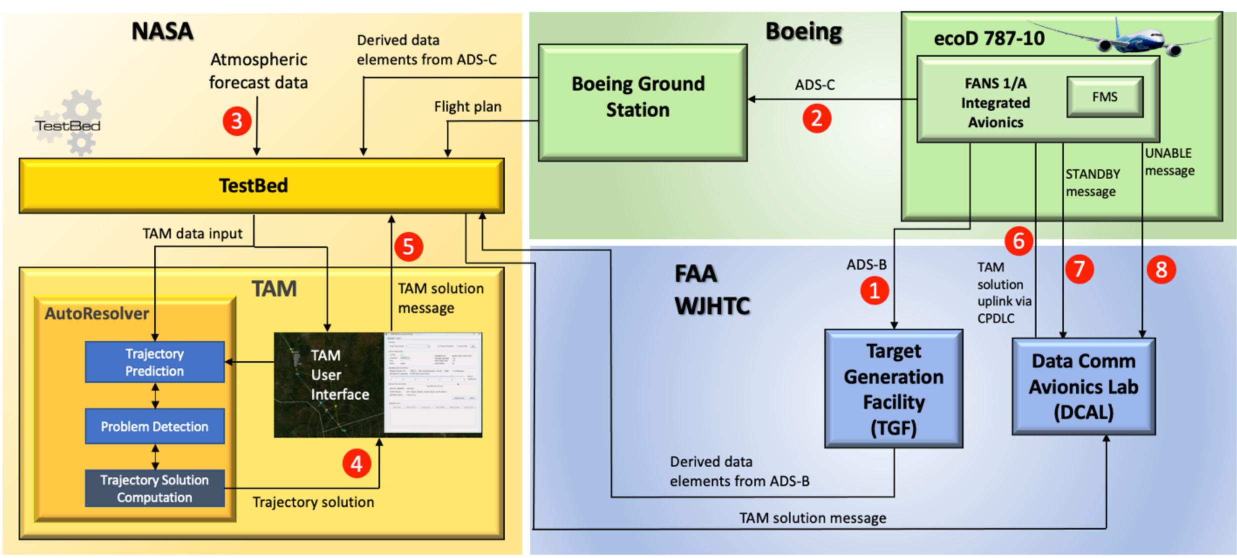


Fig. 2 System architecture.

Once a solution was generated and displayed (step 4), the TAM operator, when ready, sent it to the Data Comm Avionics Lab (DCAL) via TestBed (step 5). This electronic delivery was accomplished by pressing the *SEND* button shown in Fig. 3. Once received by the DCAL, the path component of the solution was automatically translated into a FANS-1/A-compatible Controller Pilot Datalink Communication (CPDLC) message and uplinked to the aircraft over VHF-mode-2 Data Link (VDL-2); specifically, the CPDLC Uplink Message 79 (UM 79) was used for this purpose (step 6). The descent-speed component of the solution was not uplinked for this initial demonstration in order to minimize pilot workload given the absence of an FMS auto-loadable CPDLC message type for conveying descent speed intent in today's operations.

Once the message was received on the flight deck, the crew acknowledged receipt by downlinking a CPDLC *STANDBY* message, enabled by a simple button press on the FANS-1/A avionics (step 7). The crew then loaded the FMS with the advised route solution and made observations that included recording the effect of the advised solution on the FMS-predicted TOD location and meter-fix arrival time. Although the advised path modification was displayed on the aircraft's navigational display as a provisional route, it was not activated as the primary route for flight guidance and control for the reason previously described. Once all message handling was completed, the crew downlinked a CPDLC *UNABLE* message (step 8); this message was used to confirm that TAM solutions would not be flown for this initial demonstration. Because no flight path changes resulted from the TAM solutions, the test procedures described here were easily repeated for a series of uplinked solutions.

