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Analysis of the Use of Estimated Time of Arrival Broadcast for Interval Management

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Abstract—**Interval Management (IM) is a NextGen application that requires accurate Estimated Times of Arrival (ETAs) in order to achieve a desired inter-aircraft spacing at a downstream point. Current standards require that the IM avionics calculate an ETA for the Target aircraft against which the IM aircraft is managing its relative spacing interval. In the future, this requirement could be replaced by a requirement that the Target aircraft broadcast the ETA generated by its Flight Management System (FMS). This ETA is expected to be more accurate than the ETA calculated by the IM avionics, and should thus result in more precise inter-aircraft spacing. This paper presents a comparison of IM performance between the current standards environment and a future environment where the Target aircraft broadcasts its ETA. Intuitively, basic technical IM performance metrics would improve when using the Target aircraft's broadcast ETA, but simulation results did not show increased performance benefit over the current IM avionics standard. This is due both to the environment under study, and the IM closed-loop performance being robust to inaccuracies in the calculation of the Target aircraft's ETA.**

Keywords-Interval Management; time-based spacing; airborne spacing; NextGen avionics; ADS-B In applications.

I. INTRODUCTION

Interval Management (IM) is a NextGen concept that relies on Automatic Dependent Surveillance-Broadcast (ADS-B) to achieve more precise spacing between aircraft. In a given aircraft pair, the lead (Target) aircraft is equipped with ADS-B Out[1] and the trail (IM) aircraft is equipped with ADS-B In[2] and IM avionics. The IM avionics generate speed commands for the IM aircraft to achieve a desired spacing interval between the Target aircraft and the IM aircraft at a downstream point (e.g., the final approach fix), referred to as the Achieve-by Point. In order to generate speed commands, the IM avionics relies on estimated times of arrival (ETAs) for both the Target and the IM aircraft to predict the spacing at the Achieve-by Point and to adjust the flight time of the IM aircraft accordingly.

The FAA, EUROCONTROL, and their US/European industry partners have developed standards for IM avionics systems that do not require integration with other flight-deck systems, such as the Flight Management System (FMS) and autoflight and autothrottle systems. The flight-deck IM (FIM) Minimum Operational Performance Standards (MOPS) requires the IM avionics to generate a four-dimensional (4D) trajectory for the Target aircraft from which its ETA at the Achieve-by Point may be determined [1]. This method was chosen for determining ETA because reference [1] requires only rule-compliant ADS-B, which does not include a data field for ETA. Requiring that the Target aircraft broadcast its ETA in place of IM calculating a 4D trajectory and ETA would have resulted in additional requirements on the Target aircraft. The Target aircraft's trajectory is based on its Intended Flight Path Information (IFPI), which is communicated from the air traffic controller (ATC) when issuing the IM clearance to the flight crew. The Target aircraft's IFPI can be communicated as a published Area Navigation (RNAV) procedure; waypoints with altitude and airspeed constraints are loaded into the IM avionics via a database and are used as inputs to the trajectory generation function, much as in a modern FMS. In the IM Sample Algorithm, which serves as an example speed guidance algorithm in the FIM MOPS, the trajectory generator combines kinematic models[3] with the RNAV procedure constraints to generate a horizontal path and vertical, airspeed, and ground speed profiles from which an aircraft's 4D trajectory is fully defined. Both the Target's and IM aircraft's trajectories are generated using this kinematic approach.

A second version of the FIM MOPS is currently underway and includes requirements for integrating the IM avionics with other flight-deck systems. With this update to the standards, alternative IM environments are being considered, including an

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[1] ADS-B Out means that the aircraft is broadcasting state information (e.g., position and velocity) for use by air traffic control and other aircraft within broadcast range.

[2] ADS-B In means that the aircraft is equipped to receive ADS-B messages from other aircraft that are within broadcast range.

[3] The kinematic models described here use generic assumptions on flight-path angles and decelerations. This is contrasted with a kinetic model that requires models of the forces acting on the aircraft (e.g., lift and drag) to generate the trajectory.

advanced environment where the Target aircraft's ETA is broadcast via an updated ADS-B Out message and air/ground trajectory synchronization is available. In this case, the Target aircraft's ETA would be an input to the speed guidance algorithm, and the Target aircraft would be required to periodically broadcast its ETA at the Achieve-by Point as calculated by its FMS. The FMS-calculated ETA is expected to be more accurate than the IM avionics-calculated ETA used in the current IM environment because it uses the aircraft-specific performance parameters in a kinetic model and forecast winds along the Target aircraft's route to generate its 4D trajectory. In this advanced environment, the Target aircraft also has knowledge of the speed profile that the ATC ground automation system has determined to meet the objectives of the overall arrival flow through the use of air/ground trajectory synchronization. Therefore, the Target aircraft's speed profile, as planned by ATC, will be used by the FMS in its ETA calculation. In contrast, the IM avionics in the current environment calculates an ETA for the Target aircraft without knowledge of its aircraft-specific parameters or the planned speed profile, using only the published speed and altitude constraints on its RNAV procedure and kinematic assumptions. The constraints on the Target aircraft's RNAV procedure may include "at" constraints, where a precise altitude or speed must be met, "at or above (below)" constraints, where aircraft must be at or above (below) an altitude or speed, or "window" constraints, where an aircraft must be between two speeds or altitudes. For these reasons, it is expected that the ETA calculated by the Target aircraft's FMS will be more accurate than the ETA calculated by the IM avionics, leading to a performance benefit when using broadcast ETAs in the speed guidance algorithm.

