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Wind Information Uplink to Aircraft Performing Interval Management Operations

Nashat N. Ahmad, Bryan E. Barmore, and Kurt A. Swieringa
Langley Research Center, Hampton, Virginia

May 2016

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Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Nomenclature

ADS-B	Automatic Dependent Surveillance – Broadcast
AGL	Above Ground Level
ANOVA	Analysis of Variance
ASTAR	Airborne Spacing for Terminal Arrival Routes
ATOL	Air Traffic Operations Laboratory
ATM	Air Traffic Management
BADA	Base of Aircraft Data
CPDLC	Controller Pilot Data Link Communications
Δ	Spacing interval
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FIM	Flight Deck Interval Management
FMS	Flight Management System
ILS	Instrument Landing System
IM	Interval Management
KPHX	Phoenix Sky Harbor Airport
KDEN	Denver International Airport
MOPS	Minimum Operational Performance Standards
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NCDC	National Climate Data Center
NCEP	National Centers for Environmental Prediction
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory)
nmi	Nautical Mile
RAP	Rapid Refresh
RMS	Root Mean Square
RNP	Required Navigation Performance
SPR	Safety, Performance and Interoperability Requirements
STA	Scheduled Time of Arrival
TMX	Traffic Manager
TRACON	Terminal Radar Approach Control Facility

1. Introduction

Interval Management (IM) is an ADS–B-enabled suite of applications that use ground and flight deck capabilities and procedures designed to support the relative spacing of aircraft (Barmore et al., 2004, Murdoch et al. 2009, Barmore 2009, Swieringa et al. 2011; Weitz et al. 2012). Relative spacing refers to managing the position of one aircraft to a time or distance relative to another aircraft, as opposed to a static reference point such as a point over the ground or clock time. This results in improved inter-aircraft spacing precision and is expected to allow aircraft to be spaced closer to the applicable separation standard than current operations. Consequently, if the reduced spacing is used in scheduling, IM can reduce the time interval between the first and last aircraft in an overall arrival flow, resulting in increased throughput. Because IM relies on speed changes to achieve precise spacing, it can reduce costly, low-altitude, vectoring, which increases both efficiency and throughput in capacity-constrained airspace without negatively impacting controller workload and task complexity. This is expected to increase overall system efficiency.

The Flight Deck Interval Management (FIM) equipment provides speeds to the flight crew that will deliver them to the achieve-by point at the controller-specified time, i.e., assigned spacing goal, after the target aircraft crosses the achieve-by point (Figure 1.1). Since the IM and target aircraft may not be on the same arrival procedure, the FIM equipment predicts the estimated times of arrival (ETA) for both the IM and target aircraft to the achieve-by point. This involves generating an approximate four-dimensional trajectory for each aircraft. The accuracy of the wind data used to generate those trajectories is critical to the success of the IM operation.

There are two main forms of uncertainty in the wind information used by the FIM equipment. The first is the accuracy of the forecast modeling done by the weather provider. This is generally a global environmental prediction obtained from a weather model such as the Rapid Refresh (RAP) from the National Centers for Environmental Prediction (NCEP). The weather forecast data will have errors relative to the actual, or truth, winds that the aircraft will encounter. The second source of uncertainty is that only a small subset of the forecast data can be uplinked to the aircraft for use by the FIM equipment. This results in loss of additional information.

The Federal Aviation Administration (FAA) and RTCA are currently developing standards for the communication of wind and atmospheric data to the aircraft for use in NextGen operations. This study examines the impact of various wind forecast sampling methods on IM performance metrics to inform the standards development.

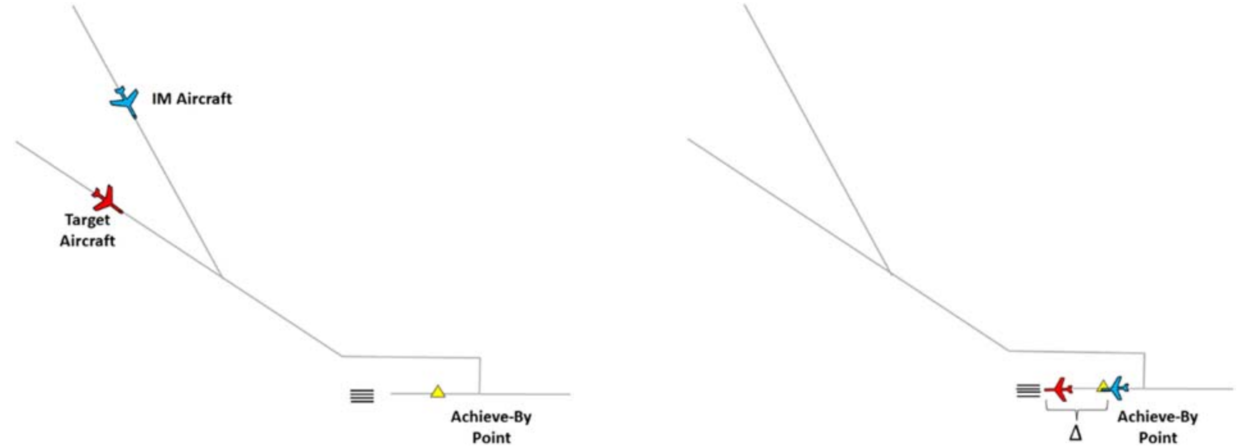

Figure 1.1: Air traffic controllers provide an IM clearance to the aircraft near the top of descent (left). The pilots follow the onboard speed guidance to achieve a precise spacing interval, Δ behind the target aircraft (right).

2. Experiment Design

This study partially addressed the following two questions:

- What subset of the full wind forecast is needed by the FIM equipment to provide the desired IM performance?
- Is the accuracy of the forecast models sufficient to achieve the desired IM performance?

The first question was addressed by testing several different wind uplink options of the same forecast data and characterizing the effect on the IM performance metrics. To address the second question, an attempt was made to validate that the wind forecast accuracy values derived from other Air Traffic Management (ATM) applications are sufficient for IM operations. The following assumptions were made in this study as part of the testing and simulation:

- All uplink data comes from the same base forecast data.
- An IM aircraft will receive wind uplink data for their route of flight as well as for their target aircraft's route of flight. This information is assumed to be available at the time of the IM clearance.
- The FIM equipment will use all wind data provided to it to generate trajectories for the IM and target aircraft.
- Sensed winds on the IM aircraft will be used to update the internal wind model that is used for both the IM and target aircraft. No sensed data will be available from the target aircraft.

The Traffic Manager (TMX) (Bussink et al. 2005; Nuic 2003) was used as the simulation platform for this study. TMX is a fast-time modeling system developed by the Dutch Aerospace Agency – Nationaal Lucht- en Ruimtevaartlaboratorium (NLR) and jointly maintained with the National Aeronautics and Space Administration (NASA). A large set of simulations of different traffic scenarios can be performed using TMX by varying relevant initial conditions. TMX has a flight management system (FMS), ADS-B models, and uses the Airborne Spacing for Terminal Arrival Routes (ASTAR) spacing algorithm developed by NASA (Abbott 2015). In this study, each traffic scenario consisted of a string of six aircraft. The first aircraft followed a selected target speed profile and the five remaining aircraft performed IM as a string of aircraft. In this section, the selected wind uplink options and the initial conditions used in various traffic scenario simulations are described in detail.

Airspace Environment

The first set of simulations investigated IM operations at the Phoenix Sky Harbor airport (KPHX), using the west flow configuration. Three arrival routes were simulated:

- CORKR transition, MAIER5 arrival;
- GUP transition, EAGUL5 arrival; and
- SSO transition, KOOLY4 arrival.

All three routes terminated at Runway 26 using the ILS26 approach (see Figure 2.1). The second set of simulations investigated IM operations at the Denver International airport (KDEN). Two arrival routes were simulated:

- HALEN transition, BOSSS1 arrival; and
- SAUGI transition, ANCHR2 arrival.

The two routes terminated at Runway 35.