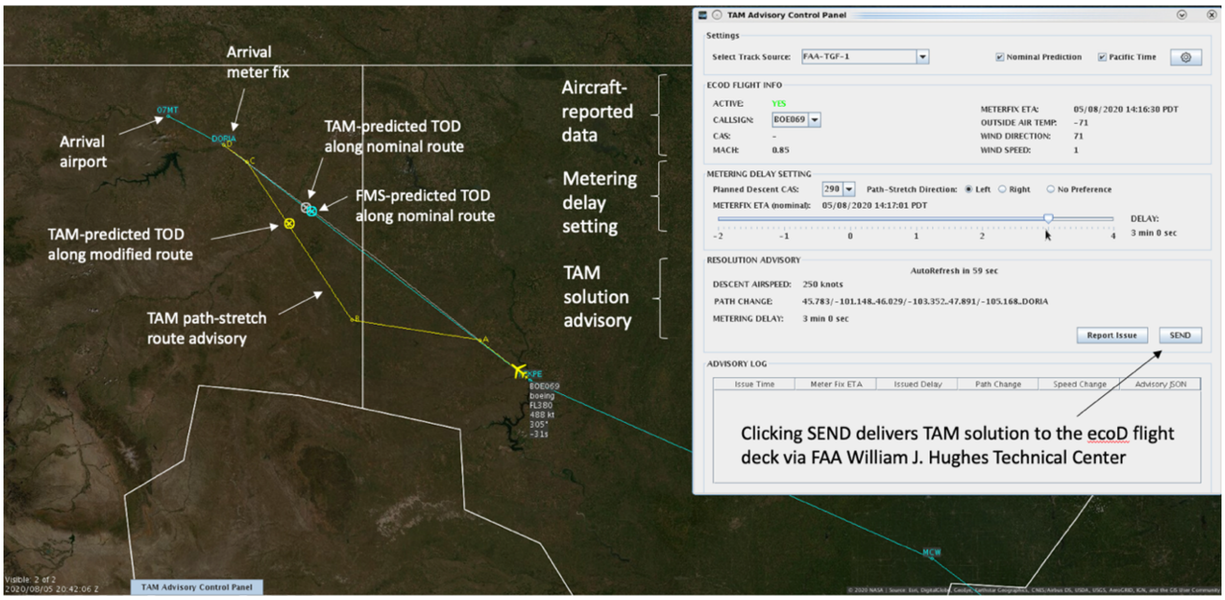


Fig. 3 TAM graphical user interface.

IV. Test Conditions

TAM operations occurred during a portion of two separate ecoD flights: Flight 1 on August 14, 2020, and Flight 2 on September 9, 2020. Flight 1 was a westbound departure from Charleston, SC (KCHS) to Boeing Field, WA (KBFI). The portion of the flight involving TAM was a 600 nautical miles (nmi) segment stretching from Mason City, IA (MCW) to Glasgow Industrial Airport (07MT), located in northeastern Montana. The cruise speed and altitude were 0.85 Mach and 38,000 ft, respectively. DORIA served as a demonstration arrival meter fix for a descent towards 07MT. DORIA had firm crossing restrictions of 250 kt Calibrated Airspeed (CAS) and 14,000 ft. The airplane did not land at 07MT but instead climbed after crossing DORIA and continued to Boeing Field, near Seattle.

Flight 2 was an eastbound departure from KBFI to KCHS. Flight 2 afforded two descent opportunities – one a descent towards the Mc Ghee Tyson airport in Knoxville, TN (KTYS) via the meter fix WINNA, and a second for the final descent to KCHS via the meter fix TRTLS. Planned cruise speed and altitude ahead of first descent was 0.85 Mach and 35,000 ft, respectively. WINNA had firm crossing restrictions of 250 kt CAS and 13,000 ft. The airplane did not land at KTYS but instead climbed after crossing WINNA to continue to KCHS. Planned cruise speed and altitude ahead of the final descent to KCHS were 320 kt CAS and 23,000 ft, respectively.

The test matrix for the two flights is shown in Table 1. The independent variables controlled by the TAM operator through the user interface were required delay, the preferred turn direction (left, right, or no preference), and the planned descent CAS. For repeatability, required delay was set to 3 minutes for all but the last solution, where it was increased to 4 minutes. The planned descent CAS was a value agreed upon between NASA and Boeing for affecting descent predictions within both TAM and the FMS. This planned descent CAS was used by pilots to configure the FMS for an automated descent along the nominal route using Vertical Navigation (VNAV) in *Path* mode. In this mode, automatic throttle and elevator inputs control to maintain a vertical path computed by the FMS based on an idle-thrust descent objective and planned descent speed profile.

Table 1 Test matrix.

Descent Segments	Planned Cruise Speed and Altitude	Meter Fix	Planned Descent CAS (kt)	Path Stretch Direction	Path Stretch Delay (min)
FLT 1 AUG 14	0.85 Mach, 38,000 ft	DORIA	290	LEFT	3
				RIGHT	3
				RIGHT	3
FLT 2-1 SEP 10	0.85 Mach, 35,000 ft	WINNA	290	LEFT	3
				RIGHT	3
FLT 2-2 SEP 10	320 kt CAS, 23,000 ft	TRTLS	290	LEFT	3
				RIGHT	3
				RIGHT	4

V. Findings

A. Flight-Deck Observations

In accordance with the test matrix, eight TAM solution messages across the two demonstration flights were delivered to the airplane and auto-loaded by pilots into the FMS through the B787 FANS 1/A interface. TAM solutions were delivered in cruise flight from approximately 200 to 100 nmi to TOD. Pilots received the expected load prompts for each TAM solution, and each solution loaded correctly into the FMS as a provisional modification to the current flight route. The crew noted that each TAM solution was received in a timely manner, meaning there was adequate time to review each solution and load it into the FMS prior to the aircraft sequencing the initial turnout point in the TAM path-stretch solution. The crew further noted that each solution was *flyable* from a guidance and control standpoint and could have been executed had procedures allowed for it. In accordance with the test plan, each solution was deleted from the FMS once observations by the crew were completed. A photo of the avionics displays after pilots loaded the FMS with a TAM solution during Flight 1 is shown in Fig. 4.