The Required Navigation Performance standard for RNAV specifies the minimum requirement on ETA accuracy for FMSs: the error between the ETA and the actual time of flight to a downstream point must be less than 1% of the time of flight remaining to that point or 10 seconds, whichever is greater [2]. The FIM MOPS includes a similarly-worded requirement on the IM avionics, except the allowable error in the ETA is 5% of the remaining flight time to the prediction point or 2 seconds, whichever is greater [1,3]. Reference [4] presents an analysis of existing FMS models and their abilities to meet the ETA accuracy requirement; results show overall that most FMS models comply with the 1% accuracy requirement. Therefore, it can be expected that FMS-generated ETA would be more accurate than those generated by the IM avionics, and would lead to an IM performance improvement.

A previous study examined the performance improvement when using FMS-calculated ETAs in an IM speed guidance algorithm. Results in that study showed that the spacing performance improvement was negligible when using FMS-calculated ETAs over an IM avionics-calculated ETA for the Target aircraft [5]. This paper revisits the performance benefit of using the Target aircraft's FMS-calculated ETA in place of the IM-avionics calculated ETA, using an updated speed guidance algorithm that meets the performance requirements in the FIM MOPS, assuming that the IFPI is provided as constrained RNAV procedures, consistent with those currently being deployed in the NAS, and assuming the Target aircraft's FMS has knowledge of its planned speed profile.

The paper is organized as follows. Section II details the performance analysis, including descriptions of the analysis objectives and approach, simulation environment, IM control law, ETA broadcast modeling, and the scenarios that were studied. Simulation results are presented in Section III. Section IV provides a discussion of the results and next steps, and conclusions are presented in Section V.

II. ANALYSIS DESCRIPTION

To quantify the performance benefit of using ETA broadcast in the advanced IM environment, IM operations were simulated at Phoenix Sky Harbor International Airport (KPHX). In all scenarios, the operational objective is for the IM aircraft to achieve the desired spacing interval, called the Assigned Spacing Goal (ASG), at the Achieve-by Point, which is located at the Final Approach Fix (FAF) approximately 5 nautical miles (NM) from the runway. More details on the analysis objectives and approach are provided in Section II.A. Detailed descriptions of the simulation environment, IM control law, ETA calculation methodologies, and simulation scenario are given in Sections II.B through II.E below.

A. Analysis Objectives and Approach

The purpose of this simulation was to compare a set of technical IM performance metrics between two IM environments: 1) the current IM environment set forth in reference [6], and 2) an advanced environment that allows both Target aircraft ETA broadcast over ADS-B and air/ground trajectory synchronization. These two environments result in different methods for deriving the Target aircraft's ETA. In environment (1), the Target aircraft's ETA is calculated by the IM avionics using current standards, while in environment (2), the Target aircraft's ETA is broadcast over ADS-B. The ETAs used in case (2) should be more accurate than the ETAs generated in case (1), since there are a number of uncertainties affecting the Target aircraft's 4D trajectory and ETA about which the Target aircraft has more accurate information. The simulation experiment was focused on modeling those uncertainties to make clear the resulting difference in performance between the two IM environments.

One source of uncertainty for the IM aircraft when calculating a 4D trajectory and ETA for the Target aircraft is the aircraft-specific performance parameters of the Target aircraft. The only information about the Target aircraft that is shared with the IM avionics is the Target aircraft's IFPI. Because the IM aircraft has no means to discern the Target aircraft's performance parameters, the IM avionics uses kinematic equations of motion and the waypoint altitude and speed constraints to generate a 4D trajectory and ETA for the Target aircraft.

Winds specific to the Target aircraft's route are another source of uncertainty for the IM-avionics calculated ETA. This simulation studies IM operations where aircraft are on different routes that merge shortly before the Achieve-by Point at the FAF. Aircraft are interleaved between the two routes, so that each IM aircraft follows a Target aircraft that is on a different route until the merge point. Because the aircraft are on different routes, they experience different wind conditions. As required by reference [1], the IM avionics use the forecast winds specific to the IM aircraft's route when calculating ETAs for both the IM and Target aircraft. The IM avionics also update the ETAs using sensed winds along the IM aircraft's route over the course of the IM operation. In contrast, the Target aircraft blends forecast and sensed winds along its own route when calculating its ETA for broadcast. Details of the blending algorithm can be found in reference [1]. This reduces the uncertainty associated with different wind conditions on the different routes.

A final source of uncertainty is a result of the metering environment in which the IM operation is assumed to take place. In this environment, the ground automation system assigns a scheduled time of arrival (STA) to each aircraft at downstream points, called meter points. In some cases, an aircraft's STA may require an aircraft to arrive later than its ETA at a meter point, in order to ensure sufficient spacing between consecutive aircraft that are crossing that point. In these cases, aircraft must be delayed in order to accommodate their STAs. Delaying aircraft can be accomplished through vectoring or by slowing an aircraft's speed for a portion of its route. In the environment assumed here, aircraft will be delayed only through speed changes. In keeping with the environment envisioned for IM in reference [6], if the Target aircraft is delayed due to schedule constraints, this information is not communicated to the IM avionics or to the Target aircraft. In contrast, the advanced environment assumes air/ground trajectory synchronization, which would be used by the ground to communicate any planned delay to the Target aircraft. To reflect this difference in environment, the IM avionics do not take into account the Target aircraft's delay when calculating an ETA for the Target aircraft, while the Target aircraft does take delay into account when calculating its own ETA for broadcast.

B. *Simulation Details*

In this study, the uncertainties described above are modeled for both the current and advanced IM environments, and fast-time simulation is used to quantify their effects.

