Development of an Interval Management Algorithm using Ground Speed Feedback for Delayed Traffic

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One of the goals of NextGen is to enable frequent use of Optimized Profile Descents (OPD) for aircraft, even during periods of peak traffic demand. NASA is currently testing three new technologies that enable air traffic controllers to use speed adjustments to space aircraft during arrival and approach operations. This will allow an aircraft to remain close to their OPD. During the integration of these technologies, it was discovered that, due to a lack of accurate trajectory information for the leading aircraft, Interval Management aircraft were exhibiting poor behavior. NASA's Interval Management algorithm was modified to address the impact of inaccurate trajectory information and a series of studies were performed to assess the impact of this modification. These studies show that the modification provided some improvement when the Interval Management system lacked accurate trajectory information for the leading aircraft.

Nomenclature

4D	=	*Four Dimensional*
ANOVA	=	*Analysis of Variance*
ASTAR	=	*Airborne Spacing for Terminal Arrival Routes*
ASTAR11	=	*ASTAR version 11*
ASTAR12	=	*ASTAR version 12*
ATD-1	=	*Air Traffic Management Technology Demonstration - 1*
ATOS	=	*Airspace and Traffic Operations Simulation*
CMS	=	*Controller Managed Spacing*
d1	=	*filter parameter applied to ground speed feedback term*
Da	=	*Delivery Accuracy*
DCT	=	*Delay Countdown Timer*
Dp	=	*Delivery Precision*
ds	=	*distance-to-go when ground speed feedback is turned off*
ETA	=	*Estimated Time of Arrival*
F	=	*Relative fuel use*
f1	=	*filter parameter applied to ground speed feedback term*
f2	=	*filter parameter applied to ground speed feedback term*

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FAA	=	*Federal Aviation Administration*
FAF	=	*Final Approach Fix*
FMS	=	*Flight Management System*
g2	=	*Maximum speed correction limit*
g3	=	*Ground speed feedback term limit*
GSC	=	*Ground Speed Correction term*
I	=	*number of inflection points*
IM	=	*Interval Management*
KDEN	=	*Denver International Airport*
KGS	=	*Ground speed feedback gain*
KPHX	=	*Phoenix Sky Harbor International Airport*
NASA	=	*National Aeronautics and Space Administration*
NextGen	=	*Next Generation Air Traffic Management*
OPD	=	*Optimized Profile Descent*
RMS	=	*Root Mean Square*
RNAV	=	*Area Navigation*
TSAS	=	*Terminal Sequencing and Spacing*
S	=	*Speed changes per minute*
TMA-TM	=	*Traffic Management Advisor with Terminal Metering*

I. Introduction

Over the next twenty years, the Federal Aviation Administration (FAA) is predicting a substantial increase in the number of revenue passenger miles flown [1]. This increase could overwhelm the current air traffic system if no improvements are made. To help increase the efficiency of arrivals, fuel efficient procedures such as Optimized Profile Descents (OPDs) are being implemented at a number of airports. However, these procedures are often not used during periods of peak traffic due to the lack of precision scheduling and spacing tools, resulting in sub-optimal arrival operations [2]. Researchers at the National Aeronautics and Space Administration (NASA) have developed technologies that enable the use of efficient arrival procedures during high demand operations.

The goal of NASA's first Air Traffic Management (ATM) Technology Demonstration (ATD-1) is to accelerate the implementation of mature NASA technologies, enabling aircraft to use speed control to remain close to their OPDs during periods of peak traffic. Three NASA technologies were selected to be integrated to achieve this goal: the Traffic Management Advisor with Terminal Metering (TMA-TM), which provides precise time-based scheduling in the terminal airspace; Controller Managed Spacing (CMS), which provides controllers with decision support tools that enable precise schedule conformance; and Interval Management (IM), which consists of flight deck automation that enables aircraft to either achieve or maintain a precise spacing interval behind the preceding aircraft [3]. These technologies extend precision scheduling into the terminal area and provide pilots and controllers with control mechanisms that increase schedule conformance and achieve precise inter-aircraft spacing.

During high demand operations, TMA-TM can produce a schedule, and corresponding aircraft trajectories, that include a substantial amount of delay to ensure that a particular aircraft is properly spaced at each of the schedule control points. Until digital data communications become standard and common, there is no method to communicate these complex delay trajectories to the aircraft. As a result, aircraft conducting IM operations, hereinafter referred to as IM aircraft, use the published speed constraints to compute Estimated Times of Arrival (ETAs) for the IM aircraft and the preceding aircraft, the latter hereinafter referred to as the target aircraft. When the target aircraft flies a delay trajectory, the ETA calculated by the IM aircraft for the target aircraft does not align with the schedule produced by TMA-TM. If the controller is managing the target aircraft to the schedule, the ETA calculated by the IM aircraft will be inaccurate, forcing the IM aircraft to tactically resolve its delay concurrently with the target aircraft. Previous spacing algorithms were not designed to compensate for large and systematic target aircraft speed deviations caused by the delay trajectories.

This paper describes a modification to the existing NASA spacing algorithm designed to improve performance when conducting spacing operations with a delayed target aircraft and a series of fast-time simulations that evaluated the new spacing algorithm. The first section discusses problems that were encountered when conducting IM operations with delayed target aircraft and algorithm modifications to alleviate those problems. The following sections describe the design, results, and conclusions of several simulations that examined the new spacing algorithm.

II. Background

Previous research and development of a trajectory-based algorithm for IM has focused on a Next Generation Air Traffic Management (NextGen) environment where the necessary information to accurately predict aircraft behavior was readily available to all relevant agents. This section describes that development in detail along with the assumptions on supporting infrastructure. It closes with identifying some of the problems that arise when those assumptions are not met, which could occur during the transition to a full NextGen environment.

A. Spacing Algorithm History

The basic goal of an airborne spacing algorithm is to provide speeds to a flight crew that, when flown, will null the current spacing error. The method used to determine the spacing error and calculate the speed, called the IM speed, is what makes each of the following approaches unique. Starting in the mid-1980's, constant time delay, or time-history, techniques were developed [4, 5]. In these techniques, the spacing error is calculated by determining the time elapsed between when the target aircraft passed the IM aircraft's current position and when the IM aircraft arrives at that position. The spacing error at any point is simply the difference between the elapsed time and the assigned spacing goal. Therefore, the IM speed is a combination of the target aircraft's speed when it passed the IM aircraft's current position and the speed required to null the current spacing error. Since the spacing error is based on both aircraft passing over the same position, this type of algorithm can only be used when the aircraft are in-trail.

Starting in the early 2000's, trajectory-based algorithms were developed. These algorithms calculate the ETA for each aircraft at the achieve-by point and then compare the difference in ETAs to the assigned spacing goal to determine the current spacing error. The IM speed is then defined as the IM aircraft's expected speed throughout that segment plus the speed needed to null the current spacing error. This type of algorithm relaxes the requirement of the aircraft being in-trail, but requires additional information to calculate the trajectory for both aircraft from their current positions to the common point.

The Eurocontrol-developed algorithm, CoSpace [5], limits the time-to-go operation when both the target and IM aircraft are headed direct to a common point. The only information required for each trajectory is the merge point and current speed. Since this constraint generally limits the operation to ranges of tens of nautical miles, the uncertainties in the time-to-go are small and manageable over the length of the direct-to leg.

