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Wind Information Requirements for NextGen Applications

Phase 3 Final Report

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16. Abstract

Many NextGen applications depend on access to high accuracy wind data due to time-based control elements, such as required time of arrival at a meter fix under 4D-Trajectory-Based Operations/Time of Arrival Control procedures or compliance to an assigned spacing goal between aircraft under Interval Management procedures. Any errors in the ground and/or aircraft wind information relative to the truth winds actually flown through can significantly degrade the performance of the procedure. Unacceptable performance could be mitigated by improving wind information in the aircraft, for example, by using higher accuracy wind forecast models to generate wind inputs for the ground or airborne systems, updating wind information more frequently, or to upgrade the way winds are handled in the avionics systems. The work described in this report summarizes the activities conducted in FY14, which builds upon prior work. It (1) establishes the relationship of wind information accuracy to 4D-TBO and IM performance for a selection of operationally relevant scenarios to identify wind needs to support them, and (2) presents examples of what wind information content and update rate to the aircraft will deliver a given target performance level to help inform concept of operations development and datalink technology needs.

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EXECUTIVE SUMMARY

Many NextGen applications depend on access to high accuracy wind data due to time-based control elements, such as required time of arrival (RTA) at a meter fix under 4D-Trajectory-Based Operations (4D-TBO)/Time of Arrival Control (TOAC) procedures or compliance to an assigned spacing goal (ASG) between aircraft under Interval Management (IM) procedures. Any errors in the ground and/or aircraft wind information relative to the truth winds actually flown through can significantly degrade the performance of the procedure. Unacceptable performance could be mitigated by improving wind information in the aircraft, for example, by using higher accuracy wind forecast models to generate wind inputs for the ground or airborne systems, updating wind information more frequently, or to upgrade the way winds are handled in the avionics systems.

The work described in this report summarizes the activities conducted in FY14, which builds upon prior work, and has two objectives:

1. Establish the relationship of wind information accuracy to 4D-TBO and IM performance for a selection of operationally relevant scenarios to identify wind needs to support them.

2. Present examples of what wind information content and update rate to the aircraft will deliver a given target performance level to help inform concept of operations (CONOPS) development and datalink technology needs.

A refined Wind Information Analysis Framework has been created, which incorporates wind scenario, Air Traffic Control (ATC) scenario, aircraft/automation simulation, performance assessment, wind requirement, and stakeholder needs elements to provide a structure to address objective 1. This framework is now supplemented with a new Wind Information Implications Flow Diagram, which provides a process by which findings from the application of the Wind Information Analysis Framework can be interpreted to address objective 2.

A selection of 4D-TBO and IM scenarios is described, which illustrates the utility of the analysis framework and implications flow diagram. The 4D-TBO studies combined the results from flight trials and extensive simulation studies of operational and prototype Flight Management System (FMS) capabilities to explore the sensitivity of RTA performance to a range of wind information qualities with a specific cruise and descent procedure. These results are summarized into a tradespace which illustrate the effects of wind forecast error and FMS capability on 95% RTA compliance error applicable for the FMS and scenarios examined in this study. The IM studies focused on a simple cruise-only scenario, but explored a range of combinations of truth and forecast wind scenarios to explore the sensitivity of IM performance to each, as illustrated through a range of IM tradespaces.

In order to interpret the wind forecast implications of the resulting 4D-TBO and IM tradespaces, an extensive analysis of wind forecast model performance is reported for three publically available models used in the aviation domain: the Global Forecast System (GFS), Rapid Refresh (RAP), and High Resolution Rapid Refresh (HRRR) models. The performance of each model as a function of forecast look-ahead time was analyzed for a period of 10 months in four geographically dispersed regions.

The utility of the 4D-TBO/IM tradespaces and wind forecast analysis findings are subsequently demonstrated through a range of cases studies, including (1) establishing wind information needs and associated CONOPS needs to support a given level of required 4D-TBO performance; (2) establishing a level of possible 4D-TBO performance given wind information limits; (3) establishing wind information needs and associated CONOPS needs to support a given level of required Interval Management performance, and (4) assessing impact of wind forecast differences between aircraft and ATC systems.

Recommendations for high value future work in each area are also described.

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1. INTRODUCTION

1.1 MOTIVATION

Many NextGen applications depend on access to high accuracy wind data due to time-based control elements, such as required time of arrival (RTA) at a meter fix under 4D-Trajectory-Based Operations (4D-TBO)/Time of Arrival Control (TOAC) procedures or compliance to an assigned spacing goal (ASG) between aircraft under Interval Management (IM) procedures. Figure 1 illustrates how wind information is used by Air Traffic Control (ATC) on the ground to develop time targets for use in a 4D-TBO procedure and for flight planning by airlines, and then wind information in the aircraft is used by the avionics to manage the aircraft trajectory to these targets. The performance of the procedure is typically measured as a mean and 95% spread of RTA compliance error at the meter fix. Note the mean error may be zero or slightly offset. Target performance is likely to be specified as a maximum allowable RTA compliance error a given fraction of the time, for example, ±*x* seconds 95% of the time. Any errors in the ground and/or aircraft wind information relative to the truth winds actually flown through can significantly degrade the performance of the procedure. Unacceptable performance could be mitigated by improving wind information in the aircraft, for example, by using higher accuracy wind forecast models to generate wind inputs for the ground or airborne systems, updating wind information more frequently, or to upgrade the way winds are handled in the avionics systems.

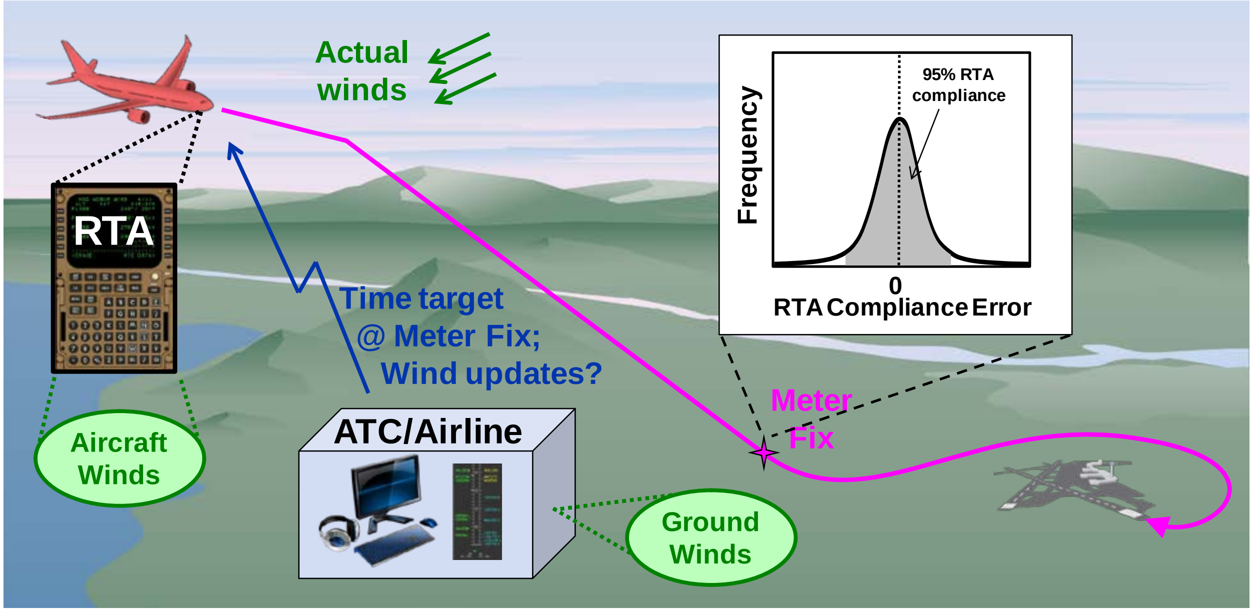


Figure 1. Wind information in four-dimensional trajectory-based operations.

A similar situation exists for the IM procedures illustrated in Figure 2, except it is complicated further by the fact there are now at least two aircraft coordinating their trajectories to achieve a given spacing by the ASG, so the wind information on both the Ownship (follower) and Traffic To Follow (TTF) is important. In addition, there are various flavors of IM, which have different sensitivities to wind information. In Ground Interval Management (GIM), speed advisories to achieve a given ASG target are calculated on the ground based on surveillance tracks, and issued via voice by ATC. Because of this workload burden on ATC, corrective speed advisories are typically limited to relatively infrequent intervals with resulting high sensitivity to wind errors. By contrast, Flight Interval Management (FIM) involves closed-loop speed control by the Ownship, which can deliver corrective speed commands much more frequently (e.g., up to once per second) and hence be much less sensitive to wind errors.

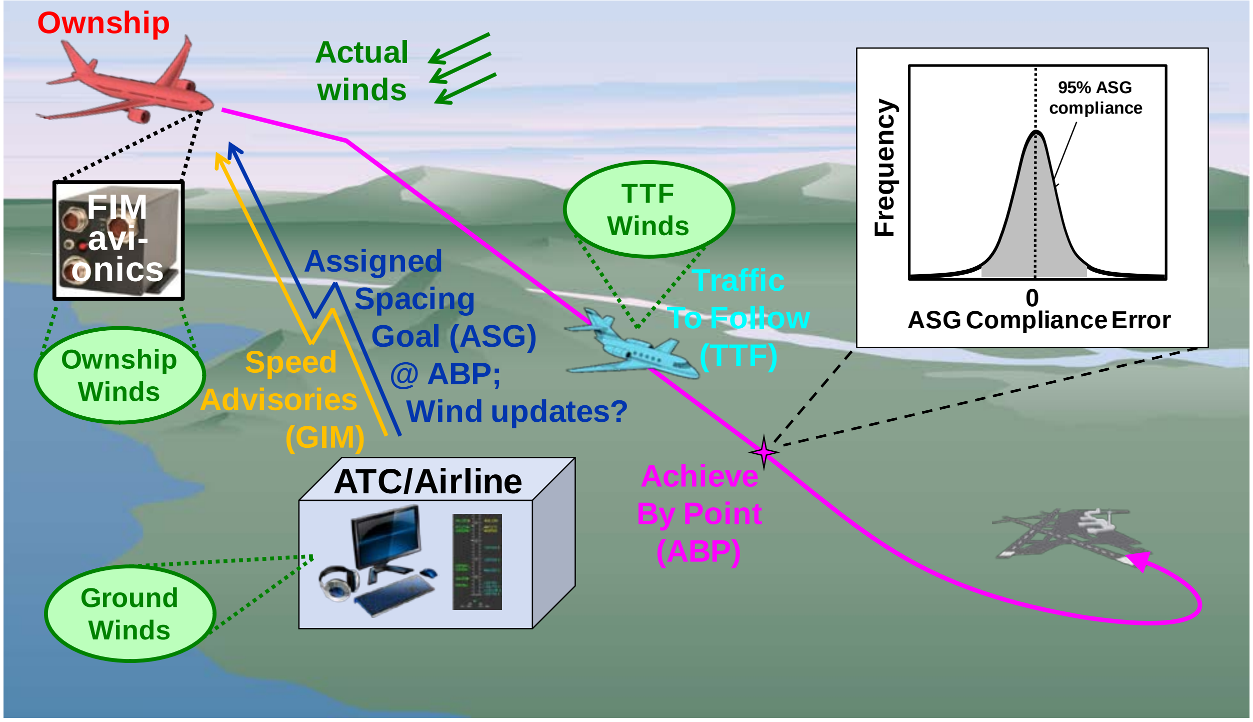


Figure 2. Wind information in interval management operations.

The objectives of the study reported in this document are twofold:

1. Establish the relationship of wind information accuracy to 4D-TBO and IM performance for a selection of operationally relevant scenarios to identify wind needs to support them.

2. Present examples of what wind information content and update rate to the aircraft will deliver a given target performance level to help inform concept of operations (CONOPS) development and datalink technology needs.

1.2 SUMMARY OF PRIOR WORK

In Phase 1 of this work (corresponding to FY12), a generic Wind Information Analysis Framework was developed to explore wind information needs across a range of NextGen applications. The framework was applied to a 4D-TBO scenario to act as a "proof of concept" of its use. It illustrated that even simplified executions of its elements could yield interesting and complex results, which could be of high value in determining how 4D-TBO performance varies with wind information quality. Phase 2 of the work (largely corresponding to FY13) built upon this foundation by using refined and expanded applications of the Wind Information Analysis Framework. It included tasks to (1) increase modeling fidelity and explore more complex 4D-TBO procedures; (2) expand the set of wind forecast scenarios and metrics; (3) assess performance of 4D-TBO with realistic future FMS wind-handling enhancements; and (4) expand the focus applications to include Interval Management (IM), both ground-based (GIM) and flight-deck-based (FIM). Prior work has also undertaken extensive assessment of wind information quality metrics, as well as the performance of a range of wind forecast models used by aviation stakeholders in the United States and overseas. Full details of all this work can be found in [1,2,3,4].

1.3 CURRENT RESEARCH QUESTIONS AND DOCUMENT OUTLINE

The Phase 3 work summarized in this report has the objective of building upon the Wind Information Analysis Framework development and application focus areas of Phases 1 and 2 to help establish wind information needs for a range of NextGen applications to directly support priorities of the sponsor and stakeholder community. The sections of the report are organized as follows:

- **Section 2** summarizes the Wind Information Analysis Framework components, refinements made to it to support the current efforts, and a new process flow diagram to identify implications of its use given the objectives of this work identified above.

- **Section 3** presents analysis to help answer the research question: "*What is the impact of wind information accuracy on 4D-TBO performance?*"

- **Section 4** presents analysis to help answer the research question: "*What is the impact of wind information accuracy on IM performance?*"

- **Section 5** presents analysis of the relevant performance of various wind information forecast products available in the aviation domain for use in the wind implications process flow diagram.

- **Section 6** presents example case studies of how all the information in the previous sections can be used to help answer research questions such as *"What are the implications of different wind* *forecast error limits from 4D-TBO and IM tradespaces for various potential 4D-TBO CONOPS?"* and *"What are the impacts of wind forecast differences between aircraft and ATC systems?"*

- **Section 7** presents a summary of the report and recommends next steps to refine and extend this work.

Note this work is not intended to specifically *recommend* concepts of operation and/or datalink technologies to support 4D-TBO or IM applications, but rather to identify the wind sensitivities of these applications and provide a process by which this information can be used by stakeholders to assess implications for operation and/or datalink technologies. This process is illustrated through the case studies contained in Section 6.

2. WIND INFORMATION ANALYSIS AND IMPLICATIONS

2.1 WIND INFORMATION ANALYSIS FRAMEWORK

In order to help explore the relationship of wind information to NextGen application performance, a Wind Information Analysis Framework has been developed and refined throughout the various phases of this work. The latest version of the framework is shown in Figure 3.

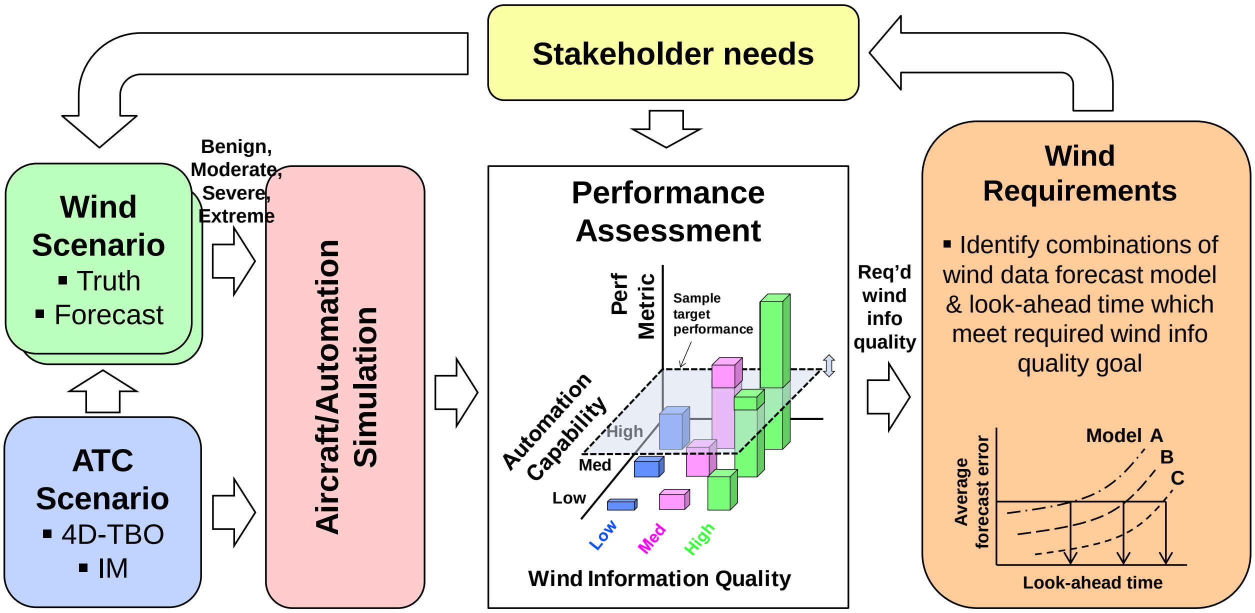


Figure 3. Wind Information Analysis Framework.

In the framework, the **ATC Scenario** represents the characteristics of the ATC environments for the application of interest, e.g., specifics of the procedures, infrastructure, demand levels, equipage. The **Wind Scenario** element represents the "truth" wind environments of relevance to the ATC scenario being studied (hence the arrow from the ATC Scenario to the Wind Scenario block), as well as the characteristics of different "forecast" winds relative to the actual wind field experienced. Truth wind fields are selected to expose the aircraft to various representative conditions (e.g., "benign," "moderate," "severe," and "extreme" impacts) to test response across a range of operationally realistic situations. In addition to wind speed and direction, the wind scenario data include associated atmospheric variables needed to accurately simulate aircraft performance including temperature, pressure, and humidity. The **Aircraft/Automation Simulation** element represents the behavior of the aircraft, engine, autopilot, and Flight Management System (FMS) in the context of the wind scenario and ATC application being studied. By running simulations of how aircraft perform in the context of a given ATC application when given varying qualities of wind forecasts when flying through various truth wind fields, it is possible to build up a tradespace of performance as a function of key independent variables such as wind information quality and aircraft capability. This is illustrated in the **Performance Assessment** element of the framework. This tradespace can then be used to establish what level of performance may be expected from a given wind information quality and aircraft capability combination. If a certain level of performance is required, this would define a horizontal slice through the tradespace from which combinations of wind information quality and aircraft capability that exceed that standard can be identified. The **Wind Requirements** element identifies which combinations of wind data content, from which specific operational wind forecast models at what forecast look-ahead times (i.e., the difference between the forecast issue time and its valid time) meet the wind information quality level identified from the previous element that achieve the target procedure performance. Finally, the **Stakeholder Needs** element represent the key role of stakeholders in determining appropriate choices in the other framework elements, e.g., in terms of which scenarios and performance metrics are of value to them to support the creation of guidance or requirements documents or to inform appropriate CONOPS. The key stakeholders consulted on this work to date were a range of Radio Technical Commission for Aeronautics (RTCA) Special Committees (SC-206, 214, 227 and 186) with representation across the FAA, airlines, and industry. Future work will continue to broaden stakeholder engagement as appropriate for the work.

The framework is designed to be scalable with respect to scope and fidelity of its individual elements, as well as flexible with respect to the specific ATC application being studied. In Phase 1 of this project, the utility of this framework was initially demonstrated using a simplified version of the framework elements applied to a simple 4D-TBO scenario. This demonstrated significant insights that could be generated from its use, as discussed in [1,2,3]. Phase 2 has further refined the 4D-TBO analysis and expanded into IM applications [4].

2.2 WIND INFORMATION IMPLICATIONS FLOW DIAGRAM

In order to interpret the findings from the Wind Information Analysis Framework, a complementary Wind Information Implications Flow Diagram has also been developed, as shown in Figure 4. This comprises six steps as follows:

1. Define the scenario of interest, corresponding to an ATC Scenario case previously assessed with the Wind Information Analysis Framework.

2. Identify the appropriate Wind Information Analysis Framework performance tradespace corresponding to the scenario of interest from step 1.

3. Select a target performance level desired to be achieved by aircraft within the context of the scenario of interest.

4. Establish whether feasible combinations of performance drivers meet the target performance level selected in step 3, i.e., are there combinations of wind information quality and automation capability which meet/exceed the desired performance level

   If “YES,” then identify required wind information level and proceed to step 5.

   If “NO,” then a need has been identified to either

      Select a lower target performance level (go to step 3), or

      Develop enhanced wind models or automation capabilities for analysis with the Wind Information Analysis Framework, resulting in a new tradespace (go to step 2).

5. Establish whether feasible combinations of wind forecast models and look-ahead times exist to meet/exceed the required wind error limit established from step 4.

   If “YES,” then proceed to step 6

   If “NO,” then a need has been identified to either

      Select a lower target performance level (go to step 3), or

      Develop enhanced wind models or automation capabilities for analysis with the Wind Information Analysis Framework, resulting in a new tradespace (go to step 2).

6. Identify procedure, CONOPS and datalink needs to get wind information of the required accuracy to the aircraft and ground systems for operational use that support the required performance.

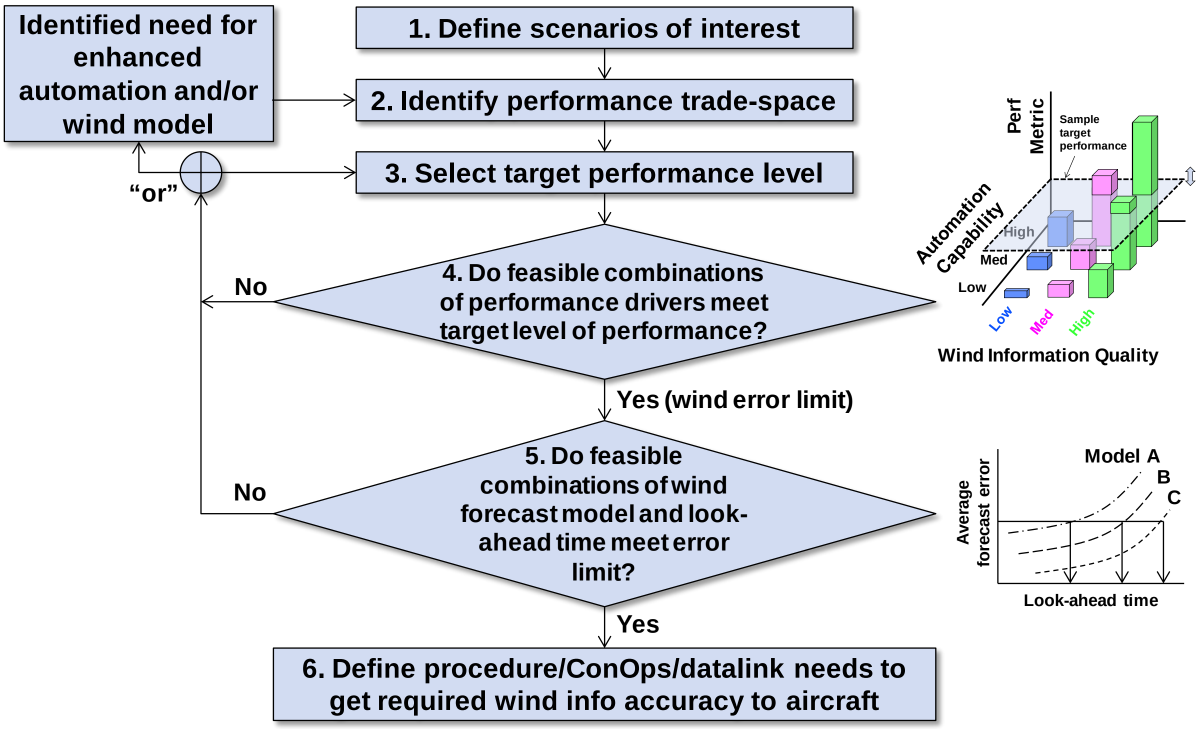


Figure 4. Wind information implications flow diagram.

Section 6 contains case study examples of the use of this flow diagram given the 4D-TBO and IM tradespaces developed in Sections 3 and 4 for use in step 2, and the wind forecast model performance developed in Section 5 for use in step 5.

3. ANALYSIS OF WIND INFORMATION ACCURACY ON 4D-TRAJECTORY-BASED OPERATIONS PERFORMANCE

3.1 INTRODUCTION

The main elements of a 4D-Trajectory Based Operations procedure were illustrated in Figure 1. The procedure involves the creation of a suitable controlled time-of-arrival (CTA) target at a meter fix, and then the aircraft implements time-based control leveraging the capability of the FMS systems to fly precise trajectories using RTA functionality. As shown by the green ovals in Figure 1, wind information is used by ground systems (airline flight planning and ATC systems to create suitable CTAs) and airborne systems (FMS to manage the aircraft's trajectory to the RTA). Any errors in the wind information used in these systems can adversely impact the ability of the aircraft to reach the meter fix within a given tolerance of the time target, which in turn may impact the efficacy of the intended 4D-TBO procedure.

This section details analysis that has been conducted to quantify the performance of a variety of 4D-TBO procedures under a range of truth and forecast wind conditions in order to better understand the impact of wind information quality. Two key RTA performance metrics are used in the analysis and reporting in this section:

- RTA Time Error (RTA TE): The difference (in seconds) between the actual time achieved at the RTA fix and RTA time assigned. Positive values indicate that a flight crossed late, negative values indicate a flight crossed early.
- RTA Time 95% Confidence Interval (RTA 95%CI): The mean and estimated interval containing 95% of RTA TE for the particular conditions in question, calculated as $\mu \pm 2\sigma$ (Mean ± 2*Standard Deviation assuming Gaussian distribution) of the distribution of time errors.