Fig. 4 TAM solution on the ecoD B787 fight deck.

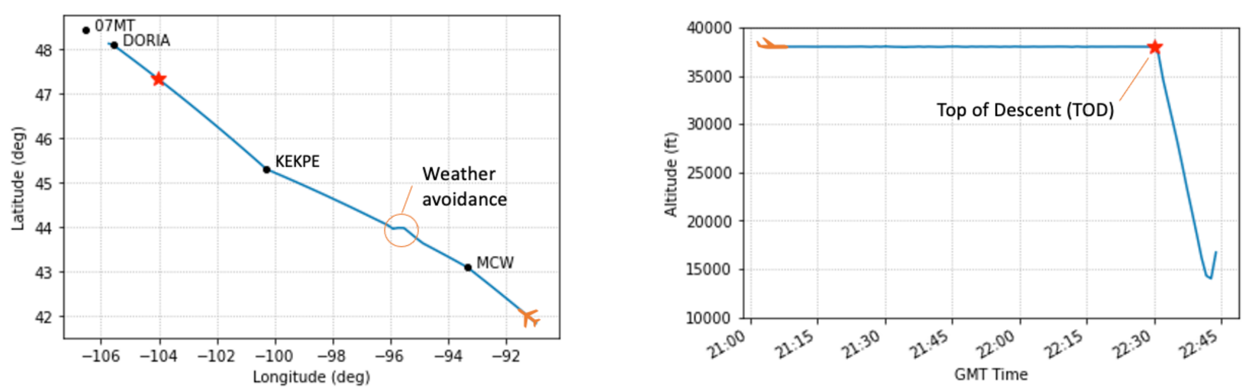
Each of the three descents were flown along the nominal flight route using FMS lateral and vertical navigation. For each descent, the FMS remained in VNAV as expected. As hoped, each descent was flown uninterrupted by air traffic control actions, i.e., all descents were continuous with no level-offs, speed changes, or vectoring for traffic. Descents were flown with minimal pilot input, except for intermittent use of speed brakes. Speed brakes were applied by pilots for two primary reasons: 1) to respond to FMS advisories to add drag in order to maintain the VNAV path and keep the actual descent CAS from exceeding 10 knots above the planned value shown in Table 1; or 2) to keep the aircraft within 10 knots of the planned descent CAS based on pilot judgement.

For the descent to 07MT in Flight 1, pilots observed that the airplane pitched somewhat aggressively at TOD in accelerating directly to the planned descent CAS of 290 kt from a cruise CAS of 270 kt; this was attributed to the lack of an initial descent Mach number specified in the FMS. With a specified initial descent Mach, the FMS would have held that Mach in order to accomplish a smoother acceleration to the planned descent CAS. Based on this observation, an explicit Mach/CAS planned descent speed profile was entered into the FMS for Flight 2, with descent Mach equal to cruise Mach. This resulted in smooth initial descents in Flight 2 with no speed-brake inputs required near TOD.

Throttles mostly remained at idle during each descent across both flights. Only occasionally did the auto-throttle system briefly increase the engine thrust from idle, usually as a transient reaction to speed-brake inputs.

B. Flight Execution

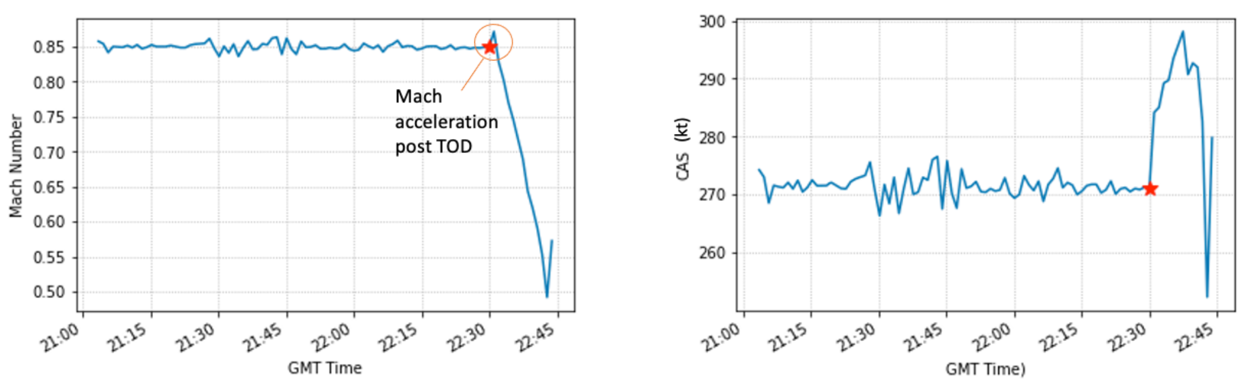
Figure 5 shows the horizontal track and altitude time history for the TAM portion of Flight 1, involving a descent towards 07MT. Prior to the descent to the meter fix DORIA, the airplane maintained the expected cruise pressure altitude of 38,000 ft. As seen in the horizontal track, there was a slight deviation for convective weather avoidance between MCW and KEKPE. After completing the deviation, pilots requested that the airplane return to the original flight plan as soon as possible rather than accept a direct to KEKPE offered by controllers. This was done to stay as close as possible to the conditions evaluated in simulation, even though TAM could have operated with deviations to the original route if needed, with or without an amended flight plan.



a) Horizontal Track – Flight 1

b) Altitude vs Time – Flight 1

Fig. 5 Track and Altitude – Flight 1.