The NASA-developed Airborne Spacing for Terminal Arrival Routes (ASTAR) algorithm uses detailed route information for both aircraft to allow spacing to begin whenever the target aircraft's route can be communicated to the IM aircraft and the target aircraft is within air-to-air ADS-B range [6, 7]. This allows for multiple turns, planned altitude changes, and planned speed changes prior to the common point, and for a much larger range between aircraft at the start of the operation. In a mature NextGen environment, the target aircraft's route information would be delivered by a data link message from the ground system. In the interim, however, it is assumed that published area navigation (RNAV) arrival routes and instrument approaches can provide sufficiently accurate information for airborne spacing. Since the spacing algorithm is continually running and providing up-to-date speed guidance, any trajectory prediction errors will eventually appear as spacing errors and be corrected.

B. NextGen Assumptions

During the early development of ASTAR, it was assumed that an advanced communications infrastructure would be in place by the time IM operations were in use. This communication infrastructure would provide aircraft with a known trajectory that represented the best estimate of their future flight and that their trajectory was shareable amongst participants as needed. This would provide ASTAR with a reference trajectory to use for calculating accurate ETAs, enabling the spacing goal to be achieved using only small deviations from the reference trajectory. Since this trajectory represented the best estimate of the future flight path, perturbations caused by wind forecast errors or other sources of uncertainty, were expected to be approximately symmetric. That is, some uncertainties would lengthen the flight time while a similar amount would shorten the flight time. It was also assumed that any speed change required would be short-lived with the aircraft either returning to their initial trajectory speed or that the trajectory would be updated. All of this information exchange provided predictability to the operation and ensured that at any given time the ASTAR-calculated spacing was close to the theoretical true spacing.

The original ASTAR algorithm was also designed to either reside within a Flight Management System (FMS), or be coupled to the auto-throttle system. This would allow the speeds to be automatically flown by the aircraft without pilot intervention, much like current-day vertical path, i.e., VNAV PATH, mode. This would also allow the algorithm to be more responsive to changes in the spacing error and provide finer-resolution speeds without significantly adding to the flight crew's workload.

C. Near-term Environment

When the arrival demand exceeds the airport or terminal acceptance rate, aircraft are delayed to ensure separation and proper spacing at a sequence of scheduling points throughout the arrival to the runway. In the near-term NextGen environment that ATD-1 is planned for, some of this delay is allocated to, or planned for, the terminal area with the rest being absorbed between the schedule freeze horizon and the meter fix (the entry to the terminal area). Controllers will use two main pieces of information to inform their decision on how to absorb the delay. The center controllers will be provided with a delay countdown timer (DCT), which displays a digital readout of the delay that should be absorbed prior to the meter fix. Terminal controllers will be provided slot markers and associated speeds that display the location and speed of a trajectory which will absorb the delay allocated to the terminal environment. When possible, controllers will use slower speeds to absorb delay; however, vectoring can also be used to lengthen the flight path if speed control is insufficient. Vectoring is generally limited to the center airspace in the ATD-1 environment.

For IM operations, the IM aircraft must be provided with information to build the target aircraft's 4D trajectory. Without data communications, the controller includes the name of the target aircraft's RNAV arrival route as part of the verbal clearance. The IM avionics then accesses an onboard database to extract the necessary information, including the published speed profile. However, the IM aircraft has no knowledge of any delay that the target aircraft may be required to absorb or how it will be absorbed. This results in ETA calculations which are incorrect by as much as a few minutes. The IM Aircraft also tries to maintain the published speed profile, only making correction for spacing errors. This situation can lead to cases where the IM Aircraft has undesirable closure rates on the target aircraft or a following aircraft.

III. Modified Algorithm

The updated version of the ASTAR algorithm described in this paper, ASTAR12, includes modifications to the speed control algorithm that improve performance when the IM and target aircraft must absorb delay. The ASTAR12 algorithm uses a proportional control term and a ground speed feedback term to compute the amount of speed compensation required to null the spacing error (Figure 1). The ground speed feedback is the new modification that enables the IM aircraft to compensate for errors in the target aircraft's predicted ground speed, eliminating the undesirable closure rates between the IM and target aircraft.

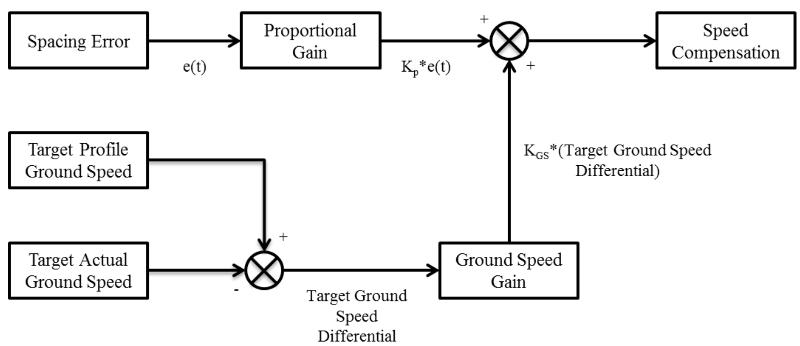


FIGURE 1. A SIMPLIFIED DIAGRAM OF THE ASTAR12 SPEED CONTROL ALGORITHM

The ASTAR12 algorithm also incorporates additional features that are designed to improve performance and improve its acceptability to both pilots and controllers. Many of the features were designed to improve the speed control behavior by decreasing the frequency of speed changes.

The first feature, which will be referred to as the ground speed lockout, disables the ground speed feedback when the difference between the target's actual and expected ground speed is positive. The benefit of the ground speed lockout is a reduction in the number of commanded speed increases. However, the implementation of the ground speed lockout can also result in less than desired performance when the target aircraft flies speeds that are faster than the published profile speeds for an extended period of time. This situation is not expected to happen very often during high demand terminal operations, since aircraft are generally delayed to de-conflict traffic at meter points along the arrival.

A second feature is the gain scheduling of the ground speed feedback term. The gain applied to the target aircraft ground speed (K_{GS}) is reduced so that it is zero when the IM aircraft is close to the achieve-by point, where the achieve-by point is assumed to be the final approach fix (FAF). This was done because the combination of the high proportional gain when the IM aircraft is on final approach and the fact that delay is not normally scheduled on final approach reduces the need for the ground speed feedback term. One potential disadvantage is that large target speed deviations from the published speed profile when the IM aircraft is on final approach may cause undesirable behavior.

The last feature is a 60 second low pass filter that is applied to the target's ground speed deviation. Since the ground speed feedback acts as a derivative term, changes in ground speed caused by wind error or target aircraft behavior could cause frequent speed changes. This filter smooths out the target aircraft's ground speed deviation, ensuring that the IM commanded speeds are not affected by noise.

IV. Design and Results of Three Studies

Three simulations were used to refine the proposed modifications to the ASTAR algorithm and validate the expected improvements in performance. The first simulation was used to optimize control law gains and filter parameters that were added to the control law. Traffic scenarios were created to simulate the expected operational environment and all combinations of a variety of control law settings were simulated. A combination of key metrics, a cost function, was evaluated for each setting. This was a simplified multidimensional optimization problem with discrete variable settings.

The second simulation modeled the traffic scenarios seen in the simulations that uncovered the problems and evaluated them in a batch simulation to ensure that the key performance metrics were met.

The third simulation was designed to examine the string stability of the ASTAR12 algorithm. Previous versions of ASTAR have all shown good string stability [6, 8, 9]. That is, performance did not degrade when a string of aircraft were all conducting IM operations. This simulation examined several strings of IM aircraft to determine if spacing performance degrades as a function of string position.

A. Optimization

1. Motivation

The objective of the optimization simulation was to select appropriate gains and filter parameters for the ASTAR12 algorithm. The ground speed compensation term added to ASTAR12 includes five new parameters that were evaluated in addition to one parameter that was reevaluated; the 10% speed limit around the profile speed that ASTAR11 used. The original 10% value was based on the full NextGen environment and may not be sufficient when there is significant delay. Discrete values were selected for each of the six parameters giving a total of 528 possible combinations. One additional run was added with settings equivalent to ASTAR11 for comparison. The breakout is shown below in Table 1. GSC is whether the ground speed compensation term is turn on (ASTAR12) or off (ASTAR11).