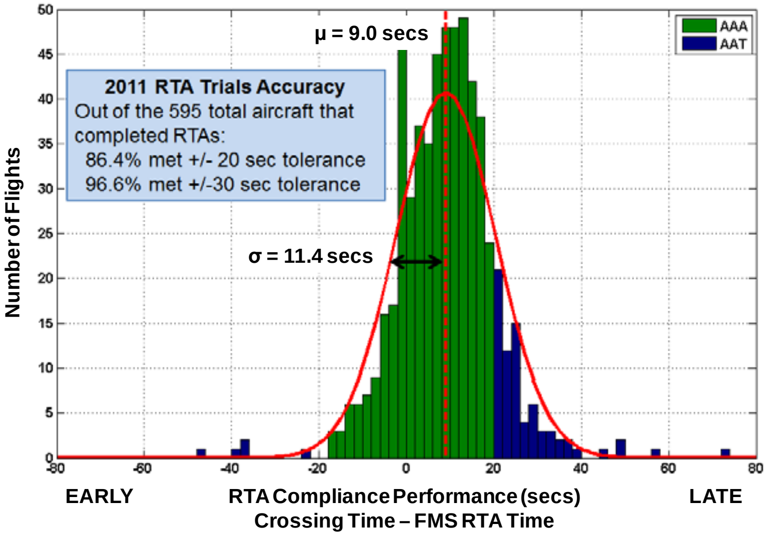
3.2 ANALYSIS OVERVIEW

The analysis in this section builds upon baseline data from a 2011 flight demonstration of 4D-TBO procedures in Seattle (funded by another program) and reports data from simulations conducted using multiple types of medium-fidelity FMS systems in varied wind and operational scenarios.

3.2.1 Baseline 2011 Seattle Flight Trials

Live flight trials were conducted in November/December 2011, sponsored by FAA ANG-C5, Neal Suchy, Program Manager, involving Alaska Airlines (ASA) and FAA's Seattle ARTCC (ZSE) [5]. MIT Lincoln Laboratory was the lead organization for planning and implementation; MITRE CAASD was the lead organization for integration and analysis, including an ad hoc datalink capability for uplink of wind information to the flight deck and downlink of intent data for display at ZSE.

In these trials, RTA operations were conducted during arrivals in all flow conductions via the three most heavily utilized corner posts (arrival fixes) at Seattle-Tacoma International Airport (SEA), in both non-metering and metering conditions. All ASA B737 flights equipped with General Electric (GE) FMS systems (version U10.8A) and arriving to SEA during operational hours via the specified procedures were candidates for participation. About 70 minutes prior to arrival, candidate aircraft received and loaded the Rapid Update Cycle (RUC) wind forecast applicable to the ETA for their arrival route, via Aircraft Communications Addressing and Reporting System (ACARS). Candidate aircraft then downlinked intent data including the range of achievable times at the meter fix to the Traffic Management Unit (TMU) at ZSE. The TMU determined and posted the RTA time according to the Traffic Management Advisor (TMA) scheduling tool. A total of 833 flights was assigned an RTA to the meter fix by ATC during the 23 days of flight trials, of which 595 flights (71%) fully executed and completed the RTA. Of the flights completing the assigned RTA, 86.4% crossed within the 20-second time tolerance used for this demonstration, and 96.6% crossed within 30 seconds of the assigned time. Nearly all flights completing RTAs met the altitude/speed crossing restrictions (unless otherwise instructed/cleared by ATC). A summary of RTA performance in this demonstration is depicted in Figure 5. The mean RTA TE for the flights completing RTAs in all conditions was 9.0 seconds late, while the estimated RTA 95%CI was –13.7 to +31.7 seconds. Note this observed range of performance was from trials conducted under a range of wind conditions and a range of wind forecast errors in the FMS wind entries. The simulation analyses which follow control for these wind factors to explicitly examine their impact.



2011 RTA Trials Accuracy
Out of the 595 total aircraft that completed RTAs:
86.4% met +/- 20 sec tolerance
96.6% met +/-30 sec tolerance

Figure 5. 2011 Seattle 4D-TBO Flight Trials RTA Compliance Performance [5]. (AAA = RTA assigned, accepted, and accomplished within programmed 20 sec tolerance, AAT = RTA assigned, accepted, and achieved but beyond programmed 20 sec tolerance).

3.2.2 Lincoln Laboratory/MITRE FMS Simulations

A series of parametric studies were conducted in collaboration between Lincoln Laboratory and MITRE CAASD using their FMS test benches. Three systems with RTA functionality were available for testing, reflecting a variety of FMS systems in current operational use:

- Boeing B737-700 utilizing a GE FMS (B737/GE) using current operational software version U10.8A in the GE-supplied "sFMS" system.
- Two variants of the B757-200, both utilizing a Honeywell Pegasus FMS in an Aerosim-packaged flight training system adapted for research purposes, including one using current operational ("Black Label") software version PS4083821-910 (B757/HW BL), and one using a "first-generation" research prototype ("Red Label v1") software (B757/HW RL). The B757/HW BL variant is representative of FMS types offering RTA capability in cruise only, i.e., limited support for RTAs that include an arrival descent segment. The B757/HW RL variant is a research prototype developed by Honeywell to explore adding full RTA capability in all phases of flight, along with several other useful features such as user-adjustable "RTA tolerance setting" (see glossary), calculation and display of achievable RTA times, and user-adjustable RTA speed limits.

3.2.3 Lincoln Laboratory FMS Simulation System

It was desired to supplement the baseline flight trial results and MITRE simulation activities with a flexible simulation system which could be used to model individual components of a 4D-TBO environment, including enhancements to FMS wind-handling capabilities, to better understand their impacts on performance.

An agent-based simulation system was developed at Lincoln Laboratory, which provides the capability to establish different levels of fidelity for each element incorporated in the simulation. Agents are created to model individual avionics units, pilots, airline operating centers, or other systems as required to ensure the appropriate characteristics of a particular system are embedded in the simulation to reflect real-world behaviors. The simulation system was also designed to be scalable: each instance can run on a virtual computer allowing multiple simulations to be executed in parallel with additional agents and components able to be started in a cloud infrastructure as needed. The simulation system incorporates both operational and research versions of the Honeywell B757/767 Pegasus FMS. The research version includes software changes undertaken during this research that permit the evaluation of enhancements to wind-blending algorithms (WBA) to enable quantification of performance improvement potential for near-term avionics refinements.

3.3 LINCOLN LABORATORY/MITRE FMS SIMULATIONS

3.3.1 Analysis Scenarios

The implementations of the different Wind Information Analysis Framework elements for this analysis are discussed below. The **Wind Scenarios** were constructed to expose the aircraft to a range of truth wind conditions, and forecast errors were superimposed to cover 5 and 20 knots Root Mean Square Vector Error (RMSVE). As detailed in [1,2,4], there are a number of ways of quantifying wind information quality, but RMSVE for wind vector (speed and direction) differences or root mean square error (RMSE) for wind component speed differences of a forecast relative to truth data were found to be the most commonly used metrics to quantify the performance of operational wind models. For scalar errors, the RMS error (or RMSE) is the square root of the average of the individual squared differences between pairs of scalar forecast (f) and observation (o) quantities, and is given by:

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(f_n - o_n)^2} \tag{1}$$

where N is the number of forecast-observation pairs. The RMSVE is the RMS error applied to the magnitudes of the forecast and observed wind vector components as given by:

$$RMSVE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(u_f - u_o\right)^2 + \left(v_f - v_o\right)^2} \tag{2}$$

where N is the number of forecast-observation pairs, u is the east-west component of the wind vector, v is the north-south component, and subscripts f and o refer to forecast and observed, respectively. The performance of wind forecast models applicable to the aviation community were assessed in [1,4] and is the basis for the 5–20 knots RMSVE range in this study. Monte Carlo simulations were conducted (up to 100 runs in each condition), i.e., each simulation run in a given scenario had a different forecast error based on a random pull from a distribution whose standard deviation was 5 or 20 knots depending on the case being analyzed. Scenarios were classified as “Benign,” “Severe Headwind,” and “Severe” based on climatologically representative statistics of wind speed and variability within the local region traversed by the scenario trajectory. Truth wind data for these classifications were obtained from archives of gridded wind numerical weather prediction model data such as the High Resolution Rapid Refresh model (HRRR) and Rapid Refresh Model (RAP). These model analyses provide realistic representations of the winds over the spatial and temporal scales of interest and preserve the spatial correlations between neighboring wind samples. Spatially correlated sequences of simulated forecast errors were created by first generating a normally distributed random error sequence having a mean of zero, and standard deviation (σ) corresponding to the amount of forecast RMSVE being modeled. The initial random error sequence was then filtered with a Gaussian filter kernel having shape parameters consistent with the desired correlation lengths to produce a spatially correlated error sequence (no temporal variation was considered in this analysis). Additional details of the wind scenario classification and error simulation approaches can be found in the prior Phase 2 study report [4]. The following summarizes the three wind scenarios chosen for these simulations to expose the aircraft to a range of wind conditions.

“**Benign” Scenario**

The “Benign” wind/trajectory scenario is characterized by winds having relatively low headwind speeds and low variability along the given trajectory. Representative wind data for this scenario were obtained from a sub-region of the HRRR model analysis centered on SFO at 12:00 GMT on 1/19/2013. Figure 6 depicts the elements of the Benign scenario for a sample set of scenario parameters used to test the B737/GE FMS.

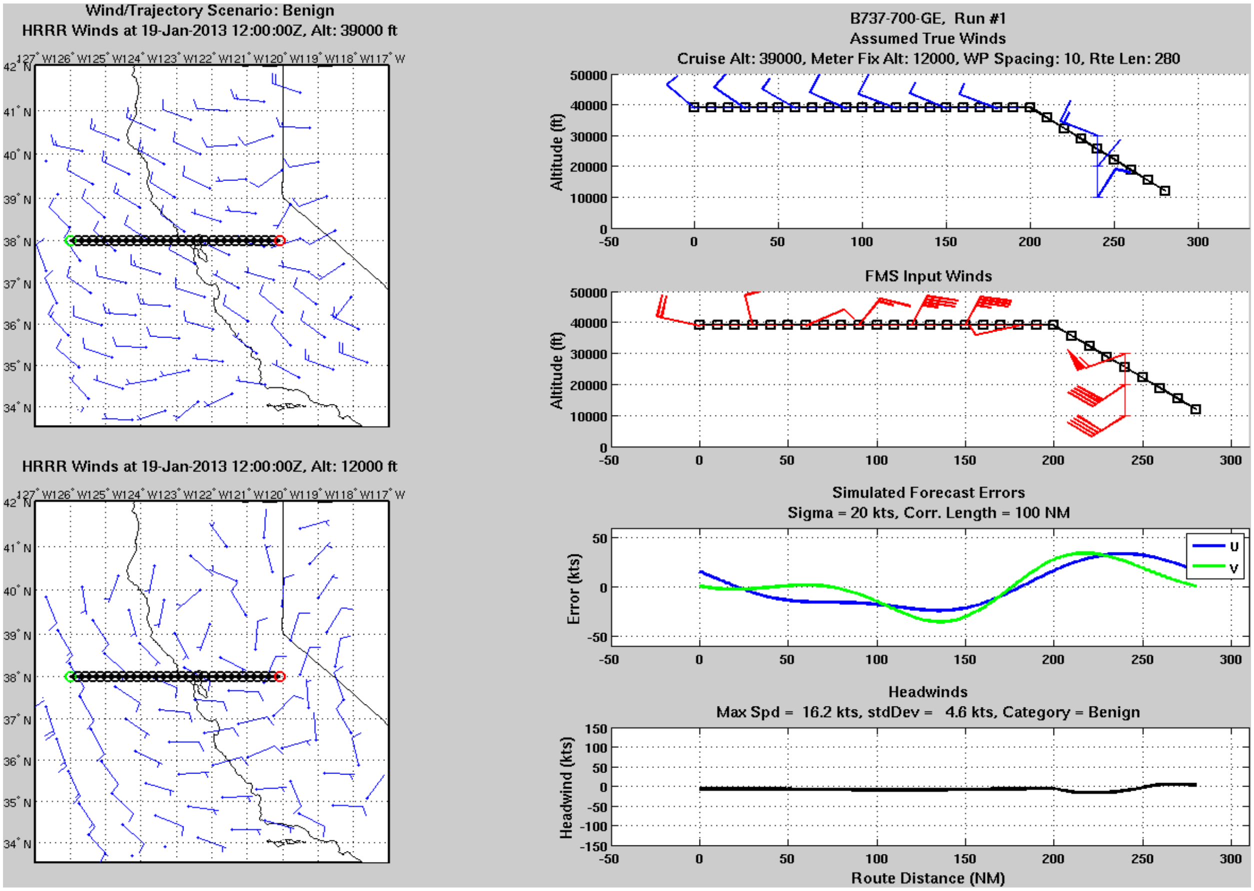


Figure 6. “Benign” wind/trajectory scenario.

The meteorological wind barb plots in the upper left and upper right of the figure are 2-D plots of the surrounding assumed true (HRRR analysis) winds at altitudes corresponding to the cruise and ending (meter fix) altitudes of the trajectory, respectively. The projection of the lateral trajectory is overlaid on each of the two wind plots, with the green circle indicating the starting location and the red circle indicating the ending location (a constant true heading descent trajectory in this case). From the plots, the winds are generally 10–20 knots from the WNW at the selected cruise altitude of 39,000 feet, becoming generally easterly at 5–10 knots near the meter fix altitude of 12,000 feet.

The upper right plot shows the trajectory vertical profile with the assumed true winds (from the HRRR) plotted with wind barbs at each waypoint location. A lateral waypoint spacing of 10 NM and a single set of three descent altitude winds (at 10, 20, and 30 kft) permitted by the B737/GE FMS are shown. The second plot in the upper right shows the simulated forecast FMS winds at each waypoint. These are the result of superimposing the spatially correlated random errors having a specified sigma and correlation length on the truth winds at each waypoint. The third plot from the top on the right shows the random simulated component wind errors (U, V) having statistics corresponding to a correlation length of 100 NM and sigma (RMS error) of 20 knots. The lowest plot on the right shows the assumed true headwinds (again based on the HRRR analysis) as a function of route distance.

“Severe Headwind” Scenario

Figure 7 depicts the elements of the “Severe Headwind” wind/trajectory scenario for a sample set of scenario parameters. The Severe Headwind scenario is characterized by very strong headwind speeds along the trajectory. Representative wind data for this scenario were obtained from a sub-region of the HRRR analysis centered on New York Newark Liberty International Airport (EWR) at 12:00 GMT on 1/23/2013. Headwind speeds for the indicated placement of the constant true heading descent trajectory range from nearly 150 knots at 39,000 feet to 50 knots near the final meter fix altitude of 12,000 feet. The plots on the right side of the figure show the assumed true and simulated forecast FMS winds for a lateral waypoint spacing of 10 NM, and for random wind forecast FMS errors having a sigma of 20 knots and correlation length of 100 NM. The truth and forecast winds for the descent were sampled at a location corresponding to the half-way point of the descent, and at altitudes of 10, 15, 20, 25, and 30 kft (for a case where five altitude levels could be entered in descent).

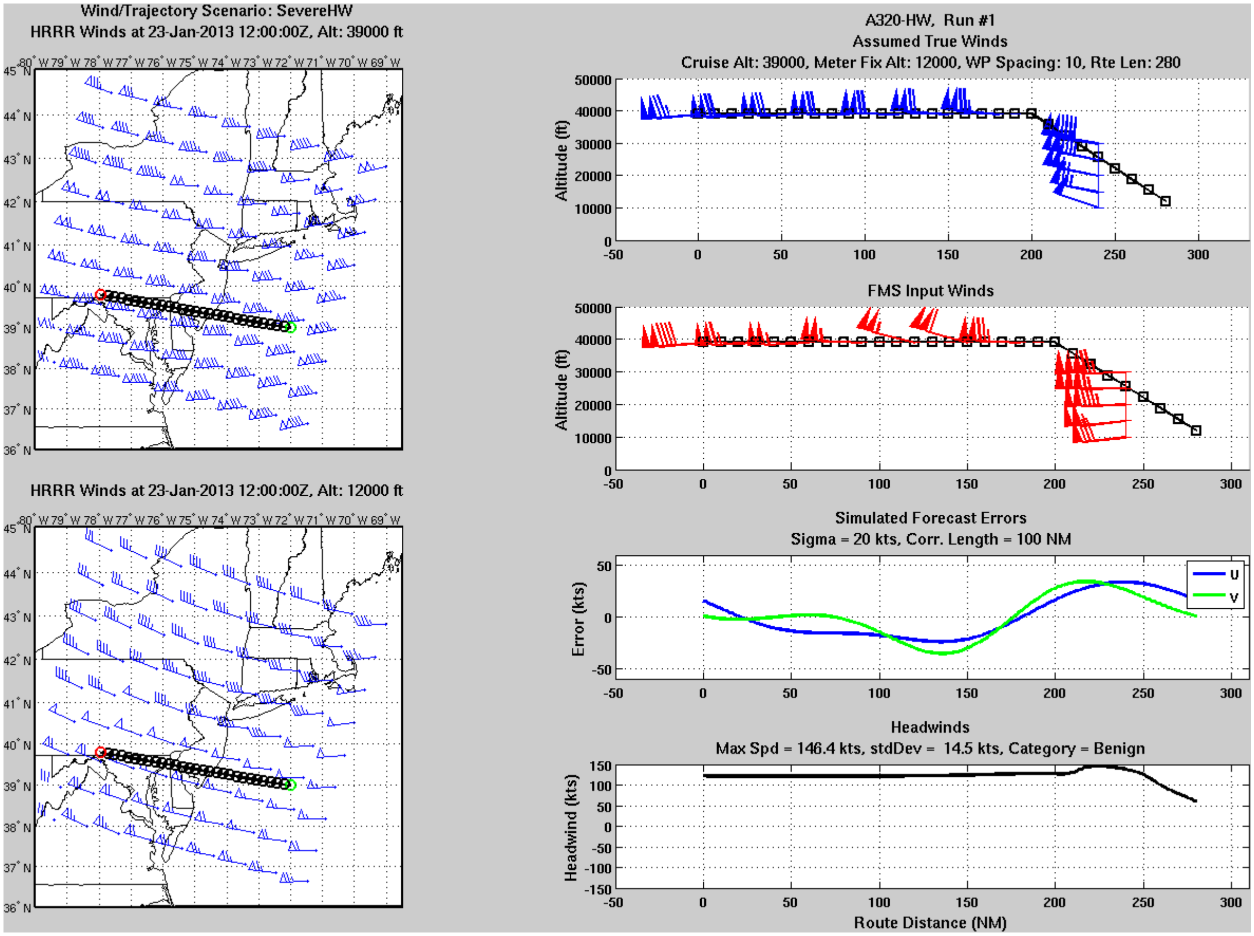


Figure 7. "Severe Headwind" wind/trajectory scenario.

"Severe" Scenario

The scenario shown in Figure 8 couples strong winds with a 180-degree course reversal that results in rapidly changing headwinds. Wind data for this scenario were based on the same sub-region of the HRRR analysis used for the "Severe Headwind" scenario described above. However, the shape and placement of the "shepherd's crook" trajectory results in rapidly varying headwinds as the aircraft turns through 180 degrees along the descent. Headwind speeds for the indicated placement of the trajectory range from nearly 125−150 knots at 39,000 feet along the cruise portion to top of descent (TOD), changing to a tailwind of –100 knots near the final meter fix altitude of 12,000 feet.

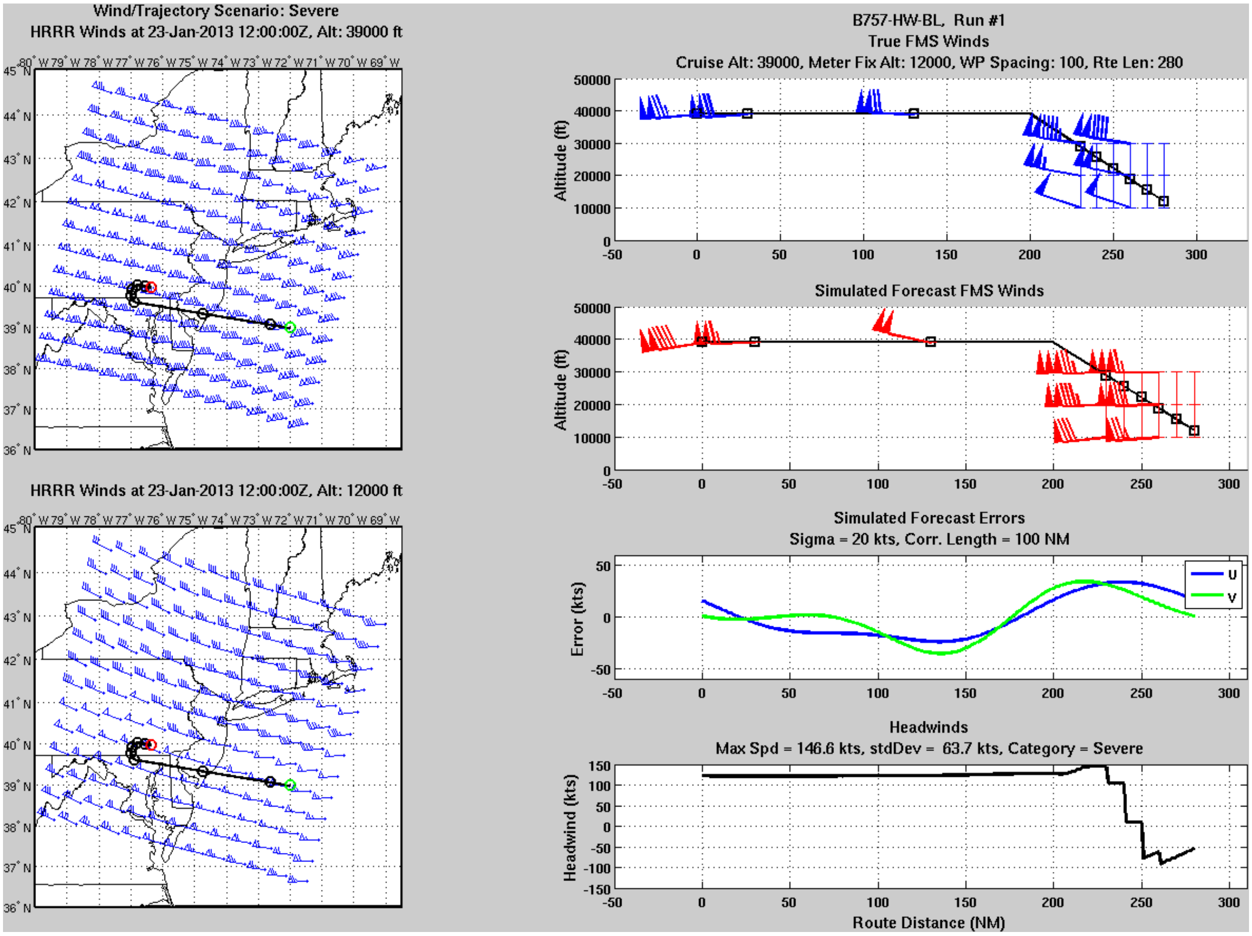


Figure 8. "Severe Headwind" wind/trajectory scenario.

The **ATC Scenarios** studied all involved flight parameters informed by the 4D-TBO CONOPS and the Seattle flight trials, although the geographic location of the simulation runs was not tied to any one location. The ATC scenario trajectories were executed using the FMS programmed with appropriate waypoints separated by 10 or 100 NM. As discussed above, for most of the scenarios studied, a straight line lateral path was used, although one case also included turns during descent to expose the aircraft to more rapidly varying wind field characteristics. The vertical profiles comprised an initial level cruise segment at FL290 or FL390, followed by a descent to a meter fix at 12,000 ft. An RTA time target was assigned at either 150 NM or 250 NM distance from the fix. The RTA target was set relative to a range of achievable RTA times estimated by the FMS under test (using the forecast winds), as either mid-range, early (20 secs after earliest achievable time), or late (20 secs prior to latest achievable time). Prior to RTA assignment, the aircraft was at a speed governed by the programmed FMS Cost Index, but after RTA assignment, the RTA function of the FMS controlled the aircraft speed as necessary in its effort to arrive at the meter fix to comply with the RTA.

The **Aircraft/Automation Simulations** were conducted using the MITRE FMS simulation capabilities for the B737/GE and B757/HW systems as previously described. The B737/GE and B757/HW RL FMS have user-adjustable RTA tolerance settings (internal FMS sensitivity parameter reflecting time-error value, expressed in seconds, that triggers recalculation of RTA speed target), while the B757/HW BL FMS has a fixed setting of approximately 30 seconds.

Performance Assessment was measured by comparing the actual time of arrival at the meter fix relative to the target time across multiple runs, from which RTA TE and RTA 95% CI statistics were compiled.

Table 1 summarizes the study conditions.

