Project Report
ATC-399

Wind Information Requirements for NextGen Applications Phase 1: 4D-Trajectory Based Operations (4D-TBO)

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16. Abstract

Accurate wind information is required to support some of the key applications envisioned for future air traffic concepts. A Wind Information Analysis Framework has been developed to assess wind information needs for different applications. The framework is described and then applied in a Four-Dimensional Trajectory Based Operations (4D-TBO) application using simplified versions of the framework's elements to demonstrate its utility. Realistic ranges of wind information accuracy in terms of wind forecast and Flight Management System wind representation errors are studied. Their impacts on 4D-TBO performance in terms of Required Time of Arrival compliance and fuel burn are presented. Interpretations of the findings to give insights on wind information requirements are provided, together with an outline of the planned next phase of the study to further refine the outputs.

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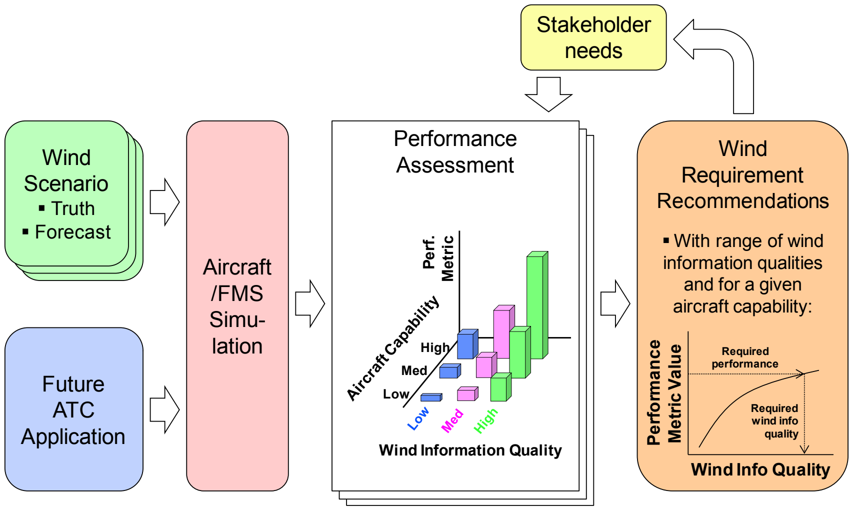
EXECUTIVE SUMMARY

Many future air transportation system concepts require access to high quality wind information if they are to be effective. The primary objective of this work is to quantify the relationship between wind information quality and benefits delivery under future applications envisioned under the Next Generation Air Transportation System (NextGen). Relevant wind information quality factors have been identified in this work in terms of timeliness, spatial resolution, temporal resolution and intrinsic forecast accuracy. Quantitative metrics that capture the impacts of these different factors have also been explored, particularly in terms of Root Mean Square Vector Error (RMSVE) that effectively captures aggregate performance, and other metrics that more effectively capture large point errors. An extensive review has been conducted against these factors and metrics of wind forecast capabilities available in the U.S. and UK operational aviation system, as well as research models which may become available to the community in the near future. This has allowed realistic ranges of appropriate wind information quality metrics to be defined for use in the context of this study.

A Wind Information Analysis Framework to achieve the objective of quantifying wind information requirements for NextGen Applications has been developed as illustrated below.



The framework contains elements of:

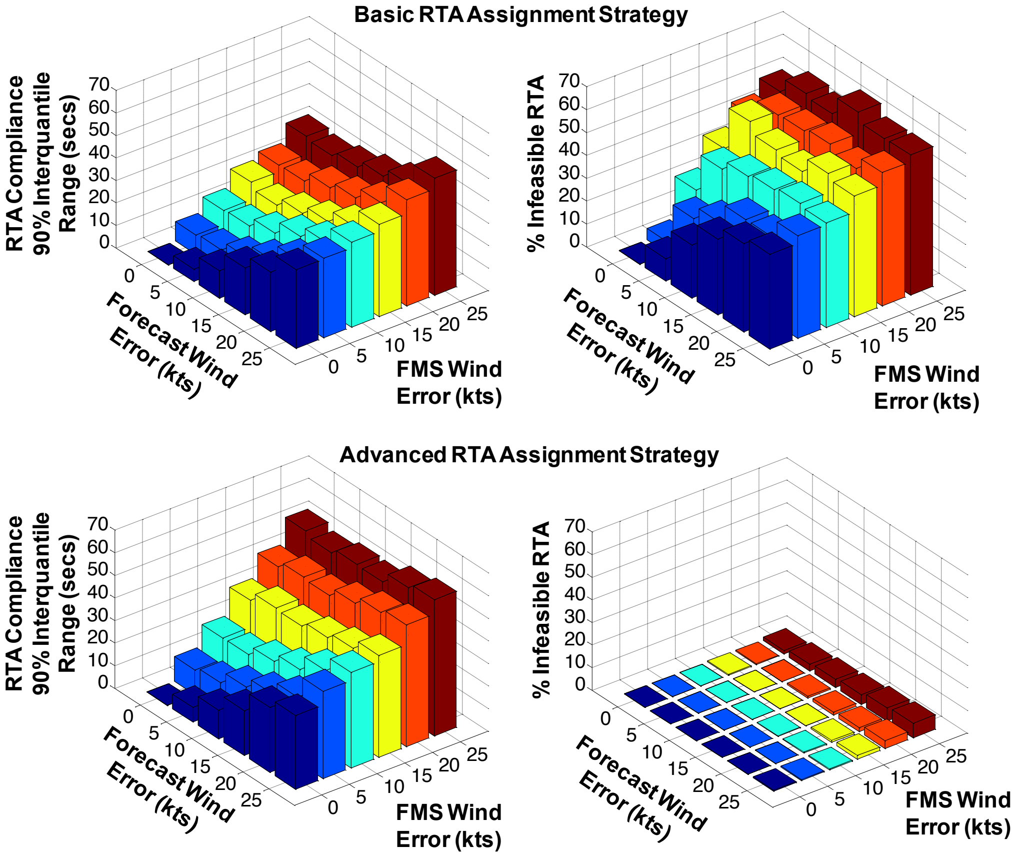
- **Wind Scenario** to represent operational wind scenarios of relevance to the application being studied and the characteristics of different wind information qualities, e.g., the accuracy of the forecast relative to the actual wind field experienced.

- **Future ATC Application** to represent the characteristics of the Air Traffic Control (ATC) environments for the application of interest, e.g., specifics of the procedures, infrastructure, demand levels, equipage.
- **Aircraft/FMS Simulation** to represent the behavior of the aircraft, engine, autopilot and Flight Management System (FMS) in the context of the wind scenario and future ATC application being studied.
- **Performance Assessment** to represent the behavior of relevant performance metrics as a function of the key independent variables given the wind scenario(s) and the future ATC application being studied, e.g., wind information quality and aircraft capability.
- **Wind Requirement Recommendations** where the key outputs from the analysis are converted into wind requirements of value to the key stakeholders for the application being studied, e.g., if a specific performance is required from the target application, the output will identify the level of wind information quality needed to meet that target (or vice versa).
- **Stakeholder Needs** to represent the key requirements of stakeholders which helps inform implementation choices for framework elements, e.g., in terms of what performance metrics are of value to support the creation of guidance or requirements documents.

This generic framework is designed to be flexible and scalable to a broad range of future ATC applications. However, in order to illustrate its use, the focus of the first phase of the work has been on a Four-Dimensional Trajectory-Based Operations (4D-TBO) application with simplified FMS and aircraft models flying through a challenging vertical wind shear environment. Performance was assessed in terms of the accuracy with which the aircraft could meet a Required Time of Arrival (RTA) at a meter fix at the end of the simulated trajectory as a function of wind forecast error and FMS wind error (i.e., the additional error introduced on top of the wind forecast due to limited wind information representation in the FMS). A Monte Carlo simulation capability was developed to allow thousands of trajectories to be simulated in fast-time in order to explore the trade-space of RTA compliance metrics as a function of forecast wind error and FMS wind error. Sample results are shown below.

The left-hand plots show the RTA compliance performance in terms of the width of the time interval around the RTA containing 90% of the simulated flights (i.e., the 90% interquantile range). The top plot contains results for the case when the RTA assignment algorithm assumed zero wind (a “basic” RTA assignment strategy), while the bottom plot contains results for the case where RTA assignment accounted for the forecast wind (an “advanced” RTA assignment strategy). The right-hand plots show the percent of simulated flights for which RTA achievement became infeasible at some point in the trajectory for the basic (top) and advanced (bottom) RTA assignment strategies.

Although these results are based on simplified versions of the Wind Information Analysis Framework elements (and actual wind information requirement recommendations will need to be based on higher fidelity models), it can be seen how, in principle, the trade-off space between relevant performance metrics, forecast wind error and FMS wind error can be identified. For example, the relative effects of forecast wind error and FMS wind error on the RTA compliance and percent infeasible performance metrics are seen to be quite different for the different RTA assignment strategies.



Requirements could be set from surfaces like these to determine what combination of forecast wind and FMS wind error limits would be needed in order to achieve a given RTA compliance performance, or define what level of RTA compliance performance would be possible with different combinations of achievable forecast and FMS wind errors. For example, these sample results show that for RTA compliance less than 30 secs for 90% of time (a horizontal slice at 30 secs in the left hand plots of the figure above), forecast wind and FMS wind errors need to be less than 15 kts RMSVE, while for less than 5% infeasible RTAs (a horizontal slice at 5% in the right hand plots of the figure above), less than 5 kts RMSVE forecast/FMS wind errors are needed with the basic RTA assignment strategy, but up to 20 kts RMSVE forecast/FMS wind errors could be tolerated if using the more advanced RTA assignment strategy.

This phase of the work has illustrated how even simplified executions of the Wind Information Analysis Framework for realistic NextGen applications can yield interesting and complex results which can be of high value in determining performance trade-spaces. Although the use of simplified models to generate these results implies the specific values in the trade-spaces still need to be refined, identification of "points of diminishing returns" are feasible from the execution of the Wind Information Analysis Framework. As such, this phase of the work has developed an effective analysis framework and acted as proof-of-concept of its utility for analyzing wind information needs for NextGen applications, which is the objective of this research program. Phase 2 will build upon this foundation by using refined and expanded applications of the Wind Information Analysis Framework to generate high value results for standards and requirements setting entities. Specific next steps for this work in Phase 2 include:

- Increasing the aircraft/FMS modeling fidelity (e.g., by using higher accuracy aircraft aerodynamic/propulsion/autopilot control simulations and re-hosted FMS software) and exploring more complex RTA procedures (e.g., adding vertical and lateral profile elements) to increase the realism and applicability of the results to stakeholder needs.
- Expanding the set of wind forecast scenarios to help identify gaps between required performance levels and current state of the art models identified through this analysis.
- Collaborating with FMS vendors to explore realistic future FMS capabilities to address some of the identified shortcomings in existing FMS capabilities, and integrating these improved algorithms into the analysis framework to analyze their impact.
- Expanding the focus applications beyond 4D-TBO, e.g., Flight Interval Management, Improved Traffic Management Advisor (TMA) and/or DataComm applications.

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1. INTRODUCTION

Accurate wind information is of fundamental importance to some of the critical future air traffic concepts envisioned under the FAA's Next Generation Air Transportation System (NextGen) and EUROCONTROL's Single European Sky (SESAR) initiatives. Examples include Time-Based Flow Management (TBFM) concepts such as Four-Dimensional Trajectory Based Operations (4D-TBO) and Flight Interval Management (FIM), as well as environmental impact reduction programs such as the Atlantic Interoperability Initiative to Reduce Emissions (AIRE). Figure 1 shows the wind information needs for some of these NextGen applications: 4D-TBO and FIM require accurate and consistent wind information between airborne and ground systems for effective time targets to be set and managed, while minimum fuel and/or noise trajectories require real-time optimized wind information to deliver benefits. Foundational wind research is needed to help understand the relationship between wind information and the delivery of benefits from the applications. A Wind Information Analysis Framework is developed and exercised in this work to address this need, as shown on the left of Figure 1. Information from effective implementation of the framework will be of high value in requirements and standards setting activities.

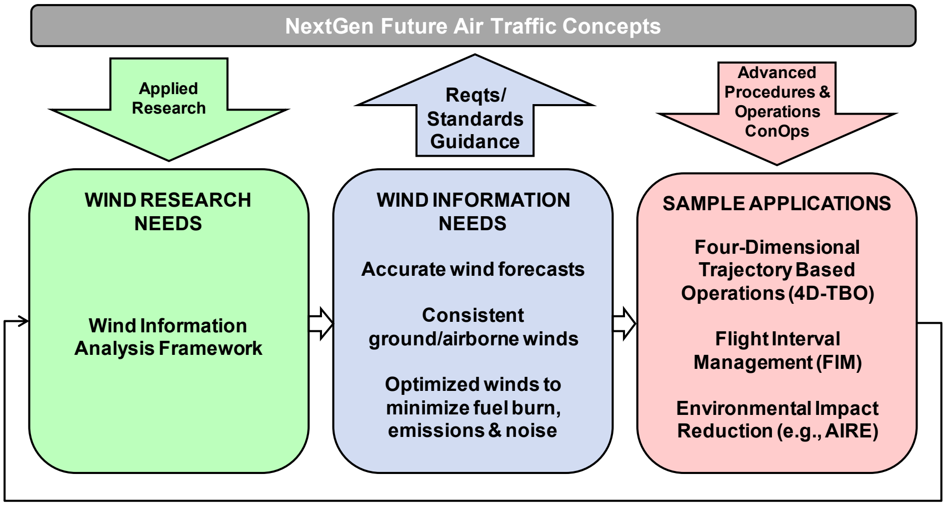

Figure 1. Wind Information Needs to Support NextGen Applications

Although a number of NextGen applications are of interest for this work, 4D-TBO was chosen to be the initial focus for the first phase of research reported in this document. 4D-TBO involving latitude, longitude, altitude, *and time-based* elements is one of the fundamental capabilities envisioned under TBFM. One concept of operations for 4D-TBO is illustrated in Figure 2. It involves aircraft trajectory information being submitted to a ground-based system which then determines time targets at appropriate "meter fix" locations along the requested route (shown as being during descent in Figure 2) to manage traffic flows as efficiently as possible. These time targets are issued to individual aircraft, which are then responsible for managing their trajectory to achieve the time target at the meter fixes through either manual speed control or via "Required Time of Arrival" (RTA) functionality of a Flight Management System (FMS). In prior studies, one major driver of the benefits achievable from 4D-TBO procedures was found to be the accuracy of the RTA compliance at the meter fix, which in turn was directly related to the accuracy and temporal/spatial resolution of the wind information available to the ground systems and airborne FMSs which are creating and managing compliance to the time targets respectively [1]. Recent simulations and flight trials have not only confirmed the fundamental importance of accurate wind information in the FMS relative to the actual wind, but also the need for consistency in the wind information between the ground and airborne systems, as well as the aircraft performance assumptions being used by each [2]. For example, even modest biases in wind models used by FMSs to control their trajectories could, in the absence of ATC intervention, result in separation violations in as many as 25% of arriving aircraft pairs when TBO procedures are applied in dense arrival airspace [3]. The various manifestations of wind information and aircraft performance elements across the ATC, airline and FMS systems are illustrated by the green and blue elements respectively in Figure 2. Inaccuracies relative to "truth" and/or inconsistencies between the wind and aircraft performance assumptions between the different agents of the ATC system can have major adverse impacts on the delivery of benefits from the 4D-TBO application.

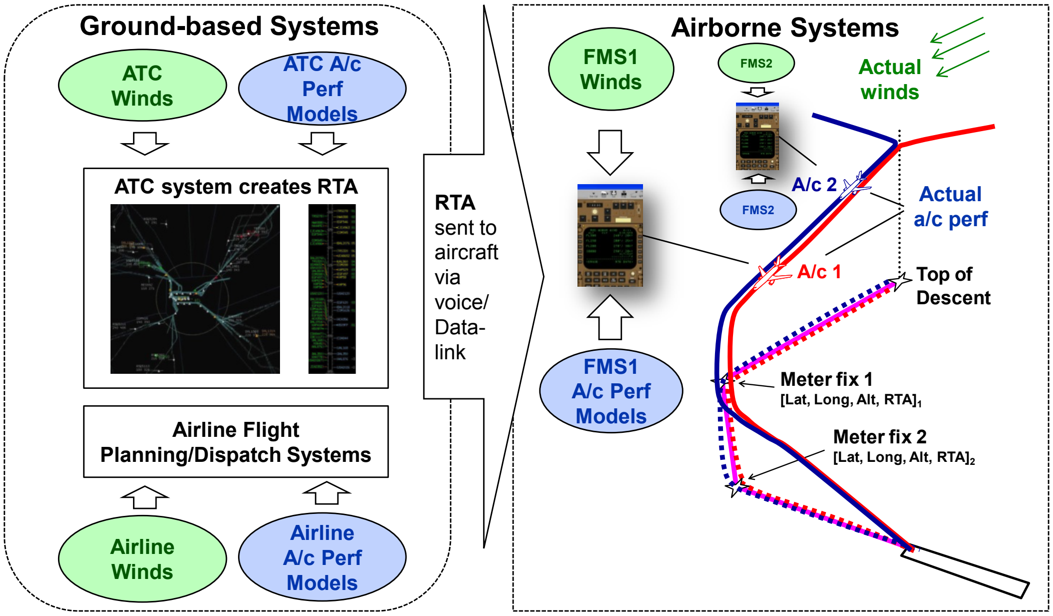

Figure 2. Four-Dimensional Trajectory-Based Operations Concept

The Wind Information Analysis Framework has been developed in this work to allow the relationships between wind information quality and system performance under different NextGen applications to be explored. This document reports the initial “proof-of-concept” of the framework using the 4D-TBO application as an initial focus. The remainder of this report is structured as follows:

- Section 2 discusses fundamental wind information background of relevance to this project, including factors affecting wind information quality, metrics that allow these factors to be quantified, and the performance of appropriate wind forecasting models against the identified factors and metrics.
- Section 3 presents the general Wind Information Analysis Framework concepts and illustrates how it is adapted for the 4D-TBO application.
- Section 4 presents results from its use for this application using simplified versions of the framework elements in order to illustrate the insights that can be gained.
- Section 5 outlines options and recommendations for Phase 2 of the work which build upon the work from Phase 1.
- Section 6 presents the summary from Phase 1 of this work.

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2. WIND INFORMATION QUALITY, METRICS AND OPERATIONAL MODEL PERFORMANCE

2.1 INTRODUCTION

The quality and consistency of wind information utilized by ground based and airborne systems has been identified as a key factor in the ability to deliver benefits under 4D-TBO, and other NextGen applications. This section describes the key factors that affect wind information quality, describes various performance metrics that quantify the impacts of these wind quality factors, and presents the results of a survey of current operational and research wind forecast models which includes a comparison of the performance of the models against some of the identified metrics.

2.2 WIND INFORMATION QUALITY FACTORS

It is important to define what is meant by wind data quality and identify factors affecting it. The types of quality factors and their relative importance are likely to be application-dependent, but the following factors have been identified as important determinants of wind information quality, at least with regard to NextGen applications such as 4D-TBO.

- **Timeliness**: Two important factors related to timeliness are update rate and latency. Update rate refers to how often the forecast model or analysis system produces new outputs. Latency is the sum total of all of the delays that occur, starting from model data inputs (e.g., observations), and proceeding through model run time, and model output post-processing and dissemination time. Latency is of particular concern for real-time applications, where the most accurate representation of the "current" winds may actually be the 1- or 2-hour forecast.

- **Spatial resolution**: Outputs from numerical weather prediction models are typically provided at regularly spaced grid points. Horizontal grid points usually follow a constant distance spacing in a Cartesian projection coordinate system (e.g., Lambert Conformal), however, some models use a latitude-longitude projection grid internally. Vertical grid points typically follow a variety of vertical coordinate systems such as pressure or potential temperature. There are typically many more grid points in the horizontal than in the vertical. Computational resources, storage capacity, and dissemination bandwidth have historically limited the spatial resolutions that the forecast models can provide, but these limitations have continued to improve over the years. In general, higher grid resolution means less interpolation between grid points is needed, and weather phenomena can be more directly represented instead of approximated via model physics and parameterizations. Higher resolution should result in more accurate representations of current and forecast conditions. However, achievable accuracy improvement is limited by the availability and density of observations that are input to the model. Spatial resolution is considered to be a key wind information quality factor since coarse resolutions may not adequately capture smaller scale wind features in situations where winds are changing rapidly with distance, resulting in aircraft trajectory prediction errors.

- **Temporal resolution**: There are two factors comprising temporal resolution. The forecast horizon (how far out in time the forecasts extend), and the forecast time step or interval. As with spatial resolution, computational, storage, and bandwidth resources limit what model forecast time steps can be output. Internal model integration time steps are often much smaller (seconds or minutes) than the output forecast time steps disseminated to end users. So, although the model may have sufficient internal temporal resolution to capture smaller scale wind features, the end user has to interpolate at intermediate times between the output forecast time steps. The larger the time steps, the greater the potential for errors from temporal interpolation. Hence, the available forecast time resolution is an important wind information quality factor.

- **Intrinsic forecast accuracy**. Intrinsic model errors encompass a broad range of numerical prediction model limitations including errors in underlying model physics (e.g., imperfect approximations) and observation errors (e.g., coverage and sensor errors, errors in assimilation and analysis), along with errors that tend to accumulate with increasing forecast lead time due to unmeasured scales of motion and unrepresented processes that cause the modeled state of the atmosphere to increasingly differ from the actual state of the atmosphere.

The above factors combine to affect the capability of a wind forecast model to represent the true wind at a particular location and time.

2.3 WIND MODEL PERFORMANCE METRICS

2.3.1 Root Mean Square Vector Error (RMSVE)

Root Mean Square Vector Error (RMSVE) is the most commonly reported accuracy metric used to assess the performance of a wind forecast model. It is the Root Mean Square (RMS) error applied to the magnitudes of the forecast and observed wind vector components as given by:

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

where *N* is the number forecast-observation pairs, *u* is the east-west component of the wind vector, *v* is the north-south (y) component, and subscripts *f* and *o* refer to forecast and observed respectively. Many of the wind forecast accuracy studies associated with the surveyed wind models included in the next section presented the RMSVE as aggregate performance measures derived from comparisons of the model forecasts with corresponding wind observations from aircraft or radiosondes over a large number of cases. For example, Schwartz [4] compared 60 km and 40 km resolution Rapid Update Cycle (RUC) model wind forecasts against aircraft reports in the Denver region over a 13-month period to investigate the factors affecting wind forecast errors and to assess the relative accuracy of the two versions of the model. The study found that the RMS wind errors were larger in winter than summer and larger at higher altitudes, but cautioned that RMS error results should be interpreted with the knowledge that the RMS error metric is sensitive to wind speeds—at large wind speeds, small direction differences can produce very large vector differences. Wind speeds tend to be higher in winter and at higher altitudes, so the sensitivity of the metric to wind speed helps explain some of the seasonal and altitude trends. Not surprisingly, the study also found that RMS vector errors increased with increasing forecast lead time by about 3 knots when going from 1 to 6 hours.

Aggregate RMS error statistics compiled over large numbers of cases may mask the performance degradation associated with occasional large forecast errors that can occur in conjunction with dynamic wind events where winds are changing rapidly in space and time and are more difficult to forecast. As an example, consider Figure 3 which compares the High Resolution Rapid Refresh (HRRR) model T = 0 analysis “truth” winds for a 200 nm × 200 nm region centered over Newark Liberty International Airport (EWR) at 3,243 feet at 12:00 GMT on 09/06/201 with the corresponding 2-hour HRRR forecast winds issued two hours earlier at 10:00 GMT.