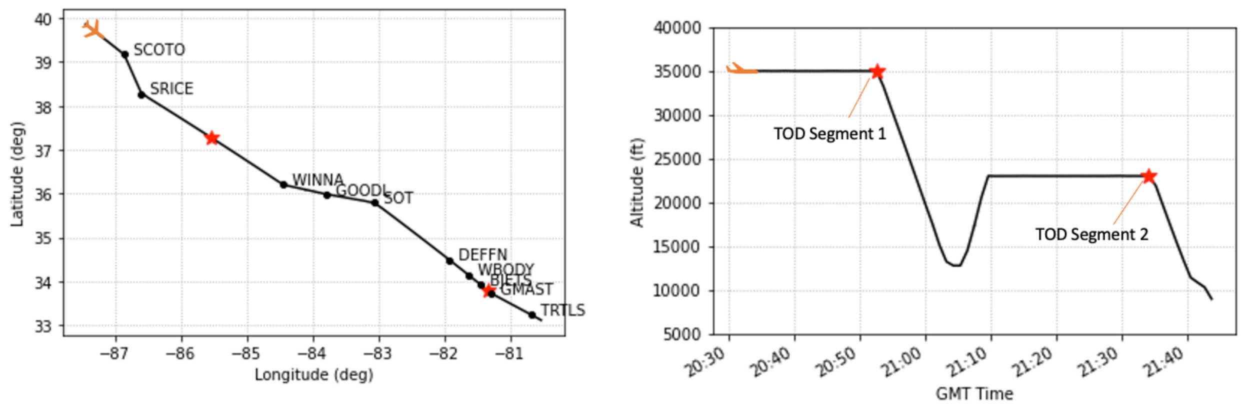


a) Mach vs Time – Flight 1

b) CAS vs Time – Flight 1

Fig. 6 Airspeed – Flight 1.

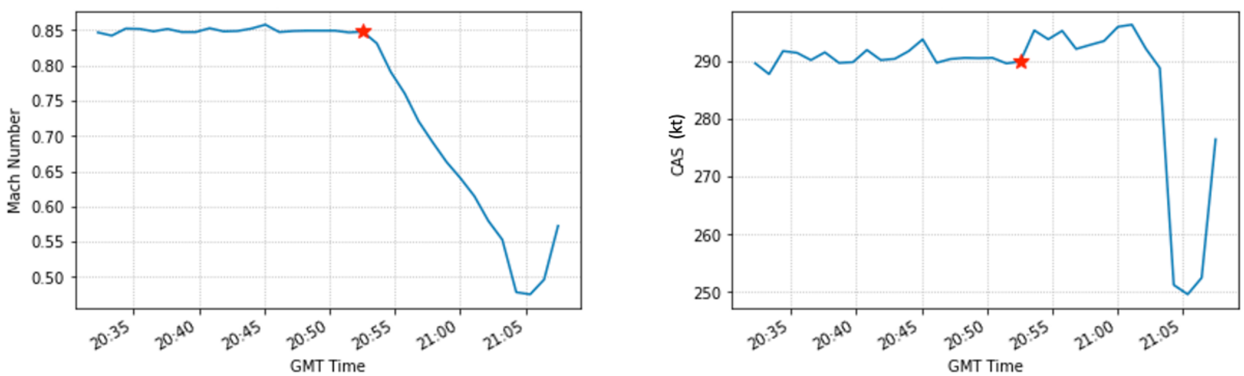
The airspeed time history for Flight 1 is shown in Fig. 6. CAS was calculated post flight from aircraft-reported Mach number and pressure altitude, an exact calculation that requires no Standard Atmosphere assumption. The airplane maintained a cruise airspeed prior to TOD close to 0.85 Mach. This equated to approximately 270 kt at the cruise altitude of 35,000 ft. A spike in the Mach number can be seen in Fig. 6 just past TOD, which was attributed to the lack of a specified descent Mach for managing the CAS transition in Flight 1. As previously described, this was rectified for Flight 2 by configuring the FMS to explicitly hold cruise Mach in the initial descent until capturing the planned descent CAS – an important procedural lesson. In VNAV Path mode, the FMS controlled to the planned descent speed of 290 kt CAS within a tolerance of ± 10 kt CAS. VNAV Speed mode was considered as a means of controlling to a planned descent speed with more precision but was found in simulation to be procedurally difficult to configure on the flight deck.