TABLE 1

Simulation Conditions for Lincoln Laboratory/MITRE Studies

Wind Information Analysis Framework Element	Independent Variable	Values Tested	Number of Permutations
Wind Scenario	Truth field	"Benign" "Severe" with 180° Course Reversal "Severe Headwind"	3
	Forecast error distribution	Ã = 5 knots RMSVE Ã = 20 knots RMSVE	2
ATC Scenario	Trajectory	Cruise FL290, FL390, Meter fix 12,000 ft	2
	RTA assignment distance (from meter fix	150 NM, 250 NM	2
	RTA time assigned (Relative to range of achievable times)	Early, Mid-range, Late	3
	Waypoint spacing	10 NM, 100 NM	2
Aircraft/Automation Simulation	Aircraft/FMS type	B737/GE (±6 secs RTA tolerance) B757/HW BL (±30 secs RTA tolerance) B757/HW RL (±6 and ±30 secs RTA tolerance)	4
	Total permutations	50–100 Runs/Condition	576

3.3.2 Analysis Results

Summary results from the analysis of the simulation runs are provided in Figure 9. Only the effects of wind forecast error, aircraft/FMS type, and RTA tolerance setting are separated out as independent variables: the impacts of the other variables were combined into these results.

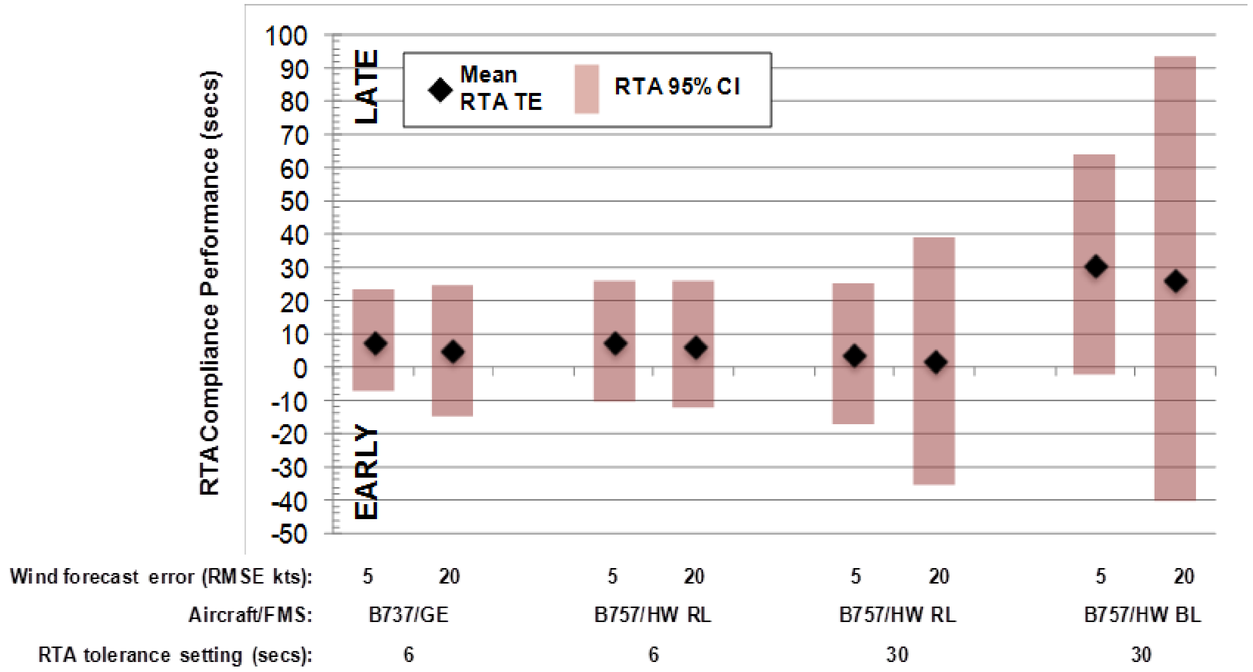


Figure 9. Summary results from Lincoln Laboratory/MITRE simulations.

A number of observations can be made based on these results, as follows:

- RTA compliance performance was observed to be much better for the B757/HW RL and B737/GE systems compared to the B757/HW BL FMS. The relative performance differences between the systems can be explained by the extent of closed-loop speed control to an RTA during descent. The B757/HW RL and B737/GE systems perform closed-loop speed control throughout the cruise and descent, while the B757/HW BL only has RTA control in cruise.

- RTA compliance performance was observed to degrade only slightly with wind forecast error level in the B737/GE and B757/HW RL FMSs, but the B757/HW BL system was much more sensitive to wind forecast error.

- The RTA tolerance setting had a medium effect on the RTA compliance performance of the HW RL system which provides for user-adjustable settings, with a slightly bigger effect when wind forecast error was at the 20 knots RMSE level.

- All results demonstrated a tendency to arrive late relative to the RTA on average (no more than 10 seconds for the B737/GE and B757/HW RL systems in this study), which is consistent with results obtained in the Seattle flight trial and other studies of RTA performance. Several hypotheses have been suggested to explain this late bias, but further studies on this point are required to understand and fully characterize this tendency

- RTA 95% CIs (estimates calculated as $\mu \pm 2\sigma$ (Mean ± 2*Standard Deviation assuming Gaussian distribution) were generally within ±20 seconds of the mean at the tighter 6 secs tolerance setting for all systems with closed-loop speed control in descent under the conditions tested.

3.4 LINCOLN LABORATORY FMSIM SIMULATIONS

3.4.1 Analysis Scenarios

In order to further diagnose and extend the results from the Lincoln Laboratory/MITRE simulations, the Lincoln Laboratory FMS Simulation System (LL FMSim) was used to test a range of hypotheses developed to address a range of open questions as follows:

1. Increased magnitude headwind forecast error causes greater magnitude RTA TE.

2. Systems that do not maintain closed-loop control until the RTA fix location have greater magnitude RTA TE as compared to systems that do.

3. Flights at lower cruise levels are less impacted by headwind forecast errors.

4. Headwind forecast errors closer to the RTA fix cause greater magnitude RTA TE.

5. Increased waypoint spacing causes greater magnitude RTA TE.

To test hypothesis (1), a series of experiments was designed to produce conditions that were expected to stimulate varying levels of RTA TE performance. These experiments encompassed simulated flights through realistic wind fields extracted from HRRR data, with wind forecast data at each waypoint determined a priori such that the error in the forecast headwind that the aircraft would experience in its flight would be constant at each waypoint. Wind forecast data were programmed in the FMS at 50 NM intervals, with one cruise-level value for each cruise waypoint, and three for the descent phase. The RTA fix and assigned time were entered 150 NM prior to the fix location. All flights maintained a cruise altitude of FL350 before starting descent to a meter fix at 12,000 ft. Constant headwind forecast errors ranging from +50 knots to –50 knots at 5 knots intervals were tested to simulate an extreme range of conditions. An example of the wind fields is given in Figure 10. For these scenarios, the synthetic wind errors were modeled as unforecast variability in the truth winds (represented by the “Modified Truth” winds in the left panels of Figure 10), thereby assuring that the aircraft experienced the full spatial extent of the error field independent of the FMS waypoint sampling of the forecast. This particular figure shows cross sections of the wind volume for flights experiencing +10 knot headwind forecast error.

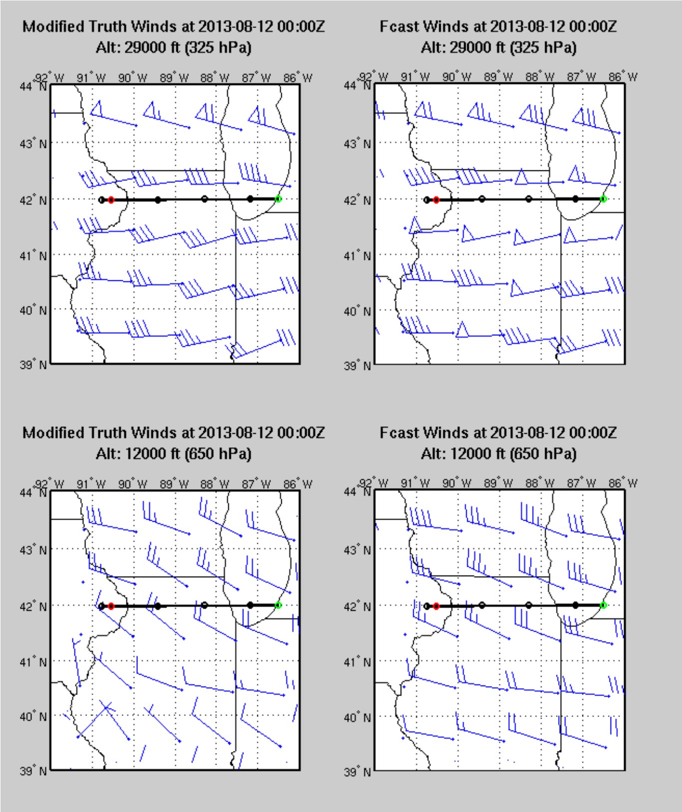


Figure 10. Example of scenario wind fields at various altitudes. The origin of the flight is indicated by the green circle. The meter fix is indicated in red.

Three trials of each experimental condition were conducted to demonstrate the repeatability of the distributed simulation system. To compare the effect if the dominant winds in these trials were either head or tail winds, the experiments were reproduced flying the flight plan in the opposite direction so the experiment would have an equal number of headwind and tailwind cases. Note that all simulations described below were conducted using the B757/HW RL FMS that maintained closed-loop control until arriving at the RTA fix location unless explicitly stated otherwise.

Experiments to test hypothesis (2) utilized the same conditions for its experiments as employed to test the headwind scenarios for hypothesis (1) except the B757/HW BL FMS software was utilized. This FMS version calculates the trajectory for the entire RTA, including the descent, but only maintains closed-loop control on time arrival until the top-of-descent (TOD) point. After TOD, the aircraft system reverts to its "ECON" descent profile. Data were compared to the results of experiments for (1) to determine the effect. This is the only set of experiments where the operational ("Black Label") HW Pegasus FMS software was utilized.

Experiments to test hypothesis (3) utilized the same conditions as employed to test hypothesis (1), but with the addition of conducting flights at two more flight levels, FL290 and FL390.

A different formulation of experiments was designed to test hypothesis (4). The underlying wind fields used in the experiments were identified by analysis of HRRR data to fall into one of three categories effectively representing wind fields representing light, moderate, or high wind magnitude environments. Experiments were conducted with flights through a representatively selected wind profile from each category, but had an additional spatially correlated wind field variation superimposed on the underlying wind field. The formation of the superimposed wind field was such that it would evaluate into a peak magnitude in wind forecast error that was consistently located at one of four locations along the flight plan depending on the experiment, as shown in Figure 11. Fifty randomly generated cases of varying superimposed wind fields were tested for each error location. Three headwind forecast error Gaussian distributions were produced constituting standard deviations with RMSVE values of 5, 10, and 15 knots. Cruise altitude was fixed at FL290 with a meter fix altitude set to 12,000 ft. Waypoint spacing was fixed at 100 NM. Figure 12 shows a collection of aircraft observed headwinds for a particular scenario set.

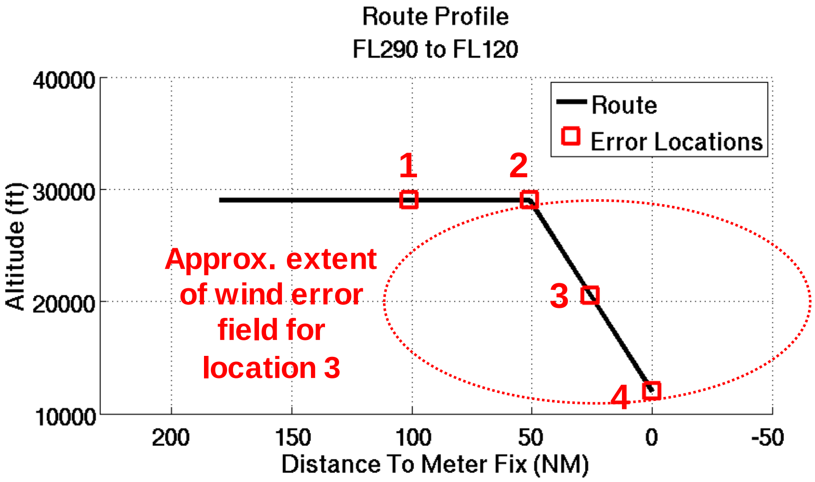


Figure 11. Wind forecast error locations.

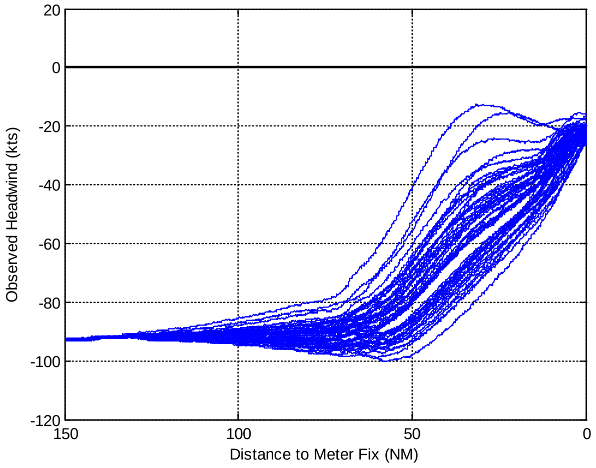


Figure 12. Sample of recorded headwinds for flights 15 knots RMSVE forecast error and centered on Test Location 3.

Experiments to test hypothesis (5) were conducted under the same conditions as for hypothesis (4), except that the waypoint spacing for its scenarios was fixed at 10 NM instead of 100 NM.

No speed brake or pilot intervention models were exercised in any of these scenarios.

3.4.2 Experimental FMS Software, Modified Wind Blending

Most FMS systems implement some form of "wind blending," i.e., trajectory predictions are based on wind values that are derived from a mix of current sensed wind values and forecast values at downstream points. Wind blending can serve to mitigate the negative impact of erroneous downstream wind forecasts. Higher wind forecast point density can tend to neutralize the potential of wind blending to mitigate the adverse impact of erroneous forecasts. Wind blending is therefore a principle component of the overall model-predictive FMS control system.

In this program, Honeywell developed a modified version of the wind-blending algorithm, which can be activated in the B757/HW RL FMS in lieu of the baseline algorithm. This algorithm is referred to as the Enhanced1 WBA in this report. The Enhanced1 WBA blended forecast data in a different fashion with the intent to reduce RTA time errors. A series of experiments was designed and conducted to analyze the effect of Enhanced1 WBA in this respect. In particular, a set of challenging wind environments with significant wind gradients was selected from RAP model data. Constant headwind forecast errors were applied to these wind fields in the same fashion as utilized to test hypothesis 1.

3.4.3 Analysis Results

Hypothesis (1): Increased magnitude headwind forecast error causes greater magnitude RTA TE.

The observed headwinds seen by the simulated aircraft are shown in Figure 13. The wind forecast data remained fixed for all experiments at the values indicated in the figure. Extracted from HRRR data, these wind fields profiles are primarily made up of headwinds which were nearly constant through the cruise phase of flight and possessed a moderate wind gradient during the descent phase. To evaluate the effect of tailwinds, the same scenarios were exercised again but with the flight plan reversed so the aircraft would be experiencing primarily tailwinds in the later tests.

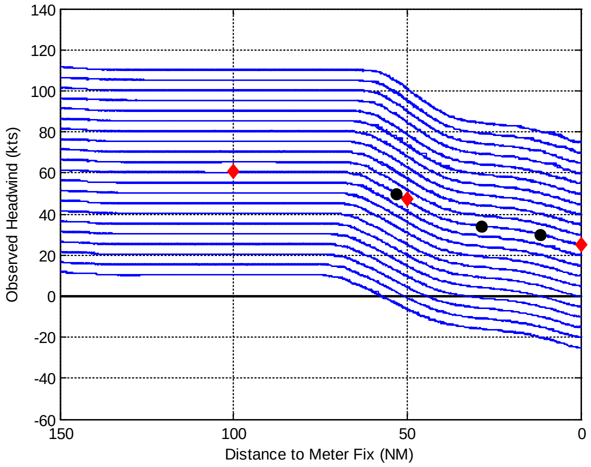


Figure 13. Recorded headwinds from hypothesis 1 scenarios. Red diamonds: the forecast headwind for all runs at indicated waypoint location. Black circles: descent wind values as taken from forecast descent location at FL300, FL200, and 10,000 ft MSL.

The upper-most traces show the headwinds experienced for flights that experienced –50 knots error. For example, in the upper trace when the aircraft was at the waypoint 100 NM from the meter fix, the experienced headwind was about 110 knots. The forecast headwind at that point, as indicated by the red diamond, is approximately 60 knots. Per the convention of error equals forecast minus truth, 60 minus 110 equates to a –50 knots error. It is understood that the large range of the headwind forecast errors tested, ±50 knots, is far outside what could be realistically expected of current wind forecast systems. This range, however, was chosen to ensure the full envelope of the aircraft's control authority would be tested. Indeed it was found that for headwind forecast errors outside the threshold values stated above, the aircraft tended to reach either maximum or minimum speed limits as set in the B757/HW RL FMS (default values M0.76/0.84 and 260/330 knots CAS as programmed in this FMS) at some point in its flight. Once the aircraft has arrived at a limit, it typically no longer has the capability to gain or lose time to meet the RTA. In general, when the aircraft were given large negative headwind forecast errors, the aircraft would eventually speed up to a maximum speed limit to compensate for the underestimate of the headwind. When headwinds were significantly overestimated (large positive headwind forecast errors), the aircraft tended reduce speeds to the minimum speed limits.

Figure 14 indicates that the RTA TE remains relatively low in the tested scenarios (well within ±10 seconds) across the headwind forecast error range of –30 knots to +15 knots. Beyond these thresholds, the magnitude of the RTA TE does increase with increasing headwind forecast error magnitude. From the data, it is clear that overestimating the headwinds on a flight drives the RTA TE towards greater negative values, that is, earlier than desired. Underestimating the headwinds on the same flight causes it to arrive later. Whether the aircraft is flying through a predominantly headwind or tailwind field had little noticeable effect in the RTA TE performance until the headwind forecast exceeded the range stated above.

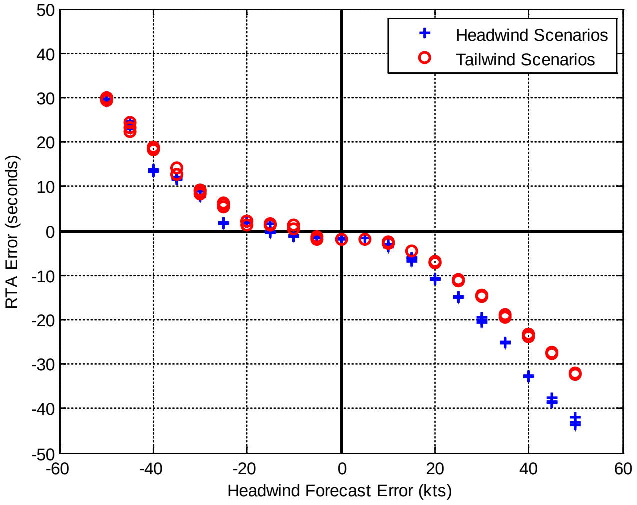


Figure 14. RTA TE as a function of constant wind error (B757/HW RL FMS).

Hypothesis (2): Systems that do not maintain closed-loop control until the RTA fix location have greater magnitude RTA TE as compared to systems that do.

Analysis of the results for experiments conducted to test hypothesis (2) clearly show that the hypothesis is true. Figure 15 presents the RTA TE values measured when applying the same scenarios conditions exercised to test hypothesis (1) on an aircraft that utilized B757/HW BL FMS, which does not maintain continuous closed-loop control. The RTA TE for this system appears to have a negative linear correlation to headwind forecast error.

According to the manufacturer, the operational B757/HW BL FMS RTA system was designed to adjust only the cruise speed to meet time constraints in the cruise flight phase with an accuracy of ±30 seconds 95% of the time, per the DO-236A requirement, so the performance of the system to a time constraint in the descent flight phase in the presence of wind errors can be expected to suffer. The figure shows that the time performance lays in a band consistent with the ±30 second design, with the large spread likely due in part to deadbands in the design put there to reduce throttle activity, based on discussions with the FMS manufacturer. The slope of the band is consistent with the fact that in the descent flight phase the speed is not adjusted to counteract the wind errors observed in the descent.

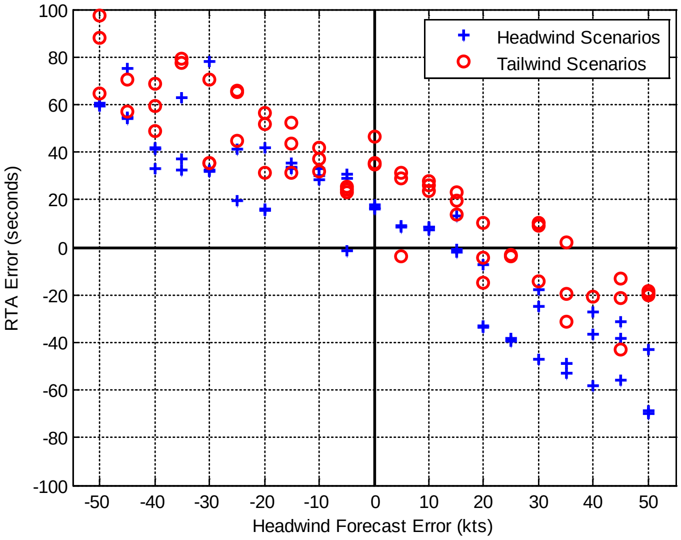


Figure 15. RTA TE as a function of constant wind error (B757/HW BL FMS).

Hypothesis (3): Flights at lower cruise levels are less impacted by wind forecast errors.

Figure 16 shows a clear trend emerges of the effect of cruise altitude on RTE TE performance: descents from higher cruise altitudes have larger RTA TE at higher wind forecast errors compared to lower cruise altitudes. This could be due to a number of reasons.

First, FMS systems have very limited wind forecast for descent. Typically, wind forecasts can be entered only for three or four selected altitudes for the entire descent, and are “geo-agnostic,” i.e., not linked to any specific latitude/longitude location. Higher cruise altitudes result in longer descent segments to a given meter fix altitude, which increases time exposure to the geo-agnostic winds as compared to geo-specific winds used during the cruise flight segment.

Alternatively, this effect could be due to speed envelope limitations at higher altitudes. As with many nonlinear closed-loop system, due to limited control authority, goal achievement is typically bounded until one or more compounding factors reaches a certain threshold. Beyond such a point, the performance will tend to degrade in a nonlinear fashion. In aircraft systems attempting to meet time goals, the constraint on control authority is directly associated with the minimum and maximum airspeeds allowable for a given aircraft while remaining inside its safe performance envelope and speed constraints set by the user as a result of their applied policies. As the altitude of an aircraft is increased, the range between minimum and maximum permissible airspeeds decreases, and thus so does the system's control authority relative to meeting time goals. The reduction in speed range of the aircraft consequently reduces the range of achievable RTA time values. Further study is recommended to better understand and characterize these effects.

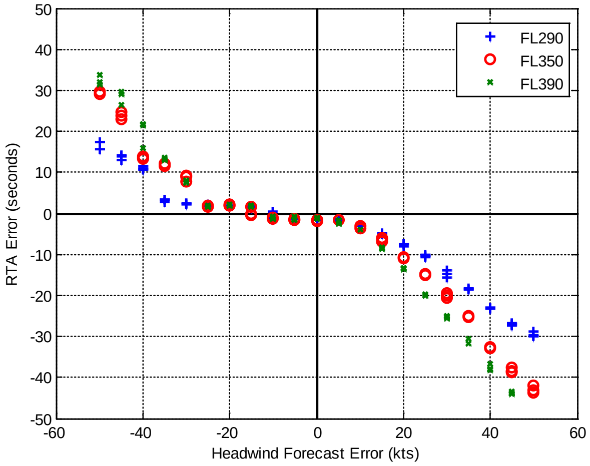


Figure 16. RTA TE as a function of cruise altitude and constant wind error (B757/HW RL FMS).

Hypothesis (4): Headwind forecast errors closer to the RTA fix cause greater magnitude RTA TE.

The results of the analysis of the data collected to test hypothesis (4) are presented in Figure 17. From these results, we see that the mean RTA TE magnitude does not tend to increase when the peak of the headwind forecast error approaches the RTA fix (location 4 is closer to the meter fix than location 1). However, it was observed that the RTA 95% CI does increase under all error conditions as the peak error location approaches the RTA fix save for the most severe forecast error case tested (RMSVE 15 knots), which had the largest CI span at location 3. This particularly large CI span is thought to arise because as an aircraft arrives near location 3 in this trajectory, there is insufficient time available for the FMS to correct for a significant forecast wind error. However, further study is required of this effect.

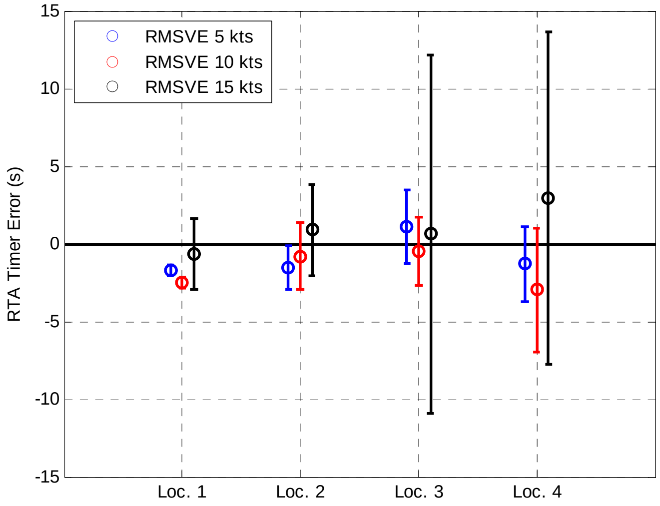


Figure 17. Averaged RTA TE and 95% confidence intervals as a function of wind forecast error location and magnitude (B757/HW RL FMS) using 100 NM waypoint spacing.