TABLE 1: LIST OF FLAG VALUES TO SET VARIOUS OPTIONS INSIDE ASTAR.

	GSC	g_1	f_1	d_1	f_2	g_2	ds
1	OFF	0.05	0	15	0	0.05	FAF
2	ON	0.10	15	20	15	0.10	10
3		0.15	30	25	30	0.15	15
4		0.20	60	30		0.20	20
5				35			25

$g_1 = g_2$ for most runs; if $f_1 = 0$ then $d_1 = 15$ and $f_2 = 0$; if $f_1 = f_2$ then $d_1 = 15$ (has no effect)

The parameters g_1 and g_2 limit the size of the total speed compensation and the ground speed adjustment respectively and represent a portion of the nominal speed profile. For example, $g_1 = 0.15$ limits the IM Speed to within 15% of the nominal speed. Parameter *ds* is called the ground speed lockout distance and describes the distance from the runway threshold where the ground speed feedback was turned off. The remaining three parameters (f_1, d_1, and f_2) are part of the filtering of the ground speed feedback.

2. Scenario Design

Twenty test cases were developed that included five speed profiles for the target aircraft, two wind conditions, and two potential route options. The five target aircraft speed profiles were created to represent expected controller behavior for a target aircraft. The calibrated airspeed[6] profiles for the target aircraft, managed by the controller, are shown in Figure **2**. To model the near-term National Airspace System, these speed profiles were not communicated to ASTAR12. Instead, ASTAR was provided with the speed profile associated with the target aircraft's Standard Terminal Arrival Route (STAR), resulting in cases where the delay that the target aircraft was required to absorb was not known by the ASTAR12 algorithm. In addition to the target aircraft speed profiles, there were two wind conditions representing truth and forecast winds from two different days: June 29, 2011 and Dec 02, 2011. Finally, the two route

[6] In our simulations, calibrated and indicated airspeed are identical and are used interchangeably.

options enabled the IM aircraft to either be in-trail behind the target aircraft or on a merging route. The two routes merge near the turn on to the base leg.

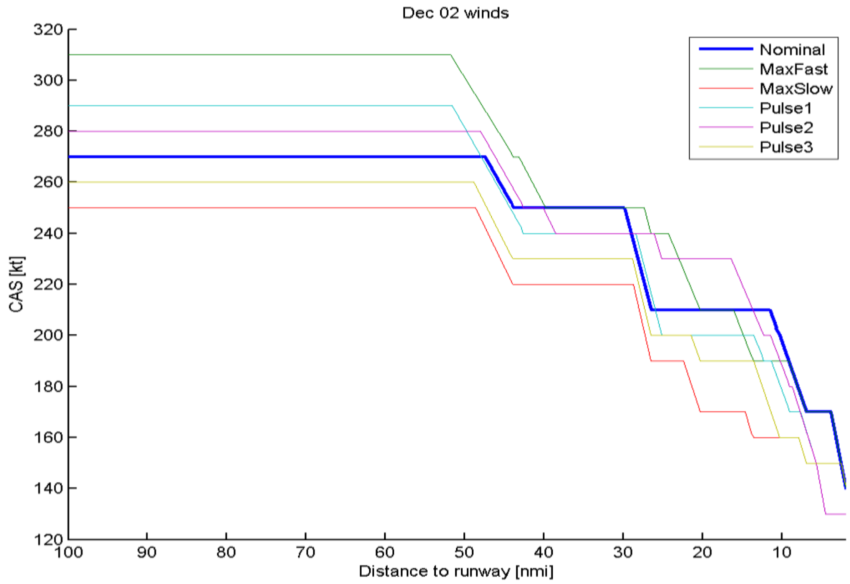


FIGURE 2: TARGET AIRCRAFT SPEED PROFILES.

The target aircraft's speed profile defined the amount of delay, or advance in some cases, that the controller was applying to the target aircraft. The IM Aircraft was started at a position and time so that the initial ASTAR-calculated spacing error was in the range of [-65, 40] seconds, where negative time corresponds to being early. The sum of the target aircraft's delay and the ASTAR-calculated initial spacing error is the IM Aircraft's delay.

3. Cost Function

The first step in the optimization phase, was to determine the set of parameters in the new control law that provided the best performance. To determine the best performance, a cost function was developed that included a weighted combination of the following five performance metrics:

1. Delivery accuracy (D_a) - The mean of the difference between the actual spacing at the Final Approach Fix (FAF) and the assigned spacing goal.
2. Delivery precision (D_p) - Standard deviation of the difference between the actual spacing at the FAF and the assigned spacing goal.
3. Average speed changes per minute (S) - Number of commanded speed changes below 11,000 ft altitude averaged over flight time below 11,000 ft.
4. Fuel use (F) – The ratio of Fuel used in the ASTAR12 run to fuel used for an ASTAR11 run with the same initial conditions.
5. Inflection points in the ASTAR-calculated spacing error (I) - An inflection point is anytime the ASTAR-calculated spacing error crosses zero. There is a 10 second deadband around zero to avoid detecting small variations centered near zero.

The cost function, C, was then defined as the sum of these five metrics with weightings.

$$C = a_1|D_a| + a_2 D_p + a_3 S + a_4(F-1) + a_5 I$$

a_1 = 1.0
a_2 = 0.75; not quite as important as delivery accuracy
a_3 = 2.0; will trade 0.5 changes per minute for 1 second delivery accuracy
a_4 = 100; will trade 1 second delivery accuracy for 1% fuel improvement over ASTAR11
a_5 = 2.0; will trade 2 seconds delivery accuracy for 1 less inflection point

4. Results

Table **2** shows highlights of the cost function. The results were mainly dependent upon the setting of g_2, so only that value is shown in the table. The parameter g_2 represents the limits on the IM speed relative to the profile speed. So the result of $g_2 = 0.15$ means that the IM speed will be limited to ±15% of the nominal speed profile.

TABLE 2: COST FUNCTION RESULTS. THE CORRECTION OFF CASE IS ASTAR11.

Rank (out of 529)	Correction On	g_2	Accuracy	Precision	Speed Change Rate	Inflection	Cost
1	YES	0.15	2.65625	3.331807	0.730115	0.1875	8.70945
2	YES	0.15	2.951389	3.155836	0.709053	0.173611	8.879598
3	YES	0.15	2.424306	3.552429	0.764188	0.215278	8.90604
4	YES	0.15	2.738889	3.352008	0.733316	0.1875	8.910971
115	YES	0.2	3.601389	2.396063	0.925228	0.138889	11.34376
116	YES	0.2	3.439583	2.174558	0.975616	0.138889	11.43109
265	YES	0.1	-6.38194	25.75679	0.574315	0.194444	26.70664
266	YES	0.1	-6.38889	25.75511	0.573834	0.194444	26.71135
267	YES	0.1	-6.38889	25.75511	0.573841	0.194444	26.71136
397	NO	0.1	-17.2132	31.76182	0.46087	0.520833	42.99796

The final ASTAR12 parameter settings were chosen to be: $g_2 = 0.15$; $f_1 = 60$, $d_1 = 35$, $f_2 = 30$; $ds = 20$. Although the ds value of 25 actually had a lower cost function, the differences were minimal and a setting of $ds = 20$ more closely corresponds to where the scheduler, TMA-TM, is expected to stop scheduling delay. That is, the delay absorption is zero within roughly 20 nmi of the FAF.