Uplink Wind Options

The uplink wind option was the main independent variable of interest in this study. Given a three-dimensional wind forecast grid, the uplink option was defined as a combination of:

- the spatial location where the wind data were sampled;
- the specific altitudes where the wind data were sampled; and
- the number of data points, i.e., altitudes, that were sampled.

This data was augmented by the sensed winds at the IM aircraft's current position. It was assumed that the FIM equipment will make use of all wind information provided to build trajectories. Figure 2.1 shows the RAP model wind forecast at an altitude of 15000 ft above mean sea level (MSL) in the Phoenix simulation airspace (left panel) and at 20000 ft above MSL for the Denver simulation airspace (right panel) for two different wind conditions. The RAP model wind data were obtained from the National Climate Data Center (NCDC).

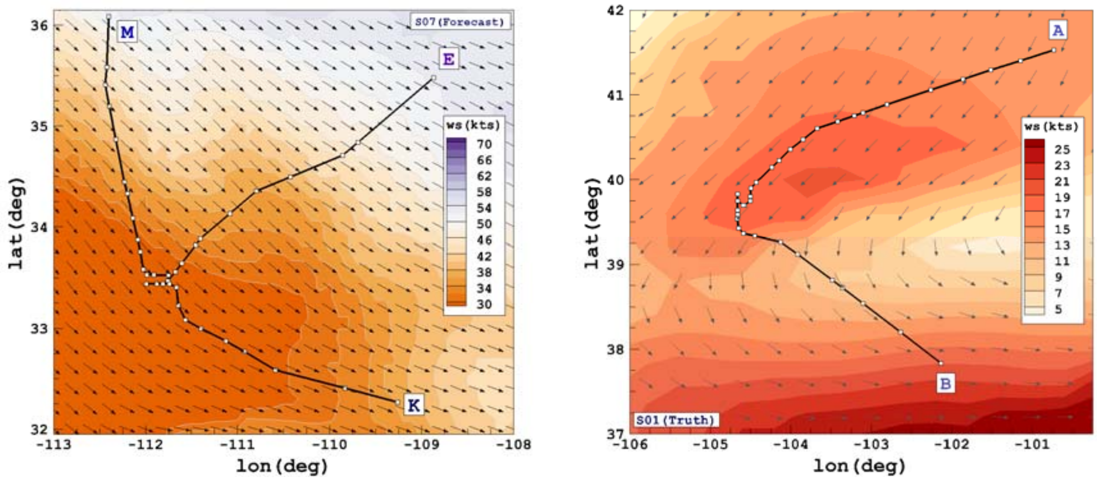

Figure 2.1: RAP model forecast for KPHX area at an altitude of 15000 ft above MSL (left panel) and RAP truth data for KDEN area at an altitude of 20000 ft above MSL (right panel). The arrows indicate the wind direction only. The magnitude of wind speed is given by the color map.

The discrete set of options consisting of the number of data points, the altitudes and the spatial location of those points along with the five selected wind forecast subset options are described below:

Spatial Location

Three different strategies were used to select the spatial location. In all cases, forecast winds at the location and altitude of the achieve-by point were included.

1. A single column at the airport – based at the airport location, the winds at different altitudes were selected and provided to both the IM and the target aircraft.
2. A single column at the mid-point on the route – at approximately the mid-point of the arrival route, for example, 60 nmi flight distance from the runway, the winds at different altitudes were selected and provided. If the IM and target aircraft are on different arrival routes, their wind forecast data will differ.
3. Along path selection – based on the expected or published vertical profile of each aircraft, a predetermined set of altitudes was selected and provided. The wind forecast was sampled at the locations where the aircraft were expected to be at each of the predetermined altitudes. If the IM and the target aircraft are on different arrival routes, their wind forecast data will differ.

It is assumed in the FIM Safety, Performance and Interoperability Requirements (SPR) (RTCA, 2011) that wind data will be provided at the expected achieve-by point crossing altitude. For the arrival operations modeled in this study, it was assumed that winds at the end of the runway and at the final approach fix (FAF is used as the achieve-by point), were close enough that no change was needed in option 1 to meet this assumption. Both option 1 and option 3 were constrained to include a lowest cross altitude at the achieve-by point. For option 2, one of the altitude points was set to the altitude at the achieve-by point.

Altitude Selection

A. A predetermined set – A fixed set of altitudes were used and remained the same for all wind conditions.

B. Optimized set – The Visvalingam-Whyatt algorithm (Visvalingam and Whyatt 1993, see Appendix A) was used to optimally select the altitudes so that the interpolated data based on the limited number of points best matched the actual vertical profile of the headwind component.

Number of Data Points

During early operational use, it is expected that data communications will not be readily available. The wind information provided will be limited to three altitudes in addition to the winds at the achieve-by point. Therefore, four altitudes, including the achieve-by point, is considered to be a minimum number or forecast wind points transmitted in a future environment where Controller Pilot Data Link Communications (CPDLC) are used. A maximum of nine points was assumed for this analysis. One of those altitude points was set to the altitude at or near the FAF. A point at the top of descent at a geographic point determined by the spatial location option was included but not counted against the total number of data points. This ensured that there was wind data bounding all expected altitudes. The draft FIM Minimum Operational Performance Standard (MOPS) being developed by RTCA assumes that the sensed winds at cruise will be used as the highest altitude winds. However, TMX does not currently support the use of sensed winds in the initial forecast data so forecast data was substituted. Since ASTAR blends the sensed winds into the forecast data provided, the cruise altitude forecast point is quickly replaced by the sensed winds at that location.

For all conditions, the full forecast data was extracted from the RAP data either along the flight path or above a fixed point. Then the specified number of points were selected from the extracted wind profile. Figures 2.2 and 2.3 show an example of wind speed at the selected altitudes for one of the wind conditions used in this analysis.

Uplink Test Conditions

The five test conditions for the uplink wind were selected from the choices described above and are described in this section. The code for each condition is comprised of three main parts. The first element is a number that indicates whether the winds were sampled at a single column (denoted by the number 2), or if they were sampled along the aircraft's intended trajectory (denoted by the number 3). The second element in the code indicates whether a standard set of locations and altitudes were used (denoted by the letter A), or if an optimization routine was used to select the optimal set of altitudes and locations (denoted by the letter B). The last element in the code indicates the number of sampling points. All altitudes are above mean sea level.

1. **2A4** – Altitude at the final approach fix, then three fixed altitudes at a geographic point approximately 60 nmi flight distance from the airport plus 35000 ft near the top of descent. The four altitudes were 10000 ft, 20000 ft, 30000 ft, and 35000 ft. These altitudes are based on those used for the FIM MOPS wind analysis.

2. **3A4** – Altitude at the final approach fix, then four altitudes along the expected flight path ending with altitude at the top of descent. The four altitudes were 8000 ft, 16000 ft, 24000 ft, and the

altitude at the top of the descent. These were approximately evenly spaced but with a preference for lower altitudes as those tend to have the largest impacts.

3. **3A9** – Altitude at the final approach fix, then nine altitudes along the expected flight path ending with 35000 ft near the top of descent. The nine altitudes were 6000 ft, 9000 ft, 12000 ft, 15000 ft, 18000 ft, 22000 ft, 26000 ft, 30000 ft, and the altitude at the top of the descent. These were spaced 3000 ft apart below 18000 ft and 4000 ft apart above 18000 ft except for the altitude point at the top of descent.

4. **3B4** – Five (four plus the one at top of descent) optimized altitudes along the route anchored by the altitudes at FAF and the top of descent.

5. **3B9** – Ten (nine plus the one at top of descent) optimized altitudes along the route anchored by the altitudes at FAF and the top of descent.