When speed error grows large (15 knots), the FMS displays the message “Drag Required” to prompt the pilot to extend speed brakes to correct the overspeed. As stated above, no speed brake or pilot models were enabled in these scenarios. As a result, no action was initiated to correct the overspeed; this likely had a negative effect to the overall statistical RTA TE performance and variance seen in these data. “Drag Required” messages from the FMS were recorded for a number of scenarios principally for those with errors peaks centered at locations 3 and 4.

Hypothesis (5): Increased waypoint spacing will cause greater RTA TE.

Analysis of the data collected to test hypothesis (5) indicates that the original hypothesis, as stated, is not true for the conditions tested; see Figure 18. There is evidence that the spacing does have an effect, but it is highly coupled to the quality of the forecast data. There is a compounding effect that is difficult to quantify relative to the over and under estimating of forecast headwinds such that it is possible that there could be offsetting effects. The impact of waypoint density varies with the accuracy of the wind forecast data provided for those points. Higher waypoint density with accurate forecasts enhances performance, i.e., better RTA TE and smaller RTA 95% CI. Higher waypoint density with erroneous forecasts is more likely to accentuate the impact of the wind errors, yielding poorer RTA TE and larger RTA 95% CI.

Note that most FMS systems implement some form of “wind blending,” i.e., trajectory predictions are based on wind values that are derived from a mix of current sensed wind values and forecast values at downstream points. Wind blending can serve to mitigate the negative impact of erroneous downstream wind forecasts. Higher wind forecast point density can tend to neutralize the potential of wind blending to mitigate the adverse impact of erroneous forecasts.

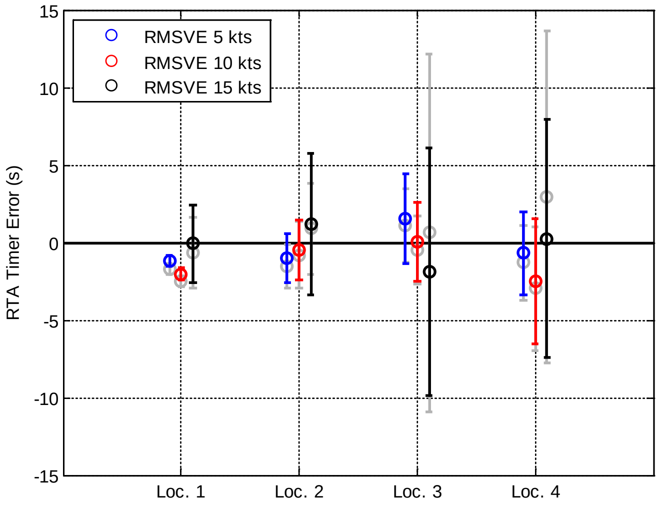


Figure 18. Averaged RTA TE and 95% confidence intervals as a function of wind forecast error location and magnitude (B757/HW RL FMS) using 10 NM waypoint spacing (results for 100 NM spacing plotted in grey).

Modified Wind Blending Test Results

An example of one of the sets of wind fields used in the testing of the different wind-blending algorithms is shown in Figure 19. This wind field, which includes a significant shear, was selected in consultation with the FMS manufacturer to exercise the wind blending algorithms under study. As can be seen in this figure, both headwind and tailwind conditions were applied. The aggregated RTA TE values measured from flights flown under various headwind forecast error conditions through these wind fields are presented in Figure 20. From these data, we see that there are no improvements in RTA TE when implementing the Enhanced1 WBA in comparison with the WBA that is implemented in the baseline Pegasus FMS.

The RTA TE performance is nearly equivalent for either WBA when the headwind forecast error is between –10 and +15 knots. Outside of this region, the RTA TE are seen to be greater for the Enhanced1 WBA than for the baseline WBA, and in particular when overestimating the headwind (see lower-right quadrant of plot).

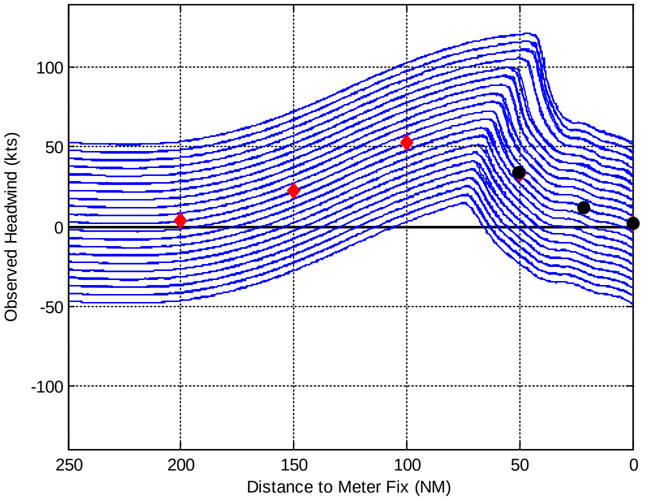


Figure 19. Observed headwinds from WBA testing flights. Red diamonds indicate the equivalent forecast headwinds at each waypoint. Black circles indicate the equivalent forecast descent headwinds.

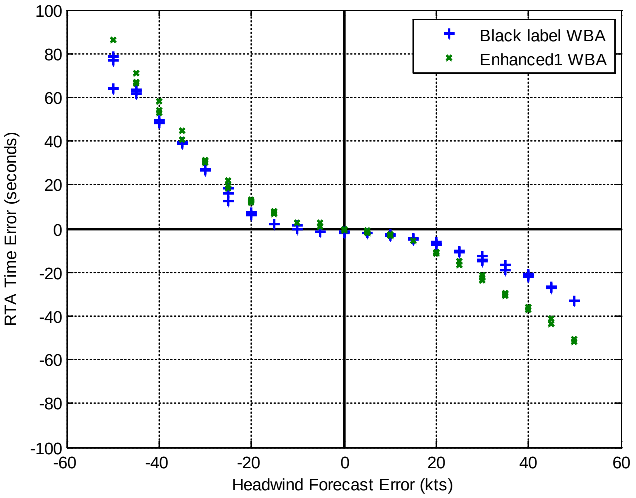


Figure 20. RTA TE as a function of constant wind error (B757/HW RL FMS) comparing black label and enhanced1 WBA.

The execution of these scenarios was essentially the first time the Enhaced1 WBA was able to be tested on a large scale. As this WBA is still experimental, it was expected that results from these experiments would lead to refining of WBA parameters and logic. While there was no observed improvement on time error when implementing the Enhanced1 WBA under the conditions tested, it is very clear from Figure 21 that the Enhanced1 WBA provides a more stable (i.e., constant) RTA speed target during cruise when compared to the baseline system, especially in the region of strong wind gradients. This could provide operational advantages such as reduced fuel consumption and reduced false-negative indications of UNABLE RTA. Additional work is required to improve this WBA logic and evaluate potential advantages.

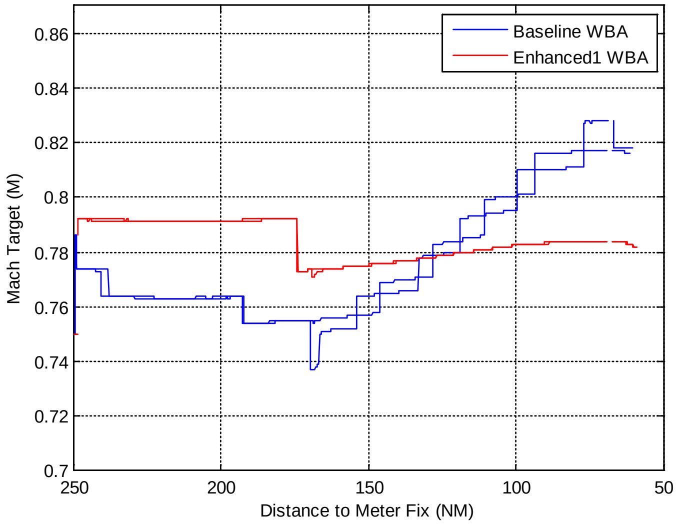
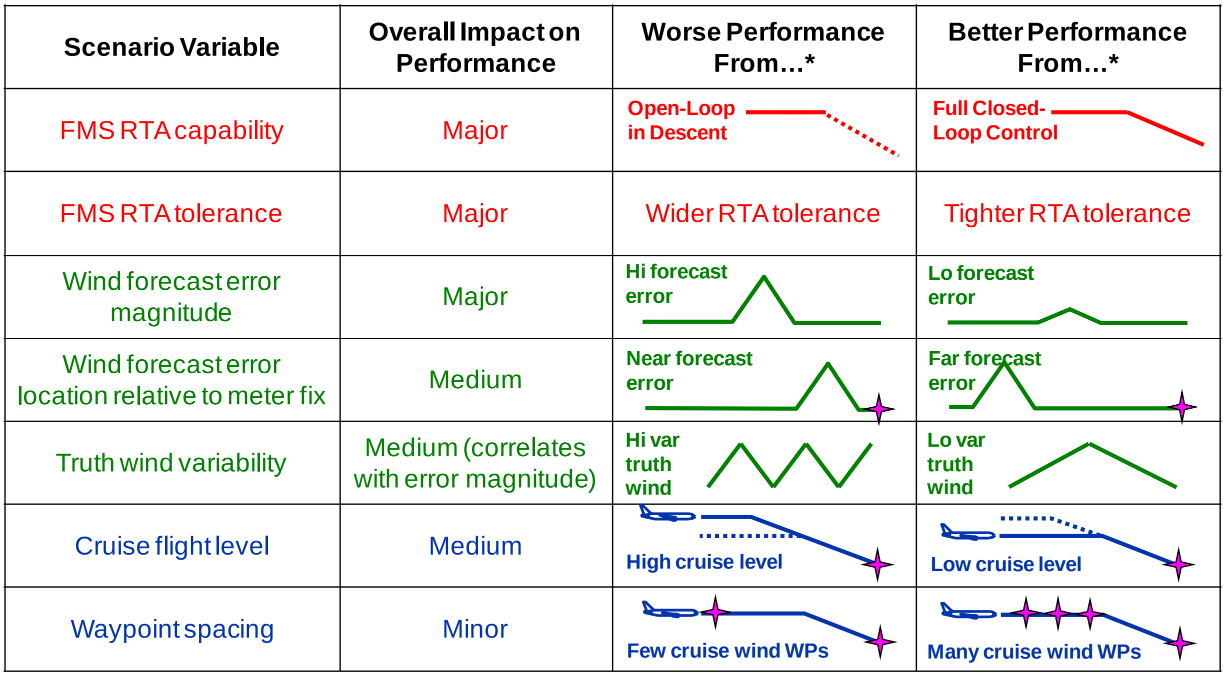


Figure 21. Comparison of FMS generated speed targets during cruise for wind-blending algorithms evaluated with constant 15 knots headwind forecast error.

3.5 4D-TBO RTA PERFORMANCE DRIVERS

Based on the results from the analysis scenarios in the previous sections, the relative impact of the key variables on 4D-TBO performance was determined. Each variable was categorized as having a major, medium, or minor impact on performance, together with what characteristics of the variable resulted in better or worse performance, as shown in Figure 22. The colors map to the colors of the elements of the Wind Information Analysis Framework.



Scenario Variable	Overall Impact on Performance	Worse Performance From…*	Better Performance From…*
FMS RTA capability	Major	Open-Loop in Descent	Full Closed-Loop Control
FMS RTA tolerance	Major	Wider RTA tolerance	Tighter RTA tolerance
Wind forecast error magnitude	Major	Hi forecast error	Lo forecast error
Wind forecast error location relative to meter fix	Medium	Near forecast error	Far forecast error
Truth wind variability	Medium (correlates with error magnitude)	Hi var truth wind	Lo var truth wind
Cruise flight level	Medium	High cruise level	Low cruise level
Waypoint spacing	Minor	Few cruise wind WPs	Many cruise wind WPs

*** All else being equal**

Figure 22. 4D-TBO performance drivers.

3.6 KEY TAKEAWAYS AND ASSOCIATED PERFORMANCE TRADESPACES

Based on the analysis of the effects of parameters studied in this work, the following are key takeaways:

1. Primary performance drivers of RTA compliance performance are forecast error magnitude for winds provided to the FMS, FMS RTA capability (specifically whether it provides full flight closed-loop speed control or not), and RTA tolerance setting.

2. Wind forecast errors beyond a situation-dependent threshold value are more likely to produce increased RTA TE and larger RTA 95%CI.

3. RTA compliance with 95% CI ±20 seconds of the mean appears possible for full closed-loop control systems in low-moderate wind error scenarios.

4. A given wind forecast error close to the meter fix has a bigger impact on RTA compliance performance than the same error further from the meter fix.

5. 4D-TBO procedures involving descents to a given meter fix altitude from higher cruise altitudes are generally less tolerant of large wind errors than descents starting at lower cruise altitudes.

There are some differences between the various results assessed in this phase of the work, which warrant further study, extension, and validation/verification in Phase 4. However, the tradespace shown in Figure 23 below shows the range of RTA compliance performance based on a synthesis of the findings from the range of analyses for the specific aircraft/FMS types and scenarios considered in this work. The major performance drivers identified above defined the primary independent variables of the tradespace. The bar heights estimate the possible "best" performance from that combination of variables, while the whiskers reflect the likely range of performance impacts from variations in the other medium and minor performance drivers.

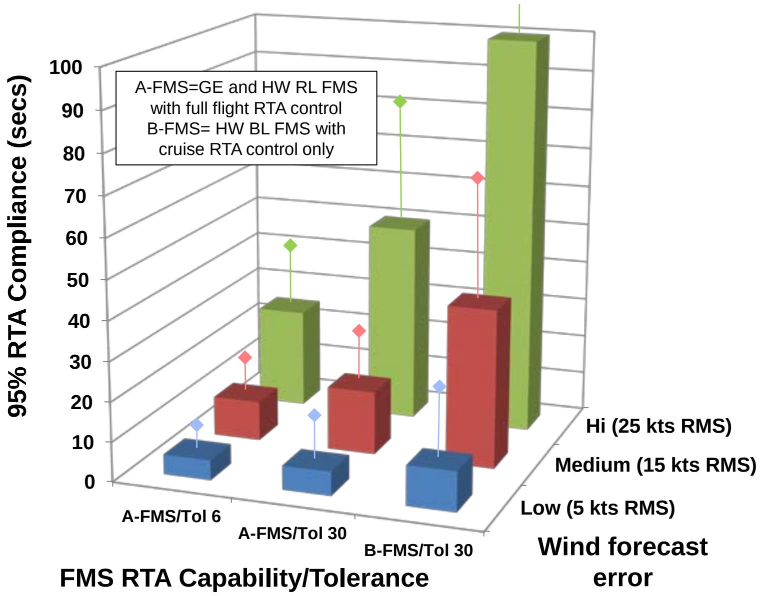


Figure 23. Summary 4D-TBO RTA compliance performance tradespace for the FMS types and scenarios studied.

3.7 RECOMMENDED NEXT STEPS

The tradespace shown in Figure 23 reflects the authors' best attempt at synthesizing the findings presented in the preceding sections and is considered to be generally reflective of the relative RTA performance across the range of aircraft/FMS, wind, and ATC conditions studied. However, care should be exercised in its use for conditions not explicitly studied in this work. The recommended next steps that could expand the applicability of the study findings include

- Expand the analyses to include more aircraft/FMS types to generate results that cover the range FMS capabilities represented in the operational fleet.

- Expand the truth and forecast wind conditions considered in this analysis to cover a broader set of environments experienced in real operations.

- Explore the performance improvement potential of a range of realistic FMS wind handling enhancements technically feasible within the next decade, which could improve RTA compliance performance, for example:

  - Increasing FMS wind definition points, e.g., using more wind altitudes, gridded wind fields, etc.

  - FMS wind-interpolation algorithms

  - Enhancing FMS wind-blending algorithms

  - Enhancing control algorithms

  - Tailoring wind entry locations and/or altitudes to mitigate FMS and/or wind model limitations

- RTCA SC-227 has published standards for Time-of-Arrival Control (TOAC) as 95% compliance with accuracy levels of ±10 seconds (RTA involving descent) and ±30 seconds (RTA in cruise only) given a defined meteorological uncertainty model (DO-236C Chg 1 Section 5.1.2.1). Analysis should be conducted to analyze implications of these specific accuracy requirements on wind information requirements.

- Various commercial vendors are now providing wind information to airlines tailored to the individual aircraft and FMS characteristics in their fleet. The research team could explore collaborating with those entities to establish the relevance and potential operational impacts (e.g., in terms of performance improvements) enabled through the use of these commercially available wind information sources compared to the publically available information.

4. ANALYSIS OF WIND INFORMATION ACCURACY ON INTERVAL MANAGEMENT PERFORMANCE

4.1 INTRODUCTION

The main elements of an IM procedure were illustrated in Figure 2. The follower aircraft in the pair is termed the “IM Aircraft” or “Ownship,” which is responsible for achieving an Assigned Spacing Goal (ASG) from a “Traffic To Follow” (TTF) aircraft by a certain Achieve By Point (ABP). Wind information and aircraft trajectory models are used by ATC systems on the ground to develop an appropriate ASG for use in the procedure. There are two main variants of IM procedure: Ground Interval Management (GIM) and Flight-deck Interval Management (FIM). After the initial capability of IM is established, additional functions and capabilities will be developed under Advanced Interval Management (A-IM). GIM is designed to assist air traffic controllers in conditioning arrival flow, using primarily speed commands to manage arrival times of the aircraft to the ABP similar to the 4D-TBO procedures with time targets at a meter fix. Periodic speed commands are communicated to aircraft if the arrival time at the ABP inferred from conventional surveillance is different than the time required to achieve the desired spacing from the other paired aircraft. GIM is similar to arrival flow management today, but controllers are provided a GIM-calculated speed advisory, that is not currently automatically calculated. Under FIM, controllers identify potential FIM pairs of aircraft, and then give an IM clearance to the following aircraft of the pair (the “IM Aircraft” or “Ownship”). This IM clearance assigns the IM aircraft a spacing goal behind the TTF, by a certain ABP. One method of achieving the IM operation is the use of avionics in the Ownship aircraft to execute an interval management algorithm that produces closed-loop speed targets to try to achieve the target separation, accounting for any wind forecast information impacting its own trajectory (the “Ownship winds”) or that of the TTF (the “TTF winds”). Any errors in the ground and/or aircraft wind information relative to the truth winds actually flown through can significantly degrade the ability to comply with the ASG and hence affect the overall integrity of the IM procedure. In GIM, corrective speed advisories are typically limited to relatively infrequent intervals (e.g., every 5 minutes or more) with resulting higher sensitivity to wind errors than FIM, which involves closed-loop speed control by the Ownship, which can deliver corrective speed commands much more frequently. Other scenario variables can also impact the overall performance of the IM procedure as measured by the time separation at the ABP relative to the target. This section details analysis that has been conducted to quantify the relative performance of different IM procedures under a range of representative scenarios.

4.2 ANALYSIS OVERVIEW

In order to analyze the performance of the IM procedures as a function of key operational variables, the Wind Information Analysis Framework was tailored to the IM application as shown in Figure 24. The **IM Scenario** contains details such as which aircraft types are being modeled as TTF and Ownship, what trajectories they are expected to fly, and specifics of the IM definition such as the ASG and the ABP parameters. The **Wind Scenario** defines the truth and forecast wind environments, but may also include sensed winds that may be available from the TTF to the Ownship through advanced surveillance, such as Automatic Dependent Surveillance-Broadcast (ADS-B) or other future systems. In order to execute the IM procedure, the **Aircraft/Automation Simulation** for the Ownship requires IM Controller and Estimator algorithms. In FIM, the TTF is assumed to broadcast its position and ground speed (e.g., via ADS-B Out), which is received by the Ownship (e.g., via ADS-B In). The IM Estimator uses this information, together with anticipated wind information (via a forecast or sensors), to estimate how long it will take the TTF to get to the ABP. The difference between this time and its estimate of how long it will take for itself to get to the ABP defines the current estimated time separation at the ABP. This is compared to the ASG from the scenario definition (also known as "clearance information" in application terminology) to determine a time error at the ABP. The IM Controller algorithm translates this time error at the ABP into a modified target speed command designed to zero-out this error (i.e., command a higher speed if the estimated Ownship/TTF spacing is too large at the ABP, command a slower speed if the estimated spacing is too small, or maintain current speed if the estimated spacing is close to the target). These speed commands are used as inputs to an autothrottle system which commands throttle changes to the engine. The resulting changes to engine thrust affect the dynamics of the aircraft, resulting in a new aircraft speed profile. The IM system iterates this cycle on some appropriate control update rate, e.g., 5 minutes (or more) update periods for GIM and less than 60 second update periods for FIM. The key **Performance Assessment** variables of interest include the Ownship/TTF time separation at the ABP, which varies as a function of the key independent variables of interest to IM algorithm and concept-of-operations development.

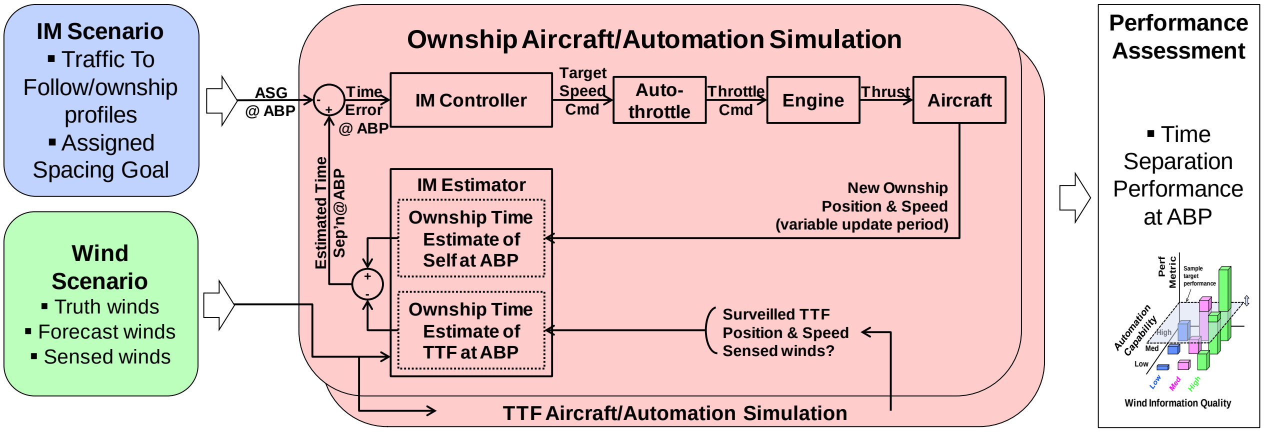


Figure 24. Interval Management Performance Analysis Framework.

4.3 SCENARIOS

Based on previous analyses [2], performance implications of the wind scenario variables shown in Figure 25 were studied for this work. The difference between the truth and forecast wind used in the scenario (i.e., the wind error) was abstracted as a spike of a given magnitude, width, and location relative to the ABP. This spike representation can be considered to be a building block of more realistic wind error profiles.

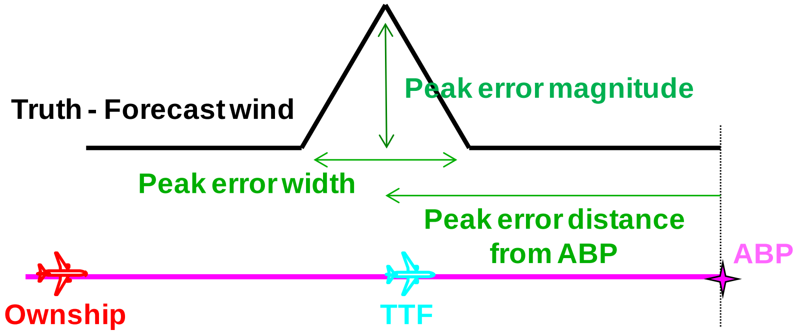


Figure 25. Interval Management Wind Analysis variables.

In addition to these wind variables, a range of ATC and aircraft/automation variables were also studied. The specific values of the full range of scenario variables are shown in Table 2.

TABLE 2

Simulation Conditions for Interval Management Studies

Wind Information Analysis Framework Element	Independent Variable	Values Tested	Number of Permutations
Wind Scenario	Ownship or TTF forecast peak error magnitude	Low (5 knots) Medium (15 knots) High (25 knots)	3
	Ownship or TTF forecast peak error width	10, 20, 40, 60, 100 NM	5
	Ownship or TTF forecast peak error location	0, 20, 40, 60, 80 NM from ABP	5
ATC Scenario	Trajectory	Lateral path: aircraft on merging (at ABP) trajectories Vertical path: Cruise flight only Longitudinal path: constant starting distances from the ABP of 100 and 120 NM for the TTF and Ownship respectively, TTF flying fixed airspeed profile at M0.75	1
	Number of waypoints	0, 3, 6	3
Aircraft/Automation Simulation	Aircraft/FMS type	Simple point mass aircraft model with maximum/minimum speed envelope characteristics of A340 from Eurocontrol BADA 3.6 IM update period: 1, 10, 30, 60, 150, 300 secs (covering range of FIM-to-GIM cases)	6
	Total permutations	500 Runs/Condition	1350

A set of six scenarios comprising different combinations of these analysis variables for an ABP merge case were created to isolate different parameters of interval management which might be performance drivers. The scenarios build upon one another to test how a specific aspect of wind forecast error for the Ownship, TTF or both affects IM performance. The key findings from each scenario are discussed in turn in the following section. The graphic to the right of each scenario name indicates for which aircraft there is a difference between the truth (blue line) and forecast (red line) wind.