The framework is a time-based simulation which employs a fixed 1-Hz step size for advancing all models. The models contained in the simulation encompass the typical components used in aircraft simulation [7]. A standard atmosphere model for all pressure, temperature, and density calculations is used. Wind speed and direction are provided as inputs from the publically-available National Oceanic and Atmospheric Administration (NOAA) Rapid Refresh (RAP) data set [8]. The aircraft dynamics are modeled using kinetic three degree-of-freedom equations of motion [9]. The six first-order differential equations are derived for a point mass in an inertial x-y frame and within a spatially-varying wind field. The final equations, repeated here for convenience, are as follows:

$$\dot{x} = V\cos\gamma\cos\psi \tag{1}$$

$$\dot{y} = V\cos\gamma\sin\psi \tag{2}$$

$$\dot{h} = -V\sin\gamma \tag{3}$$

$$\dot{V} = \frac{T-D}{m} + g\sin\gamma + V\left(\frac{\partial V_{wx}}{\partial h}\cdot\cos\psi + \frac{\partial V_{wy}}{\partial h}\sin\psi\right)\sin\gamma\cos\gamma \tag{4}$$

$$\dot{\gamma} = \frac{-L\cos\phi + mg\cos\gamma}{mV} - \left(\frac{\partial V_{wx}}{\partial h}\cdot\cos\psi + \frac{\partial V_{wy}}{\partial h}\sin\psi\right)\sin^2\gamma \tag{5}$$

$$\dot{\psi} = -\frac{L\sin\phi}{mV\cos\gamma} - \left(\frac{\partial V_{wx}}{\partial h}\cdot\sin\psi - \frac{\partial V_{wy}}{\partial h}\cos\psi\right)\tan\gamma \tag{6}$$

where the equation variables represent the following:

x, y, h – vector components of the aircraft's inertial position
V – true airspeed
γ – flight-path angle
ψ – yaw angle
ϕ – roll angle
T – thrust force
D – drag force
L – lift force
m – mass
g – gravitational constant
V_{wx} – component of wind velocity in the x-direction
V_{wy} – component of wind velocity in the y-direction

Aircraft-specific performance parameters are needed to solve the equations of motion. In this case, the data are provided by the EUROCONTROL Base of Aircraft Data (BADA) product which supplies parameters for over 100 separate aircraft types [10].

The simulation also contains a model of the major functions of a commercial FMS: trajectory prediction and lateral and vertical guidance and control [11]. The guidance and control schemes used in this model have been described in detail in reference [9]. An implementation of the aircraft dynamics as well as the control logic has also been made publically available [12].

The FMS model uses trajectory prediction to develop a four-dimensional (4D) prediction of how the aircraft will follow the RNAV route. The prediction logic solves for this information backwards (relative to the direction of flight) starting from the waypoint closest to the runway and proceeding backwards along the RNAV procedure to the initial state of the aircraft. The solution logic must take into account all information that the RNAV route describes, traversing the space between the waypoints for the lateral path and respecting all altitude and speed constraints that bound the vertical and speed profiles. The ground speed profile is an output of the trajectory prediction, and the ETA is determined by integrating the ground speed along the path. Hence, the trajectory prediction is fully 4D. The FMS trajectory prediction model, and subsequent ETA calculation, is kinetic and uses BADA aircraft parameters to calculate the drag and lift forces acting on the aircraft at each step of the prediction. Therefore, this kinetic formulation produces an aircraft-specific prediction of the aircraft's path through the lateral and vertical space that is defined by an

RNAV procedure. In the advanced environment, this kinetic trajectory is used to generate the Target aircraft's ETA.

The speed guidance algorithm in the IM avionics uses a kinematic trajectory generation model that does not take aircraft-specific (e.g., BADA) performance into account. Instead, it assumes nominal aircraft behaviors (e.g., assumed flight-path angles and decelerations) to model trajectory segments that are combined to respect the RNAV altitude and airspeed constraints. Kinematic equations for the ground speed and altitude are integrated to generate a prediction of the aircraft's three-dimensional (3D) position as a function of time. In the current IM environment, this kinematic trajectory generation model is used to determine the Target aircraft's ETA.

Both trajectory prediction models take forecast wind into account in their ground speed predictions. As described above, the environmental (truth) wind used by the equations of motion for the aircraft dynamics are modeled using the zero-hour forecast of the NOAA RAP data set. The forecast winds used for trajectory prediction are modeled using the three-hour forecast of the NOAA RAP data set. This three hour offset is consistent, but slightly different, from the truth wind. Therefore, the FMS and IM trajectory prediction functions have imperfect knowledge of the wind field, modeling realistic uncertainties in wind information. Whereas the truth wind information is queried by the equations of motion for each specific 3D location of the aircraft, the forecast wind information is only provided to the FMS and IM avionics trajectory prediction functions at a few discrete altitudes along the lateral path. As a result, the wind information available to the FMS and IM avionics calculations are discretized by a small number of altitude bands from an hourly forecast that imperfectly represents truth wind.

Sensed winds are also an input to the FMS and the IM avionics, and are modeled to be the true environmental wind at the aircraft's 3D location. The FMS and IM avionics trajectory prediction models compare the sensed wind and the predicted wind at each time step. If the sensed wind is different from the predicted wind by a specified tolerance (10-knot tolerance in wind speed magnitude and 15-degree tolerance in wind direction), the sensed wind value is blended into the predicted winds to create an improved wind prediction [1]. Each time a wind-blending operation occurs, a new trajectory is generated providing a more accurate 4D path for aircraft guidance and control.