a) Horizontal Track – Flight 2

b) Altitude vs Time – Flight 2

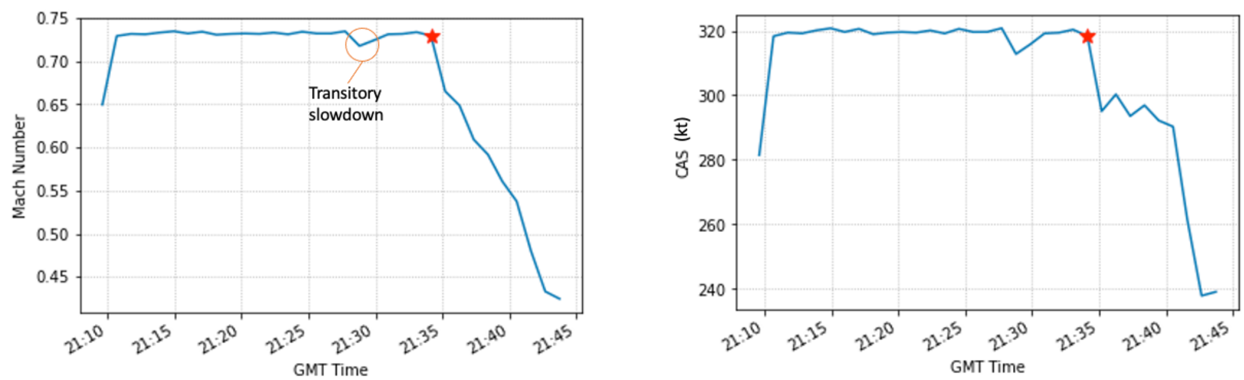
Fig. 7 Track and Altitude – Flight 2.



a) Mach vs Time – Flight 2, Segment 1

b) CAS vs Time – Flight 2, Segment 1

Fig. 8 Airspeed – Flight 2, Segment 1.



a) Mach vs Time – Flight 2, Segment 2

b) CAS vs Time – Flight 2, Segment 2

Fig. 9 Airspeed – Flight 2. Segment 2.

Plots of the track, altitude and airspeed profile are shown in Fig. 7 through 9 for the two descent segments of Flight 2. For the first segment, as can be seen in Fig. 7b and 8a, the airplane maintained the planned cruise altitude and Mach number of 35,000 ft and 0.85, respectively, prior to the descent towards KTYS via the meter fix WINNA. For the KTYS descent, the FMS maintained a CAS of 290 ± 10 kt in both cruise and descent prior to slowing to meter-fix crossing speed (Fig. 8b); this was because the CAS corresponding to the planned cruise speed of 0.85 Mach at 35,000 ft happened to be close to the planned descent speed of 290 kt CAS, i.e., the aircraft was already near the Mach/CAS transition altitude at TOD.

Once crossing WINNA, the airplane climbed to 23,000 ft ahead of the descent to KCHS via the meter fix TRTLS in segment 2. For the descent to KCHS (segment 2), the aircraft decelerated just prior to TOD from the planned cruise speed of 320 kt CAS to the planned descent speed pf 290 kt CAS. Holding Mach to keep the aircraft within its operational speed envelope was not required for the descent to KCHS, since the airplane was effectively already well below the Mach/CAS transition altitude at cruise.

Table 2 shows that the airplane closely complied with the meter-fix crossing constraints for each of the three VNAV descent segments across the two flights. The 10 kt excess speed seen in Table 2 when crossing TRTLS was due to pilots reportedly flying a slightly higher speed to better manage turbulence encountered in the vicinity of the meter fix. As planned, none of the uplinked TAM solutions themselves affected the actual flight path of the aircraft.

Table 2 Meter-fix crossing constraint compliance.

Meter Fix Name	Crossing Constraints – Altitude (ft)/ CAS (kt)	Actual Crossing – Altitude (ft)/ CAS (kt)
DORIA (Flight 1)	14000/ 250	14000/ 254
WINNA (Flight 2, Segment 1)	13000/ 250	13000/ 252
TRTLS (Flight 2, Segment 2)	11000/ 250	11000/ 260

C. Data Comm Messaging using CPDLC

A primary objective of the flight demonstration was to show that digital TAM solutions could be generated and delivered automatically to an airplane in flight using existing data communications infrastructure. Across the two flights, eight TAM solutions were successfully uplinked to the aircraft. Based on time stamps obtained from TAM and CPDLC service provider logs, message delivery latency and pilot response times were deduced.

The time between sending solutions from the TAM user interface and pilots acknowledging the receipt of those solutions on the flight deck is shown by the blue portion of the bar chart in Fig. 10. This time difference – an average of 19.8 seconds over the two flights – consisted mostly of pilot response time. This was due to pilots reviewing test procedures rather than simply pressing *STANDBY* immediately to acknowledge receipt of TAM solution messages. The *STANDBY* button can be seen highlighted in Fig. 4. As can be seen in Fig. 10, pilot acknowledgment time decreased as procedures became more familiar over the course of each flight. Each flight involved different crew members and/or responsibilities, so familiarity with procedures was not directly carried over from Flight 1 to Flight 2.