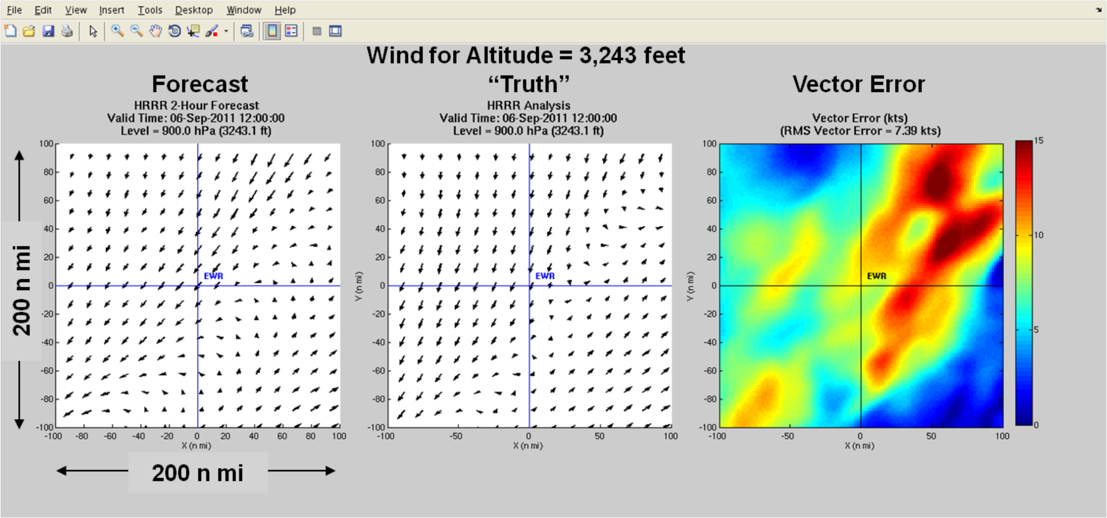


Figure 3. Comparison of HRRR 2-Hr Forecast Issued at 10:00 GMT (Left) and T = 0 HRRR Analysis “Truth” Winds (Center) Valid at 12:00 GMT on 09/06/2011. The vector error in knots is plotted at right.

The rightmost panel in the figure plots the vector error magnitude in knots between the forecast and "truth" winds at each grid location. The RMS vector error aggregated over the entire altitude level was 7.4 knots—within the typical range of forecast error reported in the literature. Note, however, the localized region of relatively large forecast vector errors exceeding 15 knots associated with the frontal wind shear zone running diagonally from NE to SW.

The Schwartz study described earlier in this section also considered wind errors from an air traffic management perspective and identified two factors that are important:

1. Peak error events. The frequency of occurrence of large errors (peak error events with vector errors exceeding 10 m/s).
2. Errors in calculating exact arrival times for a time in the future, i.e., time-to-fly (TTF) errors.

In that study, arrival time errors for over 17,000 ascent and descent trajectories into Denver International Airport (DEN) were computed. Aircraft reports were used to obtain mean ground speeds and measured (true) winds over 15-minute duration ascent/descent trajectories. Corresponding RUC 1- and 2-hour forecast winds were then used to compute forecast headwinds and resulting forecast ground speeds. The timing errors were computed by comparing the times to traverse the trajectories assuming the forecast ground speeds against the actual flight times. Figure 4 is a histogram displaying the distribution of estimated arrival time errors for the 15-minute ascent/descent trajectories examined. The mean arrival time error was reported in the study as 9.3 seconds.

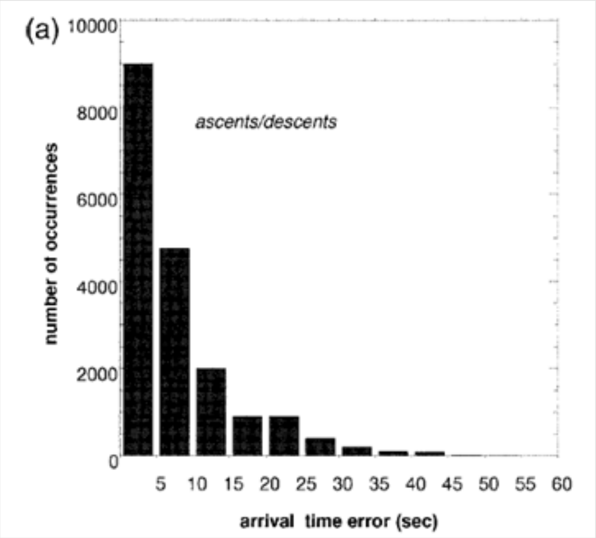


Figure 4. Estimated Arrival Time Errors from 40 km RUC 1–2-hour Forecasts for 15-minute Ascent/Descent Segments at Denver International Airport (from Schwartz [4])

Cole [5] expanded on the Schwartz study (using the same data set) and focused on wind prediction accuracy needs for Air Traffic Management (ATM) decision support tools. In order to better understand the magnitude and source of wind prediction errors and to establish metrics for quantifying large errors for ATM applications, the wind forecast accuracies of the earlier generation 60 km RUC (RUC-1) and 40 km RUC (RUC-2) models and a version of the 10 km resolution Integrated Terminal Weather System (ITWS) Terminal Winds algorithm (TWIND, or TW) adapted for en route applications (called "AW" for Augmented Winds) were assessed through comparison against the aircraft wind observations collected during the one-year Denver region experiment. The study presented and contrasted three types of metrics for quantifying large forecast errors which are discussed next.

2.3.2 Large Error Percentage

The large error percentage metric was the simplest metric examined. It identifies the frequency of wind vector errors greater than a chosen large error threshold, e.g., 10 m/s (19.4 knots). Figure 5 shows the percentage of monthly RMS vector errors greater than 10 m/s for the RUC-1 and RUC-2 models over the one-year study. Note the increase in frequency of large errors during the winter months. Over 15% of the RUC-1 forecasts had errors greater than 10 m/s in December, but only 7% of the RUC-2 forecasts had errors greater than 10 m/s.

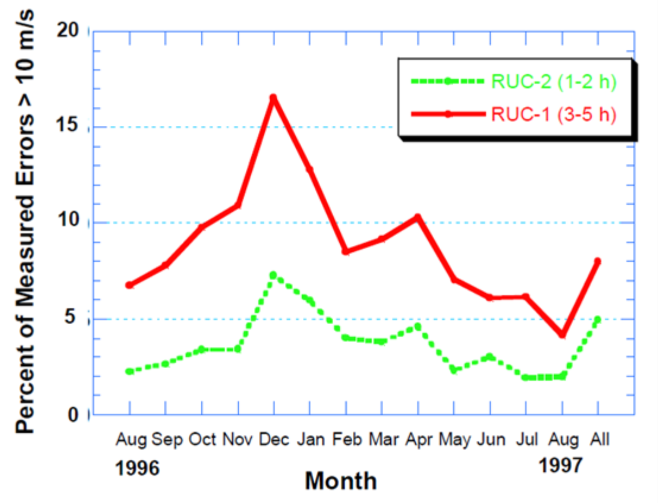


Figure 5. RUC Monthly RMS Vector Errors Greater Than 10 m/s (from Cole [5])

2.3.3 Wind Error Percentile

This metric computes percentile values of the magnitude of wind vector errors, producing a probability distribution. Its advantage over the large error percentage metric is that it doesn't require that an error value threshold be set in advance, so the data can be interpreted using any chosen large error value. Figure 6 shows the probability distributions for RUC-1 and AW over the entire Denver data set. An example interpretation of the figure is that RUC-1 forecasts had vector errors greater than 10 m/s approximately 11% of the time, while the AW reduced the occurrence to 4% of the time.

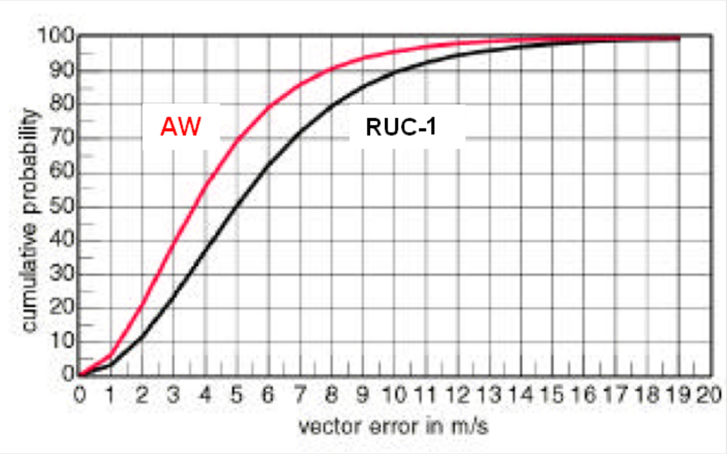
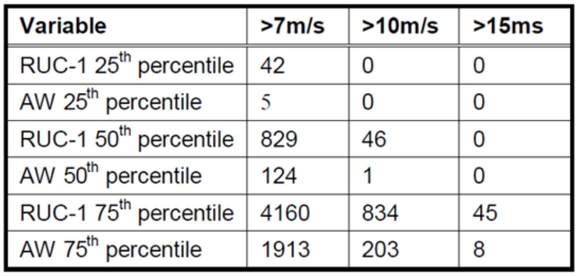


Figure 6. RUC and Augmented Winds (AW) Cumulative Probability vs. Vector Error (from Cole [5])

2.3.4 Large Hourly Error Percentage

The large hourly error percentage metric encapsulates both the spatial extent and temporal persistence of large errors within the domain of interest for ATM applications (e.g., Terminal Radar Approach CONtrol (TRACON) or terminal airspace), rather than the entire airspace. The idea behind this metric is that while isolated large point errors are not a significant problem, a collection of such errors along critical flight path regions will cause significant trajectory timing errors. Since data along individual flight paths are not dense enough to calculate the frequency of large error occurrence, selected percentile error frequencies (25th, 50th, 75th) for the wind fields over an hourly basis were used in the study. As an example (see Table 1), the study found that there were 42 hours during the year when 75% of the 60 km RUC vector errors exceeded 7 m/s (13.6 knots), while the AW algorithm reduced the number of hours with errors exceeding 7 m/s to five.

Table 1. Number of Hours with Hourly Nth Percentile Vector Errors Above Selected Thresholds (from Cole [5])



Variable	>7m/s	>10m/s	>15ms
RUC-1 25th percentile	42	0	0
AW 25th percentile	5	0	0
RUC-1 50th percentile	829	46	0
AW 50th percentile	124	1	0
RUC-1 75th percentile	4160	834	45
AW 75th percentile	1913	203	8

Another study by Cole [6] assessed RUC and TWIND accuracy using Time-To-Fly (TTF) as a trajectory-based metric that relates to wind data quality. The study compared winds from RUC and TWIND along nominal approach routes at Dallas/Fort Worth International Airport (DFW) for eleven days. Seven of the eleven days had winds greater than fifty knots for some portion consisted of the route and four of those had significant vertical shear. The study found that the more frequent updates (5 minutes) of the TWIND algorithm with respect to the hourly updating RUC led to significant changes in TTF estimates under time-varying wind conditions, with standard deviation of TTF differences between the two estimates increasing to as much as 50 seconds over a 40-minute period.

2.4 SURVEY OF WIND FORECAST MODEL CAPABILITIES

In order to assess the capabilities of current and near-term operational wind forecast models, a limited survey of wind forecast models utilized by stakeholders and aviation weather researchers in the United States and United Kingdom was conducted. The information gleaned from the survey is presented in Table 2 and Table 3. While not exhaustive, the survey catalogued a broad range of model characteristics and forecast performance statistics representative of the state of the art with respect to relevant wind forecast data parameters. Important output characteristics related to domain coverage, wind quality factors (e.g., spatial and temporal resolution, update rate), accuracy performance, operational status and usage have been identified for each of the surveyed models. Of the wind accuracy performance metrics identified in the previous section, RMSVE is reported in these tables given that it was the most common metric reported in the literature allowing direct comparison between the different models surveyed.

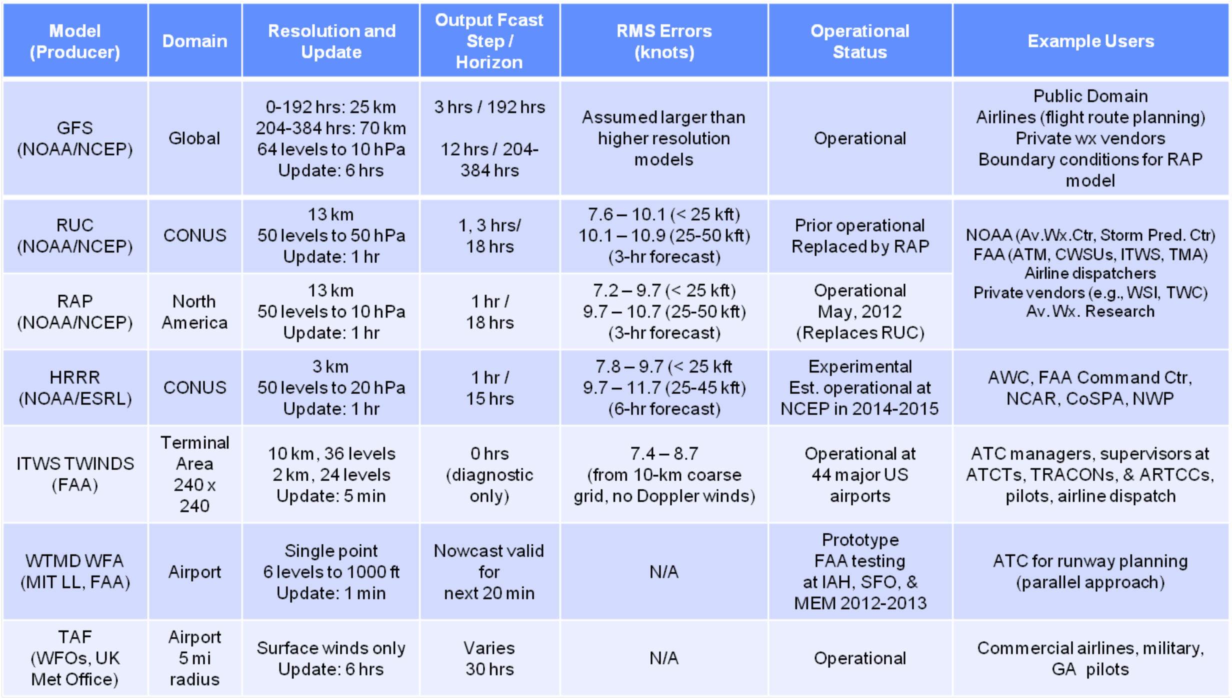
It will be seen that models of increasing spatial resolution have decreasing wind forecast error against the RMSVE metric. This is not exclusively due to the increased resolutions, but also due to accompanying improvements in model physics, number and types of observations, and data assimilation techniques. Broadly, the RMS forecast errors typically fall in the range of 5–12 kts (but note RMS error statistics reported in the examined literature were often selectively and inconsistently classified with respect to altitude, forecast lead time, etc., so the tabulated results should be compared and considered in light of those classifications).

With regard to vertical resolution and coverage, most of the models perform their computations utilizing terrain-following pressure coordinates known as “sigma” coordinates [7], fixed pressure-level coordinates, potential temperature (theta) coordinates, or hybrids of these for the vertical axis. These coordinates simplify the thermodynamic calculations. Forecast model data in the “native” pressure coordinates used for the model computations are often translated by post-processing into constant pressure level coordinate representations favored by aviation and weather service users.

2.4.1 Descriptions of U.S. Wind Models

Table 2 summarizes the characteristics and accuracy of the U.S. wind models that were surveyed.

Table 2. Summary of Key U.S. Wind Models



Model (Producer)	Domain	Resolution and Update	Output Fcast Step / Horizon	RMS Errors (knots)	Operational Status	Example Users
GFS (NOAA/NCEP)	Global	0-192 hrs: 25 km 204-384 hrs: 70 km 64 levels to 10 hPa Update: 6 hrs	3 hrs / 192 hrs 12 hrs / 204-384 hrs	Assumed larger than higher resolution models	Operational	Public Domain Airlines (flight route planning) Private wx vendors Boundary conditions for RAP model
RUC (NOAA/NCEP)	CONUS	13 km 50 levels to 50 hPa Update: 1 hr	1, 3 hrs/ 18 hrs	7.6 – 10.1 (< 25 kft) 10.1 – 10.9 (25-50 kft) (3-hr forecast)	Prior operational Replaced by RAP	NOAA (Av.Wx.Ctr, Storm Pred. Ctr) FAA (ATM, CWSUs, ITWS, TMA) Airline dispatchers Private vendors (e.g., WSI, TWC) Av. Wx. Research
RAP (NOAA/NCEP)	North America	13 km 50 levels to 10 hPa Update: 1 hr	1 hr / 18 hrs	7.2 – 9.7 (< 25 kft) 9.7 – 10.7 (25-50 kft) (3-hr forecast)	Operational May, 2012 (Replaces RUC)	
HRRR (NOAA/ESRL)	CONUS	3 km 50 levels to 20 hPa Update: 1 hr	1 hr / 15 hrs	7.8 – 9.7 (< 25 kft 9.7 – 11.7 (25-45 kft) (6-hr forecast)	Experimental Est. operational at NCEP in 2014-2015	AWC, FAA Command Ctr, NCAR, CoSPA, NWP
ITWS TWINDS (FAA)	Terminal Area 240 x 240	10 km, 36 levels 2 km, 24 levels Update: 5 min	0 hrs (diagnostic only)	7.4 – 8.7 (from 10-km coarse grid, no Doppler winds)	Operational at 44 major US airports	ATC managers, supervisors at ATCTs, TRACONs, & ARTCCs, pilots, airline dispatch
WTMD WFA (MIT LL, FAA)	Airport	Single point 6 levels to 1000 ft Update: 1 min	Nowcast valid for next 20 min	N/A	Prototype FAA testing at IAH, SFO, & MEM 2012-2013	ATC for runway planning (parallel approach)
TAF (WFOs, UK Met Office)	Airport 5 mi radius	Surface winds only Update: 6 hrs	Varies 30 hrs	N/A	Operational	Commercial airlines, military, GA pilots

Brief descriptions of each of the surveyed U.S. models follow, with the operational status of indicated in square brackets (“[]”) at the start of the description. Example operational ATC users are listed in the rightmost column of the table.

Global Forecast System (GFS)

[Operational] The Global Forecast System (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. 64 vertical levels are output for all forecast ranges.

The GFS model provides the initialization and boundary conditions for regional forecast models including the Weather Research and Forecasting Model (WRF), which in turn initializes the Rapid Refresh (RAP) and High Resolution Rapid Refresh (HRRR) models that are described below. Some airlines use the GFS for flight route planning.

Rapid Update Cycle (RUC)

[Prior Operational] The Rapid Update Cycle model was the previous state-of-the-art, hourly updating operational weather prediction system produced at NOAA/NCEP until its recent replacement by the Rapid Refresh (RAP) in May 2012. It assimilated observations from aircraft, radars, radiosondes, surface stations, and satellites. Each hourly model run produced forecasts with hourly steps out to 18 hours. Horizontal resolution was improved over the years from 60 km to 40 km, and finally, 13 km. There are 50 vertical pressure levels extending up to 50 hPa (approximately 65,000 ft under standard atmospheric conditions). Surface winds and gusts were provided at a 10 meter height (corresponding to the common anemometer height for surface observing stations). Latency was approximately 1 hour, so the 1-hour forecast was often used as the “current” analysis. RMS errors in Table 2 were obtained from [8]. RUC model outputs are used in a number of current operational FAA and weather information applications as indicated in Table 2. RMS errors in Table 2 were obtained from [8].

Rapid Refresh (RAP)

[Operational] The hourly updating 13 km resolution Rapid Refresh (RAP) model replaced the Rapid Update Cycle (RUC) in May 2012 as the operational gridded forecast model produced at NOAA/NCEP. Gridded forecasts of winds and gusts are produced for the North American domain for hourly forecast time 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). Latency is similar to the RUC at approximately 1 hour [8]. RAP model outputs are used in a number of current operational FAA and weather information applications as indicated in Table 2. RMS errors in Table 2 were obtained from [8].

High Resolution Rapid Refresh (HRRR)

[Experimental] The High Resolution Rapid Refresh (HRRR) model is an hourly updating, 3 km resolution, CONUS domain model that is initialized and run by the NOAA Earth System Research Laboratory (NOAA/ESRL) as a nest within the RAP model [9]. It is presently undergoing performance evaluation, validation, and reliability improvements, and although it is considered experimental, it is a mature and widely used model utilized by a variety of aviation agencies and weather information systems presently under research and development including the Consolidated Storm Prediction for Aviation (CoSPA) [10]. It is targeted for operational deployment at NOAA/NCEP around 2015. Like the RAP, it updates hourly, providing hourly forecast grid sequences of meteorological variables from 0 to 15 hours. The latency is approximately 1.5–2.0 hours. It provides the same wind products as the RAP model. The higher spatial resolution of the HRRR allows for improved resolution of mesoscale (2–2000 km) atmospheric features. The wind energy industry expects the HRRR to make a large, beneficial impact on the ability to forecast wind "ramp" events that dramatically affect power production [11], and has been working with NOAA and Department of Energy (DOE) to assess its performance and improve the wind forecasting skill through a Joint Wind Forecast Improvement Project (WFIP) [12]. RMS errors in Table 2 were obtained from [9].

ITWS Terminal Winds (TWINDS)

[Operational] The Terminal Winds product (TWINDS) of the Integrated Terminal Weather System (ITWS) [5] combines data from the 13 km NOAA Rapid Refresh numerical model with observations from ground stations including Automated Surface Observing System (ASOS), Automated Weather Observing System (AWOS) and Low-Level Windshear Alert System (LLWAS), together with aircraft reports, and winds from Doppler weather radars such as Terminal Doppler Weather Radar (TDWR) and U.S. National Weather Service (NWS) Next Generation Radars (NEXRAD) to provide 5 minute updated estimates of 3D horizontal winds in the terminal area. The operational system does not currently output the internally computed 3D wind grids (2 km resolution out to 120 km, and 4 km resolution out to 240 km). It outputs a limited number of vertical profiles through the 3D grids at user-specified locations (often corresponding to navigational fixes). It is currently diagnostic only (no forecast capability), but a nowcast (1–2 hour forecast) capability has recently been proposed, so it is included in the survey as a potential near-term high resolution forecast model. RMS errors in Table 2 were obtained from [13].

WTMD Wind Forecast Algorithm (WTMD WFA)

[Transitioning to Operational] The Wake Turbulence Mitigation for Departures (WTMD) algorithm was developed at MIT Lincoln Laboratory and is presently undergoing prototype testing by FAA at selected airports. It incorporates a Wind Forecast Algorithm (WFA) that has two components for forecasting winds at the surface and aloft up to 1000 feet. The surface wind forecast component applies a statistical predictive approach using recent observations of winds from 1 minute ASOS observations. The winds aloft forecast component utilizes 2–4 hour forecasts from neighboring RUC/RAP model grid points at six altitude levels up to 1000 feet. Wind profile nowcasts are generated for a single point every minute and are considered valid for the following 20 minutes. The wind forecasts from WTMD are not currently operationally available [14].

Terminal Aerodrome Forecast (TAF)

[Operational] The Terminal Aerodrome Forecast (TAF) is one of the most commonly used sources of surface wind forecasts information for aviation in the airport terminal area. TAFs provide forecasts of weather conditions within five miles of the airport over the next 24–30 hours in a coded text format. They are typically updated every 6 hours, but special intermediate updates may be issued if changing weather conditions warrant. TAFs are generated based on local forecaster knowledge with guidance from numerical model forecasts, and include expected surface winds, but no information on expected winds aloft [15].