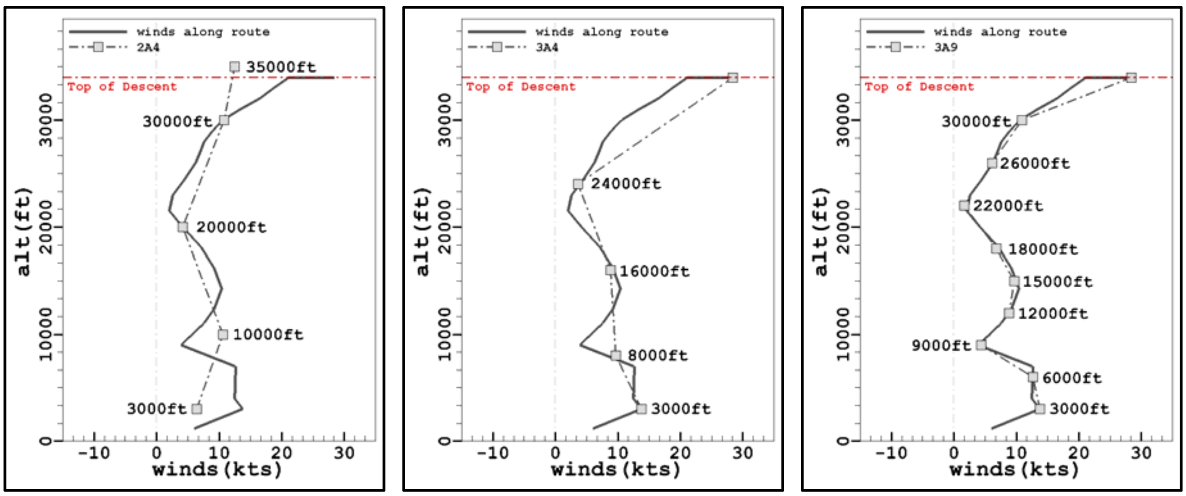

Figure 2.2: EAGUL5 Route. Wind uplink options 2A4 (left panel); 3A4 (middle panel) and 3A9 (right panel). Points with dashed lines represent the uplinked data. Solid lines are the winds along the route.

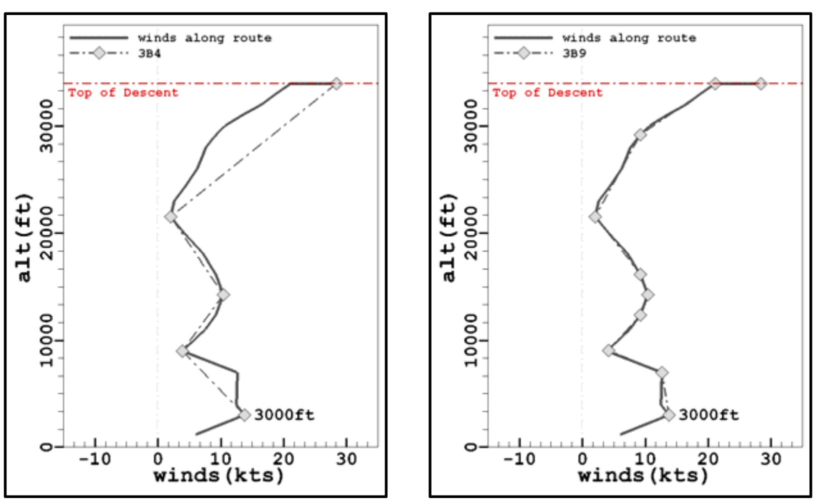

Figure 2.3: EAGUL5 Route. Wind uplink options 3B4 (left panel) and 3B9 (right panel). Points with dashed lines in the plots represent the uplinked data. Solid lines denote the winds along the route.

Test Variables

The variable of interest for this study was the uplink option as enumerated in the previous section. Each simulation consisted of one non-IM aircraft (the lead aircraft) followed by five IM aircraft. It was assumed that data from consecutive pairs of aircraft in a string are weakly correlated and therefore can be analyzed as independent samples. To represent the expected performance across an extended period of time, an average over many conditions was required. The following conditions were included in this study:

- Wind conditions:
  - Ten options sampled equally for the Phoenix airspace, see Table 2.1.
  - Eight options sampled equally for the Denver airspace, see Table 2.2.
- Lead speed profile:
  - Five options sampled equally for the Phoenix airspace (Swieringa et al. 2014).
  - Nominal speed profiles for the two routes sampled equally for the Denver airspace.
- Route assignment (uniform with no repetition)
- Aircraft type (uniform from limited set; see Table 2.3)
- Initial delay (Gaussian, mean = 30 sec; σ = 20 sec). The initial delay is the difference between the actual initiation time and the time that would be expected if the aircraft would fly the published speed profile and arrive at the scheduled time of arrival (STA).
- Aircraft weight (uniform; see Table 2.3)

The wind conditions (pairs of truth and forecast wind grids) were provided by MIT's Lincoln Lab (Troxel 2014) for the Phoenix Airspace. The wind data is based on MIT's climatological analysis of one year's RAP data covering the entire Continental United States (Table 2.1). The selection criteria of wind conditions for the Denver airspace (Table 2.2) is described in Swieringa (2015).

Table 2.1: Phoenix Airspace Weather Conditions

Scenario	Truth Data		Forecast Data	
	Date	**Time**	**Date**	**Time**
1	2014/05/17	18:00	2014/05/17	16:00
2	2014/07/18	6:00	2014/07/18	4:00
3	2014/07/31	6:00	2014/07/31	4:00
4	2013/09/11	12:00	2013/09/11	10:00
5	2013/11/08	12:00	2013/11/08	10:00
6	2014/02/02	6:00	2014/02/02	4:00
7	2014/01/04	18:00	2014/01/04	16:00
8	2014/03/05	12:00	2014/03/05	10:00
9	2014/07/18	12:00	2014/07/18	10:00
10	2013/11/23	6:00	2013/11/23	4:00

Table 2.2: Denver Airspace Weather Conditions

Scenario	Truth Data		Forecast Data	
	Date	**Time**	**Date**	**Time**
1	2011/12/10	23:00	2011/12/10	17:00
2	2012/05/31	1:00	2012/05/31	4:00
3	2012/04/03	13:00	2012/04/03	11:00
4	2011/02/04	15:00	2011/02/04	12:00
5	2013/01/04	12:00	2013/01/04	7:00
6	2013/09/23	0:00	2013/09/22	21:00
7	2013/05/10	3:00	2013/05/09	22:00
8	2012/09/12	15:00	2012/09/12	18:00

Five representative speed profiles for the lead aircraft were used to represent expected behavior from a controller using future automation for the Phoenix simulations. Nominal speed profiles were used for the Denver simulations. Aircraft type was selected from the available BADA models (see Table 2.3). Aircraft weight was also selected from BADA reference mass plus 0-50% max payload. This is a rough estimate of acceptable landing weights as BADA does not provide landing weight information.

Table 2.3: Aircraft types and weight range.

Aircraft Type	Reference Mass (t)	Max Payload	minimum	maximum
B737-700	60	16.9	60	68.45
B777-300	238	64.9	238	270.45
A320	64	21.5	64	74.75
A319	60	17	60	68.5
B757-200	95.3	21.4	95.3	106
A306	280	78	280	319

Based on a power analysis, a minimum of 200 data points per test condition was needed to detect at least a one second difference in the mean delivery error. For each test condition in the Phoenix simulations, the full set of ten wind conditions and five lead speed profiles were used. Strings of five IM pairs resulted in a total of 250 data samples per test condition for the Phoenix airspace simulations. A total of eight wind conditions resulted in 200 data samples per test condition for the Denver airspace simulations.

Analyses Metrics

The following key metrics were used in the analyses of the simulation data:

1. Delivery error – the difference between the achieved spacing interval and the assigned spacing goal at the achieve-by-point. Negative numbers indicate that the achieved spacing interval was less than the assigned spacing goal.
2. RMS of IM speed deviation – The Root-Mean-Square (RMS) value of the difference between the IM Speed and the profile speed. This provides a measure of how much control the spacing algorithm needed to apply in order to achieve the assigned spacing goal. The RMS of IM speed deviation will be effected by the speed profile flown by the Target aircraft, the winds, and the initial spacing error. However, since all of these variables were replicated for each wind uplink option in this experiment, the RMS of IM speed deviation is an indication of whether aircraft using a particular wind uplink option required a greater amount of speed control to achieve the spacing goal.
3. Number of speed commands – a count of the number of times the IM speed commanded by the ASTAR algorithm changed. It should be noted that the speeds commanded by the ASTAR algorithm were discretized into five or ten knot increments, depending on the distance to the achieve-by point. Thus, a speed change occurred every time the value of the discrete commanded speed changed.