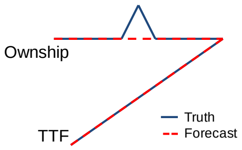
Each of these scenarios was flown over the same trajectories. These were all simple cruise-only scenarios designed to be the simplest possible to diagnose wind effects, recognizing that more complex trajectories (e.g., involved cruise and descent flight) will be needed to explore more operationally realistic issues. In each case, the Ownship and TTF were flying trajectories that merge at the ABP. The TTF began

100 NM away from the ABP and the Ownship was 120 NM away. The TTF flew a constant airspeed with the Ownship adjusting its speed as needed. The ASG at the ABP was 2 minutes, which translated to roughly 15 NM at these speeds.

For the IM speed control, the NASA ASTAR12 algorithm [6] was used to calculate the target airspeed. Depending on the IM update rate used, which ranged from 1–300 seconds, a new target airspeed was calculated for the Ownship to fly and the autothrottle was engaged to execute this speed command. There were no minimum thresholds for new commands, e.g., a new speed command was only issued when there was at least a 10 knots difference from the current speed.

4.4 RESULTS

The sections below summarize the key findings, with supporting data provided in Appendix A.

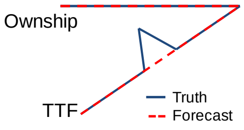


4.4.1 Scenario 1: Error in Ownship Forecast, Perfect Forecast for TTF

Setup: In the first scenario, the Ownship experiences a wind spike in its truth wind, whereas the TTF flies through a zero wind field. The forecast for the Ownship is zero, so the overall forecast error it experiences is equal to the wind spike. Because the TTF flies through zero truth wind and has a forecast of zero, it always arrives at the ABP at the same time, and the Ownship is able to accurately predict when it will arrive. Therefore, this essentially is an RTA scenario.

This simple scenario was tested using a range of wind spike magnitudes, widths, and locations. The wind spike magnitude is a separate pull on each run from a random, normal distribution with mean of zero and standard deviation equal to the given error magnitude. The error magnitudes used ranged from 5–25 knots. The widths ranged from 10–100 NM across. The location refers to the distance of the midpoint of the wind spike from the ABP. The distances tested varied from 0–80 NM from the ABP.

Results (see Section A.1 for full details): Increasing forecast error magnitude and width, decreasing distance of the error location relative to the ABP, and increasing IM update periods result in decreased IM performance, i.e., more time spread.

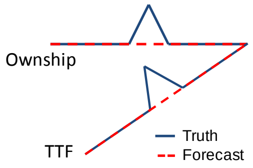


4.4.2 Scenario 2: Perfect Forecast for Ownship, Error in Forecast for TTF

Setup: The second scenario is the reverse of the first. In this case, the TTF flies through a wind spike, with a forecast of zero, and the Ownship has both a truth wind and forecast of zero. In the previous case, the Ownship was accurately predicting the TTF's arrival time but not its own. In this case, it is accurately predicting its own arrival time but must adjust speed to account for the errors in the forecast for the TTF.

These scenarios were tested using the same ranges of wind spike magnitudes, widths, and locations. The purpose was to test if the impact of the wind spike is the same on both the Ownship (in the first scenario) as it is on the TTF.

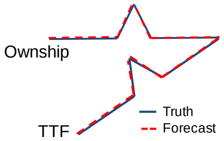
Results (see Section A.2 for full details): This scenario reinforces the takeaways from Scenario 1 in general. In addition, the time-spread at the ABP is generally lower in this TTF-only case than in the Ownship-only case because the Ownship has more time to recover from errors on the TTF path, and because the Ownship will reach the ABP after the TTF reaches the ABP.



4.4.3 Scenario 3: Error in Forecast for Ownship and TTF

Setup: The third scenario is a combination of the first two. Both the Ownship and the TTF fly through the same wind spike at the same location (although they experience the wind spike at different times because the TTF is ahead of the Ownship). The purpose of this scenario was to see the effects of the combined errors of the two aircraft. It was tested to see if an error on one aircraft had more effect than the other.

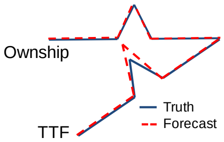
Results (see Section A.3 for full details): The IM performance in this case is somewhere between scenarios 1 and 2. The two wind spikes put together do not compound: the resulting errors are closer to the Ownship-only scenario, which again suggests that error on the Ownship has more of an impact than on the TTF.

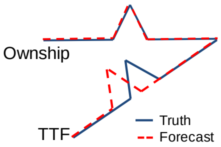


4.4.4 Scenario 4: Perfect Forecast for Ownship and TTF, Variable Waypoints

Setup: The purpose of the fourth scenario was to test the impact of having different quantities of wind forecast information for the TTF. The setup is similar to Scenario 3, where both aircraft experience the same wind spike at the same location. The main difference is that the forecast information for both the Ownship and TTF is equal to the truth. In other words the forecast, for whatever number of waypoints is used, is completely accurate at those waypoints. The Ownship always has six waypoints spaced 20 NM apart, which is enough to completely model the wind spike with accuracy. The amount of information for the TTF was varied, with either 0, 3, or 6 waypoints. The 0-waypoint case is the same as Scenario 3, except that now the Ownship has zero forecast error on its own path.

Results (see Section A.4 for full details): The TTF 0-waypoint cases generally have improved performance over the cases in Scenario 3, which is expected given the Ownship now has zero forecast error on itself. The TTF 6-waypoint cases perform much better, with almost no error, showing that having enough waypoints to characterize the winds and having good forecast information at those waypoints leads to much better performance.

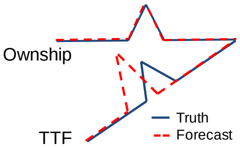




4.4.5 Scenario 5: Error in Forecast Magnitude OR Location for TTF, Variable Waypoints

Setup: This scenario is similar to Scenario 4, except it now adds forecast error. The forecast for the Ownship is still perfect, but the forecast for the TTF is erroneous in one of two ways. Either the wind spike width and location are correct in the forecast but the magnitude is incorrect, or the width and magnitude are correct but the location is incorrect. This tests the impact of different types of forecast errors.

Results (see Section A.5 for full details): For the limited number of cases run, it was more often the case that the 0-waypoint case performed better than the 6-waypoint case. This suggests that in cases of incorrect forecast information having no information can actually result in better performance. Further studies would be needed to determine where the boundaries are for these cases.



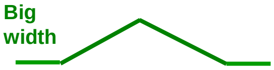
4.4.6 Scenario 6: Error in Forecast Magnitude AND Location for TTF, Variable Waypoints

Setup: This scenario combines the two types of errors from Scenario 5. The Ownship and TTF both still fly through the same wind spike. The Ownship still has a perfect forecast, but the TTF has a forecast that is erroneous both in magnitude and in location. This tests the combined impact of the two types of errors. In both Scenarios 5 and 6, the tests were run with different levels of forecast information (number of waypoints) for the TTF.

Results (see Section A.6 for full details): For these sets of test cases, there is interplay between different types of errors. Overall, there is significant decreasing IM performance with larger truth wind magnitude and larger forecast error magnitude. Having less impact is the truth wind spike distance from the ABP and the offset of the forecast wind spike from the truth. These results also show several examples of no forecast information performing better than with 6 waypoints of erroneous forecast information.

4.5 INTERVAL MANAGEMENT PERFORMANCE DRIVERS

Based on the results from the analysis scenarios in the previous section, the relative impact of the scenario variables on interval management performance was determined. Each variable was categorized as having a major, medium, or minor impact on performance, together with what characteristics of the variable resulted in better or worse performance, as shown in Figure 26. The colors map to the colors of the elements of the Wind Information Analysis Framework in Figure 3. Note that in reality there is often coupling between the effects of different variables, but the incremental nature of the analysis scenarios described in the previous sub-section allow general effects of each variable to be isolated to some degree.

Scenario Variable	Overall Impact on Performance	Worse Performance From…*	Better Performance From…*
Wind forecast peak error magnitude+	Major	**Hi forecast error** 	**Lo forecast error** 
IM update period	Major	Long update periods	Short update periods
Wind forecast peak error location+	Major/Medium	**Near forecast error** 	**Far forecast error** 
Wind forecast peak error width+	Medium	**Big width** 	**Small width** 
Number of TTF waypoint wind forecasts available to Ownship	Medium	High error at multiple WPs	Low error at multiple WPs
Ownship access to TTF winds	Medium/Minor	High error in TTF winds	Low error in TTF winds

*** All else being equal** +Bigger impact on Ownship than TTF

Figure 26. Interval Management performance drivers.

4.6 KEY TAKEAWAYS AND ASSOCIATED PERFORMANCE TRADESPACES

The results of the interval management analysis described above results in a number of key takeaways described below. Each is associated with a set of relevant performance tradespaces to illustrate the effect highlighted in the takeaway. It is seen from Figure 26 that the major interval management performance drivers are the wind forecast peak error magnitude and the IM update period. Therefore, these are the logical choices for the primary independent variable dimensions of the interval management tradespaces. The effects of the other variables can be captured by the range of performance (best-to-worst) of different combinations of these primary independent variables within a tradespace, or by comparing different tradespaces.

For each of the figures shown below, the major performance drivers identified above defined the primary independent variables of the tradespace. The bar heights estimate the possible "best" performance from that combination of variables, while the whiskers reflect the likely range of performance impacts from variations in the other medium and minor performance drivers as tested with the wind spike located at various distances from the ABP. Full results for each combination of wind spike magnitude, width, distance from the ABP, and IM update period are shown in Appendix A.

1. For the simple cruise-only cases examined here, most of the procedures tested with update periods of less than 10 secs achieved very tight 95% time spreads at the ABP of 10 secs or less.

2. Increased overall forecast error (from error magnitude and width) and update period leads to an increased arrival time spread at the ABP.

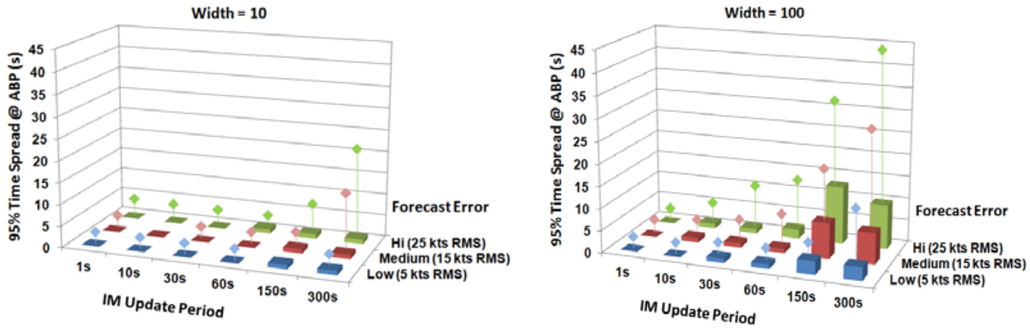


Figure 27. IM tradespace showing major effects of wind forecast error and IM update period (based on Scenario 3).

Figure 27 above shows the impacts of IM update period and forecast error on IM performance. The figure on the right has a larger wind spike width and hence a greater overall forecast error. Each solid bar and its corresponding error bar show the best and worst performance with the wind spike located over a range or 0–80 NM from the ABP. As can be seen in the figures, longer IM update period results in a higher 95% Time Spread.

3. The closer the forecast error is to the ABP, the larger the arrival time spread at the ABP; see Figure 28.

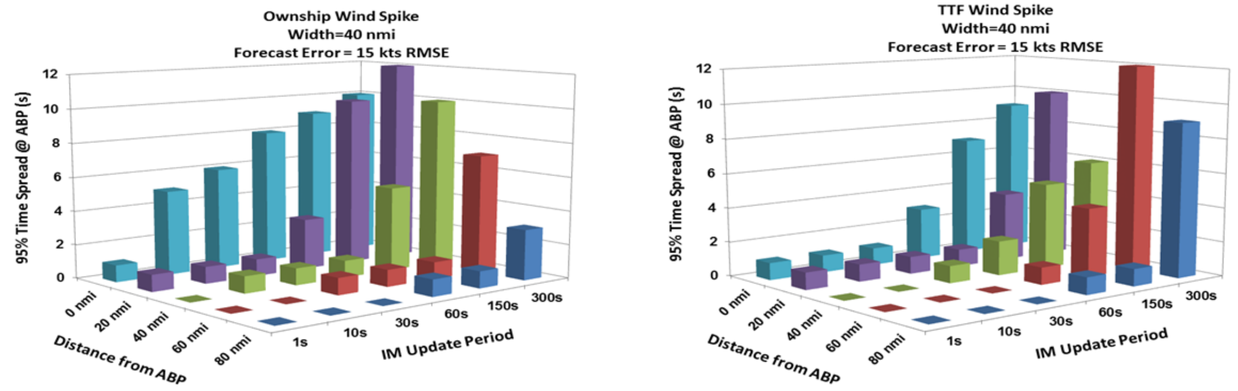


Figure 28. IM tradespace showing major effects of wind forecast error and IM update period (based on Scenarios 1 and 2).

4. A forecast error of a certain magnitude, width, and location located on the path of the Ownship will have more of an effect on arrival time spread at the ABP than the exact same forecast error on the path of the TTF. This is because the TTF is ahead of the Ownship, and the Ownship has extra time to correct for any errors on the TTF's path.

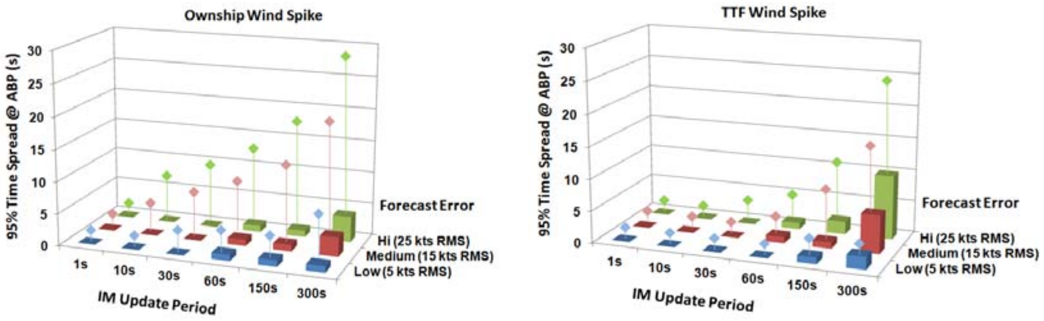


Figure 29. IM tradespace showing different performance impacts of forecast error on Ownship and TTF (based on Scenarios 1 and 2).

In the example shown in Figure 29, the width is fixed at 40 NM. Looking at the error bars, to see the performance when the wind spike is close to the ABP, illustrates the degraded performance for a forecast error on the Ownship versus the TTF.

5. If the Ownship has forecast information for the TTF, assuming that the information for TTF is low error, it generally results in better IM performance than having no information at all.

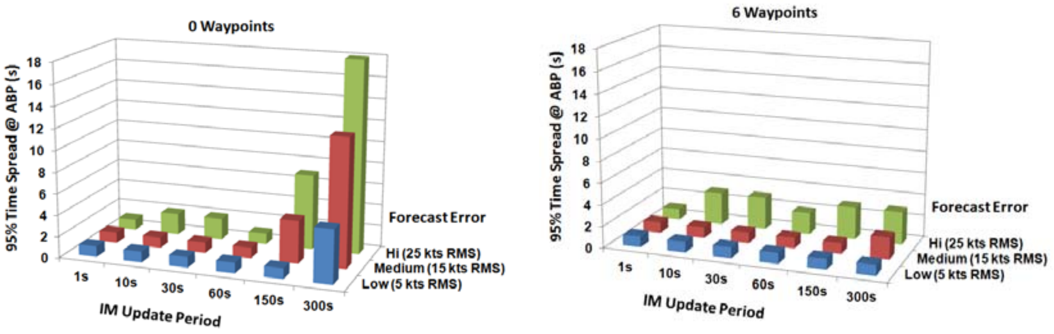


Figure 30. IM tradespace showing effect of Ownship having access to low error TTF wind information (based on Scenario 4).

In the example shown in Figure 30, the width is fixed at 40 NM and the wind spike distance from the ABP is 20 NM. Having wind forecasts at 6 waypoints for the TTF enables the Ownship to accurately reconstruct the TTF's winds, whereas having wind forecasts at 0 waypoints does not allow the Ownship to reconstruct the TTF's winds. This illustrates that, when the forecast is completely accurate, there is improved performance when the Ownship has more waypoint forecast information for the TTF.

6. The Ownship having no forecast information for the TTF can result in better IM performance than having datalinked forecast information for the TTF where the forecast has high error.

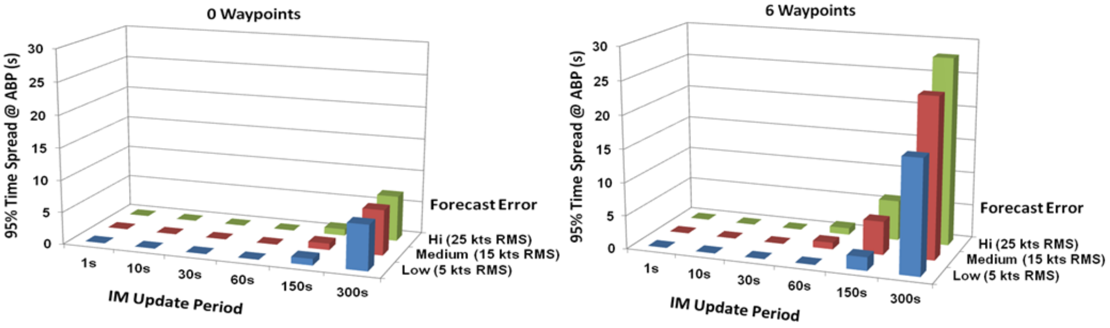


Figure 31. IM tradespace showing effect of Ownship having access to high error TTF wind information (based on Scenario 6).

The example shown in Figure 31 has both errors in forecast magnitude and location. The truth wind spike is 80 NM from the ABP, whereas the forecast is centered at 60 NM from the ABP. The truth wind spike magnitude is 25 knots and the forecast error magnitude ranges 5–25 knots from the truth. Because of the erroneous forecast information, in this particular example, the performance actually degrades with increasing waypoint information.

4.7 RECOMMENDED NEXT STEPS

These conclusions have come from the six simple scenarios described, which have been built upon each other. Further research is needed to refine the above takeaways and to expand the case studies to explore the impact of other factors in interval management. The following are recommended next steps for further analyzing the relationship between wind forecast information and IM performance:

- Continue to study the impact of number of waypoints in combination with a range of forecast error on IM performance. This is to determine a boundary between where more waypoint forecast information is beneficial and where it actually degrades performance.

- Expand the simulation environment to model descent trajectories and study the impact of wind forecast errors at different points in descent. This will also include modeling realistic truth wind scenarios for the levels of wind experienced along a descent trajectory.

- Explore the performance of more complex IM scenarios with various amounts of wind information and levels of wind information accuracy. One such scenario could be a string of three aircraft using IM procedures to maintain separation.

- Explore the practical implementation of IM algorithms in current avionics architectures, e.g., integrating additional features into current FMSs.

5. ANALYSIS OF WIND FORECAST MODEL PERFORMANCE

5.1 INTRODUCTION

Results from simulations utilizing the Wind Information Analysis Framework provide the wind error tolerances that should be met in order to achieve (on average) a given target level of performance for the procedure. The forecast error limits will then need to be compared to current and near-term wind forecast model capabilities in order to identify the feasible combinations of forecast model types and their performance as a function of forecast “look-ahead” time (also commonly known as forecast “lead time”), as shown in step 5 of Figure 4.

As documented in prior reports [1,4], our survey and literature search of current and near-term operational wind forecast models found outdated (older generation models), sparse, and inconsistent reporting of model performance with respect to forecast look-ahead time for the latest models. In order to translate wind forecast error limits to current forecast model capabilities, a more comprehensive, consistent, and updated set of wind forecast model performance statistics is needed. Therefore, an independent analysis of wind forecast model was conducted in this work for three operational models used by airline dispatchers and FAA aviation weather systems:

- **Global Forecast System (GFS)**: the GFS model is run by the National Oceanic and Atmospheric Administration’s National Centers for Environmental Prediction (NOAA/NCEP) every 6 hours and produces forecast products at two resolutions. For the 0 to 192 hour (8 day) forecast range, the model outputs forecast data on a 25 km horizontal resolution Mercator Cartesian projection with a forecast step resolution of 3 hours. For the 192 to 384 hours (8–16 days) forecast range, the model provides outputs at a coarser 70 km horizontal resolution with a forecast step resolution of 12 hours. Sixty-four vertical levels are output for all forecast ranges.

- **Rapid Refresh (RAP)**: the hourly updating 13 km resolution RAP model replaced the Rapid Update Cycle (RUC) in May 2012 as an operational gridded forecast model produced at NOAA/NCEP. Gridded forecasts of winds and gusts are produced each hour for the North American domain and provide hourly forecast look-ahead steps from 0 to 15 hours at selected altitudes (e.g., 10 meters) and for 50 pressure levels extending to 10 hPa (approximately 100,000 ft under standard atmospheric conditions).

- **High Resolution Rapid Refresh (HRRR)**: the HRRR model is an hourly updating, 3 km resolution, CONUS domain model developed by the NOAA Earth System Research Laboratory (NOAA/ESRL). It became operational at NOAA/NCEP, on September 30, 2014. Like the RAP model, the HRRR updates hourly and provides hourly forecast grid sequences of meteorological variables from 0 to 15 hours.

Table 3 summarizes the characteristics of the three models.

TABLE 3

Wind Forecast Model Summary

Model (Producer)	Domain	Resolution and Update	Output Forecast Step/ Horizon	Operational Status	Aviation Users
GFS (NOAA/ NCEP)	Global	0–192 hrs: 25 km 204–384 hrs: 80 km 64 levels to 10 MB Update: 6 hrs	3 hrs/192 hrs 12 hrs/204–384 hrs	Operational	Airlines (flight planning) Commercial vendors Boundary conditions for RAP model
RAP (NOAA/ NCEP)	North America	13 km 50 levels to 10 MB Update: 1 hr	1 hr/18 hrs	Operational	NOAA (Av.Wx.Ctr, Storm Pred. Ctr) FAA (ATM, CWSUs, ITWS, TMA) Airline dispatchers Commercial vendors Aviation wx research
HRRR (NOAA/ NCEP)	CONUS	3 km 50 levels to 20 MB Update: 1 hr	1 hr/15 hrs	Operational (as of Sept 30, 2014)	AWC, FAA ATCSCC, NCAR, CoSPA, NWP

5.2 ANALYSIS OVERVIEW

To assess wind forecast model performance, historical GFS, RAP, and HRRR forecast model data were obtained from archives for a 10-month period spanning November 2013 through August 2014. This analysis time period was limited to the 10 months due to the unavailability of archived HRRR data prior to November 2013.

5.2.1 Spatial Domain and Time Sampling

In order to represent forecast capabilities across different geographic wind environments, forecast comparisons were made over four separate regions centered on San Francisco (SFO), Phoenix (PHX), Chicago (ORD), and Newark (EWR) airports, as shown in Figure 32. Within each approximately 400 NM × 400 NM region, model wind forecasts were sampled and compared against matching wind observations (taken from the matching HRRR 0-hour analysis) at 81 horizontal grid points spaced approximately 50 NM apart, and at nine different pressure altitudes (1000–200 hPa, every 100 hPa, or roughly 350 to 38,600 feet MSL assuming standard atmospheric conditions). RAP and GFS forecasts were laterally interpolated to the HRRR truth grid points. Vertical interpolation was not required as all three models provide wind forecast data grids at the selected pressure levels. Comparisons were made eight times per day and for each of eight selected model forecast look-ahead times (1, 2, 3, 4, 5, 6, 9, and 12 hours). Because the GFS model only has 3-hour forecast look-ahead resolution, comparisons at look-aheads of 1, 2, 4, and 5 hours were made by linearly interpolating in time between the time-bracketing GFS forecasts for those look-ahead times.

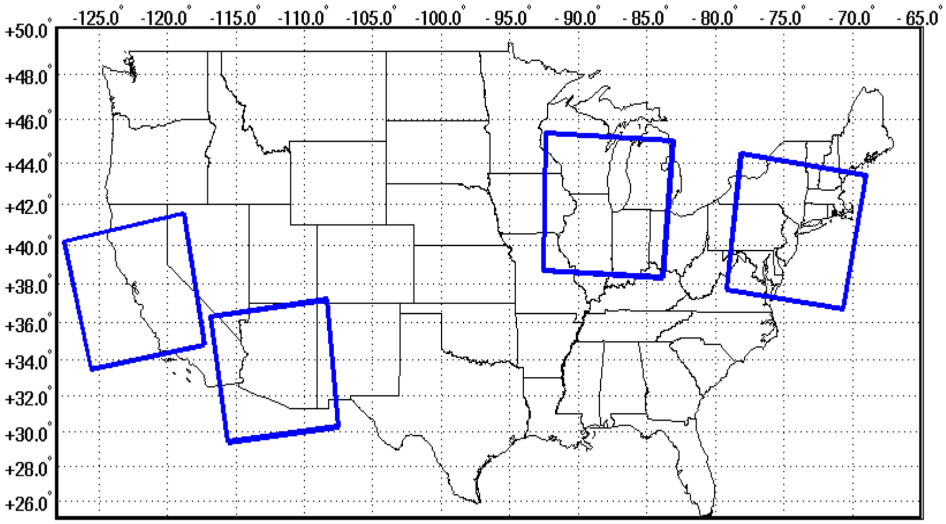


Figure 32. Regions analyzed for wind forecast model performance.