2.4.2 Summary of UK Met Office Models

Table 3 provides a similar summary for key models provided by the UK Met Office for European weather. Brief descriptions of each of the surveyed UK models follow Table 3.

Table 3. Summary of Key UK Met Office Models

Model	Domain	Resolution and Update	Output Fcast Step / Horizon	RMS Error (knots)	Operational Status	Example Users
Global	1024 x 769	25 km 70 levels to ~80 km Update: 6 hrs	3 hrs / 0-84 hrs 6 hrs / 90-144 hrs	Assumed larger than higher resolution models	Operational Replaces NAE in 2012	Forecasters, airlines, air traffic control, private aviation met. service providers
NAE	600 x 360	12 km 70 levels to ~80 km Update: 6 hrs	1 hr / 48 hrs	~6.4 – 8.2 (esimated from u,v component error graphs)	Operational. Will be replaced by 4-km Western Europe model (EUR-4) in 2013	
UK4	UK 288 x 360	4 km 70 levels to ~40 km Update: 3 hrs	1 hr / 36 hrs	TBD	Current operational. Will be retired when EUR-4 is implemented 2013	
UKV	UK+ 744 x 928	Variable (1.5, 4 km) 70 levels to ~40 km Update: 3 hrs	1 hr / 36 hrs	TBD	Current operational model for UK domain	
WAFTAGE	Stockholm 11.3 deg lon x 2.97 deg lat (Domain is relocatable)	62x70 lat-lon pts (~ 5 km) 45 levels (1000 ft intervals) Update: 1 hr (custom)	20 min 80 min	~5.8 (estimated from u,v component error graphs)	Research	In use for past 3 years; CDA studies at Stockholm, 2009 MINT support

Global Model

[Operational] The Global Model has a horizontal spatial resolution of approximately 25 km resolution and has 70 vertical levels. Its domain covers the entire globe and updates once every 6 hours with forecasts extending out to 144 hours at hourly forecast steps. It provides the boundary information for the North Atlantic European (NAE) model. A higher resolution version is expected in 2013 and will eventually replace the NAE as the operational model for the North Atlantic [16].

North Atlantic European Model (NAE)

[Operational] The NAE is a regional model initialized by the Global model with horizontal resolution of 12 km and 70 vertical levels up to approximately 80 km. It runs every 6 hours and produces forecasts out to 48 hours with 1 hour forecast steps [16]. RMS error statistics presented in Table 3 were estimated from graphs in [17].

UK4

[Operational (secondary)] The UK4 is a high (4 km) spatial resolution regional forecast model covering the UK and the western North Sea and is driven by the Global model. It has 70 vertical levels extending up to approximately 40 km, and updates every three hours with forecasts at 1 hour step intervals out to a forecast horizon of 36 hours. This model will be retired when the EUR-4 is implemented (expected 2013), which is essentially the UK4 with an extended domain coverage in western Europe [18].

UKV

[Operational] The UKV is a high spatial resolution (1.5 km), convection resolving, local area forecast model covering the UK and the western North Sea and is driven by the Global model. It has 70 vertical levels extending up to approximately 40 km, and updates every 3 hours with forecasts at 1 hour step intervals out to a forecast horizon of 36 hours.

WAFTAGE

[Research] The Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe (WAFTAGE) model utilizes a successive correction algorithm to adjust background model forecast data (from NAE for example) using the most recent Aircraft Meteorological Data Relay (AMDAR) [19] observations to produce improved wind and temperature forecasts. Forecasts are generated every hour (customizable) with 20-minute steps out to 80 minutes, with spatial resolution of approximately 5 km and 45 vertical levels in 1000 ft increments. Its coverage domain is relocatable. It has been used for over three years in support of continuous descent approach (CDA) studies at Stockholm and the SESAR MINT study in 2009 [20]. RMS error statistics presented in Table 3 were estimated from graphs in [17].

2.5 SUMMARY

Wind information quality is dictated by a combination of wind data quality factors. For NextGen applications such as 4D-TBO, the following quality factors were identified as potentially significant: timeliness (update rate, latency), spatial/temporal resolution, and intrinsic forecast accuracy, all of which combine to give a particular model its forecast skill.

In terms of wind forecast performance metrics, aggregate RMS Vector Error is the most commonly used and reported metric for quantifying overall model forecast skill against observations, and provides a common reference for comparing the relative performance of various wind forecast models, as well as providing useful bounds for our parametric studies of effects of wind forecast errors on trajectories. Although reported RMS errors provide a useful overall measure of forecast skill, they are typically obtained from samples aggregated over large data sets and can mask the occasional larger errors that occur in challenging wind events such as frontal boundaries and storm systems where winds are rapidly changing in space and time. Localized forecast errors may significantly exceed the typical aggregate RMS errors in these events, and the effects of these larger errors on NextGen applications needs to be considered. Researchers have proposed alternative metrics that quantify the spatial and temporal distributions of large forecast errors, and route-integrated metrics such as arrival time error and time-to-fly. These metrics provide additional means for assessing the capabilities of wind forecast systems in the context of ATM applications, especially when operating in challenging wind prediction scenarios.

A limited survey of current wind forecast capabilities was conducted. The survey found that RMS Vector Errors decrease with increasing spatial/temporal resolution (often coupled with underlying improvements in intrinsic model forecast capabilities), and generally fell in the range of 5–12 knots. In the US, the hourly updating 13 km resolution Rapid Refresh (RAP) model has recently replaced the RUC as the principal operational NOAA model utilized by aviation and ATC users. The High Resolution Rapid Refresh (HRRR) model is a widely used experimental model with 3 km resolution that better resolves rapidly changing winds in dynamic weather events. It is targeted to become an operational model in the 2015 time frame, and its capabilities are being examined and utilized in the context of this study.

These findings help to inform what metrics and wind forecast performance ranges are appropriate to study with the Wind Information Analysis Framework discussed next.

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3. WIND INFORMATION ANALYSIS FRAMEWORK

3.1 INTRODUCTION

A Wind Information Analysis Framework has been developed as shown in Figure 7. This is the generic form of the framework which is adaptable to any specific application, as discussed later in this section.

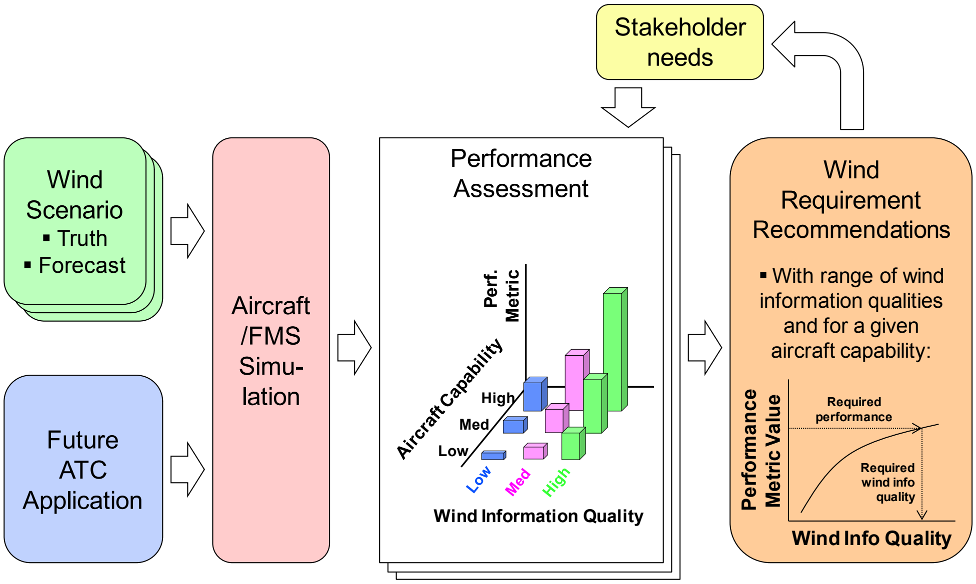


Figure 7. Generic Wind Information Analysis Framework

The generic framework contains elements of

- **Wind Scenario** to represent operational wind scenarios of relevance to the application being studied and the characteristics of different wind information qualities, e.g., the accuracy of the forecast relative to the actual wind field experienced.
- **Future ATC Application** to represent the characteristics of the ATC environments for the application of interest, e.g., specifics of the procedures, infrastructure, demand levels, and equipage.
- **Aircraft/FMS Simulation** to represent the behavior of the aircraft, engine, autopilot and FMS in the context of the wind scenario and future ATC application being studied.

- **Performance Assessment** to represent the behavior of relevant performance metrics as a function of the key independent variables given the wind scenario(s) and the future ATC application being studied, e.g., wind information quality and aircraft capability.
- **Wind Requirement Recommendations** where the key outputs from the analysis are converted into wind requirements of value to the key stakeholders for the application being studied, e.g., if a specific performance is required from the target application, the output will identify the level of wind information quality needed to meet that target (or vice versa).
- **Stakeholder Needs** to represent the key requirements of stakeholders which helps inform implementation choices for framework elements, e.g., in terms of what performance metrics are of value to support the creation of guidance or requirements documents.

This generic framework is designed to be flexible and scalable to a broad range of future air ATC applications. However, in order to illustrate its use, it was applied in the first phase of the work reported here to a simple 4D-TBO application: the tailoring of the Wind Information Analysis Framework to this application is shown in Figure 10. The implementation of each block in Phase 1 of the work is described in turn next.

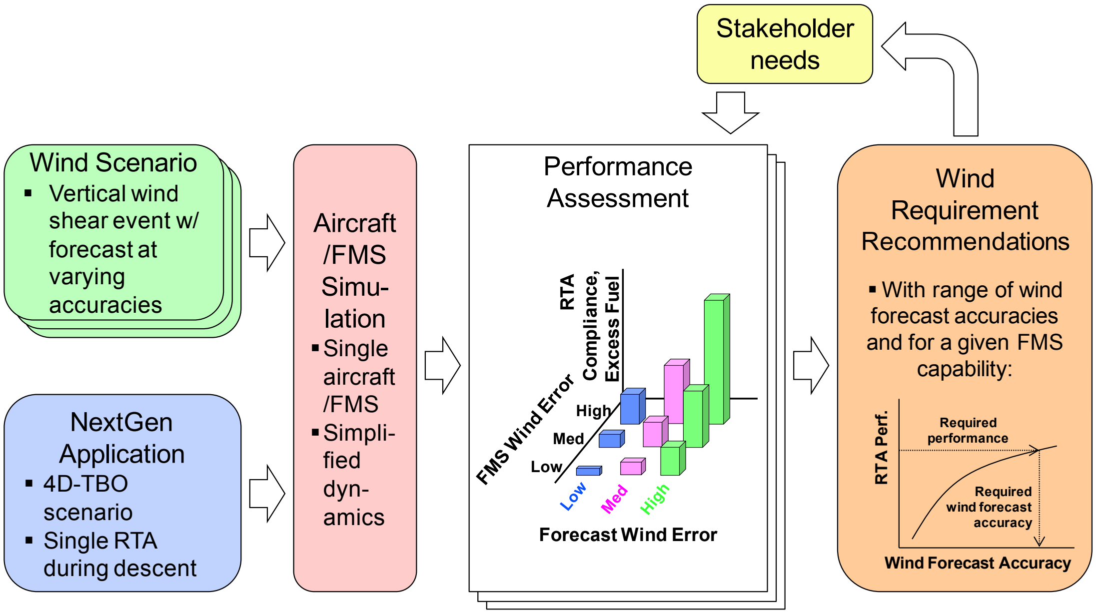


Figure 8. Initial 4D-TBO Application of Wind Information Analysis Framework

3.2 WIND SCENARIO

3.2.1 Wind Scenario Selection

To test the framework for the 4D-TBO application, a wind scenario was required that was representative of conditions occurring relatively frequently in the air transportation system and challenging from a 4D-TBO benefits delivery perspective. Several candidate wind scenario options were considered, including homogenous winds with random model errors spatially correlated over realistic length scales, lateral boundaries/fronts with a given spatial location and wind speed gradient across it, and vertical shear of horizontal wind (significant change in wind vector with altitude) of varying vertical location and magnitude of shear.

The homogeneous wind scenario was considered effective at capturing errors typically seen in wind forecasting models while also being a relatively simple case, but it was considered inadequate for capturing important effects of varying spatio-temporal resolutions characterized by current forecast models. The lateral boundary case is potentially useful for investigating effects of varying horizontal forecast model resolution and update rates, but it was difficult to find real-world cases of surface fronts that did not also have associated vertical wind shear. The vertical shear scenario is recognized as a common air traffic control problem and is also effective at highlighting error differences due to a variety of forecasting model spatial resolutions and update rates. As a result, this case was chosen as the wind scenario for the initial phases of this work.

A sample vertical wind shear case experienced in the New York area on September 6, 2011 that caused major challenges from an ATC perspective is presented in Figure 9. The figure plots a sequence of horizontal cross-sections of the winds from the 12:00 GMT run of the NOAA High Resolution Rapid Refresh (HRRR) model at selected altitudes over a 400 nm × 400 nm area centered northwest of Newark Liberty International (EWR) airport. Note the significant changes in wind magnitude and direction visible through the wind vectors at different altitude levels.

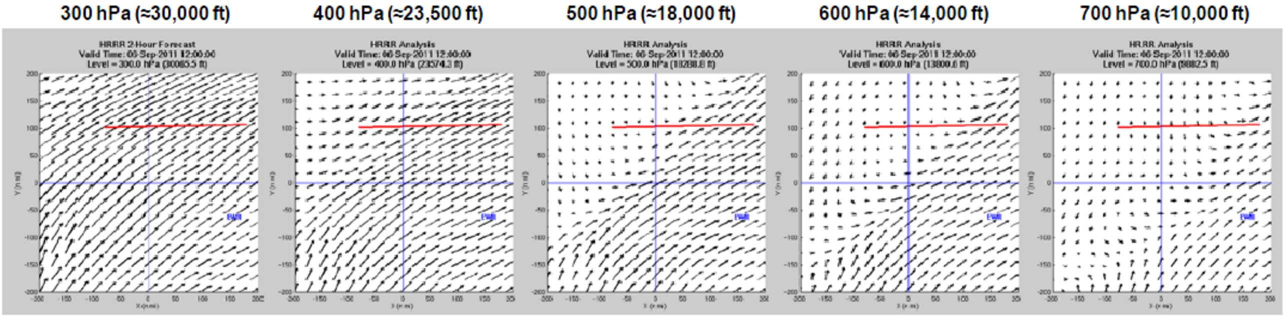


Figure 9. Sample Vertical Wind Shear Scenario (New York area, 09/06/2011 at 12:00 GMT)

3.2.2 Wind Modeling and Analysis Utility

To support various representations of real and synthesized winds in the context of the wind information analysis framework, a MATLAB-based atmosphere and wind modeling and analysis software utility was developed. Figure 10 is a conceptual depiction of the modeling framework which has a modular, object-oriented architecture that is readily extensible to accommodate additional models and atmospheric variables. For wind modeling applications, either synthesized (i.e., artificially generated to have specific features) or actual gridded wind model data (i.e., from operational data) can be generated or input into the framework.

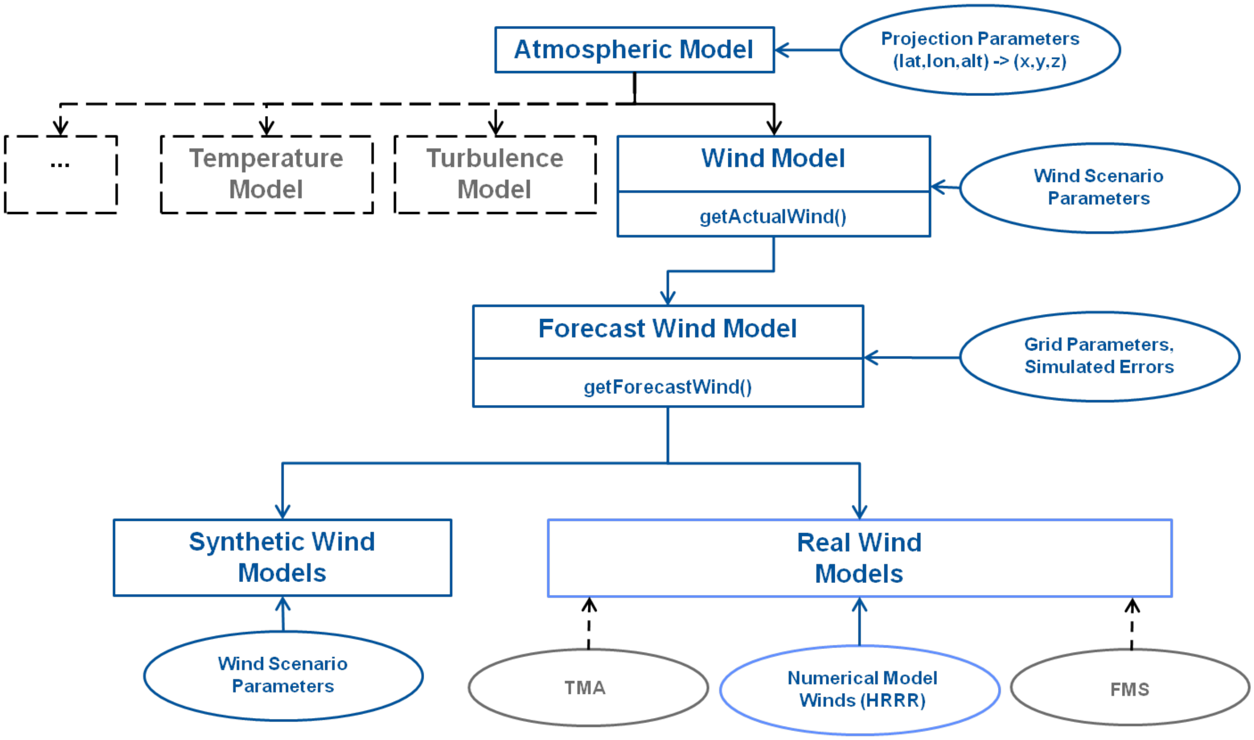


Figure 10. Atmosphere and Wind Modeling and Analysis Utility. Blue elements have been implemented. Grey elements are possible future additions.

At the lowest level (top of the object inheritance tree), projection parameters are used to set up the grid geometry and the mapping projection for converting between latitude and longitude coordinates and Cartesian grid coordinates. All of the descendant modeling classes inherit these methods for performing the coordinate transformations. For real wind model data, these grid and mapping projection parameters are obtained and derived from the metadata information included with the model data. Gridded forecast wind data from numerical forecast models such as HRRR, RUC, or RAP can be read from commonly available World Meteorological Organization (WMO) GRIB-2 or NetCDF formats. For synthesized wind fields, the grid and mapping parameters are established from a configuration file.

For synthetic wind cases, wind scenario configuration parameters are supplied that describe how the 4D winds are to be manifested in space and time. Each synthetic wind scenario model includes a custom wind generator function in the higher level "Wind Model" object that encodes a functional expression that returns the model wind value (representing the "true" or "actual" wind) as a function of location and time given the particular wind scenario parameters. If a gridded representation of the synthetic wind scenario is desired (e.g., to represent a numerical model gridded analysis or forecast), then the custom generator function is used to populate the grid with the appropriate simulated wind value at each grid location.

The "Forecast Wind Model" object includes functions for returning interpolated wind values at locations between grid points and times, and also contains functions for superimposing simulated errors. Interpolation options are currently "linear" or "nearest neighbor." If linear interpolation is chosen, wind values for locations between grid points are obtained through 3D tri-linear spatial interpolation between bracketing grid points at each bracketing time step, followed by linear interpolation in time across the spatially interpolated values at the bracketing time steps. Nearest neighbor interpolation simply chooses the nearest model grid value in space and time to the desired location and time instant. Figure 11 shows an example of a synthetic 4D wind field generated to simulate a vertical wind shear scenario.

Parameter	Value
StartWindDir	270 deg
StartWindSpd	10 knots
WindSpdSlope (ds/dz)	0.15 knots/millibar
ShrZoneWindDirDelta	-180 deg
ShrZoneCenterX	-16000.0 m
ShrZoneWidth	160000.0 m
ShrZonePropSpeed	30.0 m/s
ShrZoneSlope	-750 m/millibar

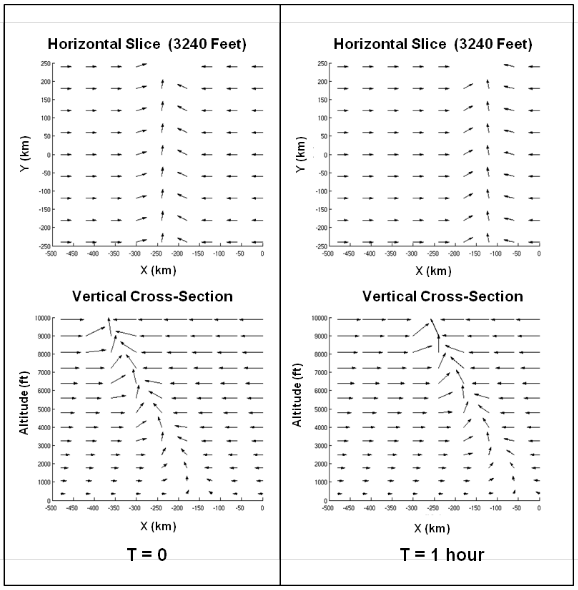


Figure 11. Example of a Synthetic Wind Field Simulating a Vertical Wind Shear Scenario. Wind field parameters are shown in the table at left and the plots show samples of winds for a selected altitude (top two plots) and vertical cross-sections (Y-Z plane) of the winds as a function of east-west (X) distance (lower two plots).

The wind modeling and analysis utility allows for addition of constant or random wind errors on top of actual or synthetic wind fields. Constant wind errors can include constant wind speed errors and/or constant wind direction errors as illustrated in Figure 12.

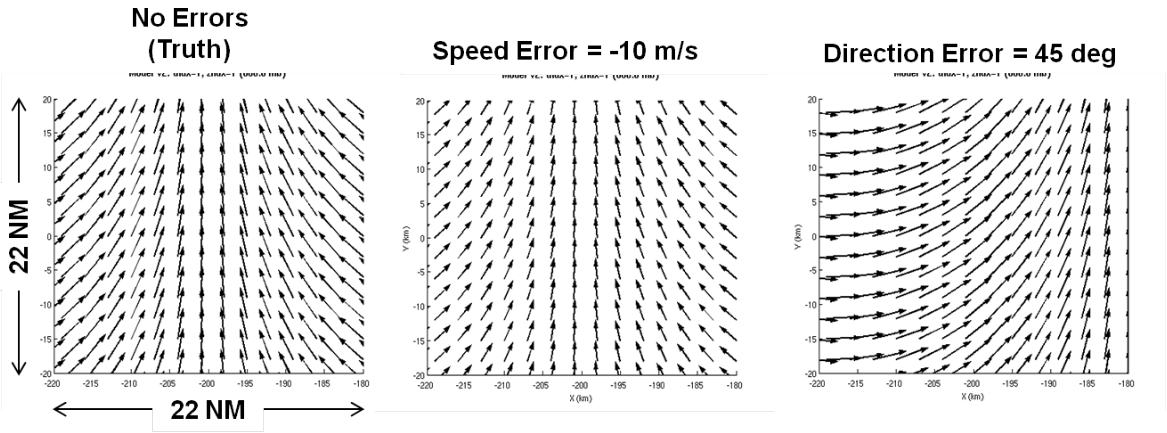
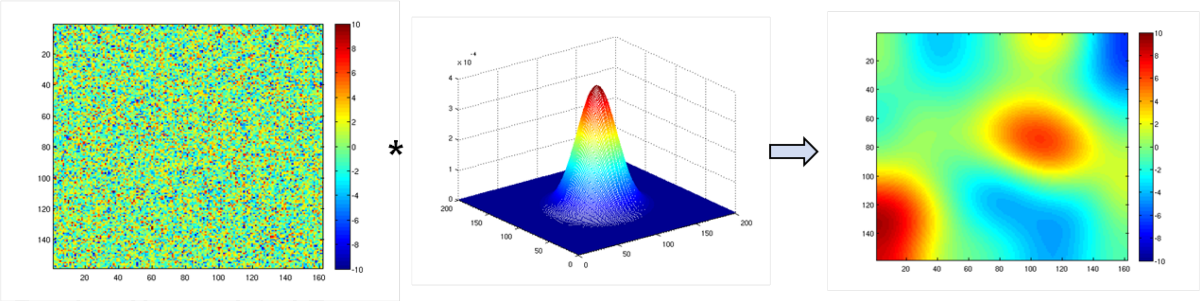


Figure 12. Modeling of Constant Wind Errors. (Left) Simulated truth wind field. (Center) Simulated winds after adding –10 m/s constant wind speed error. (Right) Simulated winds after adding constant wind direction error of 45 degrees.