5. Cost Function Sensitivity on Weightings

As described above, the cost function was mainly sensitive to the setting of g_2. Figure **3** shows the cost function as a function of two of the control parameters. The left (g_2) plot shows the strong dependence on g_2. Since g_3 was set equal to g_2, the cost index dependency on g_3 is identical. The right plot shows the dependency on f_1. All of the remaining parameters show similar behavior as f_1 with a strong dependence on g_2 but little other affect. The ASTAR11 results are shown by the solid square. Since all parameters except g_2 are only valid for ASTAR12, the settings shown are default values.

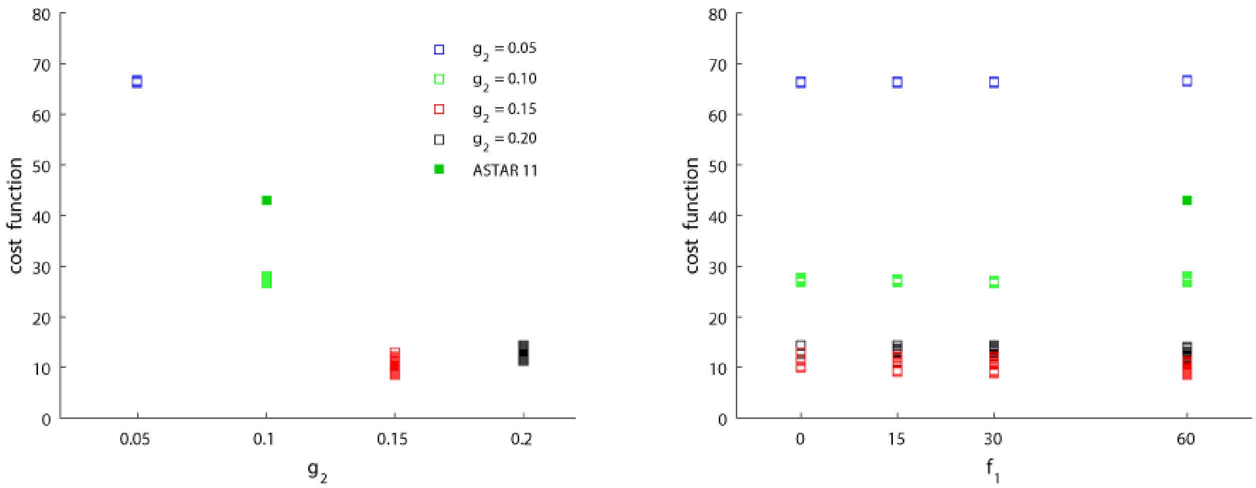


FIGURE 3: COST FUNCTION AS A FUNCTION OF EACH CONTROL PARAMETER SETTING. RESULTS ARE COLOR CODED BY VALUE OF G_2.

The weightings used for the cost function were selected to represent the relative importance of each of the metrics. Since this was not a rigorous method of setting of weights we performed a sensitivity test on the ranking of the parameters sets. Each weight was independently varied by ±15% and the cost function re-evaluated. Only minor changes in the rankings were seen, increasing confidence that the selected parameter set was the correct choice.

6. Case Study

Figure **4** and Figure **5** show specific cases to compare the ASTAR11 and ASTAR12 behavior. In both figures, the upper left plot is the ground speed deviation from the ASTAR-calculated expected speed as a function of the distance to the runway, the lower left is the ground speed (dotted for profile and solid for flown), the upper right is the commanded speed and the lower right shows the ASTAR-calculated current spacing error and the relative contributions from the time spacing error and ground speed correction terms in the control law. For ASTAR11 the ground speed correction term is always zero.

Figure **4** and Figure **5** show the respective behaviors of ASTAR11 and ASTAR12 using the same scenario. The scenario is a merging operation with the target aircraft on the EAGUL5 arrival and the IM aircraft on the MAIER5 arrival. The winds are the June 29, 2011 case. The target aircraft is following the pulse three controller speed profile and the IM Aircraft had a delay of five seconds more than the target's delay (97 seconds). The sudden change in the spacing error at the very end occurs after the aircraft has passed the final approach fix and IM is terminated (the data is still recorded).

Key features to note:

- The IM Aircraft flies about 25 nmi before the IM Clearance is issued. In this time the actual ground speed is above the profile speed due to wind forecast error.
- ASTAR11 returns the IM aircraft to the profile speed between 120 nmi and 60 nmi. The spacing error is continuously decreasing during this time due to the target being approximately 20 kt below the expected ground speed. In this region ASTAR12 slows the IM aircraft so that the ground speed difference nearly matches the target aircraft's ground speed difference.
- ASTAR12 maintains the matching ground speed difference so that the spacing error remains close to zero from 100 nmi to the FAF. This offset can be seen wherein the GSC value in the lower right plot stays close to –20 kt.

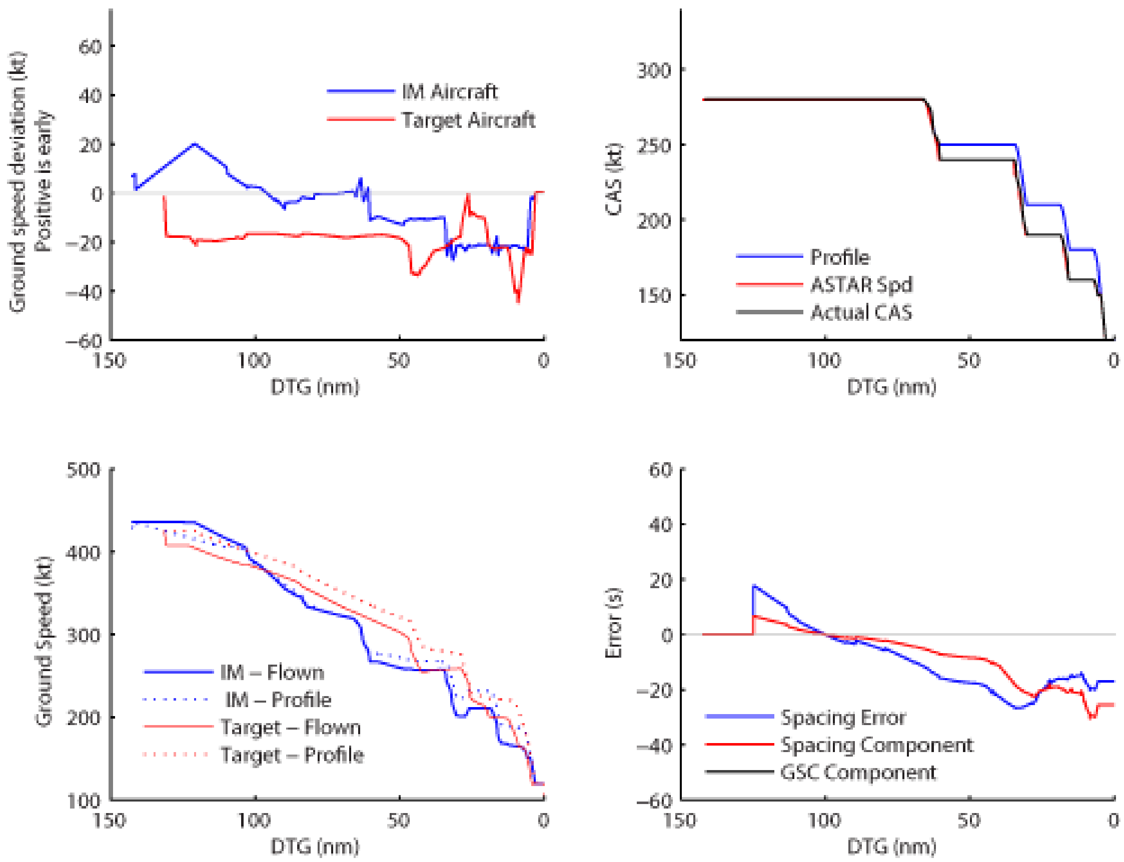


FIGURE 4: SAMPLE RESULTS FOR ASTAR11 SETTINGS.