5.2.2 Sources of Wind Observations

For computing the forecast errors, three sources of wind observations were considered: aircraft reports (e.g., Aircraft Meteorological Data Relay (AMDAR)), radiosonde (balloon) soundings, and numerical model analyses. Aircraft and radiosonde data have often been used as sources of observation truth in prior forecast model accuracy studies because they represent real wind measurements. However, there are a number of issues with their use for this type of model comparison analysis:

1. Additional errors can be introduced by the observations themselves ([7,8,9]). Reference 7 explains that these errors arise from two components: observation errors (e.g., sensor calibration errors or instrument malfunction) and errors of representativeness, wherein the instantaneous sensor observations include contributions from length scales too small to be represented in the numerical model (e.g., turbulence). These smaller scale fluctuations also tend to be of limited consequence influencing aircraft ground speeds over typical flight segment lengths of interest.

2. Compared to gridded numerical model analysis data, observation data from aircraft and soundings are more limited in space and time (aircraft data are available only along flight routes during times of meteorological data downlink, and balloon soundings are typically performed only twice per day at relatively few locations).

3. The forecast models typically use aircraft and radiosonde-reported measurements as initialization inputs, so they are not an independent verification source.

For this study, we utilized gridded wind data from the HRRR model 0-hour analysis as the source of observation truth data (similar model-based sources of wind observations were utilized by [7] and [10]). Although this is also not an independent data source, this strategy does mitigate the other concerns with observation data highlighted above. The HRRR was chosen because of its high spatial resolution (3 km horizontal) and frequent (hourly) data assimilation (which includes aircraft reports and balloon soundings). The HRRR analyses provide a good density of observation data in space and time and permits easier analysis of the spatial relationships of the forecast errors.

5.2.3 Metrics

At each of the eight daily sampling times, and for each forecast look-ahead time category, altitude layer-aggregated RMS vector errors (RMSVE) were computed between the matching forecast and observed winds using Equation (2) as defined earlier. RMSVE is the most commonly utilized metric reported in earlier forecast accuracy studies, and its use here allows these results to be compared against prior results. In addition to the layer-averaged RMSVE, minimum, maximum, median, and standard deviations of the errors for each layer were computed and stored so that outliers could be investigated and distributions understood. Error statistics were then averaged over the 10-month period and for the four regions.

5.2.4 Data Age

The above comparison approach and metrics provide the basis for a baseline determination of average forecast model performance across the forecast look-ahead times for the different models. However, this assessment does not address potential additional “data age” errors that could arise from using old forecast data at locations and times along the flight route that don’t match the intended valid time of the model forecast (e.g., using the RAP 2-hour forecast valid at 14Z from the 12Z model run as a prediction of the winds at 16Z at some location during the flight).

Reference 11 referred to this data age effect as the “forecast latency” and defined it as the difference between the time of forecast data availability (which is usually before the time at which it is uplinked to the aircraft), and the time at which the aircraft is crossing the location where the forecast is being used. Their analysis of global scale model forecasts against aircraft reports found that wind speed forecast errors increased nearly linearly from approximately 8.9 knots at 2–4 hours latency to 9.8 knots for latencies of more than 8 hours. These results suggest that using old forecast data could further increase forecast errors by approximately 1 knot.

The wind forecast performance results presented in this section should be considered a baseline of forecast error measurement that assumes the appropriate model forecasts look-aheads are being used at the nominal forecast valid times for which they were intended. Use of "stale" wind forecast data will tend to increase the forecast errors, and further analysis of these data age effects are a suggested area for further work.

5.3 RESULTS

RMS vector forecast errors from the SFO, PHX, ORD, and EWR regions were compiled for each of the three forecast models and analyzed independently and in combination. Figure 33 plots the averaged RMS vector forecast errors for the three models as a function of forecast look-ahead time for each of the four regions. To better facilitate translation of the results to wind forecast quality requirements, the statistics were combined across all altitudes.

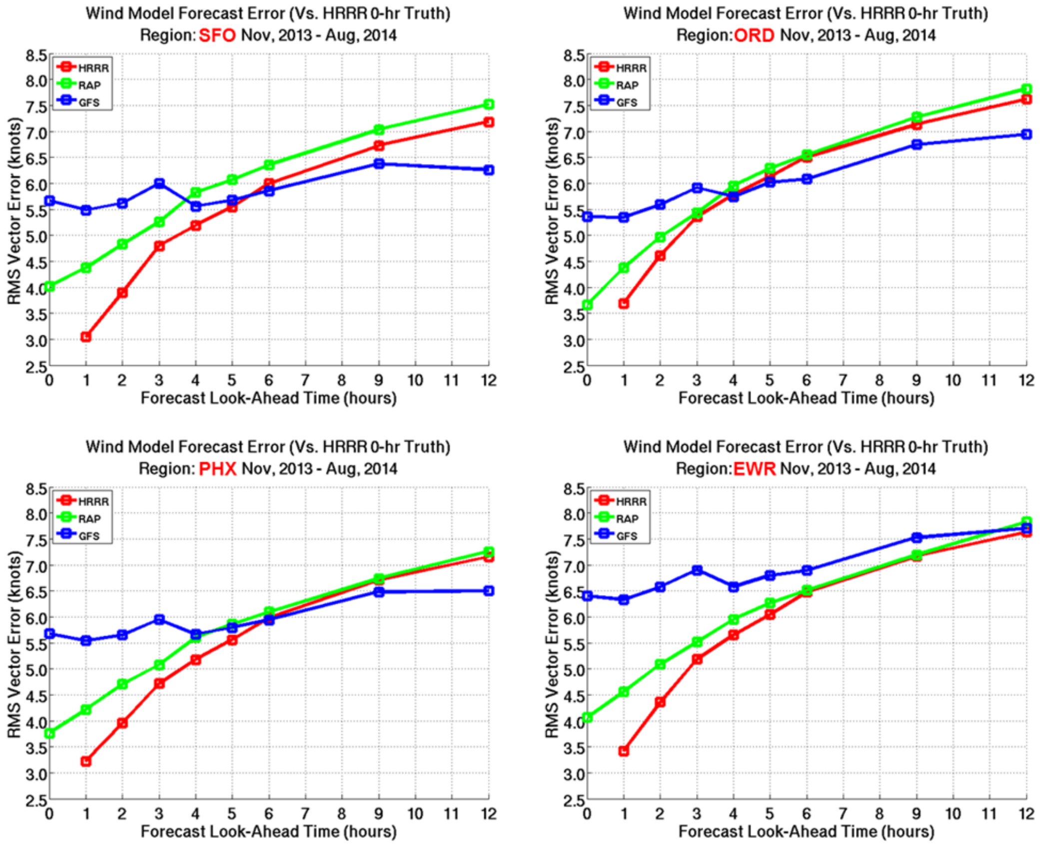


Figure 33. Wind forecast model average performance for SFO, ORD, PHX, and EWR regions.

As seen in Figure 33, forecast performance across the four regions is similar. Therefore, the regional statistics were subsequently combined and treated as representative of average wind forecast model performance across the continental United States. The combined averaged forecast errors are plotted in Figure 34, and the discussion that follows pertains to the combined results.

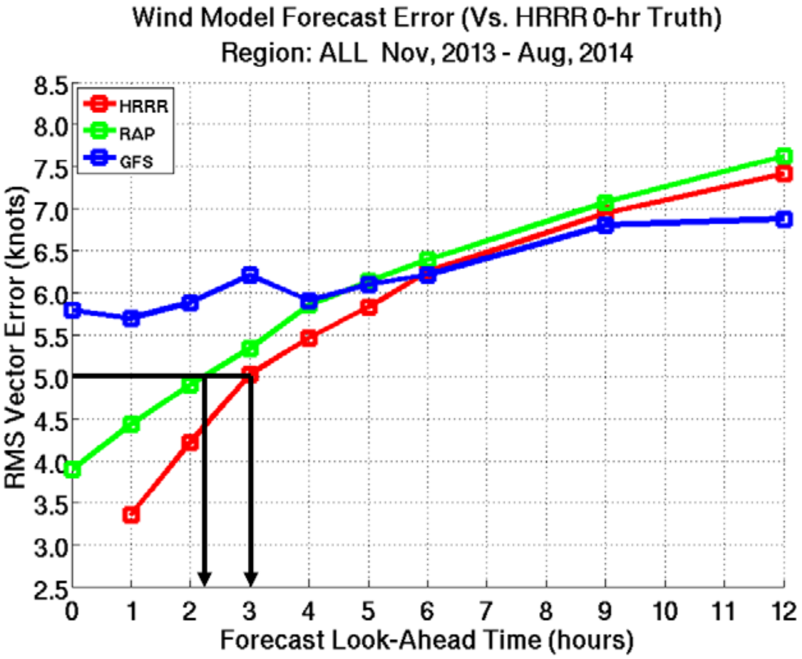


Figure 34. Wind forecast model average performance across all regions.

Average wind forecast errors for all three models were found to generally increase with increasing forecast look-ahead time, ranging from 3.4 knots to 7.6 knots over forecast look-aheads of 0 to 12 hours. This range of forecast errors is comparable to earlier findings reported in the literature (although those were often from older or different models, or for only selected forecast look-ahead times). For forecast look-ahead times of less than 6 hours, the HRRR model produced the best average wind forecast performance, with average RMS vector errors ranging from 3.4 knots at 1 hour look-ahead time to 6.2 knots at 6 hours look-ahead time. The RAP model was found to be a close second best with average errors ranging from 4.4 knots to 6.4 knots over the same look-ahead time interval. Over look-aheads of 0 to 3 hours, the GFS model has considerably more forecast error (5.2 knots–6.2 knots) than RAP or HRRR. For forecast look-ahead times between 4 and 6 hours, the average forecast errors of the three models generally increases with increasing look-ahead time, but the performance of the three models converges, and by 6 hours, they are comparable (GFS performance appears to be even slightly better than RAP or HRRR for look-aheads of 6 hours or greater). One possible explanation for the performance similarities at longer forecast look-ahead times is that the numbers and types of upper-air wind observations going into the models are similar across the three models, and at longer forecast look-ahead times, larger and longer scale atmospheric motions and dynamics tend to dominate the numerical forecasts. Differences in treatment of smaller-scale motions and physics along with differences in model grid resolutions come into play more fully for the short-term forecasts. The black lines and arrows in Figure 34 illustrate an example interpretation of the data for determining which model's forecasts would satisfy a hypothetical 5-knot error limit. In the example shown, if a 5-knot error limit is prescribed, then the HRRR forecast look-aheads of up to 3 hours can be expected to provide the required accuracy on average, while only RAP forecast look-aheads of up to 2.1 hours satisfy the requirement. None of the GFS forecasts would meet the 5-knot error limit.

Extending beyond the consideration of average forecast performance, Figure 35 shows examples of the forecast error distributions of the three models for the 3, 6, 9, and 12-hour forecasts. To permit relative comparison, the histogram frequencies were normalized for each model by the maximum frequency of occurrence for that model over the error bins. In the legend, the numbers in parentheses following the model name indicate the total number of forecast comparisons that were performed. Error means and standard deviations are also indicated in the legend

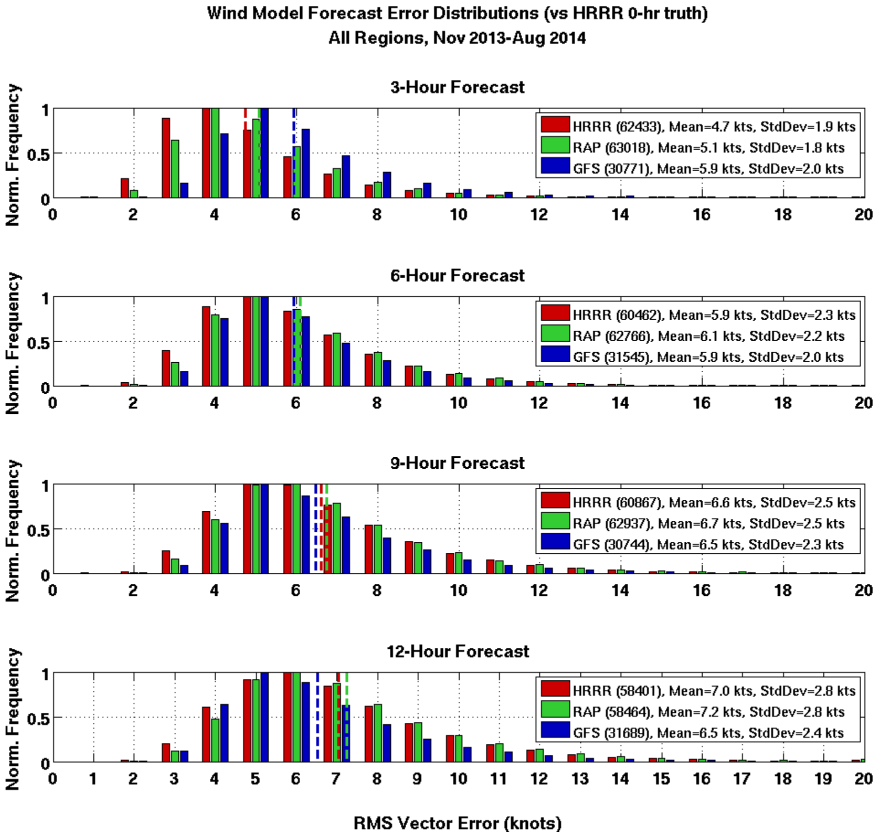


Figure 35. Wind model forecast RMS vector error distributions.

Considerable spread (standard deviations of approximately 2–3 knots) and long tails are seen in the error distributions, with the tails of the distributions containing errors of 15 knots or more. This implies that forecast errors encountered at any single time or location may be considerably larger than the aggregate means, and error limits for a procedure may be exceeded in these instances. These larger wind forecast errors may persist for hours or even days, as seen in Figure 36, which plots a 1-month time sequence of HRRR, RAP, and GFS 3-hour forecast errors from the EWR region at a pressure altitude of 300 hPa (~30,000 ft). Note the persistent errors greater than 10 knots in all models during the February 12–13 time period. Note also that the temporal error trends are very similar across all three models. This is not surprising since the GFS model contributes to the background initialization for the RAP model, and the HRRR model operates as a nested high-resolution grid within the RAP model, and is initialized from within the RAP model. Although the error trends are similar for the three models, there are periods where the GFS exhibits significantly larger errors than the HRRR and RAP models (e.g., around February 11). These may be periods where the coarser spatiotemporal resolution of the GFS fails to capture smaller-scale or more rapidly changing wind conditions. More analysis of these time periods is needed to understand the causes of the larger GFS errors.

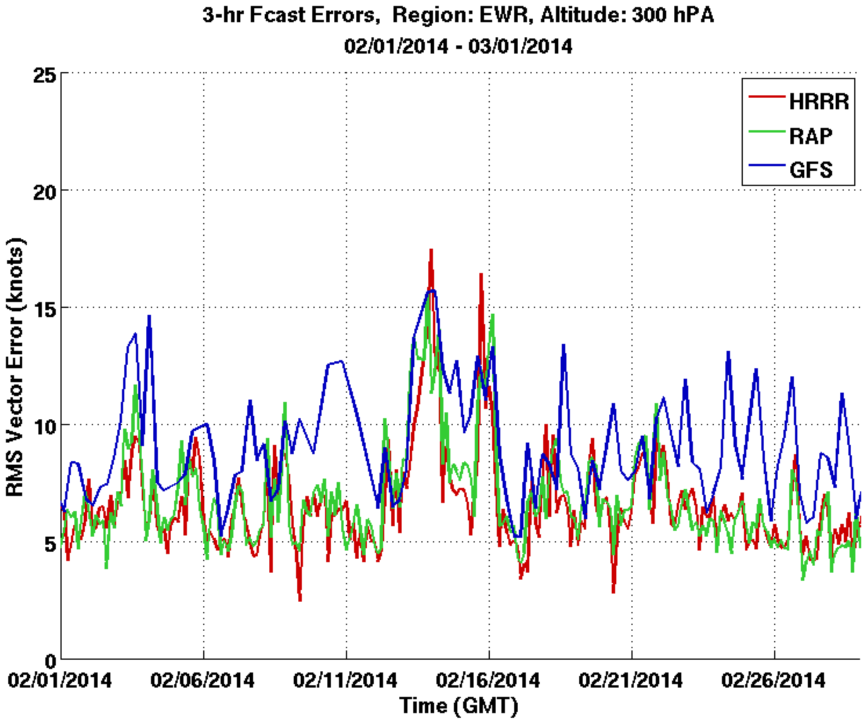


Figure 36. Time series of 3-hour wind forecast errors.

5.4 KEY TAKEAWAYS

The following summarizes the key results of the wind forecast model performance study:

1. Wind forecast errors for all three models were found to increase with increasing forecast look-ahead time, ranging from 3.4 knots to 7.6 knots over forecast look-aheads of 0–12 hours.
2. The HRRR model provided the best average forecast performance for forecast short-term look-ahead times of less than 6 hours. The RAP model was found to be a close second best. The GFS model has noticeably more forecast error than RAP or HRRR for forecasts less than 3 hours out (approximately 1–2 knots greater).
3. For forecast look-ahead times between 4 and 6 hours, the average forecast errors of the three models continues to increase with increasing look-ahead time, but the performance of the three models converges, and from 6–12 hours they are comparable, with the GFS appearing to perform even slightly better than HRRR or RAP.
4. Considerable spread was found in the error distributions. This suggests that forecast errors at any single time or location may be considerably larger than the aggregate error means. Error limits for the procedure may be exceeded in these instances. It may be possible to automatically identify and anticipate problematic wind forecast environments in order to provide forecast confidence and decision support. Further research is needed to explore this.

5.5 RECOMMENDED NEXT STEPS

The following are recommended next steps for further analysis and understanding of wind forecast model performance:

- Extend the forecast model performance analysis from the initial 10 month time period to one year or more and to more locations in order to ensure that the full expected range of seasonal and geographical variations in model performance have been captured.
- Study the “staleness” of wind forecast data at the time of use in ATC and further analyze the effects of data age/staleness if it seems to be an issue in current operations.
- Explore the ability to predict ahead of time expected wind forecast model performance, e.g., over the next 24 hours, how good are the various forecast models expected to perform? Research is needed to determine if problematic forecast wind environments can be automatically identified (e.g., from combination of real-time wind environment analysis and monitoring of recent model forecast performance) and used to provide decision support for the feasibility of successfully executing a given wind information-dependent procedure.

6. APPLICATION CASE STUDIES

In order to demonstrate the utility of the various analyses conducted in the preceding sections, a number of case studies are presented in this section covering:

1. Establishing wind information needs and associated CONOPS needs to support a given level of required 4D-TBO performance.
2. Establishing level of possible 4D-TBO performance given wind information limits.
3. Establishing wind information needs and associated CONOPS needs to support a given level of required Interval Management performance.
4. Assessing impact of wind forecast differences between aircraft and ATC systems.

6.1 CASE STUDY 1
Establishing Wind Information Needs and Associated CONOPS Needs to Support a Given Level of Required 4D-TBO Performance

This case study demonstrates the use of the 4D-TBO tradespace from Figure 23 and the wind forecast model performance results from Figure 34 in the context of the six steps of the Wind Information Implications Flow Diagram from Figure 4: see Figure 37 below.

In this example, the chosen scenario of interest is a 4D-TBO procedure consistent with the analyses reported in Section 3. This allowed the tradespace presented in Figure 23 to be used for this case. From this tradespace, combinations of FMS capability and wind forecast error that achieved a ±10 sec (i.e., 20 secs 95% CI assuming zero mean) performance were identified. This target was chosen to reflect current draft performance standards being considered by the community, which our results suggest could be a challenge to achieve under certain scenarios. Assuming a desire to enable a procedure that could be supported by any FMS capability, a need for wind forecast error <5 knots RMSVE was identified from the tradespace. Then referring to the wind forecast model average performance as a function of look-ahead time summarized in Figure 34, a need for the FMS to be using HRRR data less than 3 hours old or RAP data less than 2.1 hours old on average was identified (the GFS model cannot support this error level at any look-ahead time on average). These findings imply a concept of operations that would need to deliver wind data to an aircraft that was less than these age requirements. Based on these findings, for a short-haul flight of less than 2 hours with RAP data, or less than 3 hours for HRRR data, preflight winds loaded shortly before departure could support a 4D-TBO operation at the ±10 secs 95% of time RTA compliance performance level on average. Flights with longer durations would require wind uplinks en route to support this example level of performance (possibly multiple uplinks for long-haul flights if the aircraft was required to provide a valid ETA window prior to a ground system establishing a feasible meter fix target time).

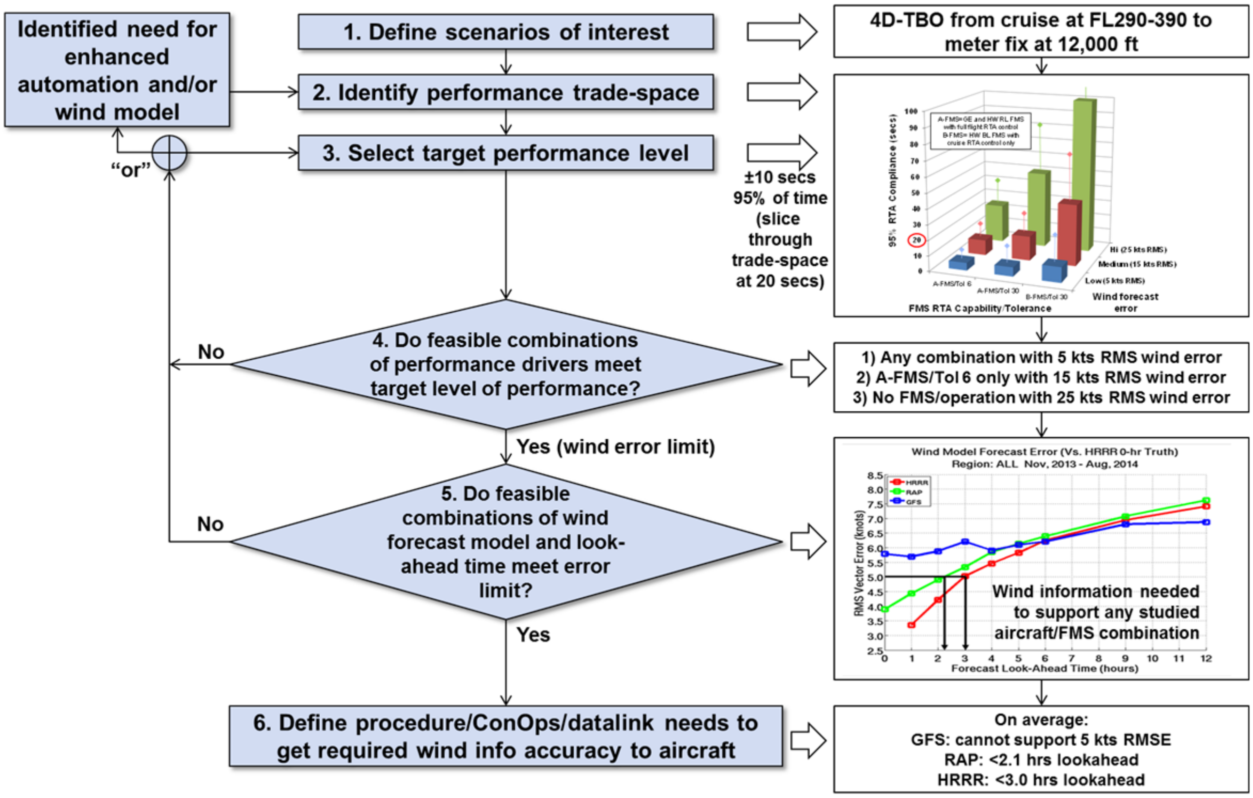


Figure 37. 4D-TBO example case study.

6.2 CASE STUDY 2
Establishing Level of Possible 4D-TBO Performance Given Wind Information Limits

This case study can be considered the reverse perspective on the previous case study. Instead of determining what combination of FMS capability and wind information can support a given 4D-TBO performance, the information from this work can also be used to determine what level of 4D-TBO performance could be expected from scenarios with different FMS capabilities and expected wind information quality. For example, if no wind updates are used (or possible), a 6-hour transcontinental flight would typically be using preflight wind data from a forecast with look-ahead time of 6–12 hours. From Figure 34, it is seen that all three forecast models have average errors of 6.2–7.6 knots RMSVE at these look-ahead times. The tradespace of Figure 23 suggests that 95% RTA compliance performance of approximately 15–30 secs could be expected from an FMS with full flight closed-loop speed control, and much greater spread (e.g., 25–60 secs) with an FMS with no closed-loop speed control beyond TOD.