The time required for the crew to auto-load each TAM solution into the FMS and complete all observations is indicated by the orange bar components in Fig. 10. This duration – an average of 72.8 seconds – was based on the difference between *STANDBY* and *UNABLE* message time stamps. *UNABLE* downlinks were triggered by pilots pressing the *REJECT* button seen in Fig. 4; this indicated that all flight deck actions pertaining to the TAM solution were complete and the solution had subsequently been deleted from the FMS as planned. As can be seen in Fig. 10, the time required for the crew to process each solution also trended lower over the course of each flight due to the familiarity effect mentioned above. It should be noted that the response times shown in Fig.10 were affected by the procedural constraints of the demonstration and are therefore not representative of what to expect in routine operations with TAM.

To gain insight into the potential application of CPDLC messaging over VDL-2 to more autonomous trajectory-based concepts in the future involving AutoResolver or similar technology, the uplink time of TAM messages was measured. This was possible based on message assurance timestamps acquired by Boeing. These machine-to-machine uplink times were limited in precision to integer seconds. As shown in Table 3, the time required for uplink was two seconds or less for 7 out of 8 solutions. It should be noted, however, that VDL-2 performance may be slower in routine operations than experienced during the demonstration; communications can be slower in busy traffic situations involving many data transmissions and when additional quality assurance checks are applied to uplinks involving operational air traffic control facilities. A detailed description of VDL-2 characteristics and network capacity can be found in Ref. [11].

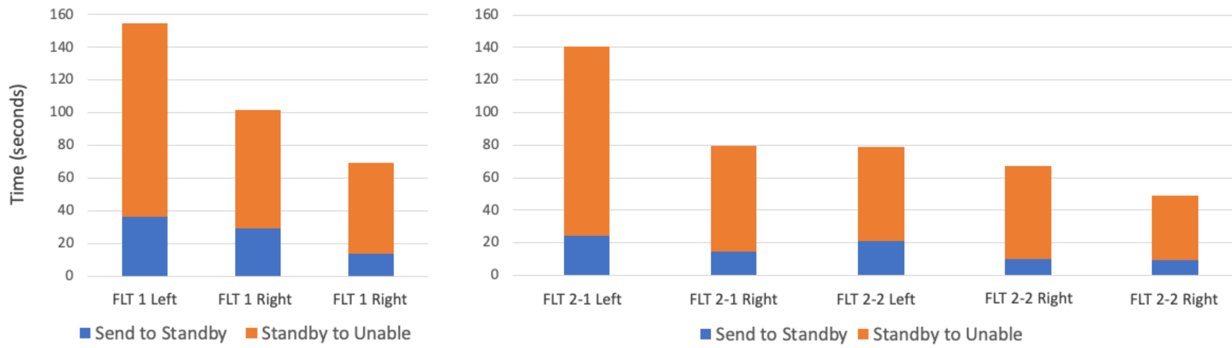


Fig. 10 Pilot response to TAM solution messages.

Table 3 Time required for uplink of TAM solution messages.

Descent Segments	Meter Fix	Path Stretch Direction	Time required for solution uplink, t_{UP} (sec)
FLT 1 AUG 14	DORIA	LEFT	$1 < t_{UP} < 2$
		RIGHT	$3 < t_{UP} < 4$
		RIGHT	$1 < t_{UP} < 2$
FLT 2-1 SEP 10	WINNA	LEFT	$1 < t_{UP} < 2$
		RIGHT	$1 < t_{UP} < 2$
FLT 2-2 SEP 10	TRTLS	LEFT	$1 < t_{UP} < 2$
		RIGHT	$0 < t_{UP} < 1$
		RIGHT	$0 < t_{UP} < 1$

D. Trajectory Prediction

Accurate predictions are essential to trajectory-based automation systems such as TAM. Trajectory computations are foundational to both detecting and resolving traffic problems. While not providing a statistically meaningful sample of operations, the flight demonstration allowed for a case study of TAM and FMS trajectory prediction accuracy under controlled conditions in a real-world environment. Since TAM solutions were not executed on the flight deck, trajectory analysis was based on nominal (un-delayed) flight path predictions. Trajectory prediction accuracy was determined by comparing TAM and FMS predictions against actual flight tracks. Post-flight trajectory analysis focused on predicted meter fix ETA and TOD, both of which were calculated by the FMS and included in the data downlinked from the aircraft over ADS-C every 64 seconds. For analysis, TAM predictions were generated every 5 seconds based on ADS-C updates of aircraft state. In the real-time system, TAM predictions could be driven by either ADS-C or ADS-B data input, depending on the track source selected from the control panel in Fig. 3.