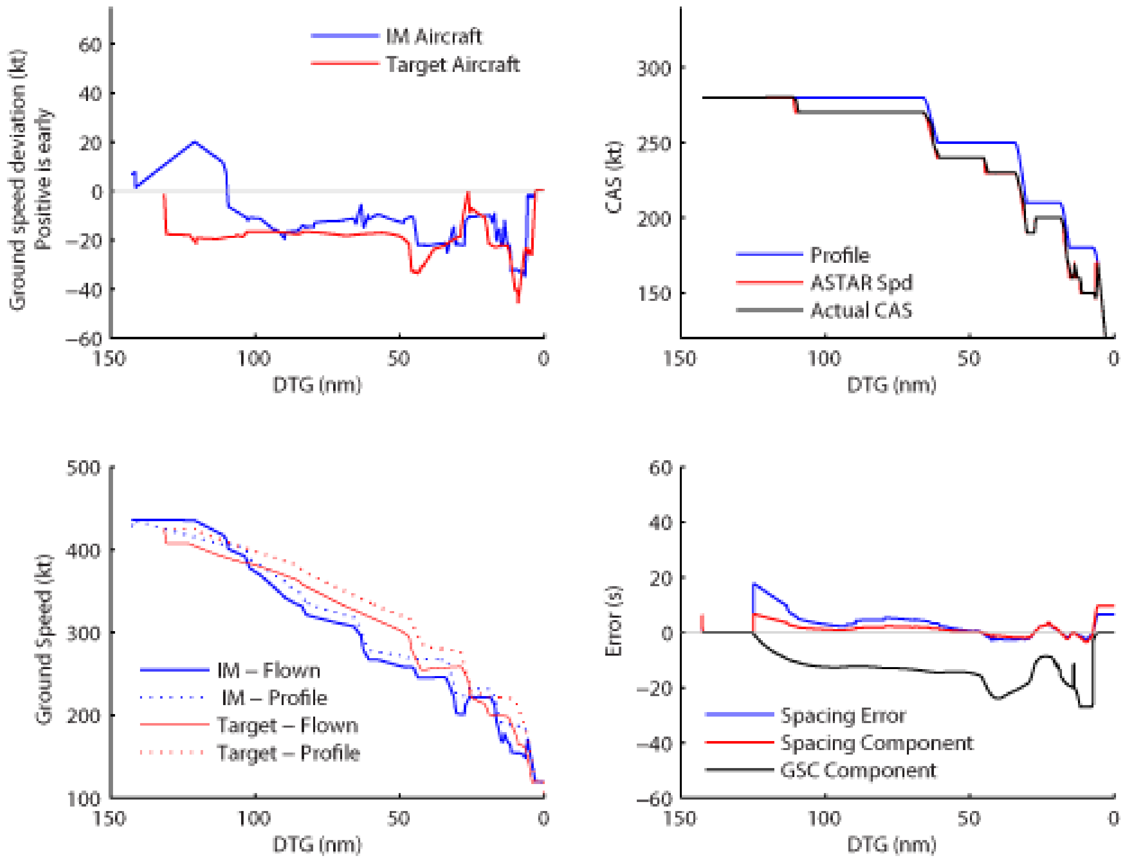


FIGURE 5: SAMPLE RESULTS FOR ASTAR12 SETTINGS.

7. Summary

The optimization phase consisted of a multidimensional optimization of several new parameters introduced into the control algorithm. It was found that the largest effect came from the parameter g_2, the limiting of the IM Speed. The addition of the ground speed feedback term clearly improved performance over ASTAR11. A case study was presented that demonstrated the improved behavior showing the nulling out of the spacing error by reacting to the target aircraft's consistent slow speed.

B. Pair-wise Study

Once the parameters in the control law were selected, validation of improvements to the spacing performance and verification of the design metrics were required. The initial focus was on a single pair of aircraft performing an IM operation. A new set of target speed profiles were developed and combined with a wider range of wind conditions in a batch simulation.

1. Scenario Description

The airspace around Phoenix Sky Harbor International Airport (KPHX) was modeled along with two RNAV arrival procedures for west flow traffic: the EAGUL5 arrival from the northeast and the MAIER5 arrival from the northwest. For this west-flow configuration, the EAGUL5 arrival is the short-side arrival and the MAIER5 arrival is the downwind arrival. All aircraft in the study landed on runway 26, the north-most runway at KPHX. Previous research has shown that the behavior of the original ASTAR algorithm does not depend on route design [10]; therefore, only one set of arrival routes was examined.

This simulation investigated 630 pairs of aircraft, consisting of one target aircraft and one IM aircraft. In each of the scenarios, the IM and target aircraft were on different routes to ensure that worse-case wind forecast errors were examined.

2. Experiment Design

A full factorial experiment was used. Two primary independent variables were examined along with several other variables intended to simulate real-life variation. The variables were seven different target aircraft speed profiles and five different wind forecast error conditions. Both of these variables were expected to excite the ground speed feedback term that was added to ASTAR12. Levels for each of these variables were carefully chosen to examine the spacing performance of the IM aircraft.

Six different target aircraft speed profiles were designed by subject matter experts to emulate different speed profiles flown by aircraft controlled by a controller (Figure 6). A seventh profile used the nominal speed profile but included an early descent that would also add delay to the target aircraft's flight time.

The truth and forecast winds used in this study were selected from a set of wind fields observed at Phoenix Sky Harbor Airport in 2011. To conform to current real-world procedures for providing aircraft with descent forecast winds, the IM descent forecast winds were sampled at a single waypoint after top-of-descent on the IM aircraft's arrival route at altitudes of 30,000 feet, 24,000 feet, 18,000 feet, and 10,000 feet. This forecast data was used in the ETA calculation for both aircraft.

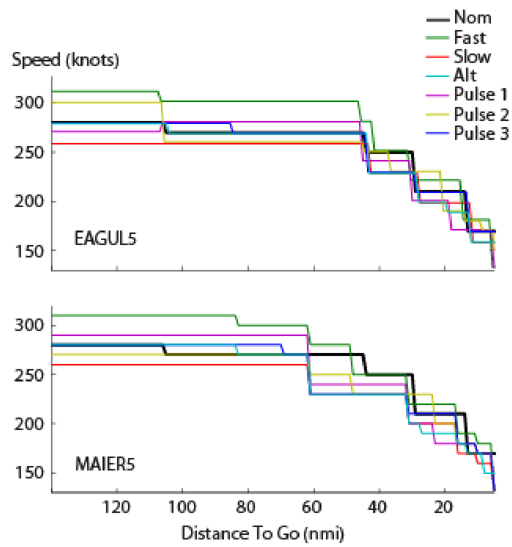


FIGURE 6: TARGET SPEED PROFILES FOR EACH ARRIVAL ROUTE IN THE STUDY

To select the wind fields to be tested, ETAs were calculated for the nominal speed profile for each day in 2011. Four wind conditions (combination of truth and forecast winds) were selected to cover all four combinations of the IM aircraft and target aircraft being early or late. Early or late refers to the flight time through the forecast wind as compared to the truth wind. One additional wind condition was selected that generated a large (high magnitude) change in the ETA.