Wind forecast errors tend to be correlated over length and time scales, which dictates how quickly errors change over space and time. Zheng [21] examined historical RUC model wind forecast errors to develop a random field model for characterizing wind errors and uncertainties. The research concluded that it is acceptable to assume (as a first order approximation) that the errors are normally distributed, and found that wind forecast errors were spatially correlated over lengths of approximately 250–350 km and time intervals of approximately 100–200 minutes.

To generate spatially and temporally correlated random wind errors, we followed an approach based on that of Forkel et al. [22] (see Figure 13). First, a random number generator was used to populate a 3D grid of initial random error values. The random number generator was configured to generate random numbers having a mean, $\mu = 0$ and standard deviation, σ, corresponding to the RMS error that is to be modeled. The initial, uncorrelated random error values were then smoothed in three stages through convolution with a 2D Gaussian filter kernel. The Gaussian filter parameters (xSize, ySize, and sigma) were chosen to produce smoothed error fields that were statistically equivalent to the desired correlation length. The first stage smoothed in the horizontal at each discrete altitude level. The second stage filtered the horizontally smoothed errors in the vertical using another 2D Gaussian kernel (asymmetrically sized to account for the different physical distances across grid points in vertical and horizontal dimensions). The third stage smoothed the 3D error grids across time. Since our initial Phase 1 scenarios span time scales that are less than the typical correlation time, we simply held the errors constant in time.



Random Uncorrelated Errors **Gaussian Filter Kernel** **Simulated Correlated Errors**

Figure 13. Illustration of Random, Correlated Error Field Generation

The filtering convolutions do not alter the distribution of the values; the smoothed values still follow a Gaussian distribution. However, the mean and standard deviation of the values are changed by the convolution process and have to be adjusted using:

$$\tilde{E}'_W(x,y,z,t) = \left(\tilde{E}_W(x,y,z,t) - \left(\mu_{\tilde{E}_W} - \mu_{E_W}\right)\right) \cdot \frac{\sigma_{E_W}}{\sigma_{\tilde{E}_W}} \qquad \text{Eqn. 2}$$

where E_W denotes the unfiltered random wind error, $\tilde{E}_W$ denotes the filtered wind error, μ is the mean, and σ is the standard deviation. Figure 14 illustrates the super-imposing of normally distributed, spatially correlated random errors on a simulated "true" wind field (center) to produce a simulated forecast with random errors (left). In this example, random errors with a standard deviation (sigma) of 10 m/s (19.44 knots) and a correlation length of 200 km (108 nm) were generated and added to the truth wind field to produce the simulated forecast. The resulting forecast error is shown at right (note that since the errors were added to a constant wind field, the aggregate 2D RMS vector forecast error is the same as the standard deviation of the random errors that were generated.

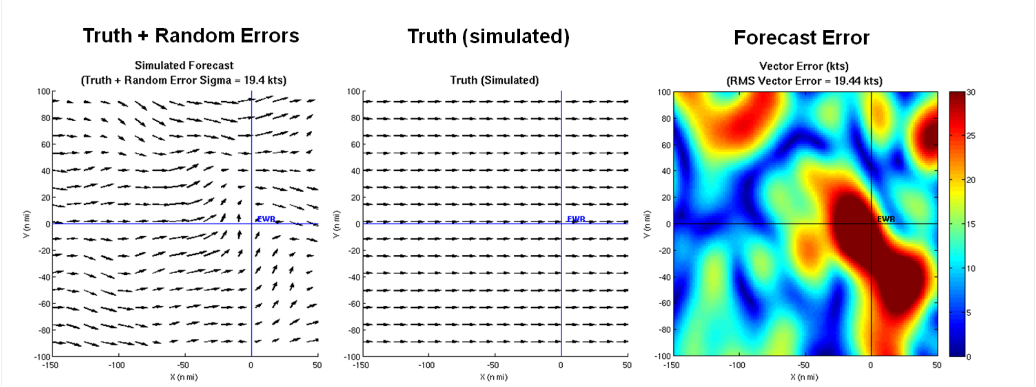

Truth + Random Errors **Truth (simulated)** **Forecast Error**

Figure 14. Example Showing Superimposing of Random, Correlated Errors on a Synthetic Constant Wind Field

3.3 NEXTGEN APPLICATION

This component of the framework captures the specifics of the ATC environment within which the 4D-TBO procedure is being flown. This could include details on demand levels, aircraft and equipage types and procedures representative of current and future operations. For the Phase 1 work, a single narrow-body aircraft flying a straight-line trajectory with a meter fix at the end was modeled. The wind field used was the one illustrated in Figure 9 and the trajectory was intentionally located so that it encountered the lateral boundary of the wind shear (shown in red in Figure 9). Two trajectory scenarios were considered as shown in Figure 15: a 1D Scenario involving a simple straight-line trajectory with a meter fix at the end through a 1D wind field, and a 2D Scenario involving a cruise and descent trajectory with a meter fix during descent. This is more realistic in terms of current 4D-TBO concepts of operations, but it is also much more challenging from an aircraft modeling perspective.

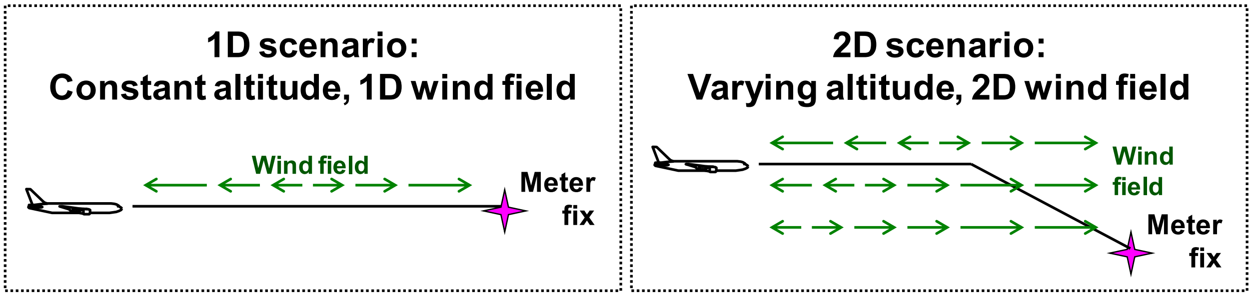


Figure 15. 1D and 2D Scenario Definitions

3.4 AIRCRAFT/FMS SIMULATION SCENARIO

In order to exercise the chosen wind and ATC scenarios discussed above, a meaningful representation of the behavior of the aircraft within those scenarios was required. Models of the aircraft dynamics, engine performance, autopilot and FMS were needed to represent the behavior of the aircraft with a given RTA in the context of the chosen scenarios. Each one of these elements could be modeled with a range of fidelities for any given aircraft/FMS configuration (e.g., for the FMS, from a simple MATLAB-based model capturing first-order behaviors to re-hosting of actual FMS logic). The approach pursued in this work was to develop a modular architecture which could support different levels of model fidelity as the work matures and for different needs. In the initial Phase 1 implementation, simple models of each element described above for a typical commercial aircraft/FMS configuration were employed and provided sufficient fidelity to prove initial utility of the framework. Aircraft performance was based on a typical narrow body commercial aircraft using aerodynamic and engine parameters and a total energy model from the EUROCONTROL Base of Aircraft Data (BADA) [23]. The FMS model was based on a feedback control representation of an aircraft controlling to an RTA, as shown in Figure 16. The Required Time of Arrival (RTA) is compared to the Estimated Time of Arrival (ETA) at the meter fix which is being continuously calculated by the FMS. A wind forecast ($\text{Winds}_{\text{Forecast}}$) is used as a basis for the expected wind field in the FMS ($\text{Winds}_{\text{FMS}}$) which is used with an aircraft performance model ($\text{A/c perf}_{\text{FMS}}$) to estimate the ETA at the meter fix. When the difference between the ETA and RTA at the meter fix location (ΔTA) is greater than a certain amount, the FMS commands a speed change to the autopilot which is transformed into an auto-throttle command to the engine. This leads to the ETA being driven towards the RTA (as long as the RTA is within the feasible region: see discussion next) with a time constant driven by the aircraft and engine dynamics.

3.5 PERFORMANCE ASSESSMENT

The performance assessment of the aircraft flying in the context of the wind and ATC scenarios discussed above was conducted in terms of how appropriate performance metric dependent variables varied as a function of appropriate independent variables, each of which are discussed in turn next.

3.5.1 Independent Variables: Forecast Wind and FMS Wind Errors

The key independent variables to quantify the relationship between wind information and benefits from 4D-TBO can be classified according to sources of wind errors among the different ground and airborne systems. Figure 16 identifies the sources of possible wind errors in the context of the aircraft control system representation in terms of Forecast Wind Errors, ATC/Airline Flight Planning Wind Errors and FMS Wind Errors.

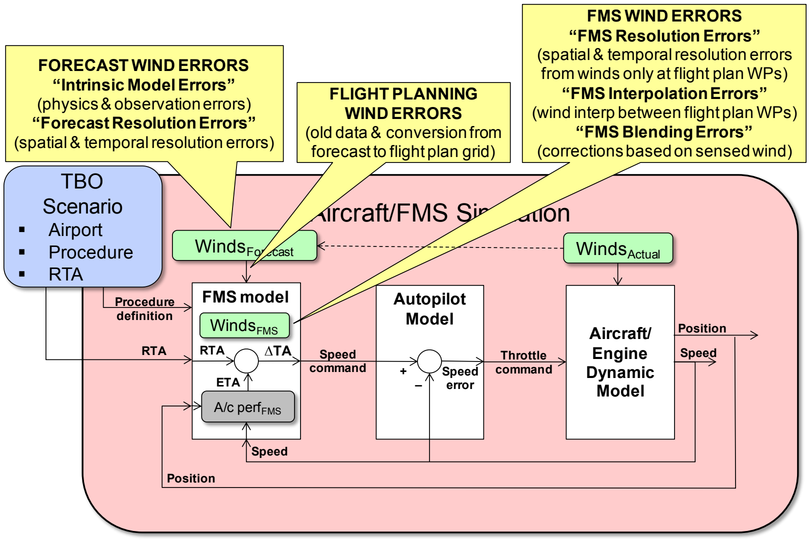


Figure 16. Aircraft/FMS Modeling and Key Wind Error Sources of Relevance to 4D-TBO Applications

- **Forecast Wind Errors** include intrinsic and resolution errors, which correlate to the wind quality factors discussed in Section 2. Intrinsic model errors encompass a broad range of numerical prediction model limitations including errors in underlying model physics (e.g., imperfect approximations) and observation errors (e.g., coverage and sensor errors, errors in assimilation and analysis), plus the forecast errors that tend to increase with increasing forecast lead time to due to unmeasured scales of motion and unrepresented processes that cause the modeled state of the atmosphere to increasingly differ from the actual state of the atmosphere. Forecast resolution errors are sampling errors that arise due to limited spatial and temporal resolution of the forecast data that is provided by the numerical models. The inability to resolve wind features that are encountered across time is a potentially significant source of error, especially where winds are changing rapidly in space or time (such as in the vertical wind shear scenario which was chosen as the focus for this phase of the work).

- **ATC/Airline Flight Planning Wind Errors** arise from the fact that flight plans are often filed several hours in advance of the flight, and hence wind information available to ground and airborne systems generating and managing compliance to an RTA based on the flight plan may be stale. Revisions using more recent wind forecasts may not be filed as the flight's departure time nears or updated on-board the aircraft (e.g., via ACARS) after a flight has departed. In addition, a flight's set of waypoints and the gridded wind forecast information need to be closely mapped and thus the flight planning software used by an airline will have to approximate via some form of spatial and temporal interpolation algorithm to estimate the winds along the route. All of these issues can lead to additional errors on top of the Forecast Wind Errors discussed above.

- **FMS Wind Errors** include resolution, interpolation and blending errors. Most currently-operational FMSs allow forecast wind magnitude and direction information to be entered for only a limited number of altitude levels (typically 3–5) and only at flight plan waypoint locations. These limitations effectively mean the gridded wind information being output from the wind forecast are being further down-sampled to a grid with lateral spatial resolution defined by the number of waypoints in the flight plan (which may be hundreds of miles apart), vertical spatial resolution dictated by the number of input altitude levels and temporal resolution governed by the time at which the input wind data was valid. This down-sampling of the wind forecast information to the trajectory-based grid that can be handled by the FMS leads to additional resolution errors on top of the Forecast Wind Errors and ATC/Airline Flight Planning Wind Errors. Although current FMSs only allow wind information to be entered at the specific trajectory-referenced locations discussed above, wind estimates can be made by the FMS at other locations by using interpolation algorithms. Although the specific details of individual systems are often proprietary, anecdotal evidence suggests lateral and vertical wind estimates may be based on linear interpolation between the "known" wind forecast at flight plan waypoint locations and vertical levels (or zero at the ground). Alternatively, they may be simply propagated forward/up/down at constant values until a defined wind entry point is reached, followed by a discrete jump to the next constant level. Such simplified wind estimation algorithms often do not accurately represent true wind fields (e.g., a wind shear boundary occurring between flight plan waypoints as illustrated in Figure 9 would not be well represented by linear or constant interpolation) and therefore interpolation errors also add to Forecast Wind Errors. In addition, if an aircraft leaves its flight plan route for any reason (e.g., ATC gives a "direct to" shortcut or a deviation is required due to weather) and gets more than a certain distance away from the defined wind information points, the FMS wind information may drop out all-together and future wind calculations are then based solely on sensed winds. Many FMSs merge their estimates of forecast wind along their programmed routes with the actual winds being sensed at the current aircraft location. For example, the difference between the expected and sensed winds at the current aircraft location may be used to define a wind correction term which is "blended" with the wind estimates for future waypoints. A heavier weighting may be given to the sensed winds for waypoints close to the aircraft, while wind estimates for distant waypoints may remain unchanged. Again, specific details on these blending algorithms are often proprietary, but in principle they are designed to correct for the other error sources identified above.

In order to quantify how much each of these error sources may introduce, a detailed assessment of current forecast models was undertaken, as was reported in Section 2. From that assessment, it was seen that there are a variety of different wind forecast models available to ATC users or under development which represent wind scenarios quite differently and therefore have different performances in terms of forecast accuracy. It was seen from that assessment that operational wind forecast model performance typically fall in the range of 5–12 kts RMSVE. ATC/Airline Wind Errors depend on the systems and procedures in place at an airline, plus the specifics of any given aircraft trajectory (e.g., route length). No studies were found to quantify this error specifically. Rather than exploring forecast and flight planning error sources independently, they were combined in this study such that the Forecast Wind Error range was taken to be in the 5–25 kts RMSVE range to account for both the additional errors introduced by both the ATC/Airline flight planning processes and the potential for large point errors highlighted in the discussion in Section 2. It was, however, desired to explore the impacts of FMS wind error independently of the wind forecast error. Due to the proprietary nature of many FMS systems, no published data was available in the open literature to quantify the FMS Wind Error, so it was also assumed to fall within the same 5–25 kts RMSVE range. Phase 2 work intends to quantify FMS Wind Errors more explicitly.

3.5.2 Dependent Variables: RTA Compliance Error and Excess Fuel Burn

A variety of dependent performance variables are relevant to quantify the relationship between wind information and the delivery of benefits under 4D-TBO, including aircraft-specific metrics such as RTA compliance error (e.g., how big a time window around the RTA contains a certain fraction of the flights) and more integrated traffic flow metrics such as throughput and fuel burn (e.g., for flights over a given fix or to a given runway). Aircraft-specific metrics are simpler in that they only need consideration of a single trajectory and therefore will be the initial focus, with the expectation that the work is likely to evolve to more integrated metrics in the future. The key performance outputs from existing RTA studies in U.S. and Europe take the form of RTA windows as a function of distance to the RTA meter fix point, as well as distributions of RTA compliance error at the meter fix, as illustrated conceptually Figure 17. The RTA window is defined at the upper end by the latest possible Estimated Time of Arrival (ETA) that the aircraft could get to the meter fix and at the lower end by the earliest possible ETA at the meter fix *given assumed winds* and aircraft performance. When an RTA is assigned at some location it must lie within the feasible region defined by these upper and lower limits. If a feasible RTA is assigned, the FMS can control the aircraft's speed (e.g., speeding up or slowing down) to meet that time target to some level of accuracy given wind uncertainty and control authority limits, resulting in some actual RTA compliance error distribution at the meter fix. This is illustrated at the right side of Figure 17. The RTA compliance error used in this work represents the time interval around the ETA which contains 90% of the flights, so a larger compliance error would imply a wider RTA compliance distribution.

RTA feasibility can also be checked after it has been assigned by determining by whether it is possible to drive the ETA to the RTA at any intermediate control point by flying at a speed within the feasible airspeed range. If this is not the case (e.g., due to gross wind errors), the RTA becomes infeasible mid-trajectory and the RTA controller commands maximum or minimum speed as appropriate to get as close as possible to the RTA at the meter fix, even though it is known this is insufficient. It is possible for the wind errors along a trajectory to push an infeasible RTA trajectory back into compliance, but typically, if an RTA becomes infeasible, it is highly improbable for it switch back to being feasible.

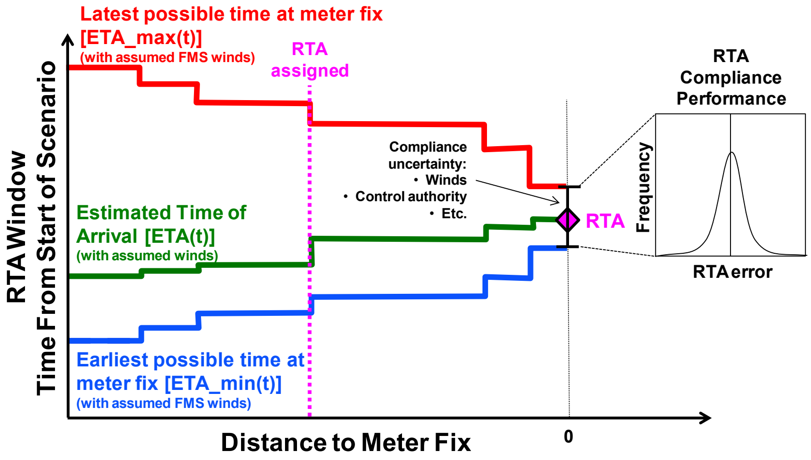


Figure 17. 4D-TBO RTA Window and RTA Compliance Performance Metrics

Another dependent variable of interest is fuel burn (which in turn maps to emissions such as carbon dioxide, which are of increasing interest in ATC). This can provide additional value over the other RTA performance metrics because it may be possible to comply with RTA constraints only at the expense of burning significant additional fuel, potentially reducing the acceptability of such procedures to some stakeholders. Explicit consideration of fuel burn allows these trade-offs to be identified and explored. In the current study, fuel burn estimates are based on BADA parameters as used for the other aircraft performance modeling previously described.

3.6 WIND/FMS REQUIREMENTS RECOMMENDATIONS

Exploration of how the dependent variables change with the independent variables allow an analysis of the key relationships of interest in this study. For example, the Performance Assessment block of Figure 8 shows schematically how the dependent variables of RTA Compliance and Excess Fuel Burn vary with “low,” “medium,” and “high” Forecast Wind Error and FMS Wind Errors. “High” error categories might correspond to the coarsest wind forecast models (reviewed in Section 2) and most basic FMS capabilities (which may provide limited or no along-route wind entry capabilities) respectively. “Medium” categories might correspond to present state-of-the-art forecast models and current generation FMSs (which allow wind information to be entered only at a limited number of altitudes and only at specified waypoints). “Low” error categories might correspond to possible future wind forecasting products and possible future generation FMSs (which may allow wind entry at more levels, gridded winds not restricted to waypoints, etc.).

It is reasonable to expect the RTA Compliance and Excess Fuel Burn metrics to increase (i.e., higher RTA compliance errors or excess fuel burn) with higher forecast and FMS wind errors, but the relative and absolute magnitude of the performance variation with the different types and magnitudes of wind error is currently unknown and will be informed by this work. This, in turn, will help provide specific recommendations regarding the required wind information fidelity and FMS capabilities needed to support different levels of 4D-TBO performance, which may in turn drive a need for better wind forecast or FMS models to meet certain performance requirements. For example, horizontal slices through the three-dimensional space defined in the Performance Assessment block of Figure 8 could specify RTA compliance or fuel burn performance requirements. Combinations of forecast wind and FMS wind errors which meet or exceed the required performance can then be identified.

3.7 SUMMARY

The generic form of the Wind Information Analysis Framework has been introduced in this section, including a description of each of its component elements. Adaptation of the framework to the 4D-TBO application has also been described for each element to provide insights into how it can be used for a specific application. The next section executes the framework elements for realistic 4D-TBO scenarios under a challenging wind environment with representative wind error models to illustrate the utility of the approach and the kinds of important insights that be gained from its use.

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4. WIND INFORMATION ANALYSIS FRAMEWORK APPLICATION

4.1 INTRODUCTION

This section presents sample results from exercising the Wind Information Analysis Framework using simplified (but realistic) representations of the different elements described in the previous Section. Results are presented for the two different scenarios previously presented in Figure 15. Most extensive results are presented for a 1D Scenario involving a simple straight-line trajectory with a meter fix at the end through a 1D wind field. Results are presented from a Monte Carlo simulation of this case for a variety of wind assumptions to illustrate how the 4D-TBO performance can be assessed as a function of wind information quality, and the insights that can be gained in terms of informing requirements setting processes. The 2D Scenario involves a cruise and descent trajectory with a meter fix during descent. As previously discussed, this is more realistic in terms of current 4D-TBO concepts of operations, but it is also much more challenging from an aircraft modeling perspective. Results from validation exercises for the 2D model are presented, as well as some preliminary insights in terms of 4D-TBO performance, but this case will be built upon extensively in Phase 2 of the work.

4.2 1D SCENARIO MODEL SET-UP

The current aircraft/FMS model is coded in MATLAB and flies the scenario trajectory through the real-world wind case from Figure 9 using BADA aircraft performance assumptions for a representative narrow-body commercial aircraft type. This model uses total energy equations (balance of kinetic and potential energy, combined with the aerodynamic forces of lift, thrust, and drag) to express the instantaneous, static response of the aircraft to the set of conditions acting on the aircraft at the time of simulation. This static response can thus be viewed as a stepwise approximation of aircraft behavior in response to endogenous and exogenous system inputs. Flight initial conditions dictate the operational envelope of the simulated scenario. Aircraft type, gross weight, altitude, speed and temperature at ground level all contribute to variations in performance by influencing the aerodynamic approximation parameters and affecting the thrust, lift, and drag forces. These, in turn, affect forward and vertical acceleration, and thus, the temporal outcome of the trajectory. Model outputs were validated using Flight Data Recorder data when available.