3. Phoenix Airspace

Analyses of Phoenix simulations is presented in this section. In these simulations a total of 1250 data points were collected with 250 data points for each of the five uplink conditions.

Simulations

As discussed below, the results were not as definitive as expected. Therefore, additional runs were performed in an attempt to eliminate sources of uncertainty that could have masked the expected effect. This section focuses on Run 1, the original design, with comments in the analysis on the effects of the modifications for runs 2-4.

The four sets of simulations were:

- Run 1: Baseline simulation as described in the previous sections. This had the full range of variability and the target aircraft following delay trajectories that were unknown to the IM Aircraft (expected condition for initial IM deployment).
- Run 2: Nominal speed profiles were used for the target aircraft and all other parameters were kept the same as in Run 1. This had the full range of variability except that the target aircraft was following the speed profile that was given to the IM aircraft. This condition was designed to emulate an Advanced IM environment where the specific speed profile of the target aircraft can be communicated to the IM Aircraft. See Appendix B for details.
- Run 3: Nominal speed profiles were used for the target aircraft. No wind forecast error was assumed (all other parameters were same as in Run 1). This removed the forecast winds as a source of uncertainty. The results focus on the effects of having a discrete forecast sent to the IM Aircraft. See Appendix B for details.
- Run 4: Nominal speed profiles were used for the target aircraft. No wind forecast error was assumed. A total of 60 wind conditions were used which increased the total number of scenarios from 250 to 1500 (all other parameters were same as in Run 1). This extended Run 3 to include a wider range of wind conditions. See Appendix B for details.

The dates for the additional 60 wind conditions were provided by MITRE and match the selected wind conditions used in the FIM MOPS analysis. These sixty wind conditions were in addition to the wind scenarios provided by MIT. The Run 4 simulations were conducted to determine if some of the unexpected behavior seen was a result of using winds from a small sampling of days.

A total of 1250 data points were collected with 250 data points for each of the five uplink conditions. Distributions of data are shown as a combined box-and-whisker plot with a mean-standard deviation overlay (e.g., see Figure 3.1). The mean and standard deviation are shown by a green rectangle extended plus and minus the standard deviation away from the central green line representing the mean of the distribution. The box portion shows the median (red vertical line) and the interquartile distance in both directions. The interquartile distances represent the 25-50 percentile and 50-75 percentile of the data and are not necessarily equal in size. The notch in the box is an estimate of significant differences. If the median of one distribution falls outside the notch on another, then the difference between the two distributions is statistically significant. On both sides of the box the whiskers extend 1.5 times the interquartile distance on that side. Any data points falling outside the whiskers are shown individually as an orange circle.

Delivery Accuracy and Precision

The delivery accuracy and precision are measures of how precisely the IM algorithm is able to achieve the desired spacing goal. Previous work has shown that the delivery error roughly follows a Gaussian distribution, at least for the central peak. Therefore, summary statistics are shown for both the mean and standard deviation of the delivery. The central 95% of the data, symmetric around the median, is also shown. The summary statistics of delivery accuracy for Run 1 are shown in Table 3.1. Uplink option 3B9 had the smallest mean delivery accuracy while option 3A9 had the smallest standard deviation. Figure 3.1 shows the box-and-whisker plot for Run 1 for each of the uplink options.

Table 3.1: Run 1 – Delivery Error at Final Approach Fix statistics.

Option	Mean (s)	σ (s)	Median (s)	95% (s)
2A4	1.809	2.719	1.800	11.225
3A4	1.921	2.798	1.500	11.375
3B4	1.606	2.507	1.300	10.300
3A9	1.973	2.368	1.800	8.350
3B9	1.562	2.624	1.500	8.850

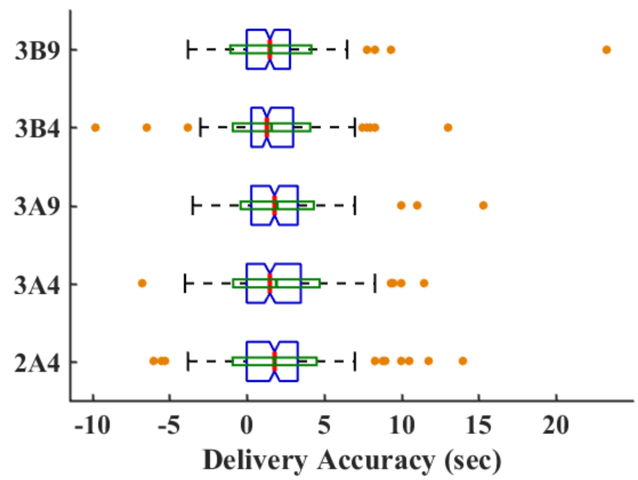

Figure 3.1: Phoenix Airspace. Box-and-whisker plot for delivery error across the five uplink options for Run 1.

For all four runs, ANOVA tests were performed to identify any statistically significant differences in the mean delivery error ($p < 0.05$). The tests identified statistically significant differences between options 3A4 and both 3A9 and 3B9 in Run 3. In Run 4, options 3B9 and 3A4 were determined to have statistically significant differences. No statistically significant differences were found in delivery error as a function of uplink option in Runs 1 and 2. Statistically significant differences were also found in delivery error as a function of uplink points (four vs. nine) in Runs 3 and 4.

For Run 1 and 2, where the wind model had forecast errors, only the options with 9 altitudes, 3A9 and 3B9, met the performance goal of having 95% of aircraft delivered within a ±10 second bound. When the forecast error was removed from the wind model, Runs 3 and 4, all uplink options met the 10 second, 95% goal. However, options 3A9 and 3B9 continued to have small 95% bounds, indicating that the delivery accuracy distributions for the 3A9 and 3B9 wind uplink options had fewer outliers in the tails of their distributions than the other wind uplink options. One possible explanation for this is that the large number of forecast points enabled a more accurate prediction of the IM aircraft's ETA and the target aircraft's ETA, and provided a more accurate wind forecast close to the achieve-by point. In some cases, this combination could have prevented large spacing errors from occurring when the IM aircraft is close to the achieve-by point.

Root Mean Square of Speed Control

The RMS of the speed control throughout the arrival was examined to determine if particular wind forecast uplink options required less speed control than others. The RMS of the speed control is sensitive to the magnitude of the initial spacing error; however, the initial spacing errors for each wind forecast method were sampled from the same distribution. Thus, an increase in the RMS of the speed control indicates less optimal performance. Statistics summaries for Run 1 are given in Table 3.2. Figure 3.2 shows the box-and-whisker plot for Run 1 for each of the uplink options.

Table 3.2: Run 1 – RMS of difference between IM Speed and profile speed.

Option	Mean (kts)	σ (kts)	Median (kts)	95% (kts)
2A4	7.702	3.508	7.184	14.066
3A4	9.393	4.099	8.744	16.119
3B4	8.190	3.097	7.610	11.824
3A9	8.583	3.326	8.060	12.829
3B9	7.965	3.116	7.771	11.781

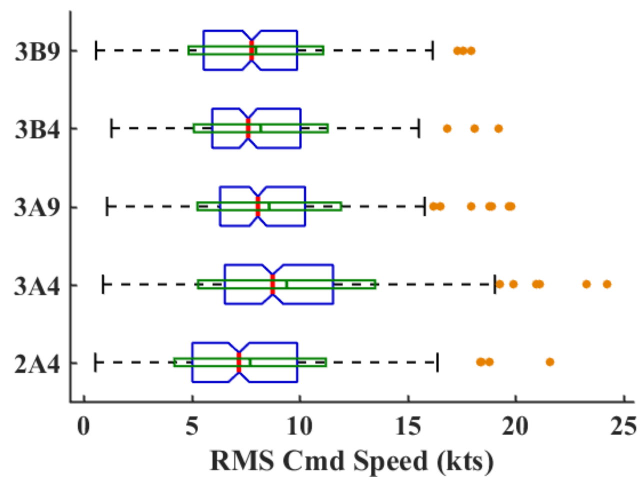

Figure 3.2: Phoenix Airspace. Box-and-whisker plot for RMS speed difference across the uplink options for Run 1.