The aircraft initial conditions were varied over expected operational ranges. These included three different initial spacing errors (-60 sec, 0 sec, 60 sec), three different target aircraft weights (light, normal, heavy), and two different target arrival routes (MAIER5 and EAGUL5).

3. Simulation Platform

NASA's Airspace and Traffic Operations Simulation (ATOS) platform was used to simulate all of the aircraft in this study. The ATOS platform contains a network of hundreds of real-time simulators that can be used for fast-time studies and real-time human-in-the-loop experiments [11]. Each simulated aircraft within the ATOS platform has a high-fidelity six-degree-of-freedom dynamics model, an emulated flight management system, and an emulated auto throttle system. The simulated aircraft can either be flown by human pilots or by an automated pilot model that simulates pilot inputs into the aircraft. In this study, all aircraft were flown by the automated pilot model.

4. Results

The main metric of interest is the delivery of the IM aircraft to the achieve-by point at the assigned spacing goal. This is measured as the elapsed time between the two aircraft crossing the achieve-by point. For this study the achieve-by point was the final approach fix. The design goals were for the mean delivery error (assigned spacing goal minus the actual temporal spacing) to be between -5 seconds and +5 seconds and for 99% of the data to fall between -15 seconds and +15 seconds. Across all 630 runs the mean delivery accuracy was estimated to be 1.76 seconds and t-tests indicated that the mean delivery accuracy was within ±5 seconds ($p<0.001$). Fourteen of the runs had delivery errors that fell outside the ±15 second goal (2.2%). All of these were associated with a combination of the fast target aircraft speed profile and either the high magnitude or early (target)/late (IM) wind forecast error condition (Figure 7). In both cases the wind forecast error would make the target aircraft fly faster than IM aircraft expected. And while in human-in-the-loop studies, the controllers will occasionally speed up, or advance, an aircraft, it is an infrequent occurrence. During high demand operations when IM would be in use, most aircraft are delayed. So while the design goal was not met in this analysis, it is assumed that it would be met in a full operational environment where most aircraft are experiencing delay.

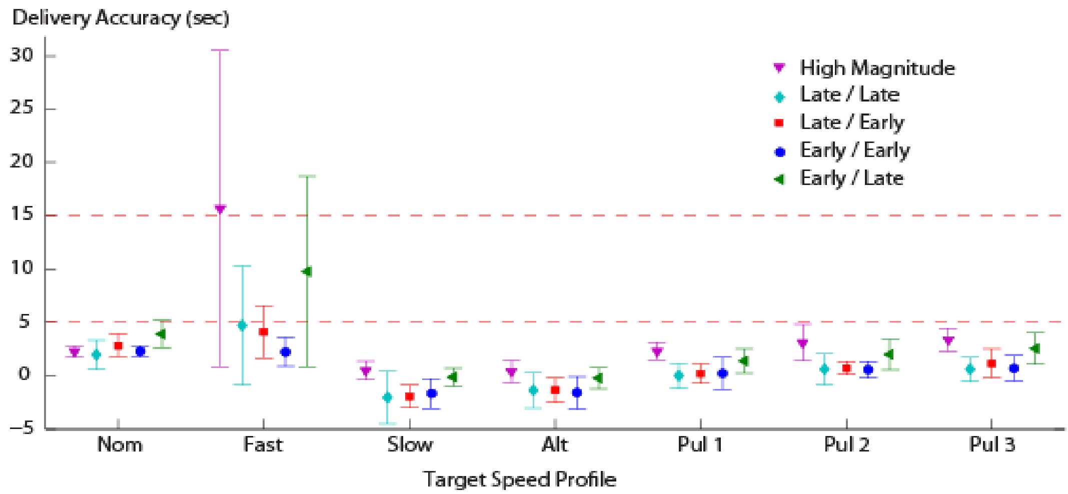


FIGURE 7: DELIVERY ERROR AS FUNCTION OF WIND CONDITION AND TARGET SPEED PROFILE.

In near-term IM Operations, the pilot will be responsible for implementing the speed presented by ASTAR. Therefore, managing the number, timing, and magnitude of commanded speed changes is important to ensuring the acceptability of the operation. Previous research [12, 13] has indicated that speed change rates of less than 2 per minute would be acceptable. Table **3** shows the mean speed change rate broken down by flight segment: Center airspace; TRACON prior to final approach, and on final approach course. The right most column is the speed changes expected if the published speed profile was flown with no modification. The rates are always well below the two per minute threshold and in terminal airspace, the total number of speed changes remains less than twice the number of procedural changes. These numbers are consistent with previous research [8] and are expected to be operationally acceptable.

TABLE 3: MEAN SPEED CHANGE RATES (NUMBER PER MINUTE) FOR EACH FLIGHT SEGMENT.

Flight Segment	Mean Speed Changes per Minute	Upper 95% Confidence Bounds	Planned Procedural Speed Change Rate
Center Airspace	0.29	0.30	0.06
TRACON	0.65	0.66	0.40
Final Approach	1.28	1.30	0.70

Closely related to the number of speed changes are the instances where the IM speed decreases then increases, called speed reversals. This is similar to the inflection points used in the optimization phase but a more operationally-relevant measure. Both metrics attempt to capture over-control by the algorithm. In an ideal operation, there would not be a need to increase the aircraft's speed unless the target aircraft’s speed increased. However, many of the uncertainties that drive the spacing error can cause the spacing to be greater than the assigned spacing goal, requiring an increase in speed to correct. A weaker than expected headwind for the target aircraft is one example. Also, the design of ASTAR will return the IM speed to the reference speed once any spacing errors are corrected. If a slowdown was needed, this will likely result in a speed up back to the reference speed. The average number of speed reversals is 2.4. One condition seen that would induce a speed reversal was if the target speed did not change speeds when a procedural speed change was expected. In this case, ASTAR was planning on the target aircraft changing speeds to meet a published speed constraint but the controller had issued a speed change at a different location. This appears to ASTAR as a speed increase by the target even though their speed did not actually increase. Being able to properly detect such cases and handling them without a speed increase but without decreasing overall performance is an area for future algorithm improvement.

5. Summary

The objective of the pair-wise spacing analysis was to verify that the ASTAR12 algorithm would meet the operational performance objectives in the expected operational environment. This first analysis focused on pairs of aircraft as a stepping stone to the inclusion of the fuller operational environment and strings of aircraft conducting IM. All performance metrics were met or determined to be acceptable although a few areas for further improvement were identified.

C. String Stability Study

1. *Motivation*

Sequences, or strings, of several IM aircraft following each other can experience differences in their performance based on string position. In the worst case, an IM algorithm may experience string instabilities where either the spacing error or the amount of speed control required to achieve a precise spacing interval grows as a function of the aircraft's position in the string.

There is a substantial amount of research that has investigated the string stability of various IM algorithms. Weitz and Hurtado examined the string stability of several IM algorithms using both an analytic approach and a fast-time simulation [14]. One of the algorithms they examined was a time-to-go algorithm that is similar to a previous version of the ASTAR spacing algorithm (ASTAR11). They found that the time-to-go algorithm was weakly string stable. Krishnamurthy et al. conducted a fast-time simulation that examined strings consisting of 100 IM aircraft [15]. The results of the fast-time simulation did not reveal any string instabilities.

The string stability of various spacing algorithms have also been validated in previous human-in-the-loop simulations. In 2005, Barmore et al. described a human-in-the-loop simulation that included strings of nine IM aircraft. The results of the simulation did not reveal any string instabilities [10]. Baxley et al. conducted a human-in-the loop simulation that examined a previous version of NASA's ASTAR spacing algorithm [9]. During the simulation, strings of 23 IM aircraft, including six pilot flown aircraft, were examined for string instabilities; no string instabilities were found.