1. Meter-fix ETA

Accurate arrival time predictions are highly relevant to TAM's time-based metering capabilities. Meter-fix ETA error was computed as a function of look-ahead time by subtracting the aircraft's actual arrival time at the meter fix from ETA. Figure 11 shows the FMS and TAM ETA error seen in Flight 1. Here it can be seen that ETA prediction error for TAM was well within ± 30 seconds, within 30 minutes upstream of the meter fix. Studies [12] have shown that such predictive accuracy is sufficient to minimize direct operating costs associated with time and fuel consumption in terminal airspace. Once ETA prediction error is within ± 30 seconds, aircraft can be issued a single trajectory solution to the meter fix and likely proceed with a continuous descent to the runway with minimal controller intervention.

Figure 12 shows the ETA error seen in Flight 2 for descent segments 1 and 2, respectively. For both segments, FMS and TAM ETA prediction error was within ± 30 seconds for look-ahead times of 30 minutes or less, except for a spike in positive error seen ~12 minutes from the meter fix in segment 2. This spike can be attributed to a transitory slowing in cruise speed seen in Fig. 9. The cause of this slowdown – quickly corrected by the pilots – was due to an altitude constraint in the STAR along the nominal route that inadvertently affected the FMS-intended speed profile; this was because of the unusually low cruise altitude flown in segment 2.

Overall, there was similar absolute ETA prediction accuracy between the FMS and TAM. This suggests that even without blending FMS and TAM predictions for further accuracy improvements, TAM predictions alone may suffice for achieving operational objectives. The exact cause of differences between TAM and FMS predictions is a subject for further analysis, but differences in aircraft performance models and forecast winds are likely factors.

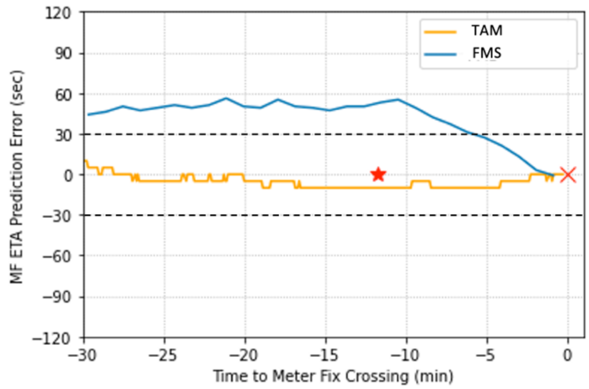
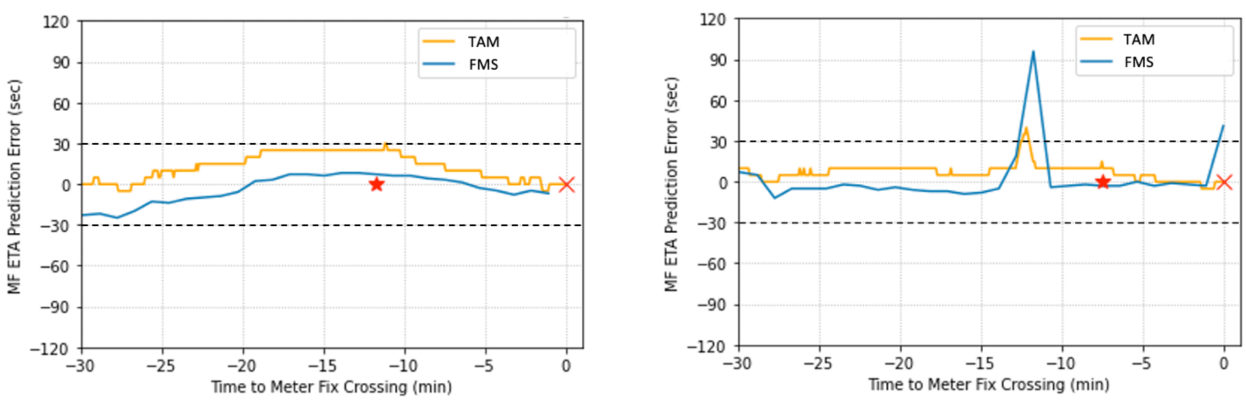


Fig. 11 Meter fix ETA prediction error – Flight 1.



a) Flight 2, segment 1 b) Flight 2, segment 2

Fig. 12 Meter fix ETA prediction error – Flight 2.

2. Top of Descent (TOD)

TOD spatial prediction error was computed as a function of look-ahead time by calculating the distance between predicted and actual TOD locations. Errors in TOD prediction are mostly relevant to conflict detection and resolution. For arrival metering operations with minimal need for corrective conflict resolutions by air traffic controllers, TOD spatial prediction accuracy of ± 5 nmi within 20 minutes of actual TOD is a general objective [13].

Figure 13 shows the FMS and TAM TOD prediction error seen in Flight 1, starting 20 minutes prior to actual TOD. Here, TOD location error was well within ± 5 nmi for both FMS and TAM, with positive values indicating a TOD predicted location that was downstream of the actual TOD. TOD prediction accuracy for both segments of Flight 2 is shown in Fig. 14; excluding the effect of the transitory slowdown previously noted in segment 2, both FMS and TAM predicted TOD location errors were within ± 5 nmi once the aircraft was within 20 minutes of actual TOD.