An ANOVA test was performed to look for differences between the five uplink options. Statistically significant differences between conditions were found in all four runs. In Runs 1 and 2 the differences between the means of groups 3A4 and 3A9 were statistically significant from 2A4 and the differences between the means of both 3B4 and 3B9 wind uplink options were statistically significantly lower than the 3A4 wind uplink option. In Runs 3 and 4 the differences between the means of groups 2A4, 3B4 and 3B9 were statistically significant from 3A4.

The results do not show a large difference in the average amount of speed control; however, it is interesting to note that the wind uplink options that used an optimization routine to select the locations and altitudes where the winds were sampled (condition 3B4 and 3B9) had a lower 95th percentile value than the other wind uplink options. Additionally, examining the subset of wind uplink options that did not use the optimization routine indicates that the wind uplink option with nine points (3A9) required less speed control than the non-optimized wind uplink options with fewer points. One explanation for this data is that a majority of the wind fields have very little variability, allowing them to be accurately sampled by any of the uplink options that were investigated. However, more complex wind patterns require either a greater number of points to sample them accurately or for the locations of the sample points to be chosen optimally to maximize the accuracy of the forecast. Thus, using a high number of sampling points or optimizing will provide more consistent performance across a wider range of wind conditions; particularly those with more complex structure.

Number of IM Speed Commands

The number of speed changes commanded by the FIM Equipment was used as a proxy for the workload on the flight crew to perform the IM operation after the operation has begun. The statistics summaries for total number of speed changes per flight are given in Table 3.3 for Run 1. Figure 3.3 shows the box-and-whisker plot for Run 1 for each of the uplink options.

Table 3.3: Run 1 – Total number of speed changes per flight.

Option	Mean	σ	Median	95%
2A4	9.98	1.67	10	6
3A4	10.82	2.11	11	8
3B4	10.61	2.02	11	8
3A9	10.49	1.88	10	7
3B9	10.03	1.77	10	7

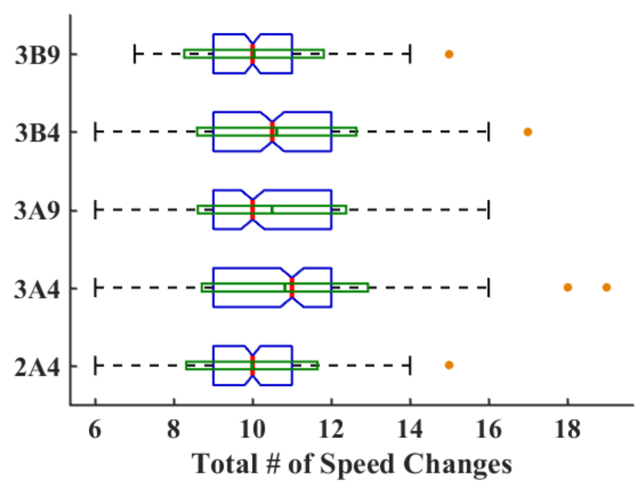

Figure 3.3: Phoenix Airspace. Box-and-whisker plot for total number of speed changes across the five uplink options for Run 1.

ANOVA tests revealed several statistically significant differences in the mean number of speed changes over the whole operation. Option 2A4 was statistically different from options 3A4, 3A9, and 3B4. Option 3B9 was statistically different from option 3A4 and 3B4. The test for differences in the number of speed changes has strong statistical power and is therefore apt to detect differences that are not operationally relevant. The mean number of speed changes never varied by more than one per arrival operation.

4. Denver Airspace

Analyses of the Denver simulations is presented in this section. A total of 1000 data points were collected with 200 data points for each of the five uplink conditions. A small number of TMX simulations did not run to completion and were not included in the analyses. The final data set used in the following analyses consisted of 915 points.

Simulations

Only one set of simulations was run for the Denver airspace which was equivalent to Run 3 described in Section 3. Nominal speed profiles were used for the target aircraft and no wind forecast error was assumed (all other parameters were same as in Run 1 for Phoenix airspace with the exception that Denver simulations had eight wind conditions instead of ten). Uncertainty due to wind forecast error was removed and the results are focused on the effects of having a discrete forecast sent to the IM Aircraft. Additional waypoints were added to the ANCHR2 route in order to simulate the RNP turn at the end of the route in TMX.

Delivery Accuracy and Precision

The summary statistics of delivery accuracy are shown in Table 4.1. Uplink option 3B9 had the smallest mean in delivery accuracy and the smallest standard deviation. Figure 4.1 shows the box-and-whisker plot for each of the uplink options. An ANOVA test showed that the options 3B9 and 2A4 had mean delivery errors significantly lower than that of 3A4. The means and the standard deviations were larger compared to the Phoenix simulations.

Table 4.1: Delivery Error at Final Approach Fix statistics.

Option	Mean (s)	σ (s)	Median (s)	95% (s)
2A4	2.583	4.689	3.000	16.062
3A4	4.024	4.466	4.500	16.925
3B4	2.799	4.267	2.800	16.237
3A9	3.421	4.333	3.400	16.775
3B9	2.254	4.253	2.300	15.537

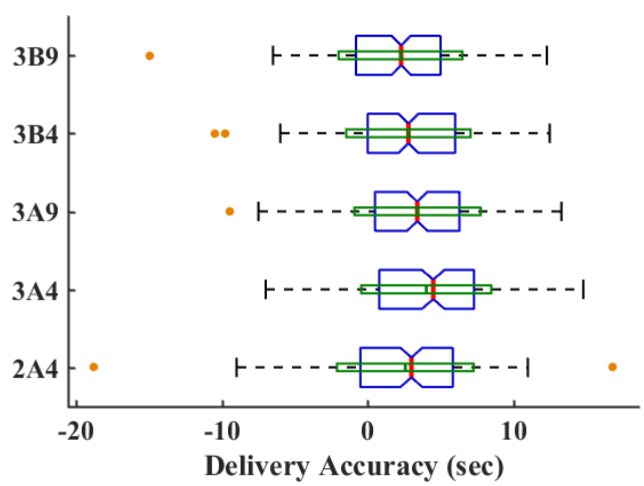

Figure 4.1: Denver Airspace. Box-and-whisker plot for delivery error across the five uplink options.

Root Mean Square of Speed Control

Statistics summaries for the speed control are given in Table 4.2. Figure 4.2 shows the box-and-whisker plot for each of the uplink options. An ANOVA test, which was performed to look for differences between the five uplink options, revealed statistically significant differences. The differences between the means of groups 2A4 and 3A4 were statistically significant from 3B9. Means for wind uplink options 3B9 and 3B4 were significantly lower than the 3A4. This indicates that the 3B4 and 3B9 uplink conditions required a smaller amount of speed control than the 2A4 and 3A4 uplink conditions

The Denver simulations showed that less speed control was required to achieve the assigned spacing goal for the optimized options (conditions 3B4 and 3B9) than the 2A4 and 3A4 uplink conditions. This difference was not obvious in the Phoenix airspace simulations. Conditions 3B4 and 3B9 also had a lower 95th percentile value than the other wind uplink options.

The 3B4 and 3B9 wind uplink options, which optimally selected the altitudes of the forecast winds, required less speed control than the corresponding options where the wind forecast altitudes were fixed.

Table 4.2: RMS of difference between IM Speed and profile speed.