Application of the forecast and sensed winds is modeled differently between the current and the advanced IM environments. In the current IM environment, the IM avionics utilize the winds forecast along the IM aircraft's route to predict the winds along the Target aircraft's route when calculating the Target aircraft's ETA. When updating the Target aircraft's ETA, the IM avionics use IM aircraft's sensed winds. In contrast, in the advanced environment the winds along the Target aircraft's route are used when the FMS generates the Target aircraft's ETA, and the Target aircraft's sensed winds are used to update the ETA. Both the current and advanced IM environments are reflective of an advanced wind environment where forecast winds are available along an aircraft's route. This is more information than is required for current-day IM by reference [1].

The kinetic and kinematic trajectory models will create different vertical, airspeed, and ground speed profiles. An example is shown in Figure II-1, which depicts vertical profiles along the EAGUL5 procedure at KPHX from a cruise level at FL350 to the FAF. The kinetic and kinematic profiles are represented by the red and blue lines respectively, while the altitude constraints are represented by the red arrows. While there are some differences between to the two vertical profiles, the altitude constraints serve to bound the possible trajectories.

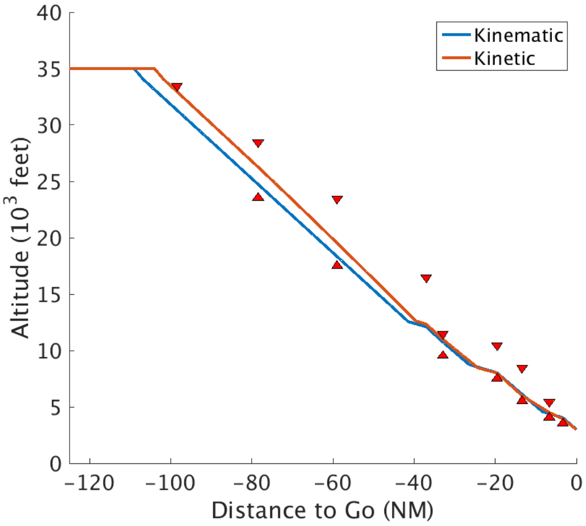

Figure II-1. Vertical Paths for Kinetic and Kinematic Trajectories

C. *IM Algorithm Description*

In order for the IM aircraft to achieve its ASG at the Achieve-by Point, it employs a control law that is designed to track a position and calibrated airspeed (CAS) on a nominal trajectory. In the current environment, the nominal trajectory is generated by the IM avionics using the kinematic trajectory model described in Section II.B, while in the advanced environment, the nominal trajectory is the kinetic trajectory used for guidance, also described in Section II.B. The algorithm first calculates the IM aircraft's desired ETA, $ETA_O^*(t)$, at the Achieve-by Point using the Target aircraft's ETA, $ETA(t)$, and the ASG, Δ, as

$$ETA_O^*(t) = ETA_T(t) + \Delta. \qquad (7)$$

The desired ETA is limited based on error thresholds that are defined linearly as a function of the IM aircraft's distance-to-go to the Achieve-by Point. The control law then determines the IM aircraft's desired position on the nominal trajectory at the desired ETA, $s_O^*(ETA_O^*(t))$, and the CAS on the nominal trajectory at the desired ETA, $V_{CAS}^O(ETA_O^*(t))$. These values are used in the control law, along with the control gain, k_{ETA}, and the current IM aircraft position, $s_O(t)$, to determine the commanded CAS, $V_{CL}^{CAS}(t)$.

$$V_{CL}^{CAS}(t) = V_{CAS}^{O}(ETA_O^*(t)) + k_{ETA}\lfloor s_O^*(ETA_O^*(t)) - s_O(t)\rfloor \quad (8)$$

The commanded CAS is limited to ±10% of the CAS on the nominal trajectory. It is also quantized before being displayed to the IM aircraft's flight crew. Full details can be found in reference [1].

D. *Description of ETA Broadcast Modeling*

To simulate the Target aircraft broadcasting its ETA in the advanced environment, the Target aircraft's current ETA was made available to the IM aircraft at a given update rate. Between updates, the IM avionics assumed that the Target aircraft's ETA was unchanged. Because there are multiple possible methods for broadcasting the Target aircraft's ETA that may result in different update intervals, different broadcast rates were simulated separately and compared. The broadcast rates were once per 1-, 10-, and 15-second intervals. In all cases, the ETA was broadcast at the Achieve-by Point only, in a double-precision floating-point format.

E. *Scenario Description*

The simulation was run for 60 wind conditions that were chosen randomly and uniformly to include dates from all months in 2012 and 2013. Forecast winds were assumed to be available at 10 levels during descent, modeling future avionics systems where more detailed wind information will be available and used. To simulate forecast and truth winds, the 3-hour and 0-hour RAP forecasts were assumed, respectively.

For each of the 60 wind conditions, strings of five aircraft were simulated, making for a total of four IM aircraft pairs per string. To simulate a range of aircraft performance capabilities, each aircraft was randomly chosen from six aircraft types (Airbus A319, Airbus A320, Boeing 737-700, Boeing 757-200, Boeing 767-300, or a Bombardier Regional Jet CRJ9).

The aircraft were pre-conditioned according to a nominal schedule established using the true trajectory times in specific wind conditions. Gaussian initial errors (mean, μ=0 and standard deviation, σ=20 sec) were added to trajectory times to simulate uncertainty in controller management to the schedule. The first aircraft in each string had a delay of approximately 30 seconds that was modeled by adjusting the speed constraints so that the aircraft flies a slower speed profile. The remaining aircraft in the string were assigned delays that were randomly chosen from a uniform distribution between 0 and 30 seconds.