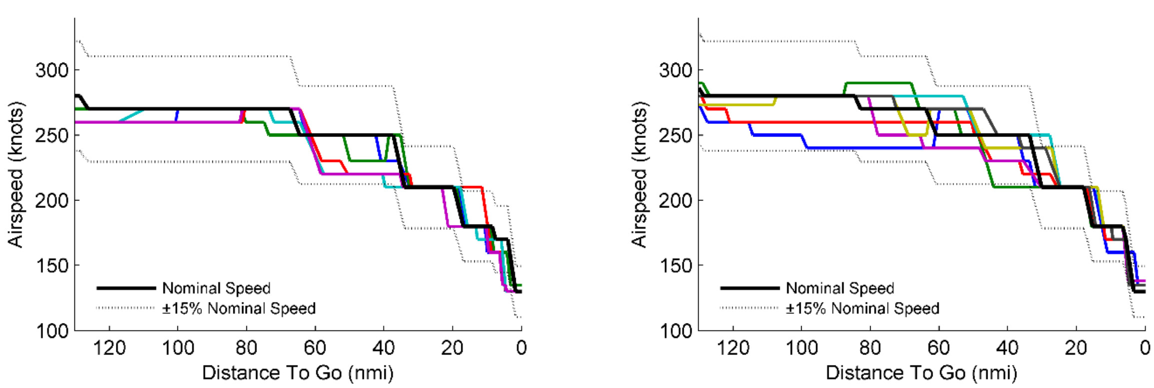
2. *Scenario / Experiment Design*

A fast-time simulation examined 6,720 strings of IM aircraft arriving into either KPHX or Denver International airport (KDEN). Each of the IM aircraft began IM operations just prior to their top-of-descent and conducted IM operations to the final approach fix. The experiment design consisted of a single independent variable: the position in the string of aircraft. Several environmental and aircraft parameters were randomly varied to sample the expected operational conditions.

The three environmental conditions, airspace, target speed profile and winds, applied to every aircraft in a simulation run. In each of the two airspaces modeled, arrivals for KPHX and KDEN, 14 different target aircraft speed profiles were investigated. The target aircraft speed profiles that were investigated at KPHX were based on observed behavior in previous ATD-1 human-in-the-loop simulations. Human-in-the-loop simulation data was not available for KDEN so subject matter experts created 12 off-nominal target aircraft speed profiles and combined those with two nominal speed profiles.

Sixteen wind conditions, eight for each airport, were selected from a set of winds observed at KPHX and KDEN. Each wind case consisted of truth and forecast wind fields. The forecast wind data field was discretely sampled using a vertical column at the runway threshold at the altitudes of 30,000 feet, 24,000 feet, 18,000 feet, 10,000 feet, and at the surface. These five points were provided to the aircraft and ASTAR. This method of sampling the forecast winds is consistent with the capability that will likely be available in retro-fit IM avionics.

To approximate conditions observed in ATD-1 human-in-the-loop simulations, the initial delay of each aircraft was selected from a normal distribution with a mean of 30 seconds and a standard deviation of 15 seconds. The aircraft dynamics model of each aircraft was randomly selected from a set of seven choices using a uniform distribution. The route of each aircraft was randomly selected from a set of two routes at KPHX and two routes at KDEN using a uniform distribution, creating different merging and in-trail conditions. Lastly, the weight of each aircraft was randomly selected. A total of thirty replicates for each combination of independent variables were used to sample the random variables.



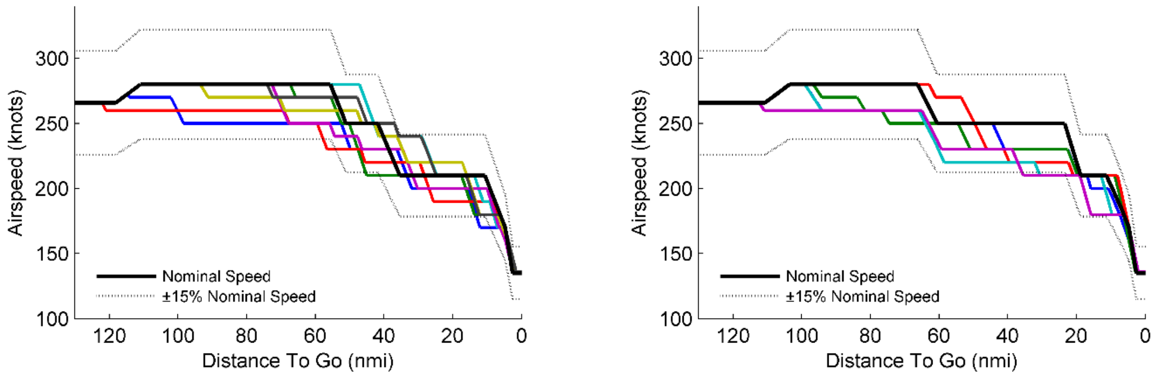


FIGURE 8: TARGET SPEED PROFILES FOR EACH ARRIVAL ROUTE IN THE STUDY

3. *Results*

Overall, the mean delivery accuracy in this simulation was 2.4 seconds and the standard deviation was 4.6 seconds. A total of 4.2% of the IM aircraft had delivery accuracies worse than 10 seconds (more than 10 seconds early or late). Parsing the data by airport revealed that there was a significant difference in both the mean and standard deviation of the delivery accuracy. The mean delivery accuracy at KPHX was 2.1 seconds with a standard deviation of 3.0 seconds, and the mean delivery accuracy at KDEN was 2.7 seconds with a standard deviation of 5.7 seconds. Additionally, only 0.8% of the aircraft at KPHX had delivery accuracies worse than 10 seconds, whereas 7.5% of aircraft at KDEN had delivery accuracies worse than 10 seconds. The large discrepancy between the delivery accuracies at KPHX and KDEN is likely caused by differences in the wind conditions or the target aircraft speed profiles used in this simulation.

The delivery accuracy was also analyzed to determine if it changed as a function of string position. An Analysis of Variance (ANOVA) and Tukey multi-comparison test revealed that the mean delivery error increased as a function of string position at both KPHX ($p<0.001$) and KDEN ($p<0.001$). However, the delivery accuracy results did not reveal any unstable string behavior, and the 12th aircraft in the string had an average delivery error of 3.3 seconds and a standard deviation of 3.8 seconds, which is within the acceptable range. While the delivery accuracy degraded as a function of string position, Figure **9** suggests that the increase reached an asymptote at the seventh or eighth aircraft in the string.

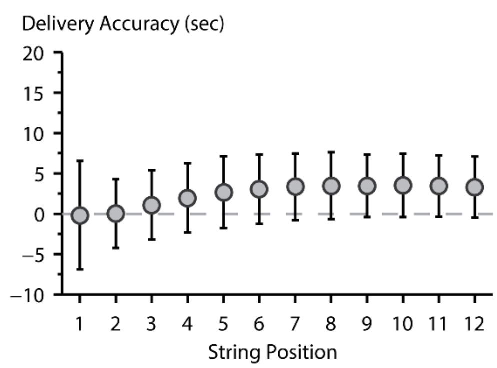


FIGURE 9: THE DELIVERY ACCURACY AT THE FINAL APPROACH FIX AS A FUNCTION OF STRING POSITION (ERROR BARS REPRESENT ± ONE STANDARD DEVIATION)

The number of speed changes commanded by ASTAR12 were evaluated to ensure that they did not increase as a function of string position, which could indicate string stability problems. Figure **10** shows that the number of IM speed commands increased slightly as a function of string position; the first IM aircraft in the string had an average of 10.6 IM speed commands and the 12th IM aircraft in the string had an average of 12.9 IM speed commands, including published speed changes. This corresponds to an average speed change rate of 0.4 speed changes per minute with a standard deviation of 0.1 speed changes per minute throughout the arrival for the first aircraft in the string, and 0.5 speed changes per minute with a standard deviation of 0.1 speed change per minute for the 12th aircraft in the string. These results are consistent with the pair-wise study.