Option	Mean (kts)	σ (kts)	Median (kts)	95% (kts)
2A4	14.399	5.423	15.032	20.658
3A4	14.913	5.816	14.047	23.103
3B4	13.273	4.810	14.169	19.607
3A9	14.059	4.960	14.675	22.835
3B9	12.900	5.016	14.228	17.432

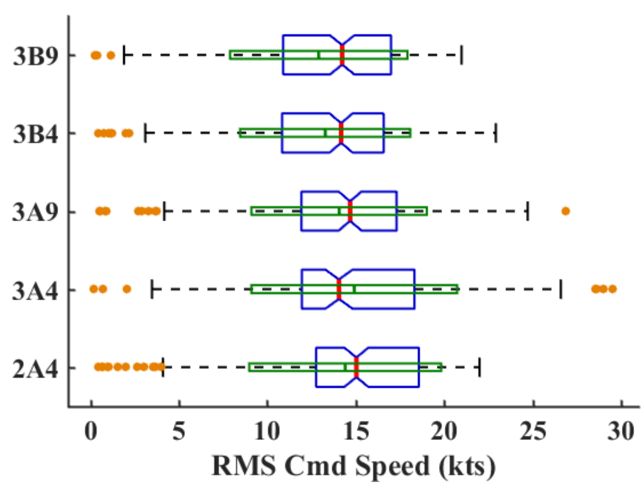

Figure 4.2: Denver Airspace. Box-and-whisker plot for RMS of speed control across the five uplink options.

Number of IM Speed Commands

The statistics summaries for total number of IM speed commands per flight are given in Table 4.3 and the Figure 4.3 shows the box-and-whisker plot for each of the uplink options.

ANOVA tests revealed several statistically significant differences in the mean number of IM speed commands over the entire operation. Options 2A4 and 3A4 had means that are significantly different than 3B9. Options 3A9 and 3A4 and options 3B4 and 3A4 were significantly different. Options 3A4 and 3B9 had means that are significantly different than 2A4. Uplink options 2A4, 3A4, 3A9, and 3B9 had means that were significantly different than 3A4. Compared to the Phoenix simulations, the mean number of IM speed commands were lower in these simulations. While there were statistically significant differences detected, the difference between the mean of IM speed changes for the various uplink conditions was always less than one, suggesting that the difference may not have a large operational impact.

Table 4.3: Total number of speed changes per flight.

Option	Mean	σ	Median	95%
2A4	8.70	2.15	9	8
3A4	9.48	2.70	9	9
3B4	8.63	2.14	8	8
3A9	8.35	1.93	8	8
3B9	8.08	1.71	8	6

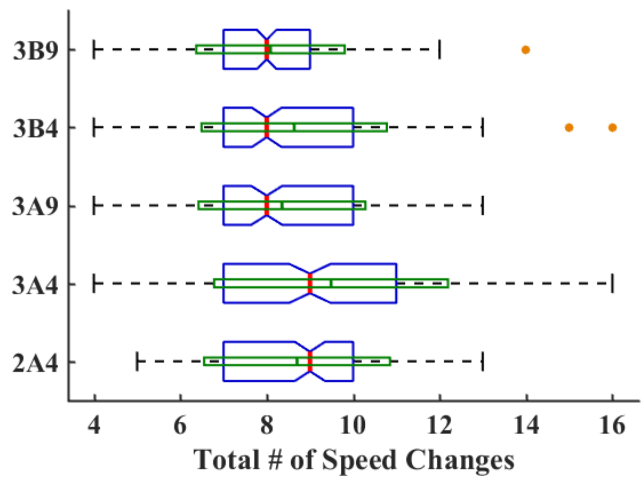

Figure 4.3: Denver Airspace. Box-and-whisker plot for total number of speed changes across the five uplink options.

5. Summary

A fast-time simulation study was conducted to examine five wind forecast uplink options to determine the effects of the uplink options on three key performance metrics. The uplink options were identified based on location, number of points and the altitudes sampled. Performance was compared for three metrics: the delivery accuracy, number of speed commands, and the total amount of speed control used throughout an arrival.

It was expected that the 2A4 uplink option would have the worst performance, since it uses the fewest number of altitudes; the altitudes are pre-selected, which means that they likely miss the actual structure of the wind profile; and all of the wind points are sampled at a single geographic point instead of along the flight profile. Option 3A4 was expected to be a slight improvement since the forecast data was sampled along the expected flight trajectory. Both the 3A9 and 3B4 options were expected to further improve performance by providing better representations of the wind profile. Option 3A9 by including samples at five additional altitudes and option 3B4 by optimally selecting the altitudes to sample. Finally, option 3B9 combined all of these improvements and was thus expected to provide the best performance. However, this was not the case. For most metrics and runs there was no statistically significant differences between the uplink conditions.

A one-way ANOVA combined with t-tests showed no significant differences in delivery accuracy for the uplink option. This was unexpected as increasing the number of altitudes sampled, using a set of altitudes optimized to best represent the actual profile shape, and sampling at points along the expected vertical path were all assumed to improve the overall performance. When removing the uncertainty added by forecast errors in the forecast model, a small difference was detected between the 3A4 and 3B9 uplink options across the full 70 wind conditions (Run 4). This difference was only 0.3 seconds in the mean and median, so the operational impact of the difference would be small.

Looking at the 95% bounds on delivery error does reveal some differences between the uplink options. The 3A9 and 3B9 options consistently show a smaller 95% bound suggesting that the greater number of forecast data points reduces the number of outliers. While the operational benefits of small changes in the mean delivery may be small, a reduction in the 95% bounds of 2-3 seconds would be operationally significant. A similar trend can be seen in the other metrics, although not as pronounced.

The means RMS commanded speed of uplink options 3A9 and 3B4 were significantly different. The RMS metric is a relatively new attempt to assess the amount of control needed to meet the final delivery. While the delivery error metric measures the end state, the RMS of the differences in speeds attempts to capture the dynamics of the entire operation into one system-level metric. Because this is a relatively new metric of consideration, it is not known what the operationally relevant differences are. For this metric in particular, the 3A4 uplink option was consistently larger than the other options, indicating that the IM algorithm required a greater amount of speed control to achieve the assigned spacing goal.

Significant differences were observed between different uplink options in the total number of speed change commands. However, the differences in the mean and median were never more than one speed change and the difference between the 95% range was also never greater than one speed change.

There are at least two possible explanations for the limited differentiation between the uplink conditions. First, four wind points may provide sufficient information to reduce the effects of the discrete forecast data to below other sources of spacing uncertainty. However, simulations done in support of the FIM MOPS, using a different FIM algorithm, showed improvement when adding more altitudes to the discrete forecast data. A similar trend can be seen when collapsing the data across location and altitude selection and just focusing on the number of altitudes provided (see Table 5.1). In the table, those differences that are statistically significant are shown in red text. Also, ASTAR constantly blends the IM Aircraft's sensed winds into the internal wind model so ASTAR is partially correcting the forecast data to match the sensed data. While the effect of this blending is limited in range, it partially offset the effects of wind forecast errors.

Table 5.1: Statistically significant differences based on location and points (KPHX).

Run	Location along-route/fixed		Number of Points 4/9	
	delivAcc (s)	**RMS Spd Cmd (kts)**	**delivAcc (s)**	**RMS Spd Cmd (kts)**
1	1.76/1.81	**8.53/7.70**	1.77/1.76	8.42/8.27
2	1.78/1.83	**8.52/7.69**	1.80/1.77	8.41/8.27
3	1.72/1.66	**8.00/7.37**	**1.82/1.55**	**8.15/7.47**
4	1.77/1.81	**7.62/7.28**	**1.85/1.68**	**7.72/7.29**

The second possible explanation is that the winds in the Phoenix area appear to be rather smooth and similar across the routes studied. As can be seen in Figure 5.1, there are only small variations along the routes, reducing the difference between sampling along the flight profile or at a single geographic point, and the vertical profile has little structure, reducing the impact of the number of altitudes selected and the specific altitudes. In fact, as Figure 5.1 shows for wind condition 7 (Table 2.1), the vertical profiles along all three arrival routes are nearly straight lines so only two altitudes would be needed to describe the winds. Additional runs were performed in an attempt to eliminate sources of uncertainty, such as wind forecast error, that could have masked the expected effect of uplink information (Appendix B).