For the 1D scenario, the focus was on the cruise phase of flight, with the model responding only to along-track components of wind, and not cross-winds. The flight trajectory was defined by a starting location in space, a number of intermediate fixes at which a Monte Carlo simulation was updated, and a final metering fix for which an RTA is assigned. Multiple aspects were simulated, including:

- RTA assignment (assumed to be determined from a ground-based system) using
    a. “Basic” assignment, where the system assumed zero wind
    b. “Advanced” assignment, where the system assumed forecast wind

- FMS airspeed control (where the FMS solved for 'constant' airspeed that drove the ETA with the FMS-assumed winds to the RTA, allowing a feasible RTA to be met as closely as possible)
- Intermediate re-evaluation of RTA compliance, with adjustment of airspeed to reflect differences between the forecast and actually experienced wind conditions

The “truth” wind data was based on the HRRR 0-hour forecast and used to compute the actual time-of-flight for each segment in between control points. A meter fix was assumed to exist at the end of the simulated trajectory and the RTA at that point was assigned at the first trajectory re-evaluation point determined by assuming a 418 kts constant true air speed (TAS) (consistent with BADA nominal speed for cruise at FL210 for the aircraft type being considered) with either zero wind up to the meter fix (the “basic” RTA assignment strategy) or using the forecast wind up to the meter fix (the “advanced” RTA assignment strategy). The difference between the forecast wind data and the truth data was the Forecast Wind Error previously discussed.

The FMS model made speed corrections (in the range 347–460 kts) at the control points spaced at 1° longitudinal intervals to try to keep the ETA compliant with the resulting RTA. FMS wind data were used at each control point to determine the ETA at the meter fix and correct the airspeed to attempt to meet the RTA. The difference between the FMS wind and the truth wind was the sum of the Forecast Wind Error and the FMS Wind Error previously discussed. The FMS/aircraft model was invoked in a Monte Carlo fashion to obtain a statistical description of the error characteristics arising from the various wind models. The forecast wind and FMS wind errors were generated for every control point using normal distributions with standard deviation equal to the RMSVE value in knots under consideration. The simulated FMS did not perform any blending; its error, thus, represents agglomerated error terms. Every sample of the error characteristics generated a new FMS error instance.

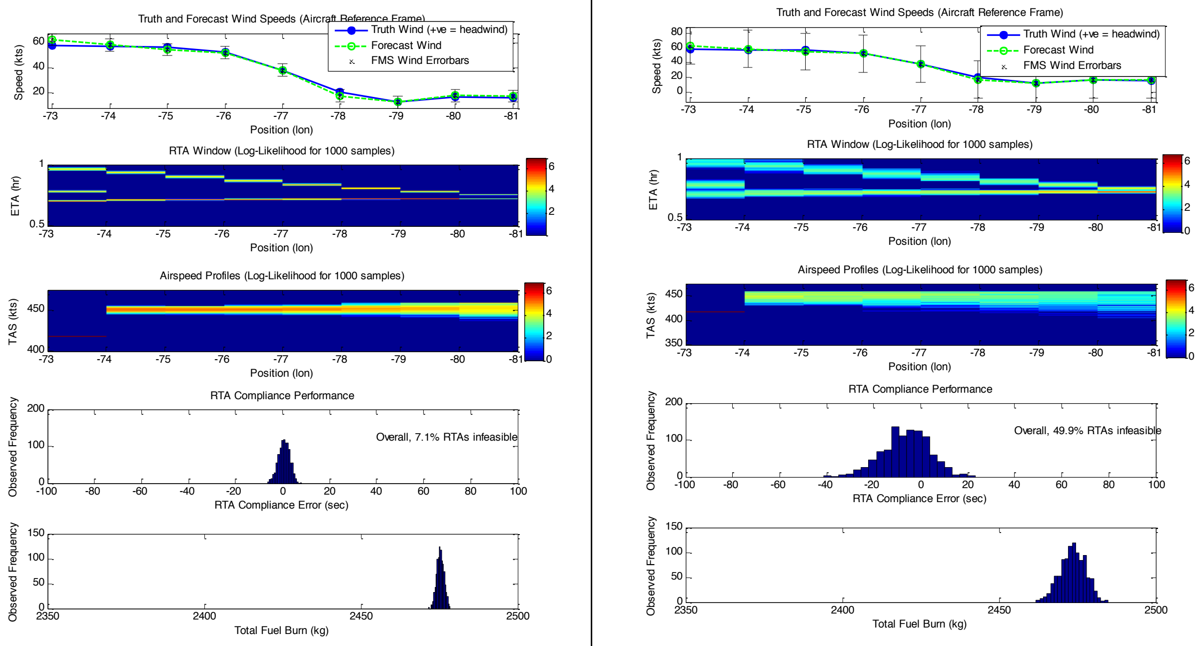
Based on the wind model assessment and error classification previously described, forecast wind errors in the range 0–25 kts RMSVE in 5 kts increments, and FMS wind errors of the same range, were tested with the simulation system. The sections that follow present results from the Monte Carlo simulations for a variety of cases to showcase the insights that can be gained.

4.3 1D SCENARIO RESULTS WITH BASIC RTA ASSIGNMENT STRATEGY

Figure 18 presents the RTA window, RTA compliance performance and fuel burn metrics (previously introduced) for each combination of low (taken as 5 kts RMSVE) and high (taken as 25 kts RMSVE) forecast wind and FMS error with the “basic” RTA assignment strategy (which does not account for forecast winds). In each case, the RTA is assigned after the first simulated prediction step, corresponding to approximately –74° longitude on the position axis.

(a) Forecast Wind Error = 5 kts, FMS Wind Error = 5 kts

(b) Forecast Wind Error = 5 kts, FMS Wind Error = 25 kts



(c) Forecast Wind Error = 25 kts, FMS Wind Error = 5 kts

(d) Forecast Wind Error = 25 kts, FMS Wind Error = 25 kts

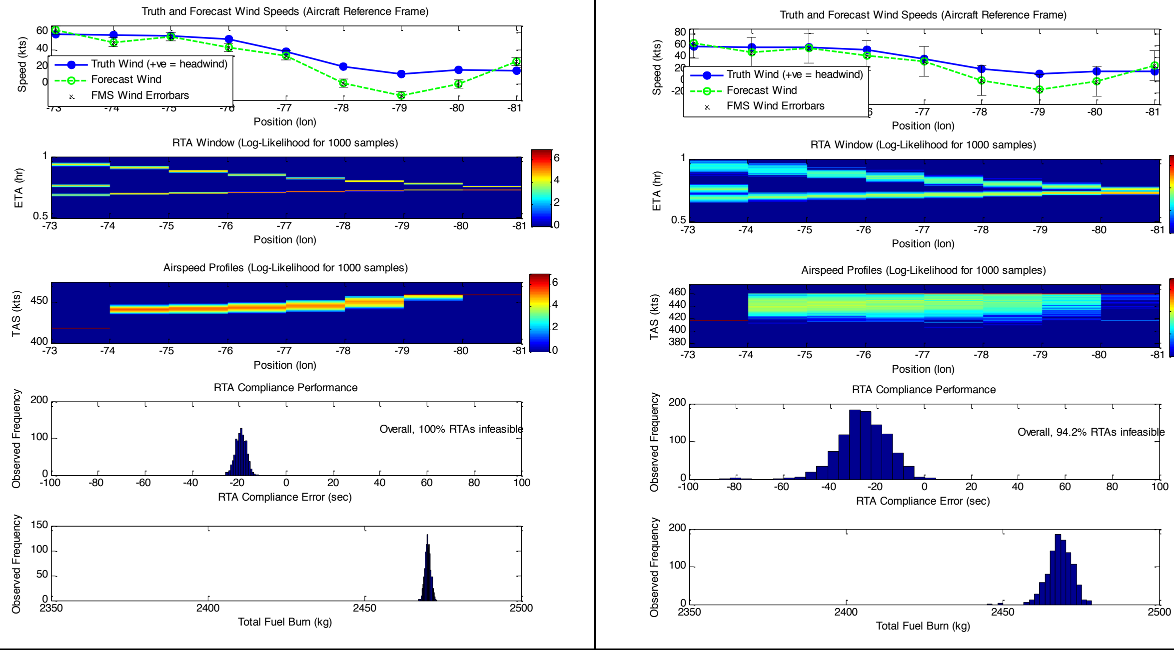


Figure 18. Sample 4D-TBO Performance Metrics for Various Forecast and FMS Wind Errors, Basic RTA Assignment Strategy

There are five subplots in each panel: the top plot presents the truth wind, forecast wind and FMS wind as a function of aircraft position (longitude) along the trajectory; the second plot presents the RTA window as a function of position; the third panel presents the airspeed as a function of position; the fourth plot shows the RTA compliance error; and, finally, the fifth plot gives the total fuel burn for the narrow-body aircraft being simulated in this scenario. The fuel burn can also easily be converted to carbon dioxide emissions by using the standard multiplier of 1 kg of fuel burn producing 3.16 kg of CO_2.

The top left panel of results is for the case of low wind forecast errors (5 kts RMSVE) and low FMS error (5 kts RMSVE). The true wind profiles are based on the wind case presented in Figure 9 at FL210 and presents as an initial strong headwind at the start of the trajectory (approximately 60 kts), but gradually transitions to a much smaller headwind (less than 20 kts) by the end. The forecast wind and FMS wind estimates are seen to be very close to this true wind profile, as expected for this case of low wind errors in each. The RTA window plots show a steadily decreasing window size with position (as expected), with the upper and lower window boundaries being tightly defined, again as expected given the low assumed errors. The airspeed profile shows interesting behavior. The initial airspeed is set to around 420 kts TAS based on the BADA parameters for the aircraft type being modeled. After the RTA is assigned, there is an initial increase in airspeed which is consistent with the FMS wind expectation of a strong headwind up to the meter fix. After this initial correction, the speed variation over time is relatively small given the small wind errors. The RTA compliance error and fuel burn (emissions) distributions are both seen to be tight distributions, and only a small fraction of the RTAs (≈7%) were deemed infeasible, all of which is as expected given the small assumed errors in the model forecast and FMS winds in this scenario.

The top right set of results is for the case of low forecast wind error (5 kts RMSVE) and high FMS wind error (25 kts RMSVE). This is evident in the much higher FMS error bars in the wind profile plot, while the forecast wind error is kept the same as the previous results. Due to the much increased errors present in the winds the FMS is using to calculate future ETAs, the RTA window high and low boundaries show much greater variability, which translates into much greater speed variability and RTA compliance error and fuel burn distributions compared to the previous set of results. Note, because of the high FMS errors, nearly 50% of the RTAs become infeasible during the profile (i.e., outside the boundary defined by the maximum and minimum ETAs at some point in the trajectory), even though the initial RTA assignment was feasible.

The bottom left set of results is for the case of high forecast wind error (25 kts RMSVE) and low FMS wind error (5 kts RMSVE). This is evident in the sizeable offsets between the truth and forecast wind profiles in the top panel, but the small FMS wind error bars about this model forecast profile. Because of the closed-loop nature of the RTA controller, it is able to compensate for the off-set between the true and model forecast profiles resulting in similar RTA window boundary and speed profile variations as for the initial set of results shown in the top left panel. The large forecast wind errors result in the truth wind being much stronger than the expected by the forecast. This causes the initial speed after the RTA assignment to be much lower than required to meet the RTA at the meter fix, and the FMS has to command increasing speeds as the trajectory is traversed to try to make up for the difference between the truth and forecast winds. The offset in the model forecast and FMS errors relative to the truth winds is not correctable in the final trajectory step even by flying at the maximum allowable airspeed, which produces as an offset in the RTA compliance error distribution at 100% infeasible RTAs. Because the expectation was for less of a headwind than actually experienced, the aircraft arrives on average 20 seconds late to the meter fix compared to the RTA. However, because the aircraft was on average flying slower than needed to make the RTA, it was flying at a lower fuel burn speed such that the average total fuel burn is slightly lower than in the previous two cases.

The bottom right set of results is for the case of high forecast wind error (25 kts RMSVE) and high FMS wind errors (25 kts RMSVE), as evident in the big differences between the forecast wind and truth wind profiles and the large FMS error bars. The RTA window boundaries, speed, RTA compliance and fuel burn variabilities are all worse than those observed in the other results. It is interesting to note that the wind errors in this case are so large that some of the profiles which were infeasible in the third set of results get pushed back into the feasible region, with 94.2% of the RTAs being infeasible compared to 100% for the previous results. The RTA compliance error distribution is also offset in the negative direction similar to that observed in the third set of results, while the mean of the fuel burn distributions are also slightly further to the left compared to the second set of results for similar reasons as for the third set of results. Hence it is seen that, in these sample results with the modeling assumptions used, the FMS error distribution is driving the amount of overall variability in the output distributions, while the wind model forecast error is driving the offset in the RTA compliance error and fuel burn distributions.

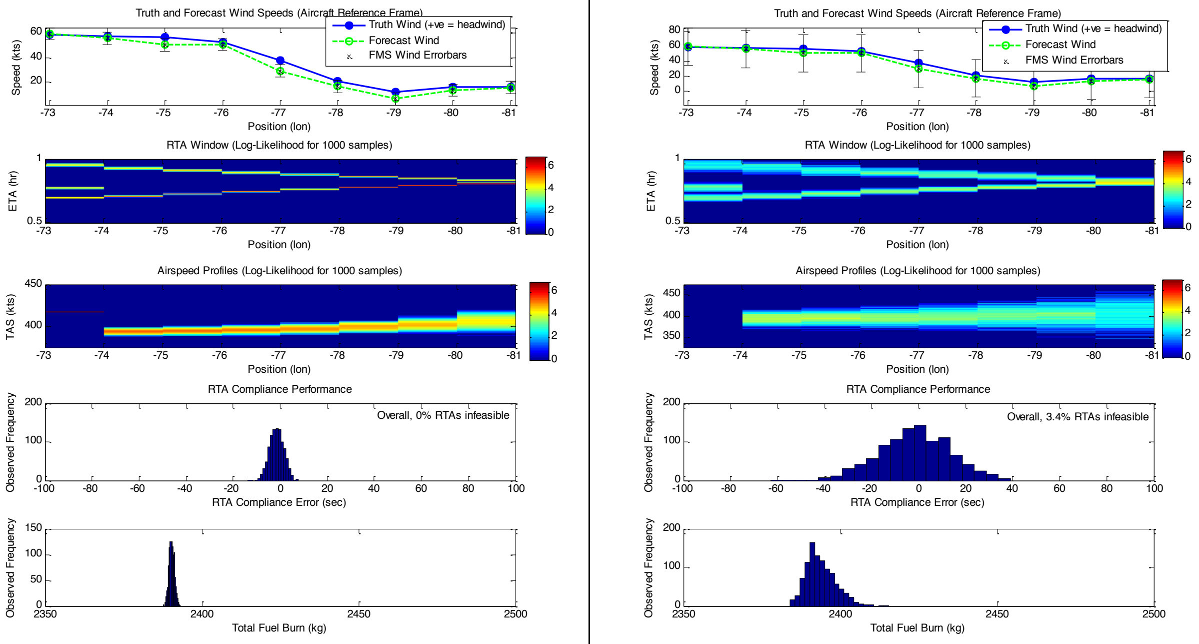
4.4 1D SCENARIO RESULTS WITH ADVANCED RTA ASSIGNMENT STRATEGY

Figure 19 presents the same results for the case of the “advanced” RTA assignment strategy (which do account for forecast winds when determining the RTA). The key differences from the results with the basic RTA assignment strategy are the percentages of infeasible RTAs and the amount of fuel burned. In all “advanced” RTA assignment cases, the aircraft speeds are reduced, as the RTA assignment algorithm is aware that a strong headwind will be encountered along the trajectory. The variation in the aircraft speed still corresponds to the local differences between the truth and forecast winds. In this case, the forecast winds tend to underpredict the truth winds, so therefore, the aircraft speed must increase locally to compensate for these errors. However, in all cases, the resultant RTA infeasibility is reduced significantly, with only high FMS Wind Errors introducing a small fraction of infeasible RTAs. This can be seen in the top and bottom rightmost panels.

Because the simulated FMS reduces speed with respect to the starting nominal airspeed, the amount of fuel burned while following these trajectories is reduced given the aircraft is commanded to fly at a more fuel efficient speed. This may not be true for all speed responses for other scenarios because of the nonlinearity in the airspeed-to-fuel burn relationship.

(a) Forecast Wind Error = 5 kts, FMS Wind Error = 5 kts

(b) Forecast Wind Error = 5 kts, FMS Wind Error = 25 kts



(c) Forecast Wind Error = 25 kts, FMS Wind Error = 5 kts

(d) Forecast Wind Error = 25 kts, FMS Wind Error = 25 kts

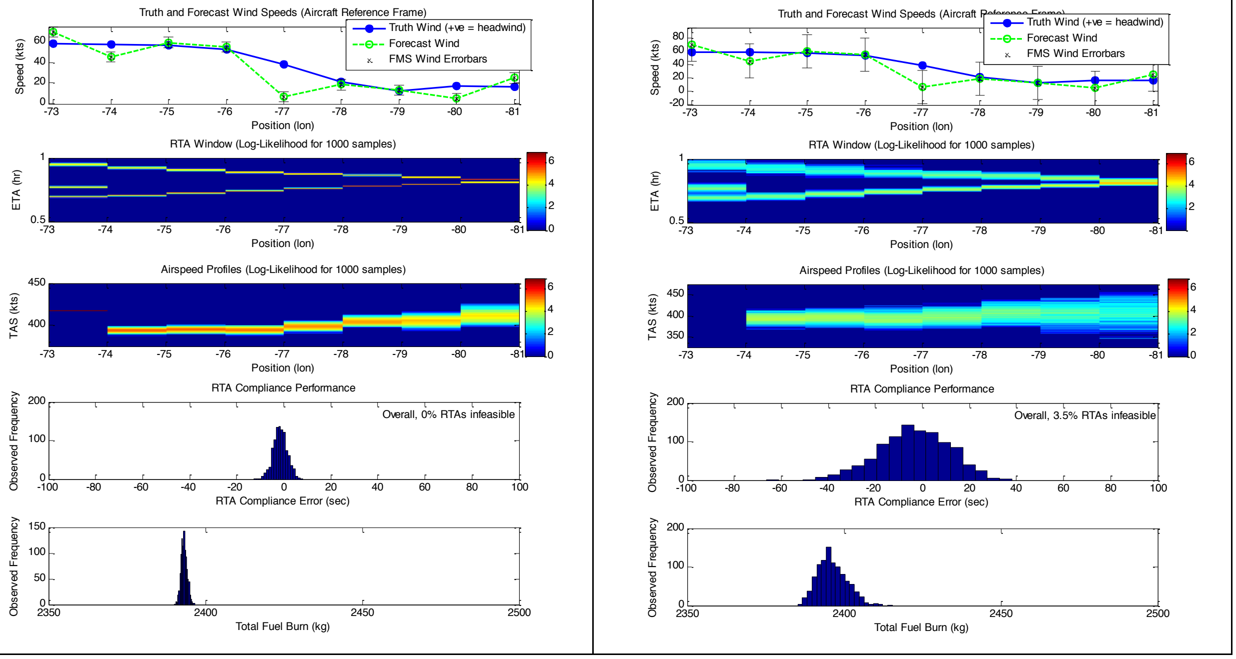


Figure 19. Sample 4D-TBO Performance Metrics for Various Forecast and FMS Wind Errors, Advanced RTA Assignment Strategy

It is noteworthy that the "basic" RTA assignment approach results in a fixed RTA value for all flights (as no winds are accounted for), while the "advanced" assignment results in a distribution of RTA values. This is significant because this distribution affects the rate at which fuel is consumed. This can be seen in the overall widths of the fuel burn distributions in the results. In addition, the differences between the "basic" and "advanced" RTA assignment strategies are only illustrative: more sophisticated RTA assignment algorithms may provide more benefits, e.g., assigning RTAs targeting optimal cruise velocities.

4.5 1D SCENARIO INSIGHTS FOR WIND INFORMATION REQUIREMENTS

By parametrically varying the forecast wind and FMS wind errors from low to high values, it is possible to obtain surfaces that are of value in setting wind information requirements that are the primary objective of this work. The example performance metrics presented here include the variation of the 90% interquantile range (i.e., containing 5–95% of the RTA compliance distribution, as shown by the example distribution in Figure 20), the % infeasible RTAs and fuel burn (emissions) distribution width as a function of forecast wind error and FMS error.

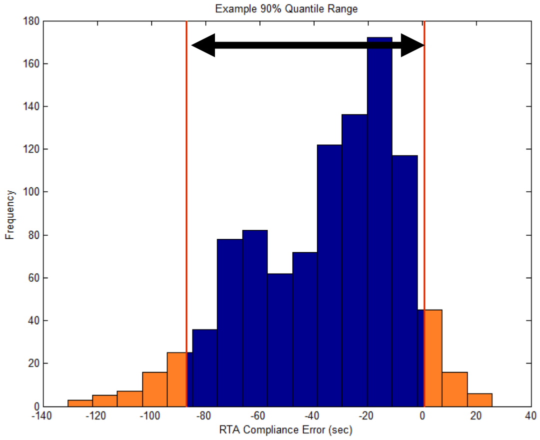


Figure 20. Example 90% Interquantile Range (shown by arrow)

Results from 500 Monte Carlo simulation runs of the simplified models described above for each forecast wind/FMS wind error combination (in the range 0 to 25 kts in 5 kts increments along each dimension) are presented in Figure 21 and Figure 22. In general, the smaller the forecast and FMS wind errors, the better the RTA compliance (smaller the RTA compliance interquantile range), the fewer % infeasible RTAs and the lower the fuel burn.