Figure II-2 shows the routes used in the simulation. Aircraft were interleaved on the EAGUL5 and KOOLY4 procedures with the first aircraft of each string assigned to the EAGUL5 procedure. The first aircraft's delay is simulated by reducing the speed constraints at TINIZ, PAYSO, and EAGUL. This speed reduction is 10 knots at each waypoint, resulting in approximately 30 seconds of delay for the Target aircraft, though the actual change in the trajectory time depends on the wind conditions. These slower speed constraints are applied only to the first aircraft in the string, the remaining aircraft generate their nominal 4D trajectories using the nominal speeds through this section of the route.

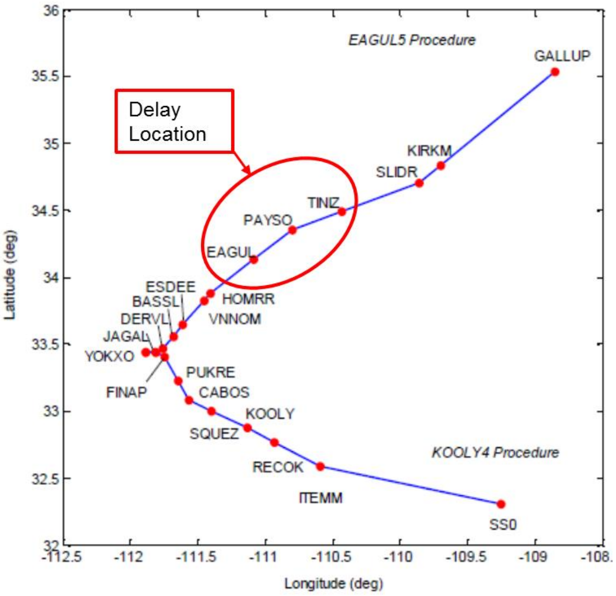

Figure II-2. Aircraft Routes Used for Analysis

III. RESULTS

The simulation results were quantified using the following metrics:

- spacing performance at the Achieve-by Point and
- reliability of spacing performance to be within specified tolerances.

Spacing performance is defined as the 95% bounds on the absolute value of the spacing error at the Achieve-by Point, where the spacing error is calculated for each aircraft pair using the following equation

$$Spacing\ Error(ABP) = t_{IM}(ABP) - \left(t_{Target}(ABP) + \Delta\right), \quad (9)$$

where $t_{IM}(ABP)$ is the time the IM aircraft crossed the Achieve-by Point and $t_{Target}(ABP)$ is the time the Target aircraft crossed the Achieve-by Point. As specified in reference [6], the IM tolerance is 10 seconds, 95%; therefore, the spacing performance is expected to be less than 10 seconds.

Reliability is defined as the number of successful IM operations over all conditions. Two levels of the reliability metric are studied, defined as the percentage of IM operations where spacing performance is less than 10 seconds and the percentage of IM operations where spacing performance is less than 15 seconds. High reliability in IM operations limits the frequency of outliers in IM performance, which lead to an erosion of user confidence in the system.

The results for these metrics for each comparison case are shown in Table III-1. Overall there is little difference between any of the performance metrics for any of the comparison cases. The most notable difference is the slight improvement in spacing performance for the advanced IM environment cases over the current IM environment case. In all cases, this performance improvement is less than 0.5 seconds, which translates into a throughput increase of less than 1 aircraft every 5 hours [6].

TABLE III-1. PERFORMANCE METRIC RESULTS

	Delivery Accuracy (sec, 95%)	**Reliability: 10 Seconds (%)**	**Reliability: 15 Seconds (%)**
Current IM Environment	5.65	99.73%	99.95%
Advanced IM Environment – 1 Second Update	5.18	99.77%	99.91%
Advanced IM Environment – 10 Second Update	5.19	99.78%	99.91%
Advanced IM Environment – 15 Second Update	5.18	99.76%	99.90%

Although there was little improvement in the aggregate metrics in Table III-1, differences in the metrics may exist between individual wind conditions. To determine any differences in reliability within individual wind conditions, the results were broken out by wind condition, and boxplots of the spacing error distributions were generated for each wind condition. Figure III-1 shows boxplots for each wind condition for the cases where the IM avionics calculates the Target's ETA in the current IM environment and the Target broadcasts its ETA in the advanced IM environment at a 1-second update rate.

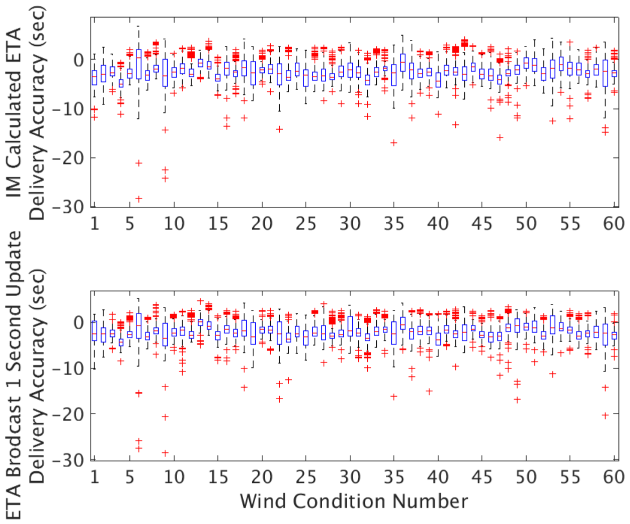

Figure III-1. Distribution of Delivery Accuracy By Wind Condition

Comparing the distributions for each wind condition between the two cases, there are no easily identifiable differences in distribution characteristics such as the number of outliers or the width of the inter-quartile range. This indicates that for the wind conditions considered, using the Target aircraft's broadcast ETA does not result in a more reliable operation for some wind conditions. Although the results are not presented here, the findings by wind condition for Target aircraft ETA broadcast with 10- and 15-second update rates were similar. The similarities found between wind conditions here are only for one geographic location (KPHX) and on one set of routes (EAGUL5 and KOOLY4). Other geographic locations, routes, or wind conditions may result in very different distributions between wind conditions when comparing the current and advanced environments.