Figure **11** shows the number of speed reversals as a function of string position, binned by the speed reversal magnitude. There was an average of 2.3 speed reversals per IM operation; however, approximately half of the speed reversals were 10 knots or less. The total number of speed reversals increased slightly as a function of string position. Additionally, the average number of 10 knot speed reversals decreased as a function of string positions and the number of higher magnitude speed reversals (greater than 20 knots) increased.

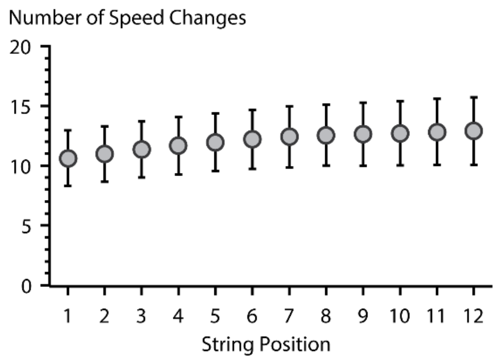


FIGURE 10: THE NUMBER OF SPEED CHANGES COMMANDED BY THE ASTAR12 SPACING ALGORITHM AS A FUNCTION OF STRING POSITION (ERROR BARS REPRESENT ± ONE STANDARD DEVIATION)

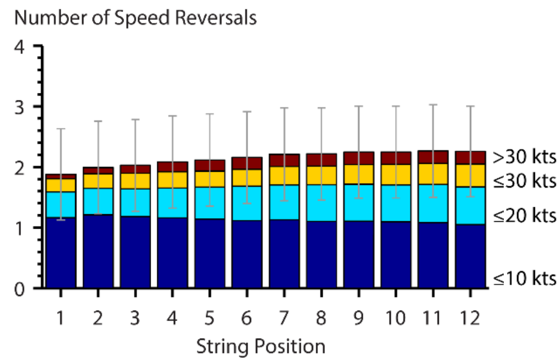


FIGURE 11: THE NUMBER AND MAGNITUDE OF SPEED REVERSALS COMMANDED BY ASTAR12 AS A FUNCTION OF STRING POSITION (ERROR BARS REPRESENT ± ONE STANDARD DEVIATION)

The root-mean-square (RMS) of the speed control throughout an arrival was examined to determine if the total amount of speed control required to achieve the assigned spacing goal increased as a function of string position. Since each string position was provided with the same distribution of initial spacing errors (Figure **13**), an increase in the total amount of speed control as a function of string position could indicate undesirable string performance. An ANOVA and Tukey multi-comparison test revealed that there was a substantial increase in the total amount of speed control as a function of string position at KPHX ($p<0.001$) and at KDEN ($p<0.001$). Figure **12** shows that the average RMS of speed control for the first IM aircraft in the string was 11.4 knots and increased to 17.9 knots for the 12th aircraft in the string. The increase in the amount of speed control required is likely the driver behind the small increase in the number of speed changes and the increase in the number and magnitude of speed reversals. This data suggests that the speed commands of aircraft at the end of a very long string of IM aircraft will be less desirable than the speed commands for the first aircraft in the string.

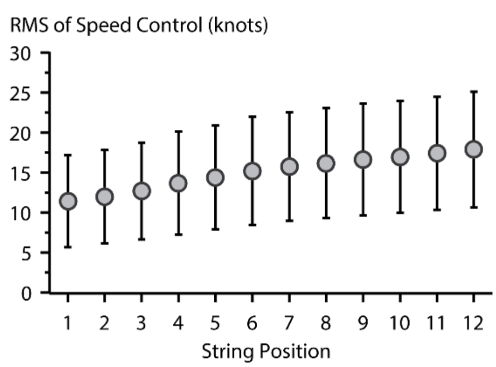


FIGURE 12: THE RMS OF THE SPEED CONTROL USED TO ACHIEVE THE SPACING GOAL AS A FUNCTION OF STRING POSITION (ERROR BARS REPRESENT ± ONE STANDARD DEVIATION)

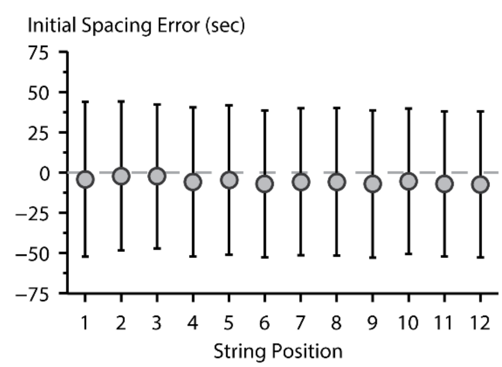


FIGURE 13: THE INITIAL SPACING ERROR FOR EACH AIRCRAFT IN THE STRING WAS SAMPLED FROM THE SAME DISTRIBUTION (ERROR BARS REPRESENT ± ONE STANDARD DEVIATION)

4. *Summary*

A fast-time simulation were conducted to characterize the string performance of the ASTAR12 spacing algorithm. The fast-time simulations examined 6,720 strings of IM aircraft arriving into either KPHX or KDEN. The independent variables that were examined were the destination airport, string position, wind field, and the speed profile of the first target aircraft in each string. Additional aircraft parameters were randomly varied to better simulate the variability expected in future IM operations. The data was examined to characterize the string performance of the ASTAR12 spacing algorithm. The results did reveal degradation of ASTAR12 performance as a function of string position; however, the performance is still in the acceptable range for strings of moderate length.

V. Subsequent Human-In-The-Loop Findings

A subsequent HITL evaluation conducted in 2015 discovered certain route designs and Terminal Sequencing and Spacing (TSAS) adaptation designs where the target aircraft may absorb delay much closer to the achieve-by point than originally anticipated. If the target aircraft is absorbing delay close to the achieve-by point (i.e., not flying speeds close to the published speeds), the trajectory based control law will provide commanded speeds that cause the spacing error do diverge from zero to a steady state error value. This problem occurs because ASTAR only uses proportional control when the ground speed term is turned off. Thus, there must be a certain amount of spacing error present for the IM aircraft to match the target aircraft's speed deviation. NASA is currently examining solutions to this problem. The addition of the ground speed term to ASTAR's trajectory based control law also increased the likelihood that ASTAR will command speed reversals. These speed reversals occur when the target aircraft is slowed several miles prior to a published speed decrease. When this occurs, the ground speed term in ASTAR adds the difference between the target aircraft's ground speed and published ground speed to the speed compensation. Later in the arrival, when the published speed decreases, the target aircraft's speed deviation changes from a large value to a value close to zero, causing ASTAR to command the IM aircraft to speed up.

VI. Conclusions

Interval Management operations are seen as a key component of the future air traffic management system. NASA, through its ATD-1 activity, is accelerating the implementation of several arrival management tools and concepts. During ATD-1 testing, it was uncovered that some of the limitations on communicating the target aircraft's planned speed profile led to unacceptable performance for the NASA IM algorithm, ASTAR. ASTAR was modified to add a ground speed feedback to partially account for deviations in the target aircraft's actual ground speed and the ground speed that was expected by ASTAR. This modification went through a three step test and evaluation to determine the best settings for internal parameters and assess the impacts of this change.

The modifications have met the performance objectives in these tests. The new algorithm has been used in further human-in-the-loop studies.

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