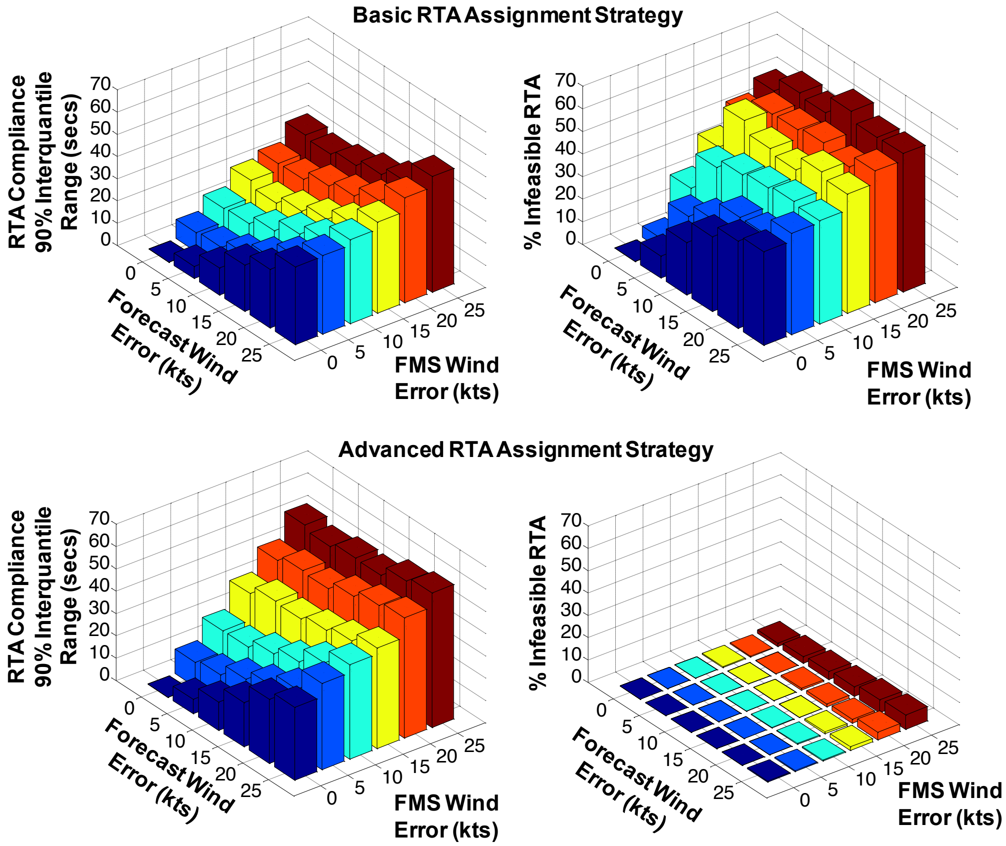


Figure 21. RTA Compliance 90% Interquantile Range (left), % Infeasible RTAs (right), and as a Function of Forecast Wind and FMS Wind Error for the Basic (top) and Advanced (bottom) RTA Assignment Strategy

RTA compliance performance degradation is seen to be more severe with FMS wind errors than with forecast wind errors, especially for the case of the advanced RTA assignment strategy. For example, performance is much worse with high FMS wind error and low forecast wind error than it is with low FMS wind error and high forecast wind error. The advanced RTA assignment strategy results in a large improvement in the fractions of infeasible RTAs compared to the basic strategy. Fuel burn and carbon dioxide emissions are also affected as shown in Figure 22, where more fuel is used with the basic RTA assignment strategy compared to the advanced strategy. This figure also shows the dependence of the amount of fuel burned/emissions produced and the width of the distributions (shown as the size of the circles) on the width of the underlying RTA distribution. Because it does not use wind information, the basic RTA assignment strategy results in a fixed RTA across all trajectories, thus, the RTA distribution width is zero and does not contribute to variation in the fuel burn/emissions distribution beyond the impact of forecast error. The advanced assignment strategy varies the RTA, thus impacting the fuel burn and emissions distributions. This can be seen in the increasing sizes of the fuel burn and emissions circles as the RTA distribution width increases. Additionally, the average fuel burn and carbon dioxide emissions produced slowly increases as the forecast error increases.

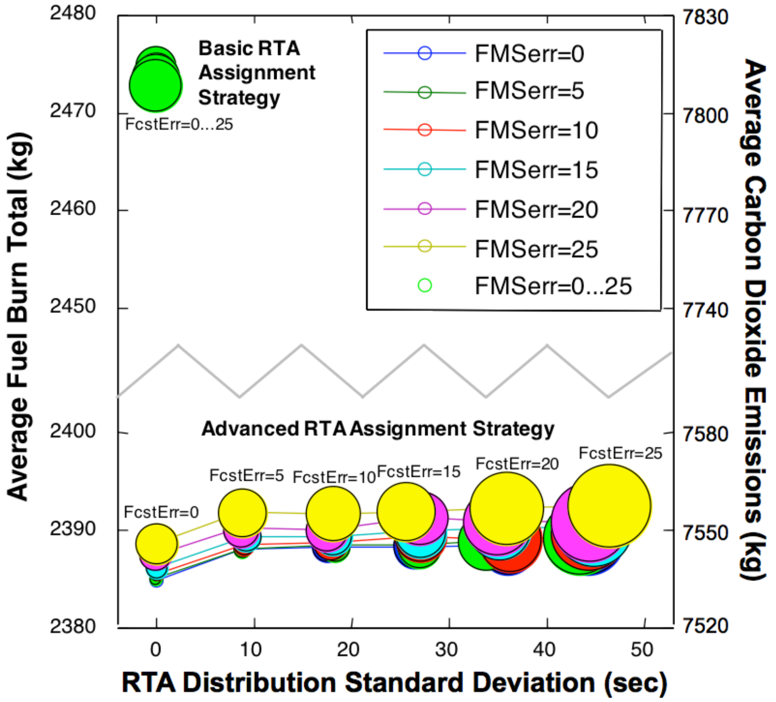


Figure 22. Fuel Burn Average and Standard Deviations for Basic & Advanced RTA Assignment Strategy

It is reiterated that these results are based on simplified versions of the Wind Information Analysis Framework elements, and actual wind information requirement recommendations will need to be based on the higher fidelity models being developed in the next phase of the work. However, it can be seen how, in principle, the trade-off space between relevant performance metrics, forecast wind error and FMS wind error can be identified. Requirements could be set from surfaces like these to determine what combination of forecast wind and FMS wind error limits would be needed in order to achieve a given RTA compliance or fuel burn performance, or define what level of RTA compliance performance would be possible with different combinations of achievable forecast and FMS wind errors. For example, these sample results show that for RTA compliance less than 30 secs for 90% of time (a horizontal slice at 30 secs in the left hand plots of Figure 21), forecast wind and FMS wind errors need to be less than 15 kts RMSVE, while for less than 5% infeasible RTAs (a horizontal slice at 5% in the right hand plots of Figure 21), less than 5 kts RMSVE forecast/FMS wind errors are needed with the basic RTA assignment strategy, but up to 20 kts RMSVE forecast/FMS wind errors could be tolerated if using the more advanced RTA assignment strategy. Such relationships are the primary objective of this analysis approach and hence these sample results demonstrate the utility of the approach being pursued which will be built upon in future work.

4.6 2D SCENARIO MODEL SET-UP

The 2D scenario comprised a cruise profile, a "Top of Descent" (TOD) point, a descent profile utilizing fixed Mach and fixed Calibrated Airspeed (CAS) segments, and a meter fix signifying the target altitude and time at the end of the trajectory. Given constant winds covering the range of altitudes throughout descent, the BADA descent trajectory can be calculated exactly by forward-calculating descent, and shifting it in space to align the bottom of the trajectory with the location at which the target altitude must be reached. However, winds varying as a function of altitude and time complicate the computation significantly, and require an iterative approximation approach. The following paragraphs detail the implementation of the BADA descent.

The BADA Total Energy Model transforms to solve for various terms, including Thrust, Acceleration, and Rate of Climb/Descent, allowing for a range of energy inputs into the point-mass aircraft system. Using a variant of the formulation called the 'energy share factor' allows BADA to model typical procedures, such as fixed Mach or fixed CAS flight given different thrust settings. Table 4 provides the combinations that can be used to model different phases of flight. We have focused primarily on the combinations highlighted in bold.

Table 4. BADA Modeling Modes

Mode	Climb Thrust	Cruise Thrust	Descent Thrust
Constant Mach	Constant Mach climb	**Cruise**	**Constant Mach descent**
Constant CAS	Constant CAS climb	Cruise	**Constant CAS descent**
Accelerated/decelerated flight	Variable speed climb	Variable speed cruise	Variable speed descent

Standard operating procedures currently require a piecewise descent that starts with a constant Mach segment and transitions to a constant CAS segment when a threshold is reached. At predefined altitudes and speeds, aircraft configuration changes occur (reflected in changes of coefficients) to simulate the use of flaps/slats and deploying the landing gear.

The 2D aircraft model used in the analysis framework used the Total Energy Model to numerically approximate the trajectory flown by an aircraft by solving for the thrust, acceleration, and rate of climb/descent terms. By using a small step size (1 second), we attempted to minimize the inaccuracies of approximation, and by storing state variables (instead of using the BADA model in look-up mode), we guaranteed continuous behavior in the state variables. Further refinements to these models are planned in Phase 2, for example implementing lateral control.

4.7 2D SCENARIO DESCENT MODEL VALIDATION

A validation of the 2D scenario model as implemented in the MATLAB environment was conducted against the published BADA point performance tables. EUROCONTROL provides input/output response tables for the various BADA aircraft models, so a cross-check of the MATLAB model input/output response against the response in the tables was used for an internal consistency check (i.e., that the BADA model implementation is faithful to the EUROCONTROL implementation and probably to their specification). Figure 23 shows the internal consistency of the BADA model with the 2D Scenario implementation for the aircraft type under consideration.

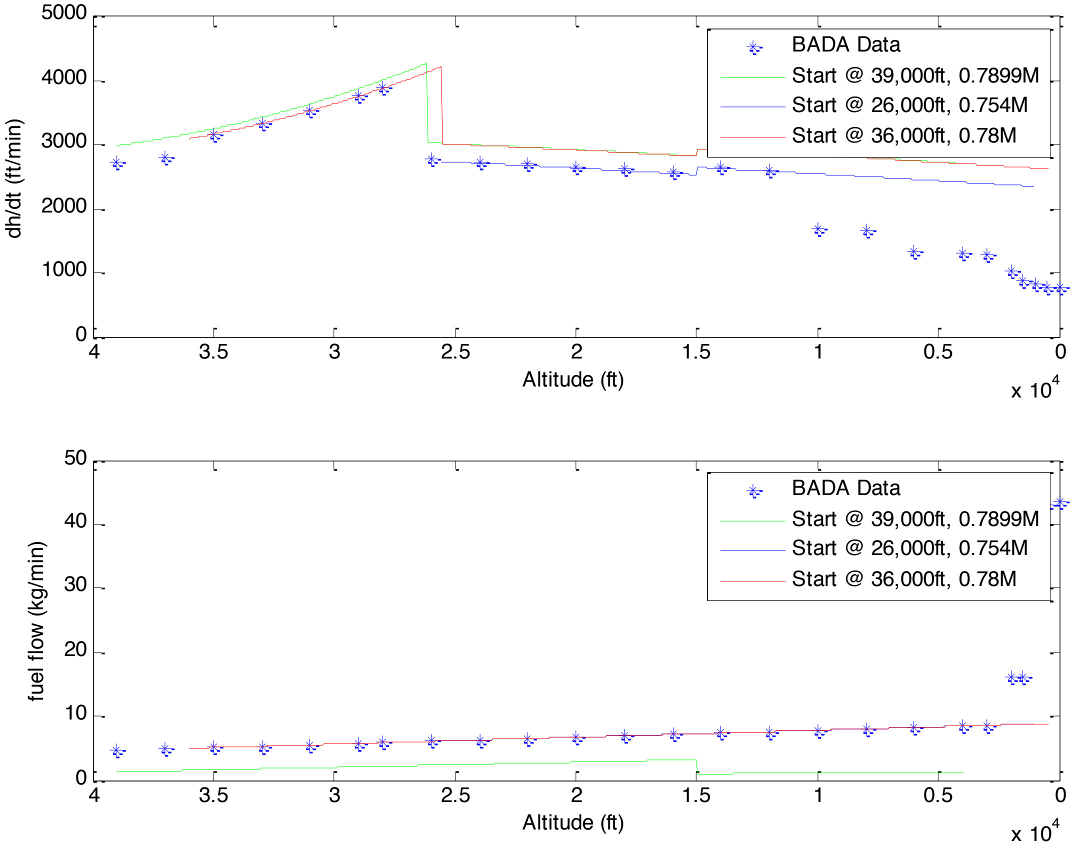


Figure 23. Validation of 2D Scenario Model Against BADA Data

The figure shows a set of descent trajectory excerpts, starting at various altitudes, and compares them with the performance data provided by EUROCONTROL. Each individual piece corresponds well to the sections they are intended to model: the blue, constant CAS descent segment, corresponds to the BADA data points from 25,000 ft down to 12,000 ft. The constant Mach data points are modeled well by the red segments, however, the transition appears incorrect. This is due to the fact that the MATLAB descent model preserves aircraft state, whereas the EUROCONTROL performance data is obtained using the model in a look-up fashion. If we initialize our implementation with the speed/altitude combination from the look-up table, the results match once again. This part of the consistency check does not affect the correspondence to real data, as our preservation of state appears to represent real data correctly in the transitions.

In addition to the internal validation of the 2D Scenario validation against BADA data, validation of the MATLAB model against operational data was also conducted. It was found that the model performs best when compared to operational data during an idle thrust descent. Our implementation properly captures the fixed Mach/fixed CAS transition, and altitude, speed, and fuel burn all approximated well given the lack of pilot/FMS intent information.

4.8 2D SCENARIO MODEL RESULTS

Using the 2D Scenario model, a set of Monte-Carlo trials were performed to evaluate the effects of the forecast and FMS wind errors on altitude, time and fuel use performance. These were assessed in the context of the descent scenario as shown in Figure 24.

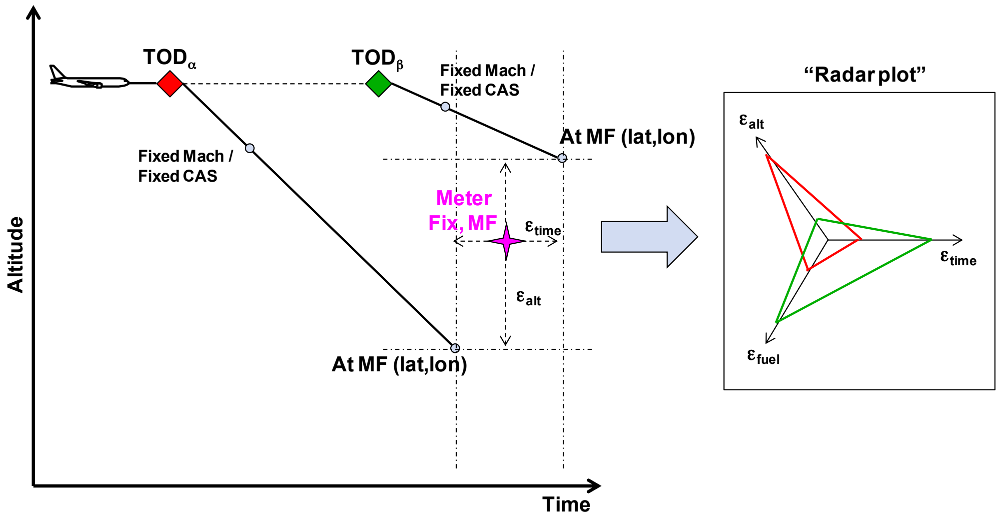
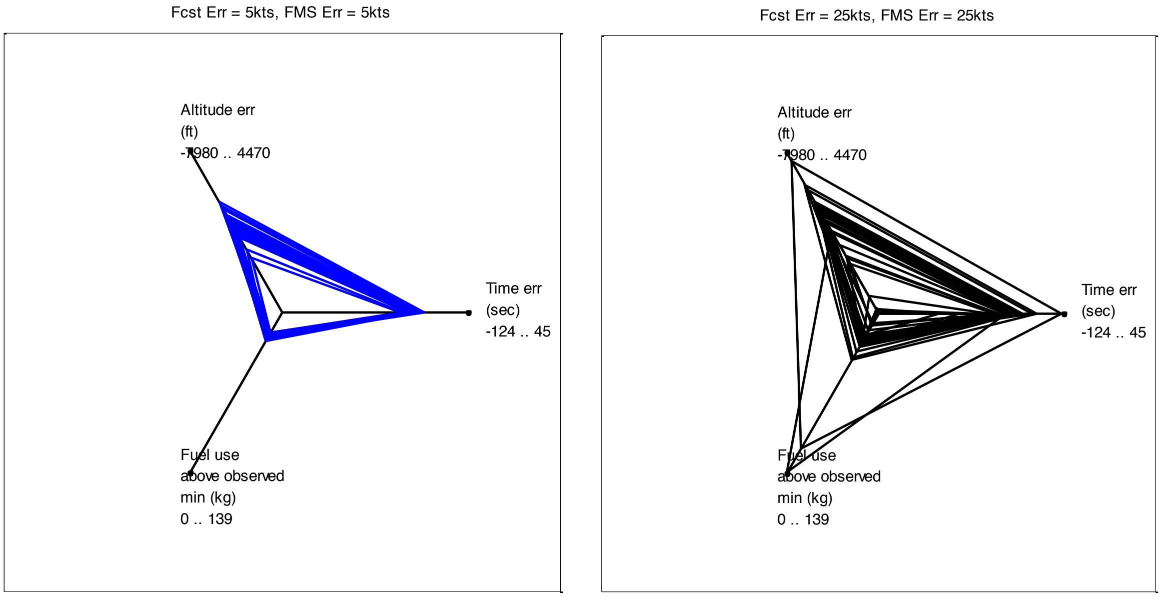


Figure 24. 2D Scenario Definitions

The aircraft flies at cruise Flight Level, and arrives at a Top-of-Descent (TOD) point, the location of which depends on the forecast winds. The aircraft starts its descent procedure and arrives in the geographic vicinity of the meter fix at a time and altitude that may be divergent from the target time and altitude due to wind and performance errors in the prediction. These errors, plus the fuel burn use over an observed minimum, are shown in the statistical 'radar' plots in Figure 25 for the cases of 5 kts wind forecast/5 kts FMS wind errors on the left, and 25 kts wind forecast/25 kts FMS wind errors on the right. It is seen that the small forecast and FMS errors in the left plot contribute to a tight overall distribution across fuel use and temporal error, although larger altitude errors exist. When forecast error and FMS error are larger, the width of the distribution is significantly increased across all three metrics. Some apparent outliers are observed also. The large fuel usages and significant deviations in altitude from the norm are a result of overshoot/undershoot of predicted vs. flown descent locations. Given a significant deviation in location, descent is either cut off too soon, or continues too far, and at later stages in simulation, proceeds rapidly in an unrealistic fashion. Only 25 samples are shown in these trials, and these results will be built upon in Phase 2 of the work.


Fcst Err = 5kts, FMS Err = 5kts

Fcst Err = 25kts, FMS Err = 25kts

Figure 25. 2D Scenario Preliminary Results

4.9 SUMMARY

This section has illustrated how even simplified executions of the Wind Information Analysis Framework for realistic 4D-TBO applications can yield interesting and complex results which can be of high value in determining performance trade-spaces. For example, the results in Figure 21 provide significant, nonobvious insights into the relative benefits enabled by different combinations of improved forecast wind and FMS wind capabilities. Although the use of simplified models to generate these results implies the specific values in the trade-spaces still need to be refined, identification of “points of diminishing returns” are feasible from the execution of the Wind Information Analysis Framework. As such, this Phase of the work has developed an effective analysis framework and acted as proof-of-concept of its utility for analyzing wind information needs for NextGen applications, which is the objective of this research program. Phase 2 will build upon this foundation by using refined and expanded application of the Wind Information Analysis Framework to generate high value results for standards and requirements setting entities, as described in the next section.

5. PHASE 2 PLANS

5.1 INTRODUCTION

The key accomplishments of Phase 1 of this work have been the development of a scalable, flexible Wind Information Analysis Framework, and a proof-of-concept application of that framework to various 1D and 2D scenarios of a 4D-TBO concept. This has demonstrated the insights that can be gained from its use to determine the trade-off space between relevant wind information metrics and performance from the NextGen application which can be used to help establish wind information requirements.

Phase 2 looks to build upon this work in two key areas:

- Refine the models used for the Wind Information Analysis Framework elements to transition from "proof-of-concept" to "application" of the approach to develop meaningful results of high value to the stakeholder community (e.g., requirements and standards-setting bodies).
- Extension beyond 4D-TBO to other NextGen applications, to demonstrate the utility of the approach to broader concepts.

Through consultation with the project sponsor and stakeholder communities, the overall objective of Phase 2 is to refine and expand the analysis approach developed in Phase 1 to identify the benefits trade-space for a set of NextGen applications in a "research portfolio" to identify points of diminishing returns from improved wind information. The research portfolio is proposed to include

- 4D-TBO applications with current FMS capabilities
  - Exercise and extend existing models
  - Possibly identify/explore other wind quality metrics, other atmospheric parameters, etc.

- 4D-TBO applications with realistic future FMS capabilities
  - Exercise and extend existing models
  - Explore impacts of potential future FMS capabilities (with industry collaboration?)

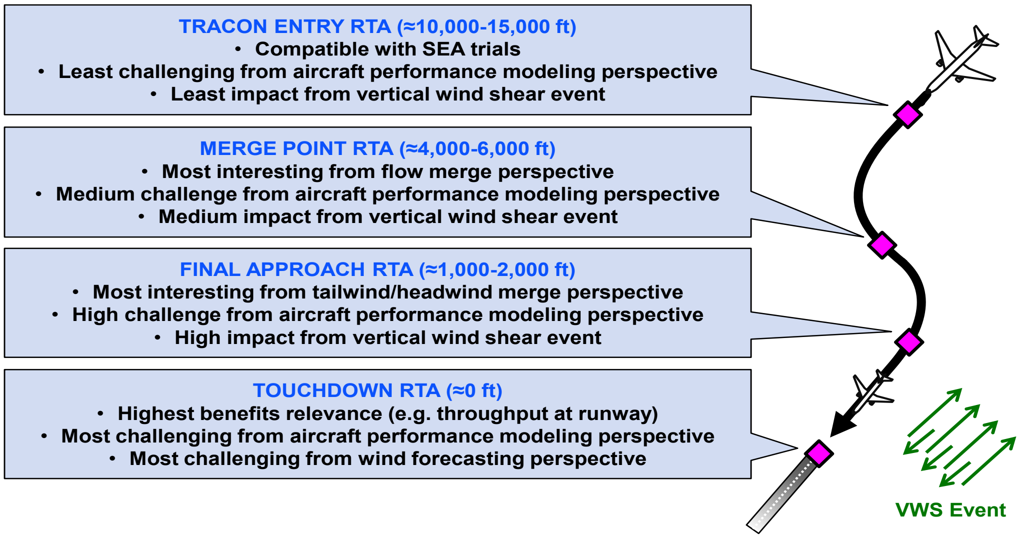
- Other NextGen applications
  - Flight Interval Management

The next subsection discusses the potential Phase 2 refinements and applications which could be studied. Following this is a discussion of evaluation of higher fidelity aircraft and FMS simulation options which was conducted in Phase 1 and which may become relevant for refined or extended applications in Phase 2. This section ends with a proposed roadmap for Phase 2 work.

5.2 PHASE 2 POTENTIAL REFINEMENTS & APPLICATIONS

5.2.1 Refined 4D-TBO Studies

Areas for refinement of the Phase 1 studies include increased fidelity aircraft and FMS models (covered in the next two subsections), exploring more wind scenarios, more RTA scenarios and other environmental metrics. As described earlier in this report, the capability to define synthetic wind scenarios and ingest any archived wind data (e.g., from HRRR data) was developed in Phase 1 of this work. Although the results presented focused on the vertical wind shear (VWS) scenario case, others will likely be explored in Phase 2. In terms of RTA scenarios, refinements could include more complex three-dimensional scenarios, procedures with multiple RTAs, and RTAs at different altitudes during descent. This last aspect is illustrated in Figure 26: lower altitude RTAs have the potential to enable higher benefits from a 4D-TBO scenario, but are associated with more sophisticated aircraft models as flights to lower altitudes require extensive aircraft configuration changes.



TRACON ENTRY RTA (≈10,000-15,000 ft)
- Compatible with SEA trials
- Least challenging from aircraft performance modeling perspective
- Least impact from vertical wind shear event

MERGE POINT RTA (≈4,000-6,000 ft)
- Most interesting from flow merge perspective
- Medium challenge from aircraft performance modeling perspective
- Medium impact from vertical wind shear event

FINAL APPROACH RTA (≈1,000-2,000 ft)
- Most interesting from tailwind/headwind merge perspective
- High challenge from aircraft performance modeling perspective
- High impact from vertical wind shear event

TOUCHDOWN RTA (≈0 ft)
- Highest benefits relevance (e.g. throughput at runway)
- Most challenging from aircraft performance modeling perspective
- Most challenging from wind forecasting perspective

Figure 26. 4D-TBO Procedural Extensions

In terms of exploration of other environmental metrics (in addition to wind), parameters of potential interest include gusts, turbulence, temperature and pressure. Gusts are short-term, large magnitude wind variations. Although these are typically easily compensated for by an RTA controller (such that they are not a major driver of performance in a 4D-TBO scenario unless a severe gust occurs right before the meter fix), they can have more significant impacts in aircraft self-separation scenarios such as Flight Interval Management (to be discussed in the next subsection). The main impact of turbulence is that it will typically cause pilots to fly slower (as they decelerate to the turbulence penetration speed) which will adversely impact the ability to meet an RTA if the turbulence was not forecast. In terms of temperature and pressure, errors in forecast temperature and pressure can translate into nontrivial airspeed and/or altitude errors as shown in Figure 27. As such, turbulence, temperature and pressure forecast issues could be interesting areas to explore in more detail in Phase 2 in addition to wind scenario cases.