The performance metrics are also considered as a function of position along the string of IM aircraft. Table III-2 shows IM spacing performance based on the IM aircraft's position within the string, where the data for IM aircraft 1 represents the spacing performance for the first IM aircraft, which is the second aircraft in the string.

Table III-2 shows a small improvement in spacing performance in the advanced IM environment as compared to the current IM environment. This improvement is attenuated over the course of the string, so that IM aircraft at the beginning of the string exhibit a larger improvement in spacing performance than IM aircraft at the end of the string. Additionally, there is little difference in spacing performance based on string position for the different update rates of the broadcast ETA. Although the spacing performance increases along the string for all cases, string stability is not a concern as prior research has shown this control law to be string stable [13].

TABLE III-2. SPACING PERFORMANCE BY IM AIRCRAFT POSITION WITHIN STRING

	Spacing Performance (sec)			
	IM aircraft 1	**IM aircraft 2**	**IM aircraft 3**	**IM aircraft 4**
Current IM Environment	5.16	5.51	5.41	6.36
Advanced IM Environment - 1 Second Update	4.40	4.81	5.24	5.93
Advanced IM Environment - 10 Second Update	4.39	4.84	5.21	5.93
Advanced IM Environment - 15 Second Update	4.39	4.81	5.19	5.95

It is important to understand the underlying reason for the lack of performance improvement seen in the advanced IM environment. This understanding can motivate further areas of study for improving IM performance, or suggest other use cases for broadcasting the Target aircraft's ETA. Figure III-2 shows three airspeed profiles for the Target aircraft in the absence of wind. The solid line represents the actual airspeed profile flown by the Target aircraft, the dashed line shows the airspeed profile predicted by the IM avionics for the Target aircraft, and the dotted line shows the airspeed profile predicted by the Target aircraft's FMS for itself. The red triangles denote speed constraints on the Target aircraft's route. These are the constraints used by the IM avionics when calculating 4D trajectories for the Target aircraft. In the advanced IM environment, the FMS uses the planned speed profile, which may deviate from the procedural constraints, determined through the air/ground trajectory synchronization.

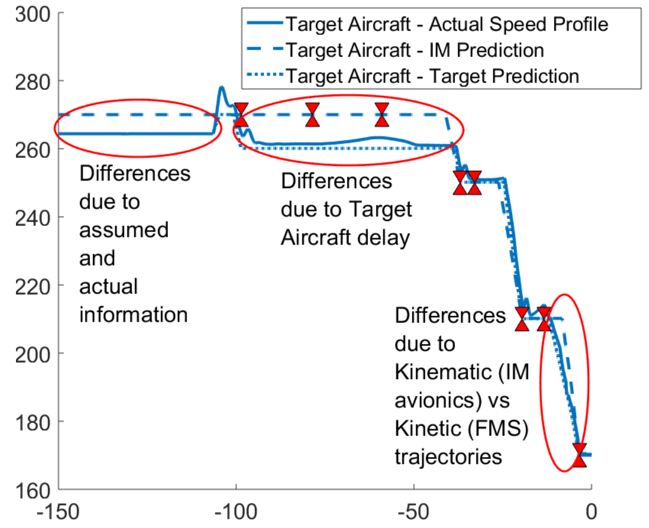

Figure III-2. Predicted and Actual Indicated Airspeed Profiles for Target aircraft

There are three main areas in which the trajectories differ. Each of these areas represents different uncertainties that must be compensated for by the IM control law. The first area can be attributed to information that is available to each aircraft. The IM avionics assumes a cruise speed for the Target aircraft that is slightly different than the actual cruise speed the Target aircraft flies. The second area where the IM and Target aircraft predictions differ is a result of the delay assigned to the Target aircraft by the ground system. The final difference is a result of the different methods employed by the IM and Target aircraft to generate 4D trajectories. The IM avionics generates a kinematic 4D trajectory using information about the Target aircraft's RNAV procedure and using assumed flight-path angles and decelerations, whereas the Target aircraft's FMS generates a kinetic 4D trajectory using information about its RNAV procedure and aircraft-specific performance parameters.

Overall, the Target aircraft's FMS generates a more accurate prediction of its speed profile than the IM avionics, however this does not lead to an improvement in IM performance when the Target aircraft broadcasts its ETA. This is likely due to a combination of factors. Although the first and second areas where the speed profiles differ are long in duration (approximately 50 NM each), they occur early in the IM operation, leaving the IM aircraft's control law sufficient time to correct for the errors introduced by these inaccuracies. The last area where the speed profiles differ is very close to the end of the operation, however it is short in duration and small in magnitude. This leads to a spacing error that is small enough for the IM aircraft's control law to correct before the end of the operation. Although the Target aircraft generates a more accurate prediction of its airspeed profile, the IM aircraft has ample opportunity to correct errors due to inaccuracies in its prediction of the Target aircraft's airspeed profile.

In addition to considering the airspeed profiles, it is also important to understand the differences in the IM aircraft's predicted flight time change between the advanced environment and the current environment. The predicted flight time change is given by

$$Predicted\ Flight\ Time\ Change(x_{IM}) = ETA_{IM}(x_{IM}) - (t_{Target}(ABP) + \Delta), \quad (10)$$

where $ETA_{IM}(x_{IM})$ is the IM aircraft's ETA from its current position. The predicted flight time change is a reflection of the amount of error that the IM avionics needed to correct at any given point along the IM aircraft's route. If the predicted flight time change for one environment is larger than the other, it would indicate that IM would need to make larger speed adjustments in order to achieve similar performance.