6.3 CASE STUDY 3

Establishing Wind Information Needs and Associated CONOPS Needs to Support a Given Level of Required Interval Management Performance

This case study demonstrates the use of the Interval Management tradespaces from Section 5 and the wind forecast model performance results from Figure 34 in the context of the six steps of the Wind Information Implications Flow Diagram: see Figure 38 below. Note that more sophisticated analyses using cruise and descent trajectories with higher fidelity models would be required to draw more definitive conclusions to establish IM needs, but this case study is intended to illustrate how these basic results could be used in the context of the flow diagram. In this example, the chosen scenario of interest is an Interval Management procedure consistent with the analyses reported against Scenario 4 in Section 5. This allowed the tradespace presented in Figure 30 to be used for this case. From this tradespace, combinations of IM update period and wind forecast error which achieved an illustrative performance requirement of ±3 secs (6 secs 95% time spread at ABP with zero mean) were identified. In this specific example, IM update periods <60 secs (e.g., FIM/A-IM concept) can use any wind model and achieve the required 95% time spread at the ABP performance. IM update periods >150 secs (e.g., GIM concepts) would require use of wind information by Ownship and TTF with <15 knots RMS vector error.

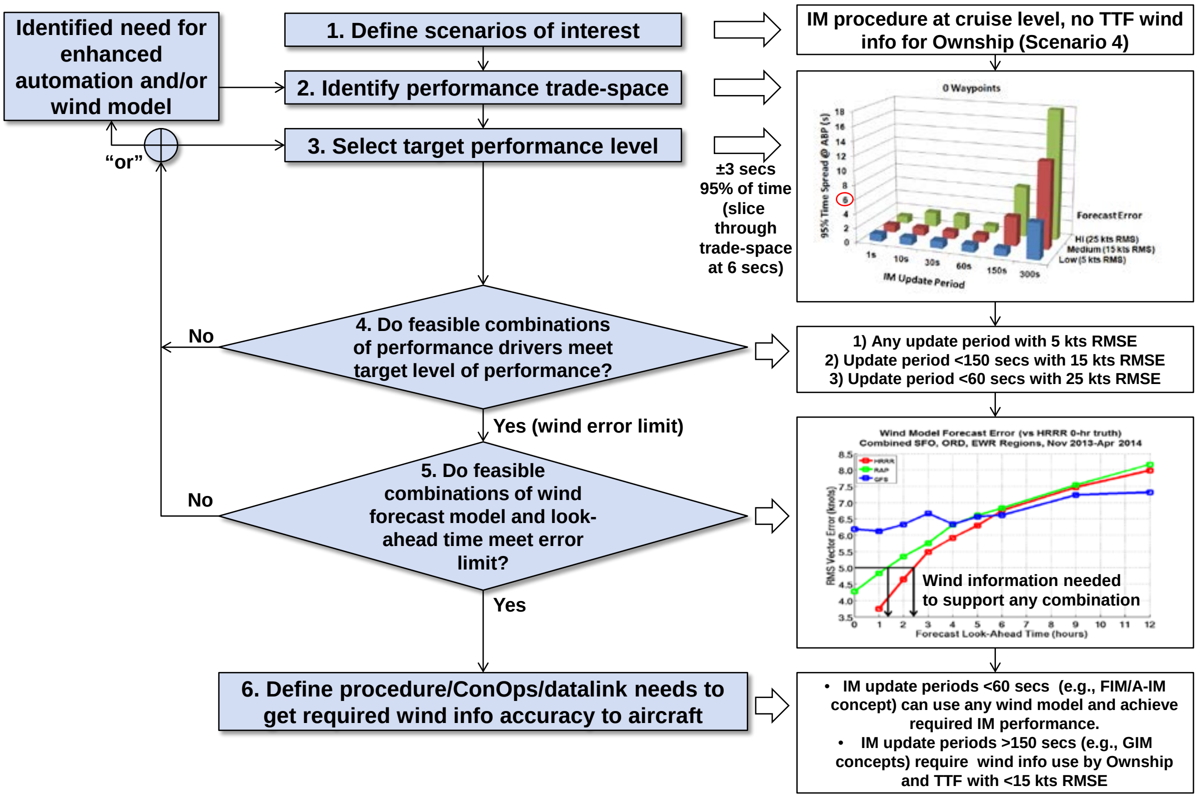


Figure 38. Interval Management example case study.

6.4 CASE STUDY 4
Assessing Impact of Wind Forecast Differences Between Aircraft and ATC Systems

It is relatively difficult to assess the impacts of wind forecast differences between aircraft and ATC systems because there are many ways in which those differences can occur, for example through inconsistent use between aircraft and ATC of

- Wind forecast models
- Forecast valid times
- Data latency
- Interpolation/blending schemes

Many of these factors have been studied separately for this work, but not combined in the context of inconsistencies between ground and aircraft systems. For example, Figure 34 illustrated the relative performance between different models at different look-ahead times. Section 5.2.4 cited other work that found that data latency (using data at times different than the model valid time) caused wind speed forecast errors to increase by as much as 1 knot for latencies of more than 8 hours. These errors could be considered as additive to the errors from the native model performance and look-ahead time reported in Figure 34. The issue of dissimilar interpolation and/or blending schemes between aircraft and ground-based systems has not been studied by anyone to the authors' knowledge, and is an area for possible future work.

As an example of how the results presented in this report could be used to assess the performance impacts of wind forecast differences between aircraft and ATC systems, consider the case where the

- ATC system is using a RAP forecast with a look-ahead time of 2 hours. From Figure 34, the average wind forecast error in this case is approximately 5 knots RMSVE.
- Aircraft FMS is using a GFS forecast with a 2-hour look-ahead but is being used at 3 hours beyond its valid time. The estimated forecast error in this data would be 6 knots RMSVE from the GFS model at a 2-hour look-ahead, plus an additional 1 knot RMSVE from the data latency. These errors may not be additive, but in the worst case a total wind error of up to 7 knots RMSVE could result. However, wind-blending schemes present on the aircraft will tend to reduce this error depending on the characteristics of the wind environment and the specific algorithms in the FMS.

In this example, there could be a large difference in the quality of the wind information between the air and the ground (before blending). One way of representing these effects is to develop performance tradespaces, which account for additional errors introduced by the dissimilar information. These tradespaces could then be used in the Wind Information Implications Flow Diagram as demonstrated in the other case studies. Undertaking this task more formally is a recommended next step below if feedback indicates this approach would be suitable and valuable.

6.5 RECOMMENDED NEXT STEPS

- Develop more case studies of direct relevance to stakeholders needs.
- Undertake more detailed analysis of impact of wind forecast differences between aircraft and ATC systems.
- Explore validation and verification of the findings and recommendations of this work using independent simulation systems or flight test activities.

7. SUMMARY AND RECOMMENDED NEXT STEPS

7.1 SUMMARY

This report has summarized the analyses conducted to date in this project to quantify the wind information impacts on a set of representative 4D-TBO and Interval Management procedures. In terms of the key research questions posed in Section 1 of the report:

- *"What is the impact of wind information accuracy on 4D-TBO performance?"*: Section 3 has synthesized the findings from flight trials and two simulation activities to estimate the impacts of a range of key performance drivers on 4D-TBO. From this, major, medium, and minor performance drivers have been identified, and a summary tradespace giving the relationship between the drivers and quantified 4D-TBO performance for a specific set of scenarios has been created.

- *"What is the impact of wind information accuracy on IM performance?"*: Section 4 has synthesized the findings from a simulation activity to estimate the impacts of a range of key performance drivers on IM. From this, major, medium, and minor performance drivers have been identified, and a set of tradespaces giving the relationship between the drivers and quantified IM performance for a specific set of scenarios has been created.

- *"What are the implications of different wind forecast error limits from 4D-TBO and IM tradespaces for various potential 4D-TBO CONOPS?"*: Section 2 has detailed a Wind Information Implications Flow Diagram process to supplement the Wind Information Analysis Framework that allows CONOPS and datalink implications of the findings to be explored. In order to implement the Wind Information Implications Flow Diagram process, a systematic performance evaluation of a range of wind forecast models used in the aviation community was undertaken as reported in Section 5. The utility of the results from this analysis, together with the 4D-TBO and IM tradespaces, was demonstrated through a set of case studies reported in Section 6.

- *"What are the impacts of wind forecast differences between aircraft and ATC systems?"*: a preliminary assessment of how the results presented in this report can be used to start to answer this research question were included in Section 6. However, further work is warranted on this question.

7.2 RECOMMENDED NEXT STEPS

The sections below synthesize the recommended next steps presented at the end of each of the preceding sections.

7.2.1 Analysis of Wind Information Accuracy on 4D-Trajectory Based Operations Performance

- Expand the analyses to include more aircraft/FMS types to generate results which cover FMS capabilities present in more of the operational fleet.
- Expand the truth and forecast wind conditions considered in this analysis to cover a broader set of environments experienced in real operations.
- Explore the performance improvement potential of a range of realistic FMS wind handling enhancements technically feasible within the next decade that could improve RTA compliance performance, for example:
  - Increasing FMS wind definition points, e.g. using more wind altitudes, gridded wind fields, etc.
  - FMS wind interpolation algorithms
  - Enhancing FMS blending algorithms
  - Enhancing control algorithms
  - Tailoring wind entry locations and/or altitudes to mitigate FMS and/or wind model limitations
- RTCA SC-227 has published standards for Time-of-Arrival Control (TOAC) as 95% compliance with accuracy levels of ±10 seconds (RTA involving descent) and ±30 seconds (RTA in cruise only) given a defined meteorological uncertainty model (DO-236C Chg 1 Section 5.1.2.1). Analysis should be conducted to analyze implications of these specific accuracy requirements on wind information requirements.
- Various commercial vendors are now providing wind information to airlines tailored to the individual aircraft and FMS characteristics in their fleet. The research team could explore collaborating with those entities to establish the relevance and potential operational impacts (e.g., in terms of performance improvements) enabled through the use of these commercially available wind information sources compared to the publically available information.

7.2.2 Analysis of Wind Information Accuracy on Interval Management Performance

- Continue to study the impact of number of waypoints in combination with a range of forecast error on IM performance. This is to determine a boundary between where more waypoint forecast information is beneficial and where it actually degrades performance.

- Expand the simulation environment to model descent trajectories and study the impact of wind forecast errors at different points in descent. This will also include modeling realistic truth wind scenarios for the levels of wind experienced along a descent trajectory.

- Explore the performance of more complex IM scenarios with various amounts of wind information and levels of wind information accuracy. One such scenario could be a string of three aircraft using IM procedures to maintain separation.

- Explore the practical implementation of IM algorithms in current avionics architectures, e.g., integrating additional features into current FMSs.

7.2.3 Analysis of Wind Forecast Model Performance Analysis

- Extend the forecast model performance analysis from the initial 10-month time period to one year or more and to more locations in order to ensure that the full expected range of seasonal and geographical variations in model performance have been captured.

- Study the “staleness” of wind forecast data at the time of use in ATC, and further analyze the effects of data age/staleness if it seems to be an issue in current operations.

- Explore the ability to predict ahead of time likely model performance, e.g., over the next 24 hours, how good are the various forecast models expected to perform? Research is needed to determine if problematic forecast wind environments can be automatically identified (e.g., from combination of real-time wind environment analysis and monitoring of recent model forecast performance) and used to provide decision support for the feasibility of successfully executing a given wind information-dependent procedure.

7.2.4 Application Case Studies

- Develop more case studies of direct relevance to stakeholders needs.

- Undertake more detailed analysis of impact of wind forecast differences between aircraft and ATC systems.

- Explore validation and verification of the findings and recommendations of this work using independent simulation systems or flight test activities.

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APPENDIX A
IM PERFORMANCE DETAILED RESULTS

The data presented in this appendix are the individual results of the Interval Management scenarios described in Section 4. The takeaways from these results were summarized in Section 4, but an array of individual cases is presented here.

Figure 39 is a sample tradespace to show the axes labels for each set of results. Unless otherwise noted, these are the labels for every tradespace presented. The x-axis is the IM update rate (from 1–300 seconds), the y-axis is the distance of the wind spike peak from the ABP (from 0–80 NM), and the z-axis is the 95% time spread of arrival at the ABP. If the labels are other than what is shown in the sample here, they will be shown on the bottom-right tradespace of that figure.

Each vertical bar of each tradespace represents 500 Monte-Carlo runs of the simulation.

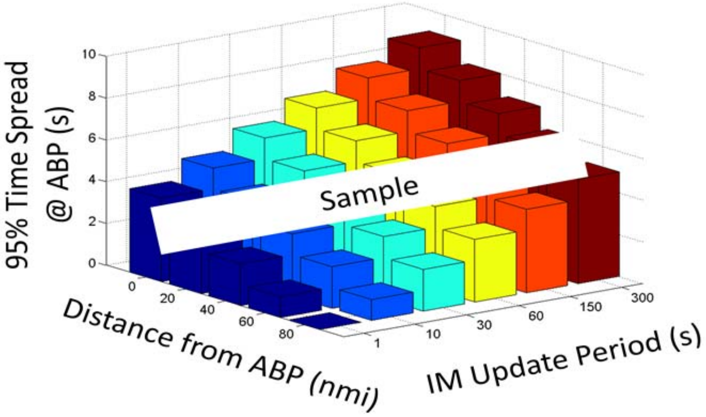

Figure 39. Sample IM tradespace with axes labels.

A.1 SCENARIO 1 RESULTS

The Ownship-only wind spike scenario (Scenario 1) was run over a range of wind spike widths and heights with the summary presented in Section 4. The individual results for various combinations of widths and heights are presented here. The widths ranged from 10–100 NM. The magnitudes were chosen from three distributions of RMS error: 5, 15, and 25 knots. Each vertical bar represents 500 Monte-Carlo runs, with the magnitude on each run being an individual pull from the same distribution. The results are shown in Figure 40.

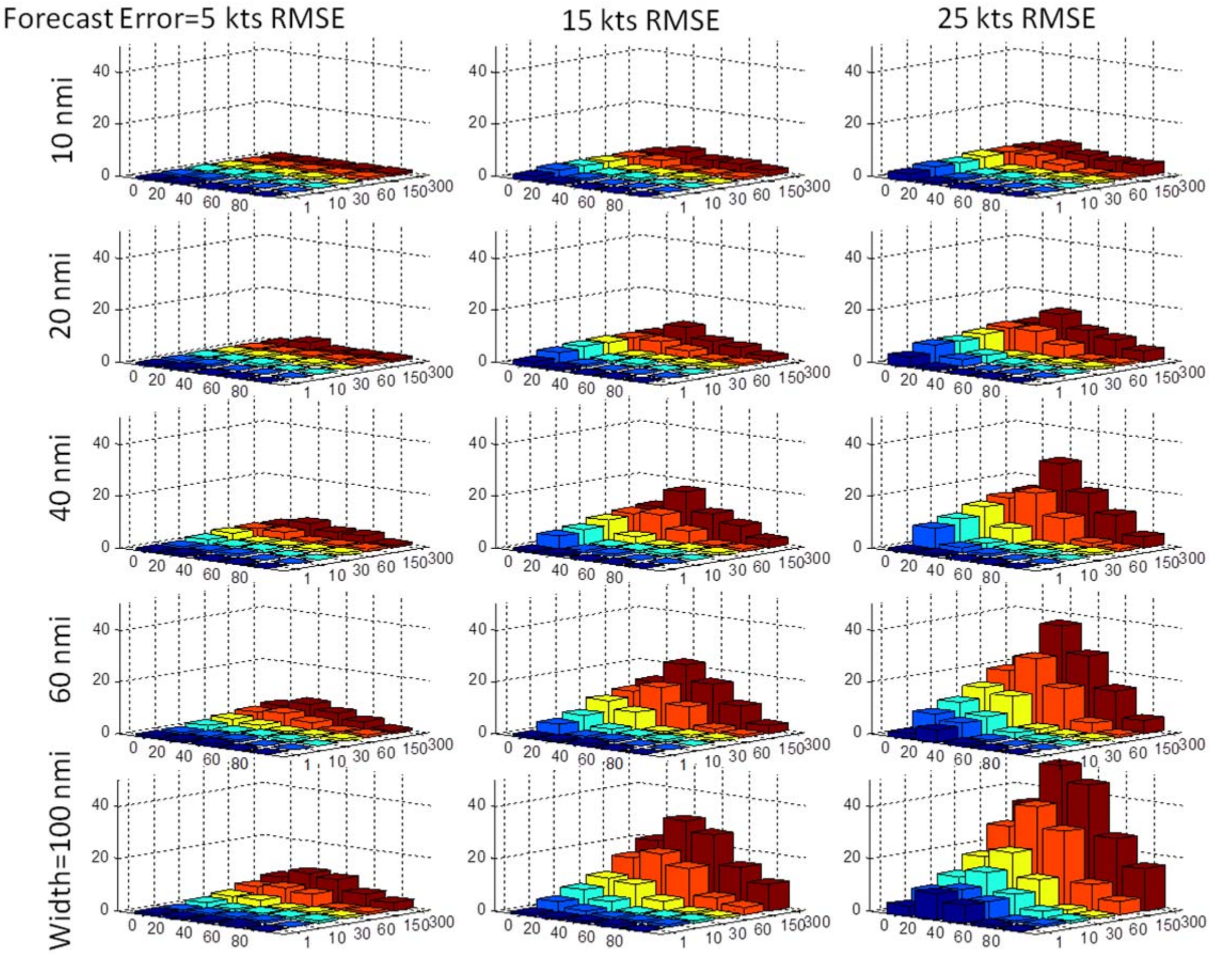

Figure 40. IM tradespace showing effects of error in Ownship wind forecast.

A.2 SCENARIO 2 RESULTS

The TTF-only wind spike scenario (Scenario 2) was also run over the same range of wind spike widths (10–100 NM) and heights (5–25 knots RMSE). The summary was presented in Section 4, and the individual results for various combinations of widths and heights are presented here. As in Scenario 1, each vertical bar represents 500 Monte-Carlo runs, with the magnitude on each run being an individual pull from the same distribution. The resulting tradespaces are shown in Figure 41.

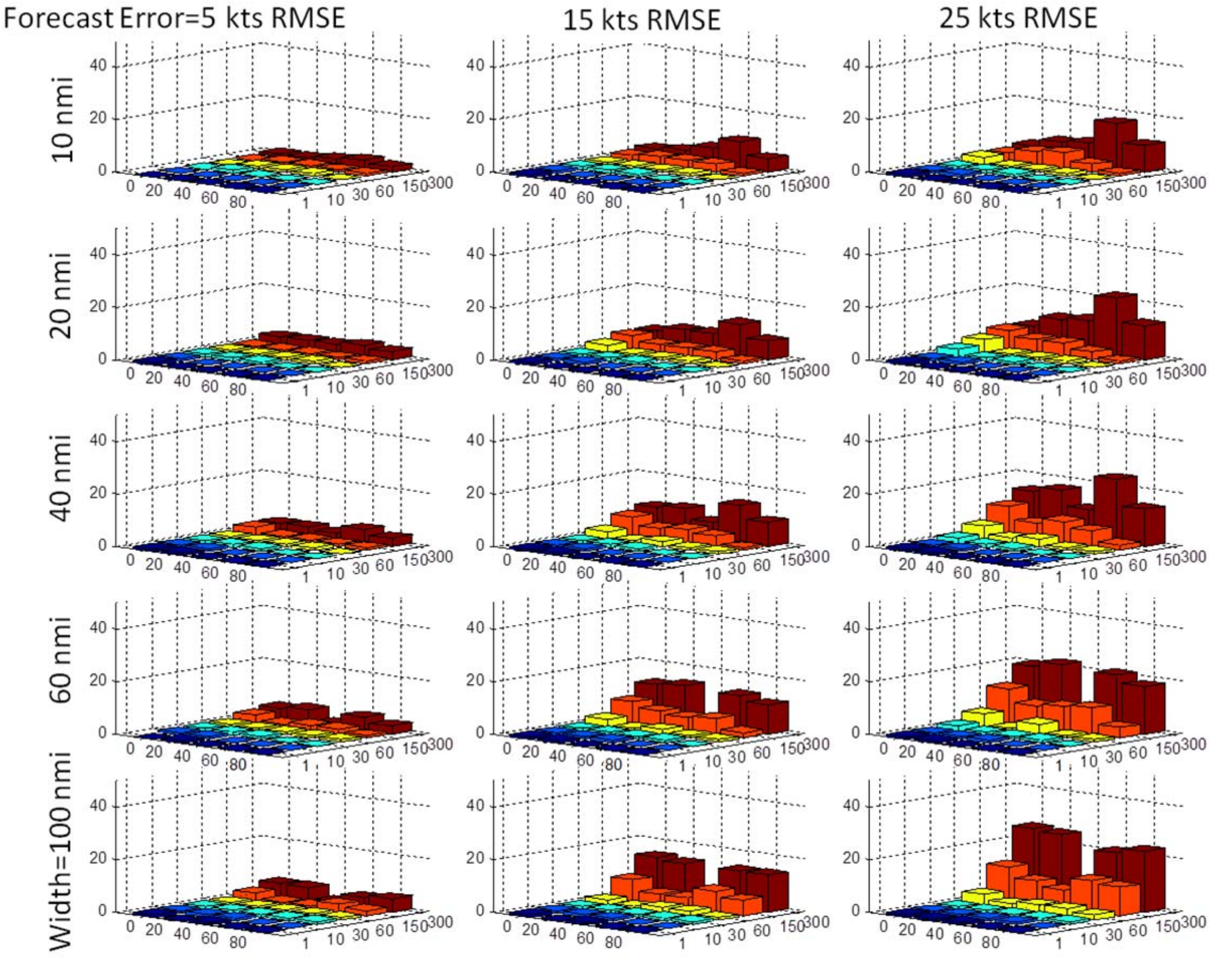

Figure 41. IM Tradespace showing effects of error in TTF wind forecast.

A.3 SCENARIO 3 RESULTS

The Ownship and TTF wind spike scenario (Scenario 3) was also run over the same range of wind spike widths and heights as Scenarios 1 and 2. In this case, the wind spikes for the Ownship and TTF were identical, with the height (magnitude) coming from the same pull from the distribution. They were placed the same distance away from the ABP on the path. Figure 42 shows the resulting tradespaces with widths from 10–100 NM and forecast errors from 5–25 knots RMSE.

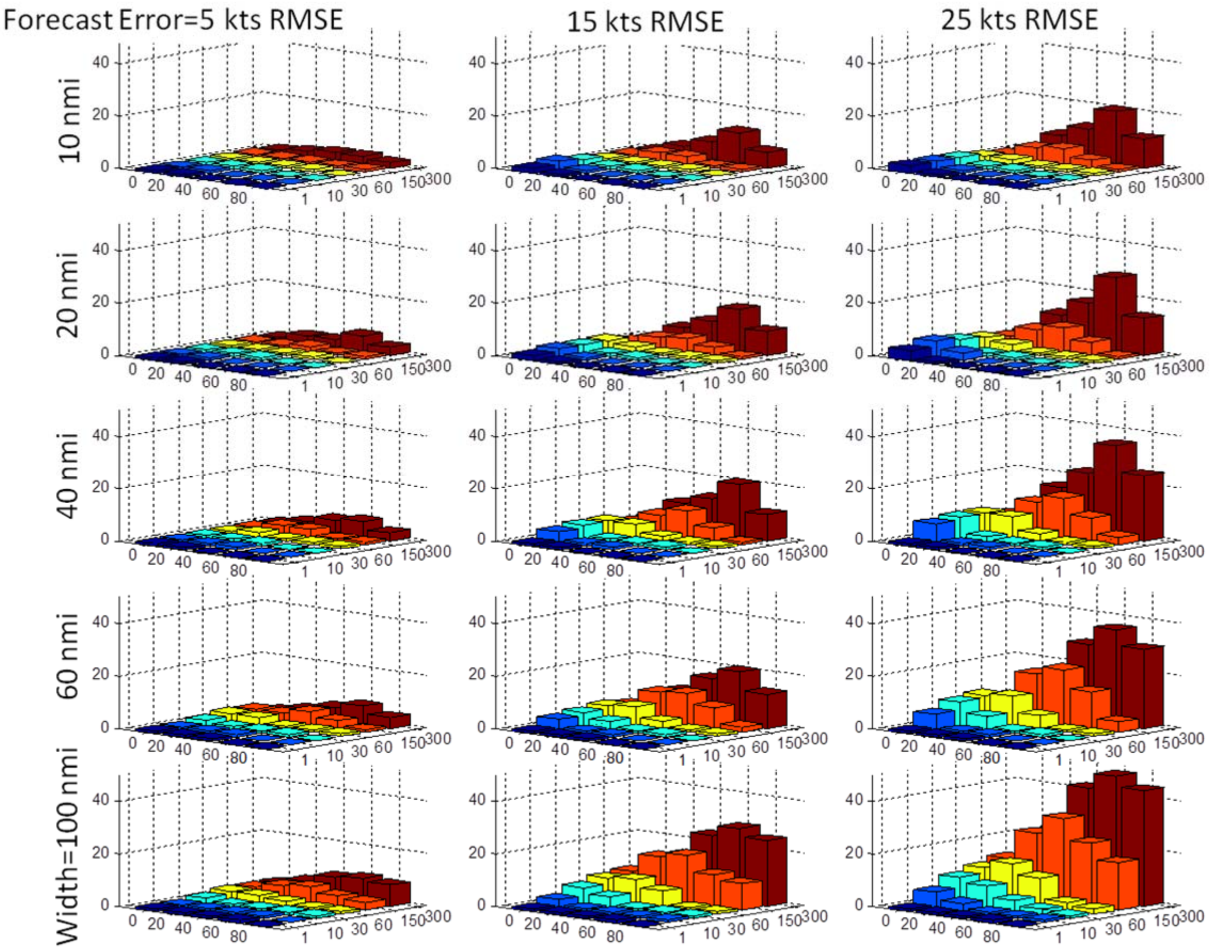

Figure 42. IM Tradespace showing effects of error in Ownship and TTF wind forecast IM waypoint locations.