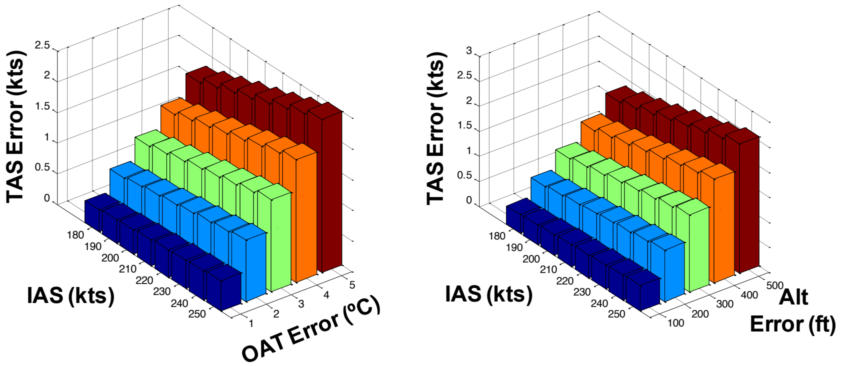


Figure 27. Potential Impacts of Temperature and Pressure Altitude Forecast Errors

5.2.2 Flight Interval Management Applications

Interval management is a complementary NextGen application being proposed for study in Phase 2 of this work where accurate/consistent wind information is again critical. Figure 28 illustrates the concepts of Ground Interval Management (GIM) and Flight Interval Management (FIM). Under the GIM concept of operation, a ground system (e.g., TMA) creates a recommended arrival sequence and aircraft-specific speed targets to achieve this sequence assuming forecast wind conditions and trajectories to achieve appropriate aircraft separation, and then flight crews monitor performance against this speed target. Any errors in the wind forecast used to develop the sequence or speed advisories will result in different-than-planned sequences and/or separations which can only be corrected by recalculating modified speed advisories. By contrast, under the FIM concept of operations, a ground system creates recommended arrival sequences and inter-aircraft time spacing given the forecast wind conditions and trajectories, and then flight crews monitor the *specific spacing* relative to the aircraft ahead. By controlling time separations between aircraft, FIM is more robust to wind errors and a key variable of operational interest (inter-aircraft time spacing) is being directly controlled. However, FIM does require greater aircraft equipage (e.g., Automatic Dependent Surveillance-Broadcast (ADS-B)-out) than the GIM concept.

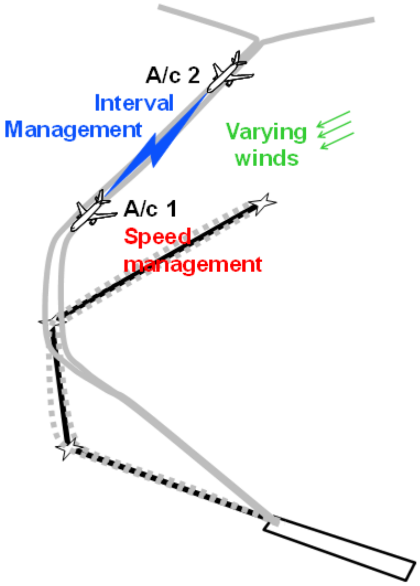


Figure 28. Ground and Flight Interval Management Concept

These concepts are both important to NextGen and sensitive to wind information quality, and therefore would be appropriate areas for study in Phase 2 of this work.

5.3 HIGHER FIDELITY AIRCRAFT SIMULATOR OPTIONS

5.3.1 Motivation

The motivation for obtaining a highly accurate aircraft simulation system is that it is desired to have less spatial-temporal errors in the system being modeled than in the variances of the complete system performance that is being investigated. For example, if the goal is to analyze the variance of selected aircraft/FMS systems in compliance to meeting a 10 second RTA target window under various atmospheric conditions, then it is required that the system being modeled consistently have less than 10 second spatial-temporal error in order to have meaningful representative statistics. This is particularly important when attempting to reproduce the flight trajectory of a particular aircraft make and configuration as FMS software is typically programmed to match a particular configuration.

In addition to the spatio-temporal (ST) accuracy of the aircraft and atmosphere models, the model of the propulsion system's fuel burn is of potential interest which can be leveraged for cost and emissions analysis.

Figure 29 lays out the principle components of the Aircraft/FMS Simulation architecture analyzed in this study. The components under study can broadly be broken into three particular systems: the FMS model, the autopilot model, and the aircraft/engine dynamic model. The accurate representation of each of these systems is generally considered of equal importance.

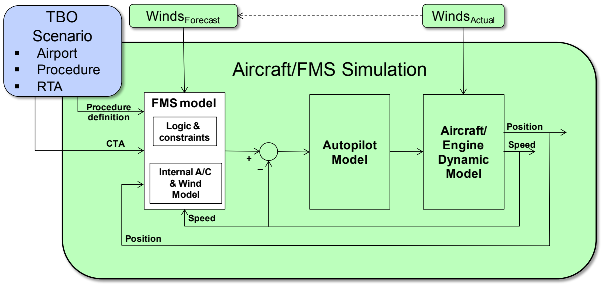


Figure 29. Key Aircraft Simulation Components

5.3.2 Candidate Flight Simulation System Identification

It was decided early in the assessment effort that it would be more advantageous to obtain an existing flight simulation system than to develop one internally. As such, a search and evaluation of candidate "off the shelf" simulation systems was conducted. The search included the consideration of commercially available simulators as well as zero-cost simulation systems, as illustrated in Figure 30. Note that the descriptor "zero-cost" is only an indicator of the initial cost of the system and in no way infers a limitation on the candidate systems' quality nor that the goal of this effort was to concentrate to the utmost on minimizing cost.

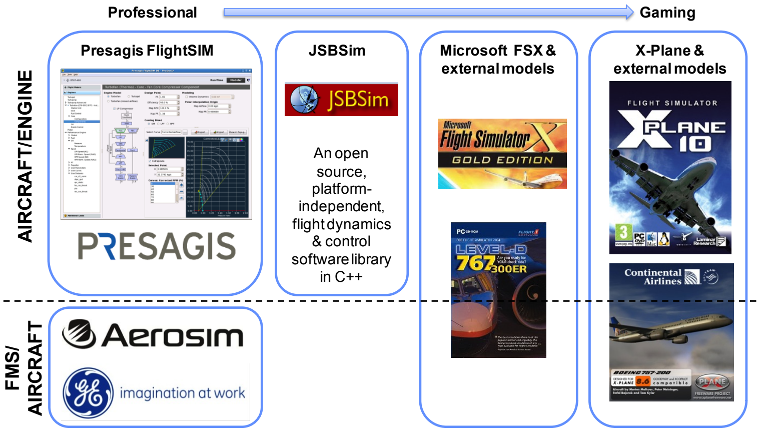


Figure 30. Aircraft Simulation Systems Evaluated

Commercially available flight simulators fall under two particular categories: those that are intended for professional use and those that are intended for gaming. Systems intended for professional applications were found to primarily be designed for use as Flight Training Devices (FTDs) or Full Flight Simulators (FFSs). Gaming systems, which were primarily intended for entertainment, turn out to be surprisingly mature and were also found to be utilized in a number of commercial systems.

Professional Flight Training Systems: The underlying performance/accuracy of flight training systems appeared to vary greatly as described by the various providers contacted. Almost universally the providers indicated that their FTDs and FFSs are required to only provide representative behaviors of the systems. High-end FFSs, such as those that implement 6-degree of freedom moving platforms, improve their fidelity and accuracy by incorporating concrete instances of avionics hardware such as actual FMS and autopilots control heads and processors. All FFSs however, regardless of the concrete avionics employed, are still subject to a software representation of the aircraft aerodynamics and propulsion systems. Manufacturers of high-end FTD/FFSs, including Frasca, CAE and others, were contacted in an effort to determine if they could be candidates for providing appropriate flight simulation systems.

Professional Flight Dynamics Simulators: Not all professional flight simulators are used for training. There are also simulators that exist as engineering tools which are used by professionals that required highly accurate representations of one or more components of an aircraft's system under evaluation or development. Presagis is one such provider who was contacted and evaluated as a candidate provider.

Commercial Gaming Flight Dynamics Simulators: There are two principal gaming-type flight simulators that exist commercially, both of which were evaluated. They are Laminar Research's X-Plane and Microsoft's Flight Simulator. Each product is delivered with a set of modeled aircraft. Both products allow for the incorporation of third-party developed aircraft models and subsystems. The ability to extend the simulation systems turns each application into a generic flight dynamic modeling (FDM) system. When used as an FDM, the accuracy of the simulation is thus dependent on the accuracy of the third-party model, some of which, as discussed later, can be quite sophisticated. The general infrastructure of these FDMs and the addition of the third-party interfaces are so mature that both systems are routinely used outside the gaming arena and are incorporated as the FDM in professional training systems such as Lockheed Martin's Prepare3D® and Precision Flight Controls FAA-certified FFS. There is a very large flight simulator community that also utilizes these systems. The community is clearly made up of sophisticated enthusiasts and experts which have driven the necessary acceptable accuracy of third-party aircraft models to very high levels.

Zero Cost Flight Simulators: Although there are a number of existing zero-cost and or open-source FDMs that are available, the most obvious candidate for evaluation as an FDM is a product called JSBsim. Because it is open-source, it can be adapted and corrected as part of this project as necessary. It is relatively mature, is reasonably easy to integrate into various architectures, and has been vetted, to a limited degree, by respectable third parties.

Zero-cost Non-FDM Simulators: In addition to evaluation of FDMs, EUROCONTROL maintains an aircraft performance database known as BADA (Base of Aircraft Data) which can be used for, among other things, fuel use and emissions modeling (and was used in the Monte Carlo simulations for Phase 1 of this work). It is well-suited to straight/level flight and engine idle descent trajectory modeling, but is less appropriate for determining aero-, propulsion or actuator dynamics. Provided it is used in a well defined manner, it can also be extended with the development of appropriate integration components, into a three degree of freedom point mass aircraft simulator. BADA has already been extended to a simplified 1D and 2D point mass simulator as part of this project and has the important advantages of being widely used in the ATC research community and contains performance data for a wide range of commercial aircraft types.

5.3.3 Flight Simulator Evaluations

Characteristics of Interest: The goal of this evaluation was to identify performance of candidate high fidelity models against characteristics relevant to the project tasking. The following questions were identified as the application dependent decisions that are required to be answered in order to weight the characteristics of interest:

1) Is high spatial/temporal accuracy required?
2) Is accurate fuel use/emission generation estimation required?
3) Is concurrent multiagent simulation required?
4) Is multi-airframe support required?
5) Is fast-time required?
6) How much does it cost?

Other questions, such as whether the systems can be programmatically controlled and programmatically extended, have already been answered in the affirmative in order to be consider for detailed evaluation.

Spatial/Temporal (ST) Accuracy: This characteristic is concerned with how accurately the aircraft translates across geodetic space, as well as how accurately it crosses space in time relative to that of the system being modeled. This accuracy is dependent on a number of elements, in addition to the model and subsystems of the aircraft, including the modeling of the local atmosphere and its properties (pressure, density, temperature, movement) and the underlying geodetic model used to represents the Earth's surface. The greater the distance and time of flight that is to be modeled, the more relevant ST accuracy becomes. To measure ST accuracy, flight data records which include an aircraft's make, model and variant, its mass loading and distribution, its measured local atmospheric conditions and its flight path intentions, are all required. Flight path intentions include the flight plan itself and the specific mode and target values provided to the autopilot.

Fuel Use/Emissions Generation Estimation: Propulsion dynamics, the modeling of the rate of change of engine rotation and of independent thrust creation, has a first-order effect on ST accuracy.

There is a second-order effect on ST accuracy as well which is subject to the modeling of the fuel required to generate the calculated thrust. For example, as the aircraft flies, fuel is consumed and thus over time the mass of the aircraft is reduced. In highly-detailed aircraft models, the inertia and trim of the aircraft are also affected because they are dependent on the quantity of fuel stored in each tank. From an emissions point of view, however, the quantity of fuel consumed and the specific engine settings are of paramount performance.

Concurrent Multiagent Simulation: Concurrent multiagent simulation is the ability of a system to support interaction with other local or remote processes where at least one independent agent is dependent on the state of a second agent. This is sometimes referred to as multiplayer simulation. An example use case would be a simulated aircraft flying in the National Airspace System (NAS) and a simulated air traffic controller process "providing" speed instructions to the simulated aircraft based on its own independent logic. The FIM application previously discussed would also require multiagents in the simulation.

Multi-airframe Support: This characteristic describes the ability of the system to inherently support more than one type of aircraft model or variant. In reality, all systems under investigation can support more than one aircraft model. The more relevant characteristic is related to the number of sufficiently accurate and pertinent aircraft models that are readily available without having to spend effort in developing new models which can be time consuming and expensive.

Fast-time Execution: This characteristic describes the ability of a simulation system to produce the same arithmetical results as produced when executing at a real-time rate even if the time to process the simulation takes less actual time to execute than the period of time that was simulated. Fast-time execution may not be desirable if the simulated elements of the system are interacting with human users or avionic systems that are programmed to run in real-time, but fast-time execution can be high value when exploring large numbers of test cases. Some simulation systems do not support fast-time and only provide accelerated translation (movement without dynamics).

Cost: The cost of the simulation system can be estimated as the cost of the acquisition plus the cost for additional software and model development which could include adaptation for remote programmatic control, code fixing (if source code is provided) as applicable and aircraft model development.

5.3.4 Evaluation Methodology

It is very difficult to quantify the performance of a flight simulator system. One of the principal reasons is that the system has a large number of degrees of freedom and that the accuracy in the modeling of any particular degree of freedom often differs in various phases of flight. It is therefore problematic to assert that one particular simulator is superior without applying context-specific evaluation criteria. Other characteristics of a simulator also play a role into the determination of superiority that are independent of calculated accuracies, such as fast-time capabilities, and which may be of more importance depending on the application of the system.

Comparisons of simulated output to actual Flight Data Recorder (FDR) data is one way to measure errors in various degrees of freedom of the simulators. There are limitations to this approach in that, as mentioned earlier, the large number of degrees of freedom presents problem in calculating a combined performance. For fair comparison, it is also required that each simulated system have representations of the model and variant of the aircraft that provided the recorded flight data and that the flight data itself is accurate and sufficient to excite all the degrees of freedom required for the simulation. Flight data is often difficult to acquire and it is even more difficult to find with a completely populated set of states to use in comparisons. For this study, FDR data were available from a series of B757-200 approaches to a particular airport with data below 10,000 ft, as well as complete flight data from a set of A320 aircraft flights. Neither sets contained complete autopilot settings or target states, so the intent of the aircraft was not always known. This means that when programming the simulated aircraft to reproduce the flight, it was typically required to follow the recorded states, such as airspeed and altitude, instead of setting the autopilot to reference values. As such, the simulation would always lag the reference aircraft relating to these states. This also means that the spatial-temporal relationship would also differ even if the simulated aircraft was a perfect model.

5.3.5 Analysis of Individual Simulation Systems

Presagis FlightSIM

Presagis' FlightSIM was provided with a temporary license to evaluate the performance of the system. The software came with a very detailed model of a B767-400, apparently developed jointly with Boeing for internal Boeing use. The system also came with one other commercial airline model, a B747-200, which was not evaluated as this is now not a commonly flown aircraft type.

FlightSIM is made up of two principal components shown in Figure 31. The first is a FlightSIM Developer package which is used to build or modify component of a simulated system. Each aircraft is made up of a multitude of sub-systems including hydraulics, aerodynamics, propulsion, various avionics and additional systems. The second component of FlightSIM is a C/C++ accessible software library which allows for user applications to programmatically exercise the developed models.

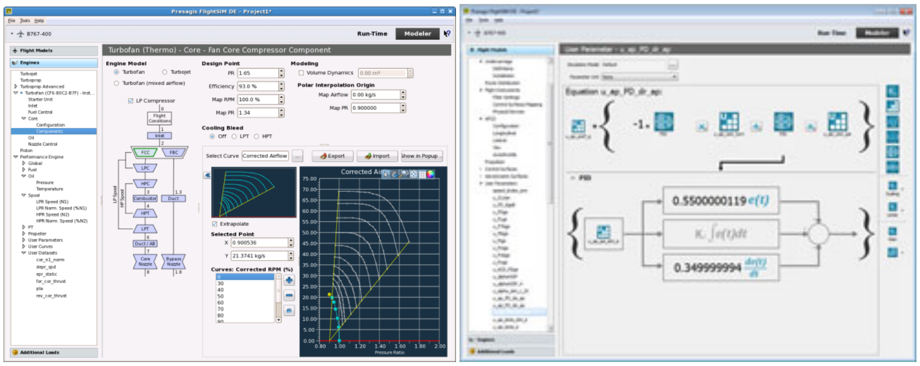

Engine Model: ● Turbofan ○ Turbojet ○ Turbofan (mixed airflow)
☑ LP Compressor
Design Point
PR 1.65
Efficiency 93.0 %
Map RPM 100.0 %
Map PR 1.34
Modeling
☐ Volume Dynamics 0.00 m³
Polar Interpolation Origin
Map Airflow 0.00 kg/s
Map PR 0.900000
Cooling Bleed: ● Off ○ LPT ○ HPT
Select Curve Corrected Airflow
☑ Extrapolate
Selected Point
X 0.900536
Y 21.3741 kg/s
0.5500000119 $e(t)$
$K_i \int e(t)dt$
0.349999994 $\frac{de(t)}{dt}$

Figure 31. Presagis FlightSIM System

Licensing and Cost Arrangement: MIT LL has spent a great deal of effort working with Presagis to develop a licensing agreement that is both cost and feature satisfactory for both parties. To date, the most favorable agreement that would be accepted by all MIT LL implicated departments would be at a cost of the order of tens of thousands of dollars. One user license is required for each running process of the simulation. This agreement would only provide the two commercial aircraft models mentioned. Any other models would have to be developed in-house or out-sourced to Presagis or some other third party for development.

Programmatic Utilization: Presagis, at two times provided temporary licenses so their system could be evaluated. MIT LL developed a stand-alone C++ application to programmatically simulate the provided aircraft models flying though a dynamically updated atmosphere following a programmatically assigned flight plan. The internal autopilot and FMS logic included with FlightSIM was not modified. MIT LL also developed C++ code and linked this with the FlightSIM library to produce a headless application, meaning that there was no display used or required to exercise the program. Debug data was printed to a console window as necessary. Executions were run as fast as possible and their rates were limited to the processing speed of the computer used to run the application. System state data were written to disk during execution, and KML files were also produced to be used for visual comparison against recorded flight data using Google Earth.

Analysis: Without any particular effort to maximize performance, fast-time simulation rates of up to ×100 were seen. The rate was dependent on the time step utilized in the simulation and the quantity of data written to disk. No FDR data for a B767-400 were available for comparison. At the time the FlightSIM temporary licenses were available, only the data for approaches to an airport for a B757-200 were accessible. This meant that, at a minimum, the fuel consumption rates of the propulsion system could not be evaluated. This is unfortunate because one of the key characteristics of the B767-400 model is supposedly its highly accurate engine models. Unlike many other aircraft simulators, which often use simple two-dimensional performance tables, the engine model in this simulation system is thermodynamically based and includes models of individual subcomponents of the turbine engine. Evaluation of the engine model using the FlightSIM Developer application clearly showed a detailed and complex engine model, but there was no way to validate its accuracy give the reference data at hand. Despite this limitation, a comparison of the FlightSIM B767-400 trajectory information was compared to the B757-200 FDR data to see how they compared. The FDR data for the B757-200 approaches were programmatically reduced to produce sets of initial conditions, segments of the flight plan, and extraction of sensed wind data for execution in the simulation application. The aircraft was started at the initial conditions as best estimated from the automatic extraction and assigned to follow a 15 point flight plan which ended near the surface of the target runway.

Figure 32. Sample Presagis FlightSIM Evaluation

Figure 32 shows an example of the resulting output of the simulation. In the figure, the magenta circles are the assigned waypoints, the orange polyline is the trajectory from the FDR data and the green line is the simulated trajectory. Evident in this image is the fact that the simulated aircraft system did a very good job qualitatively flying through the assigned waypoints and compared favorably at a trajectory-level to the FDR data.

Laminar Research X-Plane

Licensing and Cost Arrangement: Individual single-user licenses and software can be purchased commercially for less than $100. A number of free third-party aircraft models are available for download at various websites. Only a small number of third-party commercial aircraft models are available for purchase.

Analysis: A copy of X-Plane was acquired for evaluation. It was found that X-plane can provide programmatic control for many elements of interest. However, the initial evaluation found several characteristics that warranted the termination of further evaluations. Chiefly among these was that the software cannot operate in fast-time. There is no requirement at this time that states fast-time is required, but it is assumed that it will be a necessity to have some form of computation acceleration to promote rapid or statistically numerous simulations. Note that the software does have the ability to “speed up” the aircraft, but it only accelerates the translation speed. It has no effect on simulation clock or fuel consumption. The system also requires the existence of a DVD or special USB to execute a single instance which makes it less than ideal for scaling or running on a server.

Microsoft Flight Simulator X

A copy of Microsoft Flight Simulator X (FSX) was acquired for evaluation. Additionally, a number of third-party aircraft models were acquired for evaluation since FSX came with only three commercial aircraft models (B737-800, B747-400 and CRJ700) and no FDR data was available for these types at the time of the evaluation.

Licensing and Cost Arrangement: Individual single-user licenses and software can be purchased commercially for around less than $100. Many third-party commercial aircraft models of various sophistications can be purchased for similar amounts.

Programmatic Utilization: A software application was developed at MIT LL that allowed for programmatic control of many elements of the FSX environment. The C++ application is able to, from a remote computer, connect to an FSX instance, load a particular aircraft model, initialize some (but not all) aircraft states, load a flight plan into an FMS, set the simulation rate, activate the flight plan, control the autopilot modes and reference values and perform many more actions programmatically. The application also continuously updates the environmental conditions such as local winds and temperatures. The application has also been utilized to programmatically set spoiler and flap positions as necessary or as reported via FDR data when trying to reproduce recorded flights.

The application is a headless, command-line drive application and utilizes a Microsoft-provided library to communicate with the FSX instance. For this reason, the application must be executed on a machine running the Windows operating system. An additional application can be written that would act as an additional transport layer to allow the application to run on non-Windows machines. System state data are stored to disk during execution. Debug data is printed to a console window as necessary.

Analysis: Commercial aircraft models were acquired from seven third-party vendors for evaluation, including Airbus A318/319/320/330-200/330-300/340-300/340-600, and Boeing B737-300/737-400/737-500/737-800/757-200/757-300/767-200/767-300/777-200 and MD11 types. There are additional variations on many of these models for choices of the engines available to that airframe and the support of winglets or wing fences as appropriate. For example, the B767-300 is available from the manufacturer with Rolls Royce, General Electric, or Pratt & Whitney engines. A number of airframes and variants were tested for compatibility with external control and it was found that not all were able to be initialized and controlled using the current version of the developed application. An effort to resolve why some aircraft models were not compatible was not undertaken.