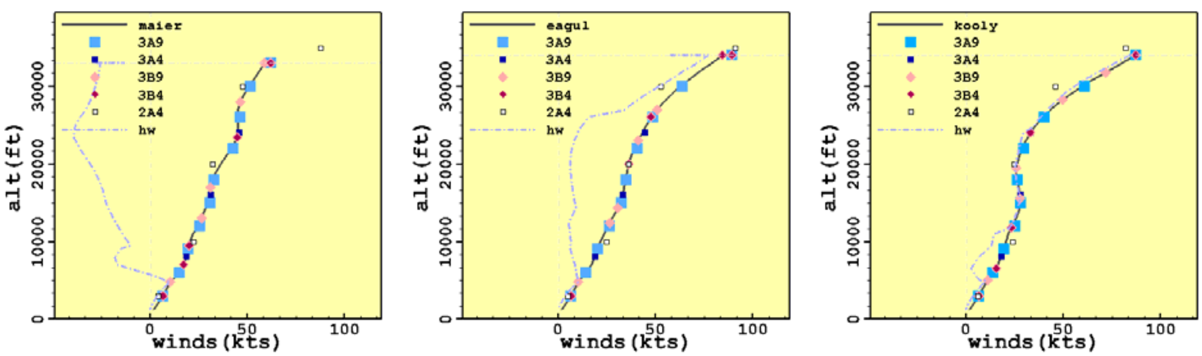

Figure 5.1: Phoenix Airspace. Wind uplink options for wind condition 7. From left to right are the MAIER5, EAGUL5, and KOOLY4 routes. Points in the plots represent the uplinked data. Solid lines denote the winds along the route and dashed lines are the headwind component.

The study was extended to the Denver airspace which was expected to have greater spatial wind variability and it was hoped that larger differences between the uplink options may become apparent. Although the spatial variability was larger in the Denver simulations, the results were similar to the behavior observed in the Phoenix simulations.

Acknowledgment

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Appendix A: Visvalingam-Whyatt Algorithm

Polyline simplification is used extensively in cartography and several algorithms of varying complexity have been proposed in the past (Figure A.1). Shi and Cheung (2006) provide a detail description and evaluation of nine such algorithms.

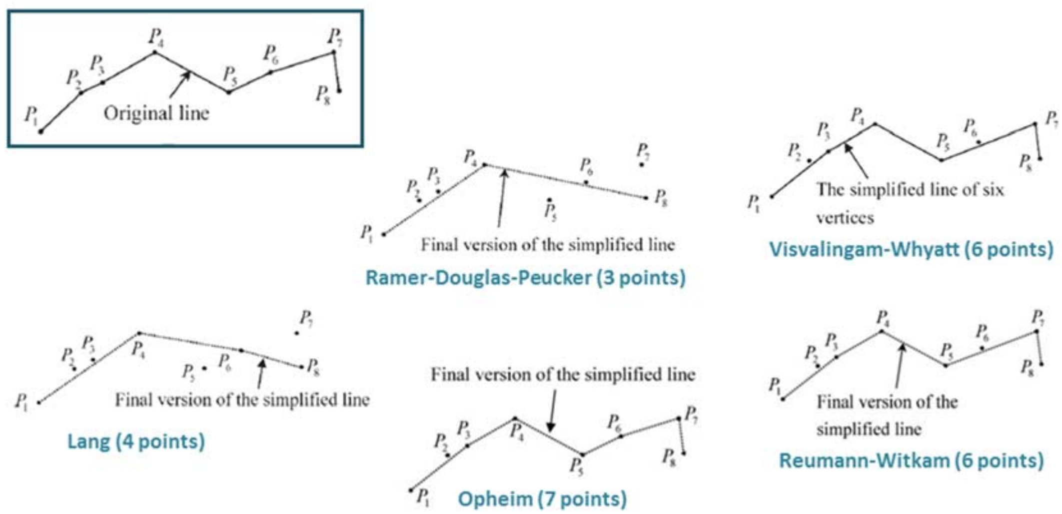
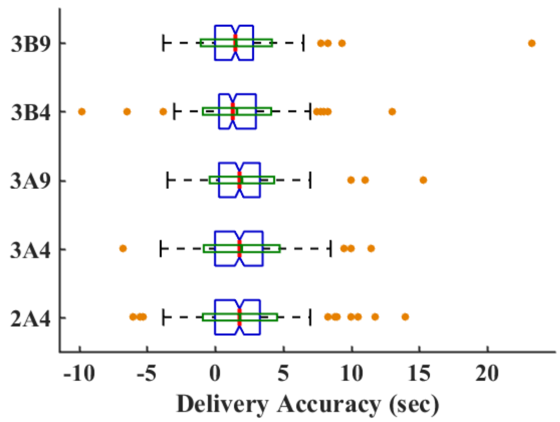


Figure A.1: Performance of different polyline simplification algorithms. Figure adapted from Shi and Cheung (2006).

In this study the Visvalingham-Whyatt algorithm (Visvalingam and Whyatt 1993) was used to generate an optimized reduced set of wind uplink data in order to efficiently represent the entire vertical wind profile. In the Visvalingam-Whyatt algorithm, each point of the polyline is assigned an *effective area*. The *effective area* is the area of the triangle formed by the point and its two neighbors. The point with the smallest *effective area* is deleted from the list. The method is repeated until the polyline is reduced to the required number of points. The algorithm is simple to implement and computationally inexpensive.

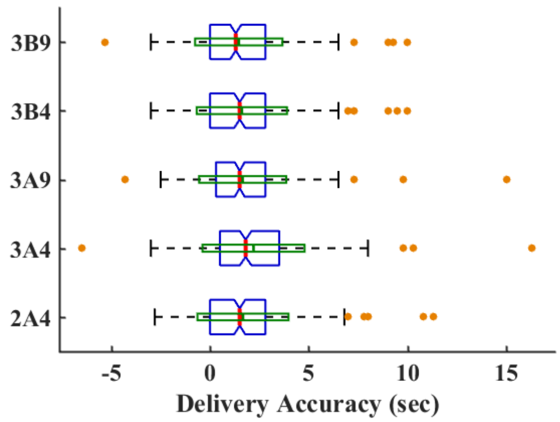
Appendix B: Phoenix Simulation Results

Delivery Error at Final Approach Fix



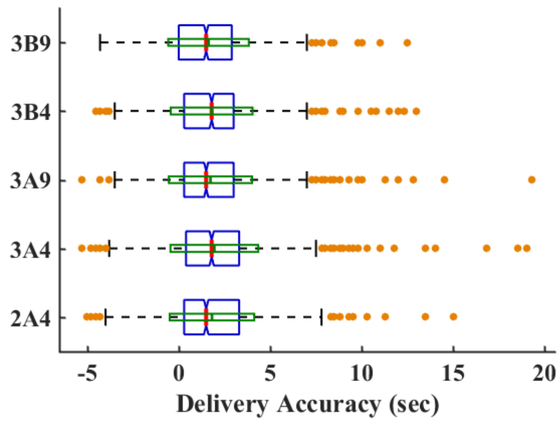
Run 2

Option	Mean(s)	σ(s)	Median(s)	95%(s)
2A4	1.832	2.728	1.800	11.225
3A4	1.964	2.795	1.800	11.375
3B4	1.615	2.513	1.300	10.300
3A9	1.977	2.369	1.800	8.350
3B9	1.567	2.616	1.500	8.800



Run 3

Option	Mean(s)	σ(s)	Median(s)	95%(s)
2A4	1.665	2.305	1.500	9.075
3A4	2.200	2.585	1.800	9.975
3B4	1.611	2.286	1.500	9.300
3A9	1.649	2.206	1.500	7.960
3B9	1.454	2.213	1.300	8.650