Scenarios 4, 5, and 6 include the aspect of different levels of forecast information. The test cases are run with the Ownship having access to forecast information at 0, 3, or 6 waypoints along the TTF's route. In each of these cases, the truth wind spike is fixed to a width of 40 NM and centered on one of the six waypoints. The full six waypoints are spaced 20 miles apart starting at 20 NM along the route and finishing at 120 NM, which is the ABP. These are shown by the small red circles in Figure 43. When there are only 3 waypoints, the ones used are at 40, 80, and 120 NM, as shown by the dashed red line. The spacing of the waypoints in these situations should be noted when interpreting the results. The cases of 0 and 6 waypoints are fairly straightforward. When there are 0 waypoints, the Ownship has no information at all and just assumes that the wind speed will stay constant. When there are 6 waypoints, given the particular spacing chosen, the Ownship has enough information to characterize the wind spike. However, with 3 waypoints, depending on the wind spike distance from the ABP, the Ownship will either miss the wind spike completely (such as in the case of 60 NM from the ABP) or construct a much larger wind spike than is actually there (such as in the case of 40 NM from the ABP).

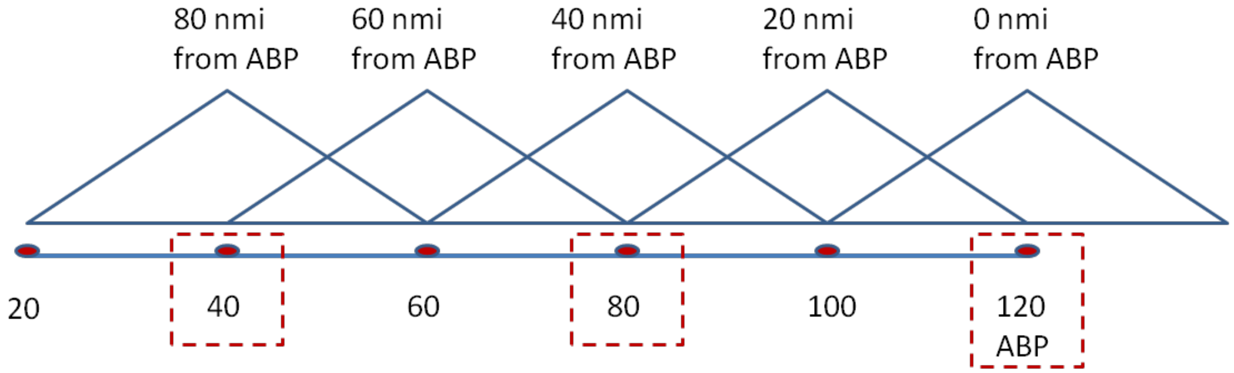

Figure 43. IM tradespace showing effects of error in Ownship and TTF wind forecast.

A.4 SCENARIO 4 RESULTS

The Ownship and TTF wind spike scenario with varying levels of forecast information (Scenario 4) was run with a wind spike width of 40 NM and a range of magnitudes from 5–25 knots RMSE. The individual results for the range of magnitudes and levels of forecast information are presented in this matrix of tradespaces. The magnitudes were chosen from three distributions of RMS error: 5, 15, and 25 knots. Each vertical bar represents 500 Monte-Carlo runs. Figure 44 shows the tradespaces for 5, 15, and 25 knots RMSE and for 0, 3, and 6 waypoints of forecast information.

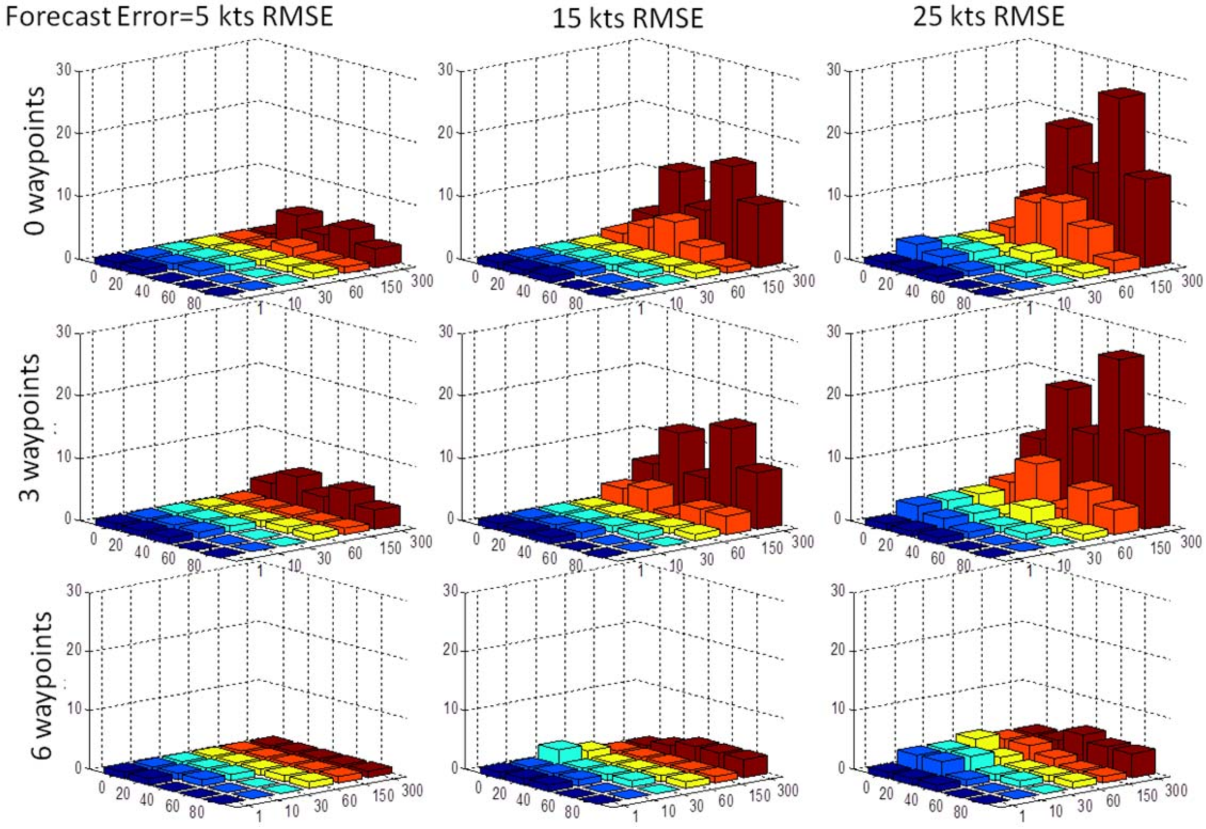

Figure 44. IM tradespace showing effects of perfect forecast with variable waypoints.

The cases of wind spikes at 20 and 60 NM from the ABP when the update rate is 300 seconds bears further explanation. When doing speed calculations, the Ownship assumes the TTF is flying a constant airspeed. The Ownship only knows the groundspeed of the TTF, and in the case of no information, it assumes the winds are constant, thereby making the groundspeed constant. If the IM speed update occurs when the aircraft is flying through the wind spike, it assumes that groundspeed (and thereby that wind speed) will continue for the duration of the flight. The farther away the wind spike is from the ABP, the more error is accumulated, and the worse the speed command is. However, the farther away it is, the more chances the aircraft has to recover from this. In the case of the 300-second update, there are only a small number of updates throughout the course of the flight. If the wind spike occurs at 60 or 40 NM from the ABP, the aircraft probably has one opportunity to correct after the wind spike. If it occurs at 20 or 0 NM from the ABP, the aircraft likely has no opportunity to correct after the wind spike. In this respect, the wind spikes at 60 and 40 NM from the ABP can get grouped together, as they have the same number of chances to recover from any error. However, the 60 NM case occurs much farther away and has more accumulated error so it has more speed error to recover from. This is why the time spread is greater at 60 and 20 NM.

A.5 SCENARIO 5 RESULTS

There were two parts to Scenario 5, testing the impact of errors in forecast location and magnitude. In the first part, the truth magnitude was fixed to a certain number, either 5 or 15 knots. The forecast error was chosen from a distribution of 5, 10, 15, 20, or 25 knots RMSE. This showed the impact of having a forecast that was incorrect in magnitude, either larger or smaller. The results are shown for truth winds of 5 and 15 knots and for 0, 3, and 6 waypoints in Figure 45.

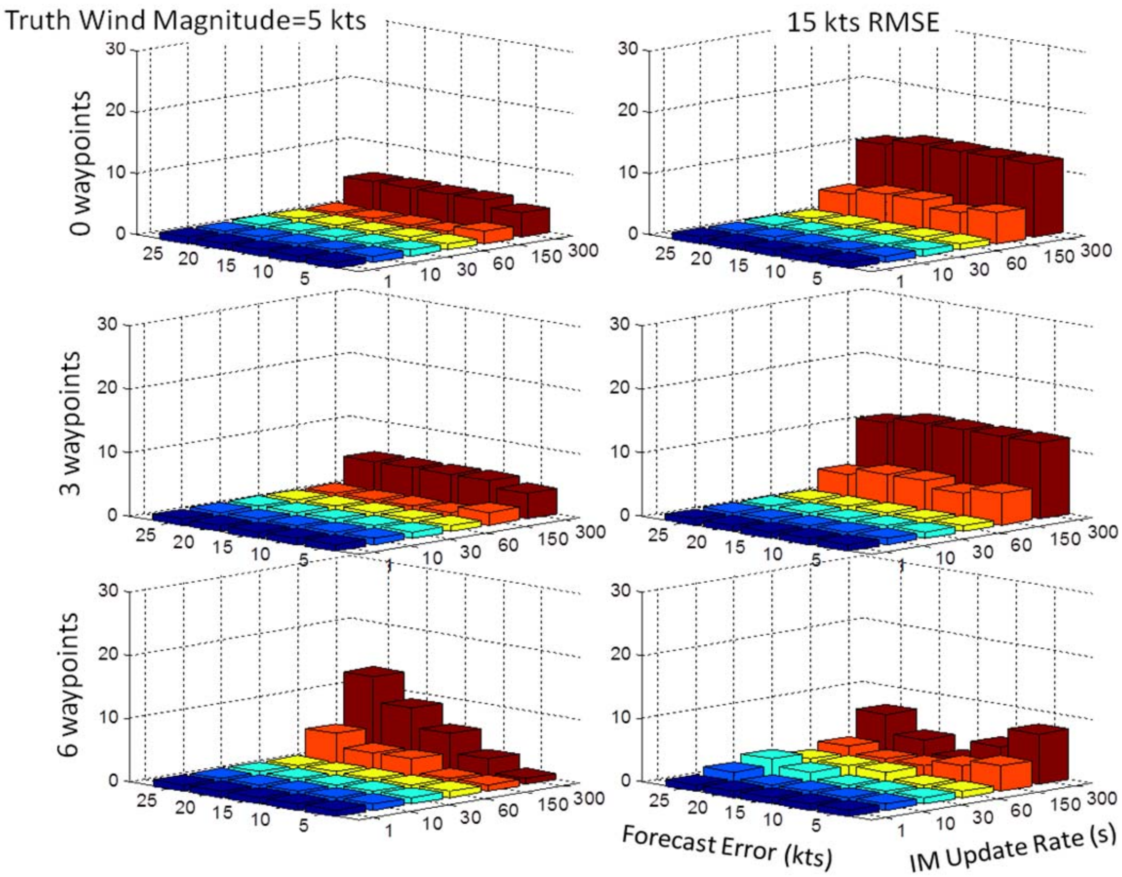

Figure 45. IM tradespace showing effects of error in wind forecast magnitude.

In the second part, the forecast magnitude was correct, but the location was offset from the truth wind. In this case, the truth wind spike was centered at 20 NM from the ABP. Figure 46 shows the results for three different levels of forecast information (0, 3, and 6 waypoints).

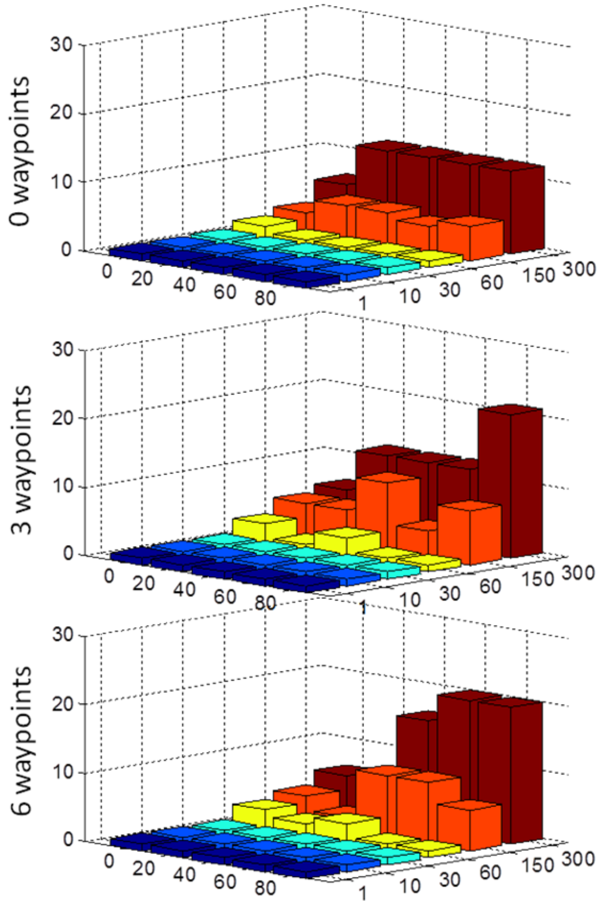

Figure 46. IM tradespace showing effects of error in wind forecast location.

A.6 SCENARIO 6 RESULTS

This scenario had different combinations of errors in both magnitude and location. Figure 47 shows two examples in the vertical columns with three different levels of forecast information (0, 3 and 6 waypoints). Each column is labeled with the truth wind magnitude, the location of the truth wind spike, and the location of the forecast wind spike. Contrary to Scenario 5, in this example, the forecast magnitude is the amount of forecast error on top of the truth forecast magnitude.

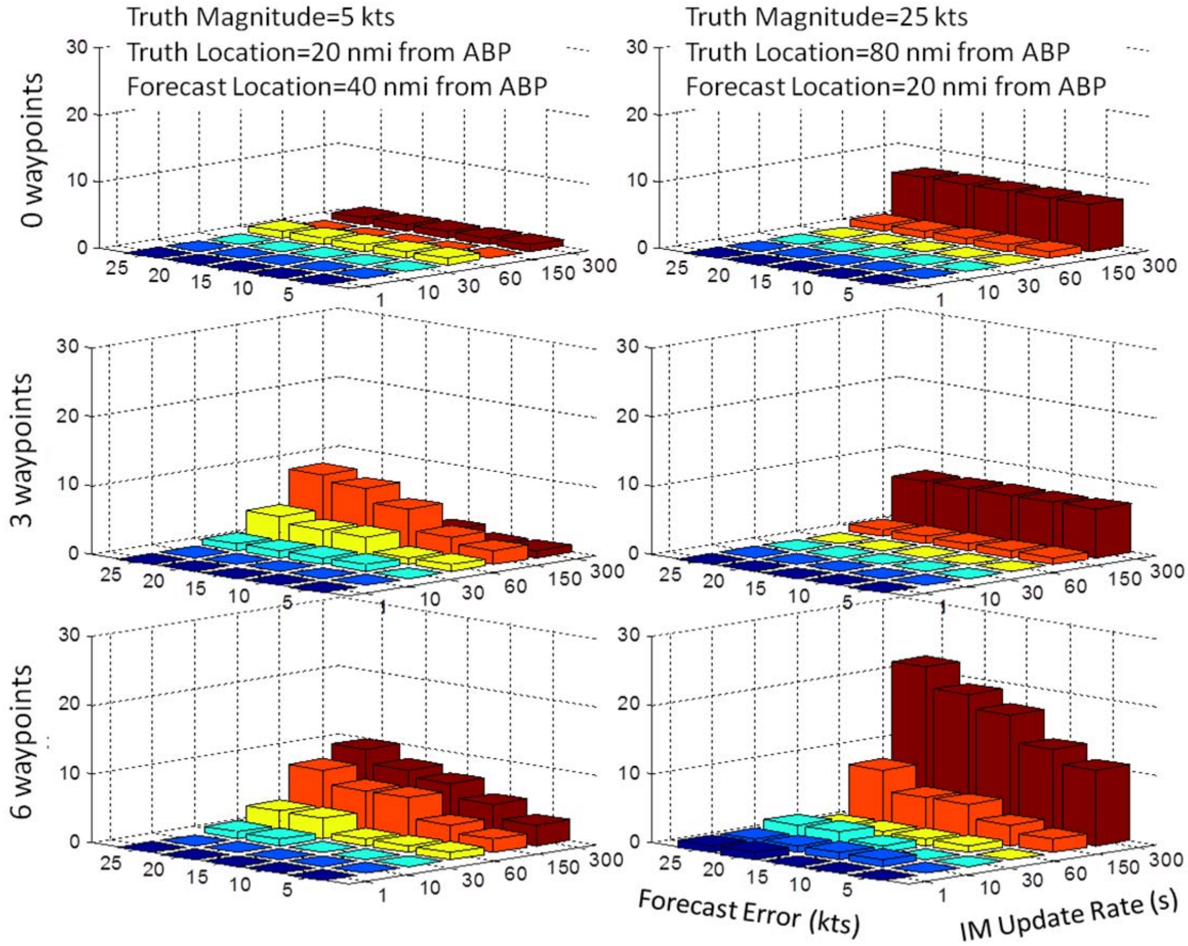

Figure 47. IM tradespace showing effects of error in wind forecast magnitude and location.

GLOSSARY

4D-TBO	Four-dimensional Trajectory-Based Operations
ABP	Achieve By Point for interval management procedures, equivalent to meter fix in TOAC procedures
ACARS	Aircraft Communications Addressing and Reporting System
ADS-B	Automatic Dependent Surveillance-Broadcast (Out = transmit, In = receive)
A-IM	Advanced Interval Management
AMDAR	Aircraft Meteorological Data Relay
ARTCC	Air Route Traffic Control Center
ASA	Alaska Airlines
ASG	Assigned Spacing Goal
ASTAR12	NASA Airborne Spacing for Terminal Arrival Routes version 12 interval management algorithm
ATC	Air Traffic Control
ATCSCC	Air Traffic Control System Command Center
ATM	Air Traffic Management
AWC	NOAA Aviation Weather Center
B737/GE	Boeing 737-700 with General Electric FMS
B757/HW BL	Boeing 757-200 with Honeywell Pegasus FMS using operational “Black Label” software
B757/HW RL	Boeing 757-200 with Honeywell Pegasus FMS using research prototype “Red Label” software
CAS	Calibrated AirSpeed, the speed shown by a conventional airspeed indicator after correction for instrument error
CI	Confidence Interval

CONOPS	Concept of Operations
CoSPA	Consolidated Storm Prediction for Aviation, provides 2-8 hours weather forecasts for aviation strategic decision-making
CTA	Controlled Time of Arrival
CWSU	Center Weather Service Unit
DO-236C Chg 1	RTCA document implementing changes to standards for TOAC
ECON	FMS mode that calculates an efficient altitude/speed profile based on user-defined Cost Index reflecting the trade-off between fixed and variable operating costs
ESRL	NOAA Earth System Research Laboratory
ETA	Estimated Time of Arrival
EWR	New York Newark Liberty International Airport
FIM	Flight Interval Management
FL	Flight Level, an altitude level of constant atmospheric pressure relative to international standard sea level pressure of 29.92 inches of mercury. Every flight level is stated in hundreds of feet, with the last two zeros removed.
FMS	Flight Management System
FMSim	MIT Lincoln Laboratory FMS Simulation System
FY	Fiscal Year
GE	General Electric
GIM	Ground Interval Management
GFS	Global Forecast System Model, US NOAA/NCEP wind forecast model with 25 km spatial resolution used as basis for many airline flight planning products
hP	Hectopascal, a unit of pressure equal to 100 Pa or 1 mbar
HRRR	High Resolution Rapid Refresh Model, US NOAA/NCEP/ESRL wind forecast model with 3 km spatial resolution used as basis for FAA high resolution weather forecasting products
HW	Honeywell

IM	Interval Management
ITWS	Integrated Terminal Weather System
Look-ahead time	The difference between the forecast issue time and its valid time. Also commonly referred to as forecast “lead time.”
Meter fix	Location where aircraft is targeting to get to by the CTA/RTA is controlled to by FMS in TOAC procedures
MSL	Mean Sea Level altitude
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NM/nmi	Nautical Mile (1,853 meters or 6,080 ft)
NWP	NextGen Weather Processor
ORD	Chicago O’Hare International Airport
PHX	Phoenix Sky Harbor International Airport
Radiosonde	Instrument package used to measure and transmit atmospheric parameters sensed during an ascent profile (typically by weather balloon)
RAP	Rapid Refresh Model, US NOAA/NCEP wind forecast model with 13 km spatial resolution used as basis for many FAA operational tools
RMSE	Root Mean Square Error
RMSVE	Root Mean Square Vector Error
RTA	Required Time of Arrival function of an FMS which manages aircraft speed in an attempt to comply with CTA at the meter fix
RTA 95% CI	RTA Time 95% Confidence Interval, the estimated interval containing 95% of RTA TE for the conditions in question, calculated as $\mu \pm 2\sigma$ (Mean ± 2*Standard Deviation assuming Gaussian distribution) of the distribution of time errors.
RTA TE	Required Time of Arrival Time Error, actual time of arrival at meter fix relative to the target time

RTA Tolerance Setting	An internal FMS sensitivity parameter reflecting the time-error value, expressed seconds, that triggers recalculation of RTA speed target
RTCA	Radio Technical Commission for Aeronautics, a US organization that develops technical guidance for use by government regulatory authorities and industry
RUC	Rapid Update Cycle, US NOAA/NCEP wind forecast model, predecessor of RAP
SC-186	RTCA Special Committee for Automatic Dependent Surveillance-Broadcast
SC-206	RTCA Special Committee for Aeronautical Information Services Data Link
SC-214	RTCA Special Committee for Standards for Air Traffic Data Communication Services
SC-227	RTCA Special Committee for Standards of Navigation Performance (including TOAC)
SEA	Seattle-Tacoma International Airport
SFO	San Francisco International Airport
TMA	Traffic Management Advisor scheduling software
TMU	Traffic Management Unit at FAA facility
TOAC	Time of Arrival Control
TOD	Top Of Descent (end of cruise, start of descent)
TTF	Traffic To Follow
WBA	Wind Blending Algorithm, internal FMS calculation that applies corrections to wind forecasts at downstream points to account for differences between sensed and forecast winds at current location. Correction factor decreases as function of distance of downstream waypoint from current location.
Z	Zulu time, equivalent to Greenwich Mean Time
ZSE	FAA Seattle ARTCC

REFERENCES

[1] Reynolds, T.G., Y. Glina, S.W. Troxel, and M.D. McPartland, “Wind Information Requirements for NextGen Applications Phase 1: 4D-Trajectory Based Operations (4D-TBO),” MIT Lincoln Laboratory, Lexington, MA, Project Report ATC-399, 2013.

[2] Glina, Y., T.G. Reynolds, S. Troxel, and M. McPartland, “Wind Information Requirements to Support Four Dimensional Trajectory-Based Operations,” 12th AIAA Aviation Technology, Integration, and Operations Conference, Indianapolis, IN, AIAA 2012–5702, 2012.

[3] Reynolds, T.G., S. Troxel, Y. Glina, and M. McPartland, “Establishing Wind Information Needs for Four Dimensional Trajectory-Based Operations,” 1st International Conference on Interdisciplinary Science for Innovative Air Traffic Management, Daytona Beach, FL, 2012.

[4] Reynolds, T.G., P. Lamey, M. McPartland, M. Sandberg, T. Teller, S. Troxel, and Y. Glina, “Wind Information Requirements for NextGen Applications Phase 2 Final Report: Framework Refinement & Application to 4D-Trajectory-Based Operations (4D-TBO) and Interval Management (IM),” MIT Lincoln Laboratory, Lexington, MA, Project Report ATC-418, 2014.

[5] Wynnyk, C., and D. Gouldey, “2011 Seattle Required Time of Arrival (RTA) Flight Trials Analysis Report,” MITRE CAASD, July 2012.

[6] Abbott, T.S., “An Overview of a Trajectory-Based Solution for En Route and Terminal Area Self-Spacing: Fourth Revision,” NASA/CR-2013-218044, September 2013.

[7] Lee, A.G., S. Weygandt, B. Schwartz, and J. Murphy, “Performance of Trajectory Models with Wind Uncertainty,” AIAA Modeling and Simulation Technologies Conference, Chicago, IL, 2009.

[8] Schwartz, B.E., S.G. Benjamin, S. Green and M. Jardin, “Accuracy of RUC-1 and RUC-2 Wind and Aircraft Trajectory Forecasts as Determined from ACARS Observations,” *Weather and Forecasting*, 15, June 2000.

[9] Cole, R.E., C. Richard, S. Kim, and D. Bailey, “An Assessment of the 60 km Rapid Update Cycle (RUC) with Near Real-Time Aircraft Reports,” MIT Lincoln Laboratory, Lexington, MA, Project Report NASA/A-1, 1998.

[10] Zheng, Q. Maggie, and J.Z. Zhao, “Modeling Wind Uncertainties for Stochastic Trajectory Synthesis,” 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, September 2011.

[11] Robert, E., and D. De Smedt, “Comparison of Operational Wind Forecasts with Recorded Flight Data,” 10th USA/Europe Air Traffic Management Research and Development Seminar, Chicago, IL, June 10–13, 2013.