The simulation rate of the system is governed by the FSX instance, not the remotely controlling application. Stable simulation rates of up to ×5 were seen using the Acceleration Expansion Pack along with FSX Service Pack 2. Note the term “Acceleration” is a marketing term and is not meant to imply that FSX can execute faster. Review of commentary on various internet sites indicate that the simulation may be able to stably achieve a ×16 rate by using the earlier Service Pack 1.

The principal amount of FDR data came from B757-200 aircraft with Rolls-Royce RB211-535E4B engines and no winglets. Two third-party FSX models were available for this airframe and variant with the same engine and winglet option. One model was tested. Comparison of the simulation and FDR data was undertaken as illustrated in Figure 33. Sections of nonaccelerating flight at various flight levels and initial transition from cruise into descent were used for the comparisons. The simulated aircraft was initialized with the best estimate of the aircraft states at the beginning of each of the segments of flight.

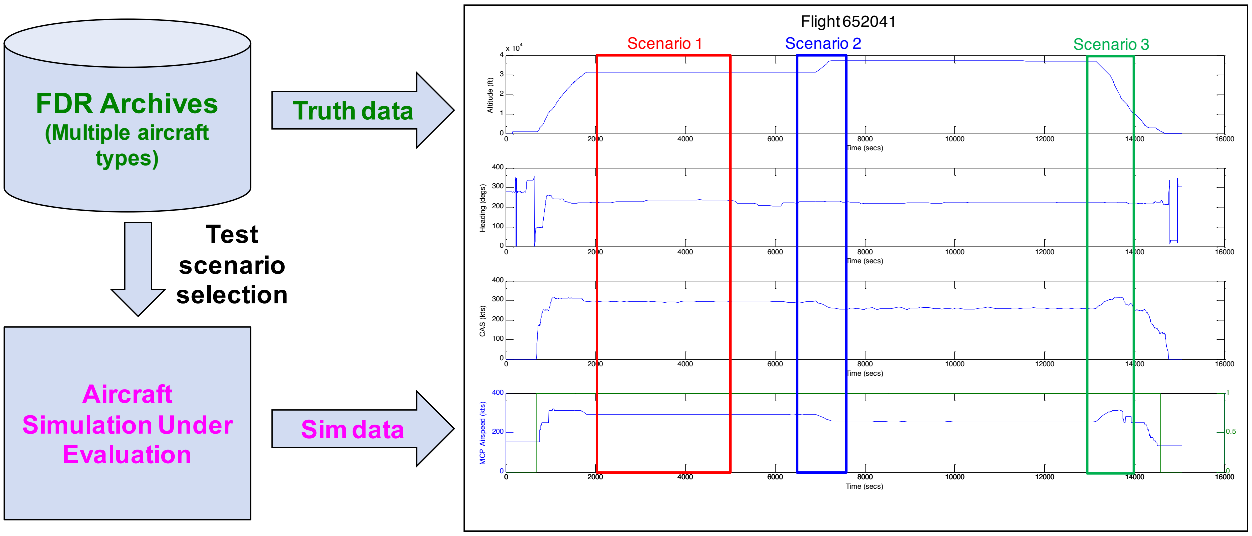


Figure 33. FDR-based Flight Evaluation Scenarios

Data were collected for each of the scenarios for use in the comparisons. Figure 34 presents simulated altitudes and fuel flow rate comparisons. Closed-loop states such as required altitudes and airspeed align quite well with the flight data. State-dependent systems such as fuel flow also align quite well after engine states stabilize after initial instability.

JSBSim

Licensing and Cost Arrangement: JSBSim is an open source FDM project. It is available under the GNU Lesser General Public License such that there is no cost for its use or modification. There are ten applicable commercial aircraft models readily downloadable at no cost for use with JSBSim.

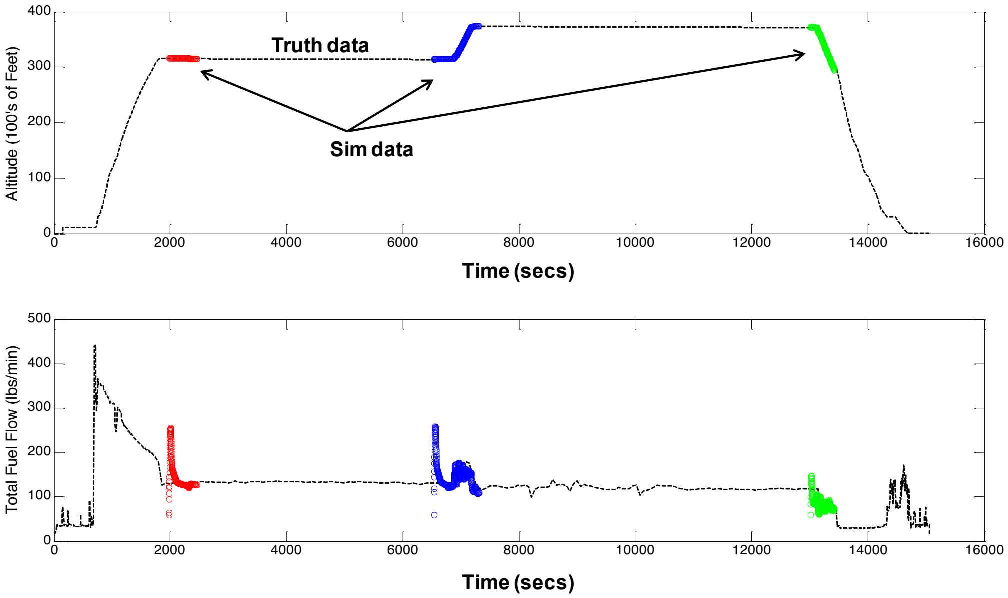


Figure 34. Sample Microsoft Flight Simulator X Evaluation

Programmatic Utilization: JSBSim was obtained as C++ source code, modified slightly to correct some run-time bugs, and locally compiled for evaluation. The software was evaluated but not modified nor extended to operate under external programmatic control such as was done for FlightSIM and FSX. Evaluation of the source code indicated that incorporation of JSBSim into a dedicated application or extending to be controlled via a remote application was feasible and not overly burdensome.

The compiled code was executed as a command line application and was used for fast-time performance analysis. Further evaluation was conducted by utilization of the open source flight simulation project FlightGear. FlightGear can be set to utilize JSBSim as its underlying FDM. FlightGear's user interface permitted manipulation of the aircraft conditions and the atmospheric environment which provided a means for a quick evaluation of JSBSim's capabilities.

Analysis: Aircraft models, including their definitions of their aerodynamics, propulsion and control systems, are specified via XML configuration files. JSBSim internally constructs internal representations of these models at run-time which are then used internally during the numerical integration of the system dynamics and states. Review of the code that conducts the actual state integration of the represented models appears organized and correct.

There are no for-purchase commercial aircraft models available for JSBSim. Only a limited number of commercial aircraft models were found: they are the Airbus A320/321/340 and Boeing B737-300/747-

100/747-200/747-400. Versions with selectable engine models were not found. FDR data was available for an A320-214 aircraft installed with CFM56-5B4 engines. The closest available JSBSim model that could be used for comparison was an A320-200 with CFM56-5A1 engines which have about 7% lower maximum thrust. Similar to the evaluation of FSX, inspection of the recorded data for the A320 was undertaken to select appropriate sections of flights to use for comparison. Periods of flight that were determined to be appropriate for comparison from the available data were during non-accelerating fixed altitude flight. The required autopilot modes were engaged throughout the evaluation and atmospheric conditions were set to match that reported in the FDR data. The resulting performance was poor, with 75%, 82%, and 180% greater fuel use at three different test altitudes compared to the FDR data.

5.3.6 Summary of Results

Individual results including analytical and anecdotal findings are presented for each of the systems evaluated. The results are compiled to help answer the questions posed under *Characteristics of Interest* outlined earlier.

Presagis FlightSIM

The ST accuracy was determined by inspection of its real-time flight trajectory as compared to the FDR approach data. The combination of its aerodynamic, thermo/propulsion and atmospheric modeling and embedded autopilot control laws proved to be precise. Roll and pitch controls appeared accurate and dynamically correct providing transitions without overshoots. No truth data were available to analytically determine the accuracy of the provided engine model(s). Inspection of the engine models themselves suggested great detail in the thermodynamic inertial dynamic models. Vender assertion to their accuracy is believed to be factual considering the models were made with the aircraft manufacturer. Because the system operates as a set of library calls from a custom application built as part of this project, it is possible to support large-scale multiagent simulations with this system. The only known technical constraint is the requirement for a license server manager to allow user application access to the library. Note that Lincoln Laboratory has worked with the vendor to develop an arrangement that could provide unlimited number of user seats. Negotiations on that arrangement have ceased for the time being. As delivered, FlightSIM only supports two specific aircraft models. Additional models may be created or existing models could be modified to grow the number of available aircraft with tools provided by the Developer package or by employing Presagis to develop the requested models. Simulation speeds of up to 100 times faster than real-time have been observed with FlightSIM. FlightSIM is clearly the most expensive system as related to initial costing. Costing for additional software development for programmatic use is low as demonstrated by the quantity of software that was written to exercise the library programmatically.

Laminar Research X-Plane

The ST accuracy of the X-plane systems and models was not determined given early evaluation that it could not support fast-time execution. However, X-Plane could be readily used for multiagent simulation if real-time was acceptable.

Microsoft Flight Simulator X

A large number of aircraft models are available for FSX, but only a limited number have been exercised for evaluation. Of those exercised, their combination of aerodynamic, propulsion and atmospheric modeling and embedded autopilot control laws proved to be precise. Roll and pitch controls appeared accurate and dynamically correct providing transitions without overshoots. Analysis of the output of the B757-200 simulation compared to FDR data showed fuel consumption rate errors of –2.4% to –6.7% during cruise at flight level altitudes and up to –9.7% error during initial descent. No conclusions can be drawn about other aircraft models. FSX can be used for multiagent simulation. The known limitations come in the requirement that the software execute on a machine running the Windows operating system, and that only a single instance of the software can be started at a time. Multiple agents could be run on a single computer if each instance of the Windows operating system and FSX software are run on separate virtual machines. FSX has been executed programmatically at up to five times real-time rates without loss of stability or meaningful changes of states, such as total fuel consumption at the end of a flight. A speed up of ×16 has been manually verified using an older Service Pack for FSX. Costing for the base FSX software and additional aircraft models is low.

JSBSim

JSBSim was not directly tested for ST accuracy. From evaluation of the JSBSim FDM source code, we have concluded the underlying elements, dynamics integrators, earth and atmospheric models, etc., are adeptly implemented and mathematically robust. However, ST accuracy is in question due to the inaccuracy of the available aircraft models. For example, inspection of the flight characteristics of the tested A320-200 model showed unacceptable closed-loop autopilot performance with significant overshoots in step changes to various target values. The fuel consumption values of the aircraft model tested with JSBSim was very poor. As the source code is available for manipulation as required, JSBSim is well suited for multiagent simulation including on a large scale across multiple computers. There are a very limited number of commercial aircraft models and their derivatives available for use with JSBSim. JSBSim provides the easiest methodology for modifying or creating new aircraft models as all models are defined in text files including definitions of the autopilot control laws. JSBSim has been demonstrated to run at up to ×60 faster than real-time when running as a scripted application. The effects of fast-time execution on the autopilot (AP) control laws have not been investigated. JSBSim is open source C++ code and there is no cost to acquire or utilize. Based on the current known inaccuracies of the model tested, a significant amount of labor may be required to improve existing or develop new aircraft models that are accurate enough for use in future investigations.

Summary

Table 5 is an aggregation of both objective and subjective ratings of key characteristics for each of the systems evaluated. Costing scales are based on the assumed cumulative cost for initial outlay plus cost associated with developing a multiagent infrastructure and associated licensing for at least two instances. The scalability characteristic is a combination of the multiagent capabilities and the ability to run large-scale simulations.

Table 5. High Fidelity Aircraft Simulation Evaluation Summary

	FlightSIM	X-Plane	MS FSX	JSBSim
Dynamics	★★★	No data	★★★	★★
Control Systems	★★★	No data	★★★	★✮
Fuel Burn Model	★★★	No data	★★★(-5%)	★✮(+140%)
# of Airframes	✮	★★	★★★	★★
Fast-time	★★★(x100)	(x1)	★✮(x5, x16*)	★★✮(x60)
Scalability	★★★	★	★	★★★
Cost	$$$	$$	$$	$

*Manually, not programmatically verified.

5.4 HIGHER FIDELITY FMS SIMULATOR OPTIONS

In addition to the aircraft simulation fidelity, the representation of the FMS is of fundamental importance to any NextGen concept requiring FMS capabilities, such as 4D-TBO. Some of the aircraft simulation capabilities discussed in the previous section also have models of currently operational FMS capabilities, but they are typically unvalidated (and often highly-simplified) representations of the actual systems. At the other end of the realism spectrum, it is also possible to acquire "re-hosted" versions of the actual software used in the airborne systems. Figure 30 shows two such re-hosted FMS options which offer validated performance of the actual systems, but these are often very expensive to acquire and are limited in their ability to run fast-time.

In Phase 2 of this work, it is proposed to explore both high fidelity versions of current systems, as well as impacts of feasible future FMS capabilities. Some of the key future FMS capabilities of interest include:

- Enhancing FMS wind definition points beyond the current FMS capability to enter wind at flight plan waypoints and at a limited number (typically 3–5) altitude levels, e.g.,
  - More altitude levels.
  - Gridded wind fields.

- Enhancing FMS wind interpolation algorithms.
    - Current systems are assumed to typically use linear interpolation between waypoints and altitude levels.

- Enhancing FMS blending algorithms, e.g., how FMS forecast winds are modified due to sensed wind errors.
    - Current systems use proprietary blending algorithms, but generally correct future wind estimates in proportion to the error between the expected and sensed wind at the current location, and distance into the future. For example, wind estimates close to the current position will have a larger correction factor applied based on current sensed winds compared to points further away, which would then be assumed to be nearer to the forecast estimate.

- Enhancing control algorithms, e.g., flight idle versus higher than flight idle thrust control during descent to increase RTA compliance capability.

Given the proprietary nature of many of these aspects, realistic exploration of current and future FMS algorithms would ideally involve direct collaboration with FMS industry partners. To this end, a Request For Information (RFI) was released to appropriate FMS industry vendors to explore collaboration options.

5.5 PHASE 2 PROPOSED ROADMAP

Phase 2 planning is highly dependent on whether FMS industry collaborators are engaged or not. Advantages of engaging include potential access to accurate current FMS models, development of realistic future FMS capabilities, and industry expertise in evaluating results, while the main disadvantage includes additional costs, potentially resulting in reduced Phase 2 study breadth. By contrast, not engaging FMS industry collaborators could enable resources to be dedicated to expanded study breadth and extensive "in-house" research development, but at the cost of lack of industry input on future FMS capabilities and results interpretation.

A Request For Proposals (RFP) has been released to solicit formal collaborations on research tasks of relevance to Phase 2 of this project. Initial Phase 2 planning is carrying two parallel Phase 2 roadmap options that outline plans with and without FMS industry collaboration, as shown in Figure 35.

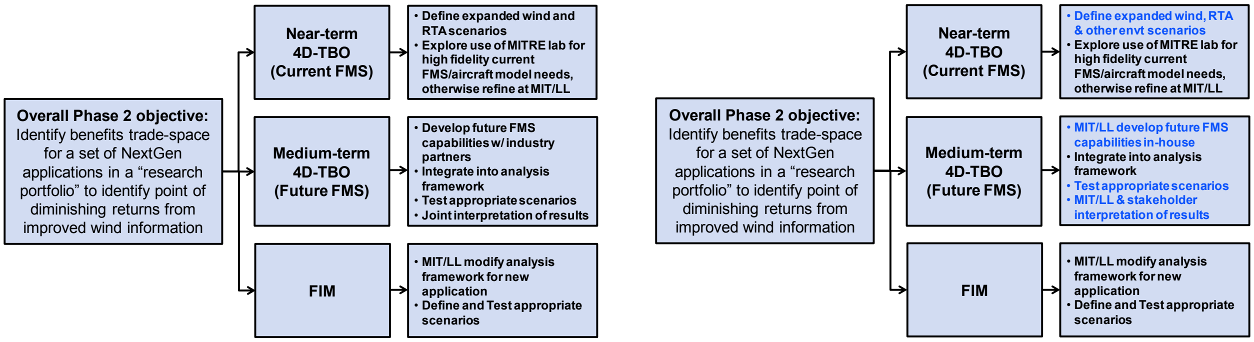


Figure 35. Phase 2 Planning With FMS Industry Engagement (left)/Without FMS Industry Engagement (right)

With FMS industry collaboration, the Phase 2 plan is to explore near-term 4D-TBO with current FMS capabilities and expanded wind and RTA scenarios; medium-term 4D-TBO with future FMS capabilities developed in collaboration with industry partners, which would then be implemented in the context of the Wind Information Analysis Framework and results jointly interpreted; and FIM where the analysis framework will be modified and exercised for this new application. Without FMS industry collaboration, the key differences (highlighted in blue in Figure 35) are that expanded scenarios will be tested for the near-term 4D-TBO case (e.g., including other environmental metrics such as turbulence and temperature issues discussed previously), and future FMS capabilities will be developed, implemented and interpreted solely by the research team. High-level illustrative tasking and schedule for the Phase 2 activity is shown in Table 6 below.

Table 6. Generic Phase 2 Tasking and Schedule

Task	Sub-Task FY13	O	N	D	J	F	M	A	M	J	J	A	S
1	Identify appropriate wind quality metrics	■	■										
2	Identify NextGen applications for study under Phase 2	■	■										
3	Refine Wind Information Analysis Framework for Phase 2 applications		■	■	■	■							
4	Exercise refined Wind Information Analysis Framework for Phase 2 applications to explore wind information quality/benefits trade-space					■	■	■	■	■			
5	Document and Promote the findings of the work to stakeholder community to help address identified needs								■	■	■	■	■
6	Work with RTCA Special Committee (SC) 227	■	■	■	■	■	■	■	■	■	■	■	■
7	Make recommendations for follow-on work							■	■	■	■	■	■

6. SUMMARY

Many future air transportation system paradigms require access to high quality wind information. The primary objective of this work is to quantify the relationship between wind information quality and benefits delivery under these future ATC applications. This information will be of high value to stakeholders, for example in terms of determining forecasting performance and automation technology requirements in ground and airborne systems to achieve NextGen goals. In the first phase of the work described in this report, a Wind Information Analysis Framework has been developed which is designed to be flexible and scalable to explore wind information needs across a broad range of applications. It has also been applied to a realistic 4D-TBO scenario with simplified versions of the framework elements under a challenging wind environment with representative wind error models to provide proof-of-concept of the utility of the framework. This exercise has illustrated that even simplified executions of the framework can yield interesting and complex results which can be of high value in determining performance trade-spaces.

Phase 2 will build upon this foundation by using refined and expanded applications of the Wind Information Analysis Framework to generate high value results for standards and requirements setting entities. Specific next steps for this work in Phase 2 include

- Increasing the aircraft/FMS modeling fidelity (e.g., by using higher accuracy aircraft aerodynamic/propulsion/autopilot control simulations and re-hosted FMS software) and exploring more complex RTA procedures (e.g., adding vertical and lateral profile elements) to increase the realism and applicability of the results to stakeholder needs.
- Expanding the set of wind forecast scenarios to help identify gaps between required performance levels and current state of the art models identified through this analysis.
- Collaborating with FMS vendors to explore realistic future FMS capabilities to address some of the identified shortcomings in existing FMS capabilities, and integrating these improved algorithms into the analysis framework to analyze their impact.
- Expanding the focus applications beyond 4D-TBO, e.g., Flight Interval Management, Improved TMA, and/or DataComm applications.

GLOSSARY

a/c or A/c	Aircraft
4D-TBO	4-Dimensional Trajectory-Based Operations
ADS-B	Automatic Dependent Surveillance-Broadcast - B
AIRE	Atlantic Interoperability Initiative to Reduce Emissions
AMDAR	Aircraft Meteorological Data Relay
AP	Autopilot
ARTCC	Air Route Traffic Control Center
ASOS	Automated Surface Observing System
ATC	Air Traffic Control
ATCT	Air Traffic Control Tower
ATM	Air Traffic Management
AW	Augmented Winds (experimental wind analysis system)
AWC	Aviation Weather Center
AWOS	Automated Weather Observing System
BADA	Base of Aircraft DAta (EUROCONTROL aircraft data base)
CAS	Calibrated Air Speed
CDA	Continuous Descent Approach
CO_2	Carbon Dioxide
CONUS	Contiguous United States
CoSPA	Consolidated Storm Prediction for Aviation
CTA	Controlled Time of Arrival
CWSU	Center Weather Service Unit
DEN	Denver International Airport
DOE	Department of Energy
DFW	Dallas/Fort Worth International Airport
ETA	Estimated Time of Arrival
EUR-4	4-km resolution European weather prediction model
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FDM	Flight Dynamic Modeling
FDR	Flight Data Recorder
FFS	Full Flight Simulator
FIM	Flight Interval Management
FMS	Flight Management System
FTD	Flight Training Device
GA	General Aviation
GFS	Global Forecast System (weather prediction model)
GIM	Ground Interval Management
GMT	Greenwich Mean Time
GNU	“GNU's Not Unix” (free Unix-like operating system)
GRIB-2	GRIdded Binary data format version 2

HRRR	High-Resolution Rapid Refresh (weather prediction model)
IAH	George Bush Intercontinental Airport
IAS	Indicated Air Speed
ITWS	Integrated Terminal Weather System
KML	Keyhole Markup Language
LL	Lincoln Laboratory
LLWAS	Low Level Windshear Alert System
MEM	Memphis Airport
MF	Meter Fix
MINT	Minimum CO2 in Terminal Maneuvering Area
MIT/LL	Massachusetts Institute of Technology Lincoln Laboratory
NAE	North Atlantic European (weather prediction model)
NAS	National Airspace System
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NetCDF	Network Common Data Format
NEXRAD	Next Generation Radar (WSR-88D)
NextGen	Next Generation
NOAA	National Oceanic and Atmospheric Administration
NOAA/ESRL	NOAA Earth System Research Laboratory
NOAA/NCEP	NOAA National Centers for Environmental Prediction
NWP	NextGen Weather Processor
NWS	National Weather Service
OAT	Outside Air Temperature
RAP	Rapid Refresh (weather prediction model)
RFI	Request For Information
RFP	Request For Proposals
RMS	Root Mean Square
RMSVE	Root Mean Square Vector Error
RTA	Required Time of Arrival
RTCA	Formerly the Radio Technical Commission for Aeronautics
RUC	Rapid Update Cycle (weather prediction model)
RUC-1	RUC version 1 (former 60-km resolution RUC model)
RUC-2	RUC version 2 (former 40-km resolution RUC model)
SEA	Seattle-Tacoma International Airport
SESAR	Single European Sky ATM Research
SFO	San Francisco International Airport
ST	Spatio-Temporal
TAF	Terminal Aerodrome Forecast
TAS	True Air Speed
TBFM	Time-Based Flow Management
TBO	Trajectory-Based Operations
TDWR	Terminal Doppler Weather Radar
TMA	Traffic Management Advisor
TOD	Top Of Descent

TRACON	Terminal Radar Approach CONtrol
TTF	Time-To-Fly
TW	Terminal Winds (same as “TWIND”)
TWIND	Terminal WINDs (same as “TW”)
UK4	UK 4-km resolution weather prediction model
UKV	UK Variable resolution weather prediction model
VWS	Vertical Wind Shear
WAFTAGE	Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe (weather prediction model)
WFA	Wind Forecast Algorithm
WFIP	Wind Forecast Improvement Project
WFO	Weather Forecast Office
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting (weather prediction model)
WTMD	Wake Turbulence Mitigation for Departures
XML	Extensible Markup Language
wx	weather

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