Figure III-3 shows 95% bounds on the absolute value of the predicted flight time change of the IM aircraft when simulating the current and advanced environments in all wind conditions. The predicted flight time change for the current environment is denoted by a solid line, while the predicted flight time change for the advanced environment is shown by a dashed line. Results are shown for each IM aircraft in the string separately. The predicted flight time change for the current and advanced environments shows some differences until about 10 NM to the Achieve-by Point, when the predicted flight time change is nearly identical for the two cases. The similarities in the predicted flight time change shown here are likely due to the constrained nature of the RNAV routes, as well as the limited scope of the simulation, which considered only one geographic location (KPHX), and a limited number of wind and delay conditions.

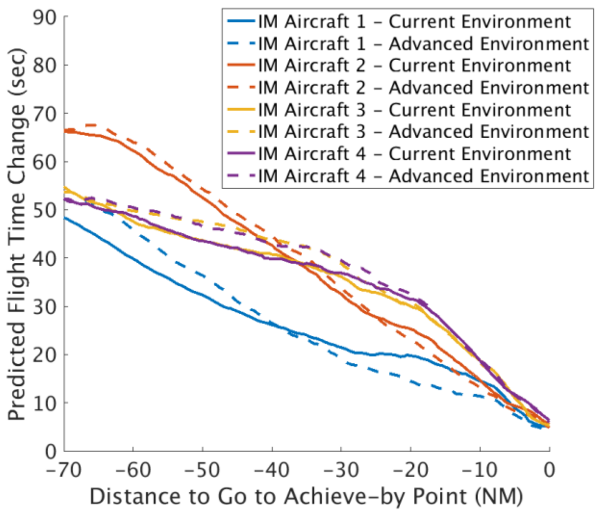

Figure III-3. Predicted Flight Time Change in the Current and Advanced Environments

The 95% bounds on the absolute value of the predicted flight time change as a function of distance-to-go to the Achieve-by Point for the advanced environment with 1- and 10-second update rates for the 60 wind conditions are shown in Figure III-4. The predicted flight time change for the 1-second update rate is shown in solid lines, while the predicted flight time change for the 10-second update rate is given by the dashed lines. The predicted flight time change is shown individually for each IM aircraft. The predicted flight time change for both update rates is nearly identical, with only very small variations between the two update rates. The results for the 15-second update rate, although not shown here, are similar.

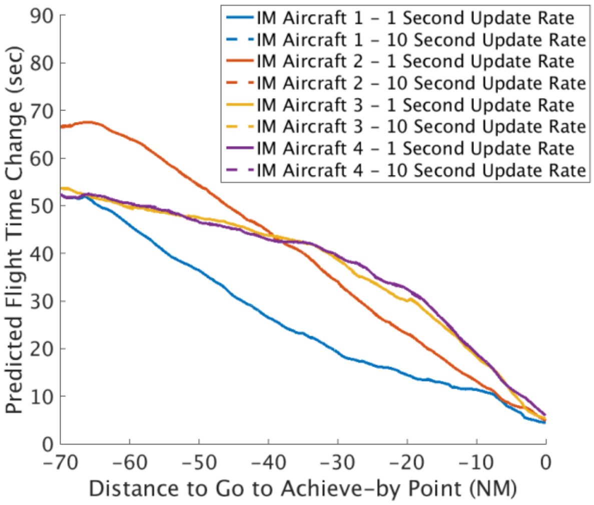

Figure III-4. Predicted Flight Time Change for the Advanced Environment when using a One and Ten Second Update Rate

To understand the similarities in predicted flight time change between update rates, factors that impact the flight time change should be studied. These factors are similar to factors which will affect the ETA accuracy, as the predicted flight time change is dependent on the IM aircraft's ETA. Among these factors are aircraft flying speeds different than their planned 4D trajectories, errors within an aircraft's planned 4D trajectory, and differences in wind conditions. Of these factors, differences in wind conditions that lead to a full trajectory recalculation result in some of the larger changes in ETAs, and thus, larger changes in predicted flight time change. To understand how this differentially impacts predicted flight time change between broadcast update rates, consider the amount of time between trajectory updates for the Target aircraft, shown in Figure III-5.

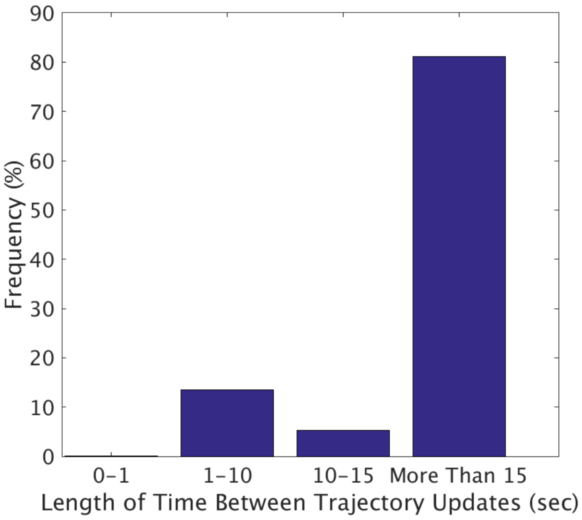

Figure III-5. Distribution of the Length of Time Between Full Target Trajectory Updates

For a trajectory update to cause a difference in ETA for the broadcast rates considered here, it must occur less than 10 seconds from the previous update for differences between the 1- and 10-second update rate, and less than 15 seconds from the previous update for differences between the 15-second update rate and the 1- and 10-second update rate. As shown in Figure III-5, more than 80% of the time, full trajectory updates are greater than 15 seconds apart, meaning most trajectory updates will not cause a difference in ETA between the different broadcast rates.