As explained in Ref. [14], FMS-predicted TOD was defined as the geometric intersection between cruise and descent segments in the FMS trajectory, whereas the actual TOD for error computation herein was defined as a 200 ft departure from cruise altitude based on aircraft position reports. This difference in TOD definition likely explains why FMS TOD error did not converge to zero as might otherwise be expected.

TOD predictions for idle-thrust descents depend on factors such as descent-speed intent, wind forecasts, aircraft weight, aerodynamic performance models, deceleration procedures, and residual thrust assumptions. Detailed examination of the exact cause of TAM and FMS TOD prediction differences – both spatial and temporal – is a subject for further study.

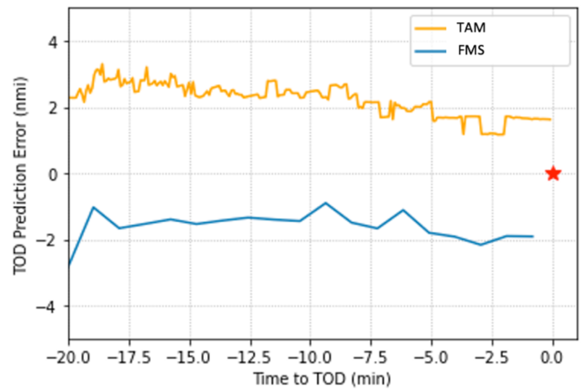


Fig. 13 TOD prediction error – Flight 1.

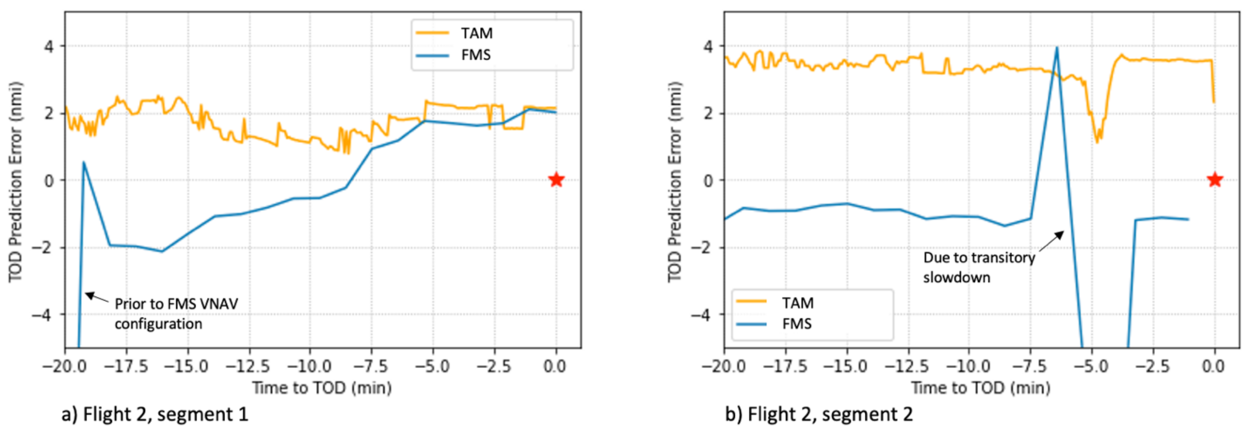


Fig. 14 TOD prediction error – Flight 2.

VI. Conclusion

An initial evaluation of TAM was successfully completed through the ecoDemonstrator flight program. It was shown that trajectory-based arrival solutions could be computed in real-time, delivered within seconds to the airplane using data communications, and integrated with FMS automation for potentially guiding and controlling the airplane along the intended arrival trajectory. Crew observations and real-time data exchange provided key insights for maturing the TAM concept, automation, and air-ground procedures towards increasingly autonomous arrival operations. Continuous descents along nominal arrival routes were flown with minimal pilot input using guidance and control functions that are widely available on commercial aircraft today. The uninterrupted descents together with real-time data exchange allowed for a case study of trajectory prediction accuracy. Results showed that ground-based arrival time predictions to meter fixes were within ± 30 seconds over look-ahead times of up to 30 minutes. TOD prediction accuracy was found within ± 3 nautical miles over similar look-ahead times. The predictive accuracy observed through this case study is promising and provides motivation for continued research and development of TAM. Future research will investigate the NAS-wide environmental benefits and fuel savings of TAM-related technology in the arrival domain and beyond.

Acknowledgments

The authors would like to acknowledge the substantial technical support and expertise provided by Boeing and the FAA William J. Hughes Technical Center. The authors also thank individuals on the NASA TAM and TestBed team that provided data acquisition, data analysis, and software engineering support for this research, specifically Todd Lauderdale, Scott Sahlman, Jim Phillips, Cody Evans, Christian Plaunt, Mohamad Refai, Saugata Guha, Lucy Tang, Franklin Gu, Joe D'Amore, Swapnil Gaikwad, Kee Palopo, Alan Lee, Chok Fung Lai, and Huu Huynh.

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