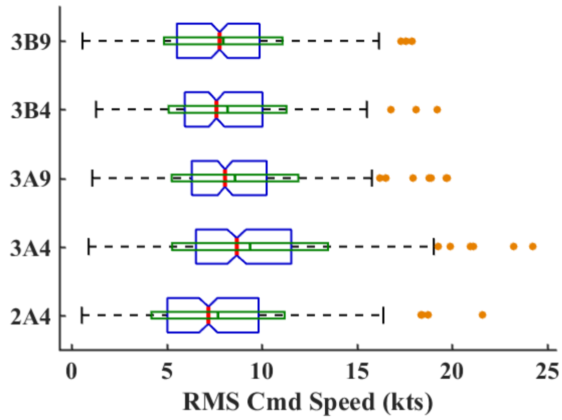


Run 4

Option	Mean(s)	σ(s)	Median(s)	95%(s)
2A4	1.817	2.311	1.500	9.1
3A4	1.946	2.396	1.800	9.1
3B4	1.798	2.234	1.800	9.1
3A9	1.734	2.272	1.500	8.3
3B9	1.629	2.203	1.500	8.5

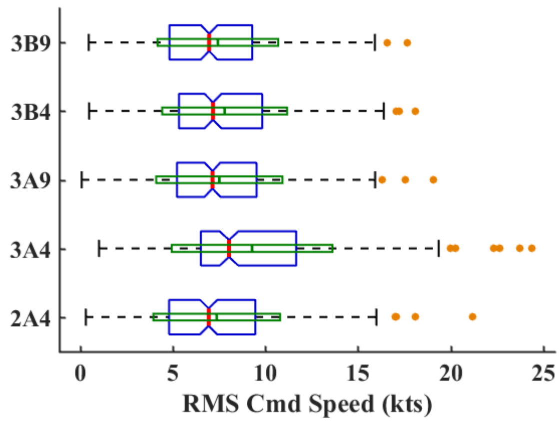
Figure B.1: Statistics and plots for delivery error across the five uplink options. Run 2 (top row); Run 3 (middle row); and Run 4 (bottom row).

IM Speed Difference from Profile Speed



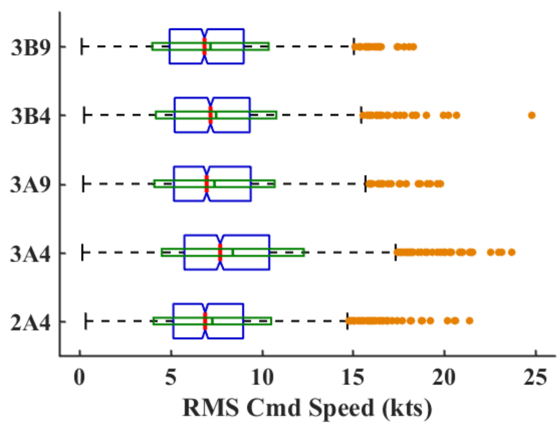
Run 2

Option	Mean(kts)	σ(kts)	Median(kts)	95%(kts)
2A4	7.692	3.501	7.184	14.066
3A4	9.377	4.095	8.676	16.11
3B4	8.191	3.098	7.611	11.832
3A9	8.583	3.326	8.060	12.829
3B9	7.965	3.115	7.771	11.781



Run 3

Option	Mean(kts)	σ(kts)	Median(kts)	95%(kts)
2A4	7.377	3.420	6.942	13.095
3A4	9.283	4.339	8.036	16.801
3B4	7.802	3.371	7.173	13.690
3A9	7.513	3.407	7.145	14.413
3B9	7.436	3.258	6.965	12.822

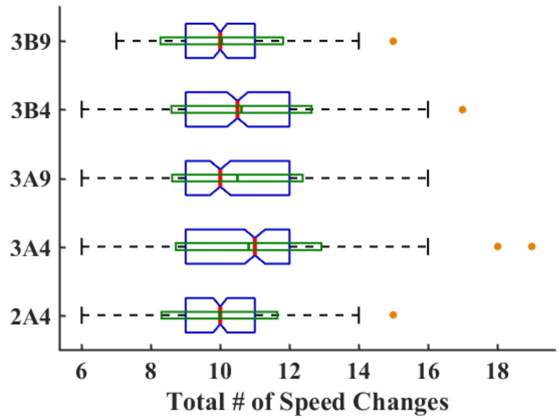


Run 4

Option	Mean(kts)	σ(kts)	Median(kts)	95%(kts)
2A4	7.284	3.229	6.891	13.508
3A4	8.407	3.898	7.715	15.461
3B4	7.493	3.307	7.185	13.235
3A9	7.405	3.303	6.976	13.533
3B9	7.184	3.194	6.853	13.082

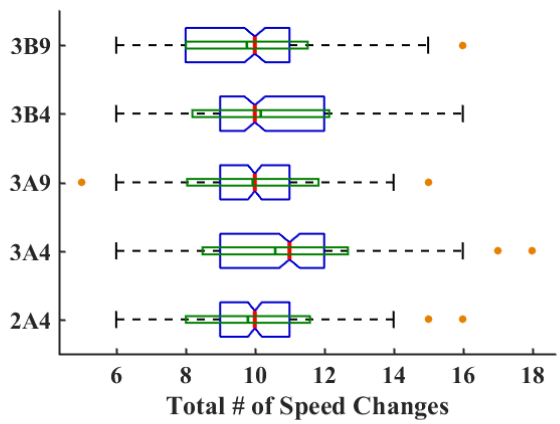
Figure B.2: Statistics and plots for RMS speed difference across the five uplink options. Run 2 (top row); Run 3 (middle row); and Run 4 (bottom row).

Number of IM Speed Commands



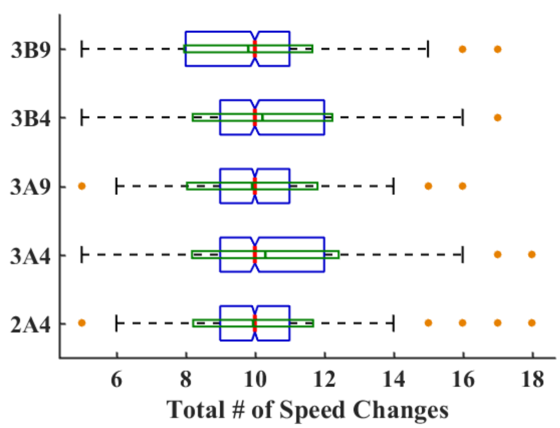
Run 2

Option	Mean	σ	Median	95%
2A4	9.97	1.67	10	6
3A4	10.82	2.1	11	8
3B4	10.61	2.02	11	8
3A9	10.49	1.88	10	7
3B9	10.04	1.77	10	7



Run 3

Option	Mean	σ	Median	95%
2A4	9.80	1.79	10	7
3A4	10.58	2.09	11	8
3B4	10.17	1.97	10	7
3A9	9.94	1.89	10	7
3B9	9.76	1.75	10	6



Run 4

Option	Mean	σ	Median	95%
2A4	9.95	1.73	10	7
3A4	10.30	2.11	10	8
3B4	10.21	2.01	10	8
3A9	9.92	1.88	10	7
3B9	9.80	1.85	10	8

Figure B.3: Statistics and plots for total number of speed changes across the five uplink options. Run 2 (top row); Run 3 (middle row); and Run 4 (bottom row).

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Interval Management (IM) is an ADS–B-enabled suite of applications that use ground and flight deck capabilities and procedures designed to support the relative spacing of aircraft (Barmore et al., 2004, Murdoch et al. 2009, Barmore 2009, Swieringa et al. 2011; Weitz et al. 2012). Relative spacing refers to managing the position of one aircraft to a time or distance relative to another aircraft, as opposed to a static reference point such as a point over the ground or clock time. This results in improved inter-aircraft spacing precision and is expected to allow aircraft to be spaced closer to the applicable separation standard than current operations. Consequently, if the reduced spacing is used in scheduling, IM can reduce the time interval between the first and last aircraft in an overall arrival flow, resulting in increased throughput. Because IM relies on speed changes to achieve precise spacing, it can reduce costly, low-altitude, vectoring, which increases both efficiency and throughput in capacity-constrained airspace without negatively impacting controller workload and task complexity. This is expected to increase overall system efficiency.

15. SUBJECT TERMS

Aircraft; Flight characteristics; Flight deck; Interval management; Spacing

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