IV. DISCUSSION AND NEXT STEPS

When comparing an advanced IM environment that includes the use of Target aircraft broadcast ETA and air/ground trajectory synchronization with the IM environment assumed in the current standards, which requires the Target aircraft's ETA to be calculated by the IM avionics, there is little performance difference between the two options in terms of IM spacing performance at the Achieve-by Point and reliability. These results are unexpected due to the increased information available in the advanced environment as compared to what is available in the current environment. In the advanced environment, the Target aircraft has access to its own performance parameters, sensed winds along its trajectory, forecast wind information specific to its route, and delay allocation, while in the current environment, the IM aircraft relies only on waypoint airspeed and altitude restrictions along the Target aircraft's planned route. Despite the uncertainties that arise from the IM aircraft having less information about the Target aircraft, the IM aircraft is still able to generate a reasonably accurate 4D trajectory for the Target aircraft using the altitude and airspeed constraints from its RNAV procedure. Furthermore, the differences that do arise between the 4D trajectories are easily corrected for by the IM control law, making the current method of the IM avionics calculating the Target aircraft's ETA robust to the uncertainties studied here that arise from limited knowledge of the Target aircraft.

One reason that the 4D trajectories generated by the IM avionics closely match the 4D trajectories generated by the Target aircraft's FMS is the highly constrained nature of the RNAV procedures simulated here. Although it is assumed that IM will be used in an environment where either the procedures are highly constrained, or there is a mechanism available for the Target to share its planned 4D trajectory, future work should investigate lesser-constrained procedures. Specifically, analysis should be done to understand to what degree RNAV procedures must be constrained in order for the IM avionics to continue to generate accurate 4D trajectories for the Target aircraft. This information can be used in procedure design to ensure new procedures accommodate the needs of IM. It can also be used as a guide to understand the information a Target aircraft would have to communicate about its 4D trajectory to enable a successful IM operation (e.g., waypoints defining the horizontal path with their associated planned speeds and altitudes).

In addition to studying the degree to which the Target aircraft's route should be constrained, further analysis should also be undertaken to determine the amount of uncertainty that is tolerable in other parameters about which the IM aircraft has no knowledge or inaccurate knowledge. For instance, there should be an understanding of the tolerable differences in wind conditions between what the IM aircraft and Target aircraft experience before it is no longer feasible for the IM control law to be robust to these differences. At that point, the IM aircraft would begin to require information about the Target aircraft's winds. Similarly, the amount of unknown delay that is allowable for the Target aircraft should be understood. Although the IM control law was robust to the winds and delay conditions studied here, this scenario was specific to one location, KPHX, with delays less than or equal to 30 seconds. Expanding the simulation to other geographic locations or route geometries that result in larger wind forecast errors will allow for the determination of when the robustness of the current environment breaks down.

Section III also presented differences in predicted flight time change between the current and advanced environments. Due to the similarities between the 4D trajectories calculated by the IM avionics and the Target aircraft's FMS, differences in the predicted flight time change between current and advanced environments were small. Given that the spacing performance and reliability were similar for the two cases, the small differences between the two environments were readily corrected by IM. Results for the differences in predicted flight time change for different Target aircraft broadcast rates within the advanced environment were also presented. The difference in predicted flight time change for different broadcast rates was negligible due, in part, to the frequency with which the Target aircraft performs a full trajectory recalculation. Future work should compare these update rates to actual trajectory update rates seen in FMSs to determine if further study of broadcast rates is required. If current FMSs update trajectory rates more frequently than once per 10 or 15 seconds, the impact of broadcast rate should be more closely studied.

V. CONCLUSIONS

A critical component in the success of Interval Management (IM) operations is the accuracy of the Target aircraft's Estimated Time of Arrival (ETA) used when calculating the IM speed guidance. Two environments that lead to different methods of providing ETAs for use in IM were presented here. The first environment is the current environment specified by the IM avionics standards. The ETA calculation method in this environment relies on the IM avionics to calculate an ETA for the Target aircraft using information about its own winds and the Target aircraft's planned Area Navigation (RNAV) procedure. The second environment reflects an advanced environment where the Target aircraft broadcasts the ETA calculated by its Flight Management System (FMS). This environment also assumes air/ground synchronization, which results in the Target aircraft's ETA including knowledge of any delay allocated to the Target aircraft by the Air Traffic Control ground automation system. Three broadcast rates were studied: once per one-, ten-, and fifteen-second intervals. It was expected that the ETA broadcast by the Target aircraft in the advanced environment would exhibit better performance due to the knowledge of the Target aircraft's performance parameters, wind, and planned speed profile.

Simulation results showed that there was little performance difference between the current and advanced environments. The lack of performance differences between the two environments suggests that the methodology of calculating a trajectory for the Target aircraft based on a constrained RNAV procedure and correcting for errors through the use of IM speed guidance is robust to some uncertainties in wind conditions and the planned speed profile of the Target aircraft.

Future work should consider the degree to which the Target aircraft's procedure must be constrained to yield successful IM operations. Furthermore, the amount of tolerable uncertainty in wind conditions and delay allocation should be quantified in order to understand the limits of the robustness of the current methodology. Finally, a study of FMS trajectory update rates should be undertaken to determine if further study of ETA broadcast rates is necessary.

VI. ACKNOWLEDGMENTS

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