Establishing Wind Information Needs for Four Dimensional Trajectory-Based Operations*

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Accurate wind information is of fundamental importance to the delivery of benefits from future air traffic concepts. A Wind Information Analysis Framework is described in this paper and its utility for assessing wind information needs for a four-dimensional trajectory based operations application is demonstrated.

I. Introduction

Accurate wind information is of fundamental importance to the delivery of Next Generation Air Transportation System (NextGen) and Single European Sky (SESAR) system enhancements. Figure 1 below illustrates how key future applications have needs for improved wind information (amongst other things).

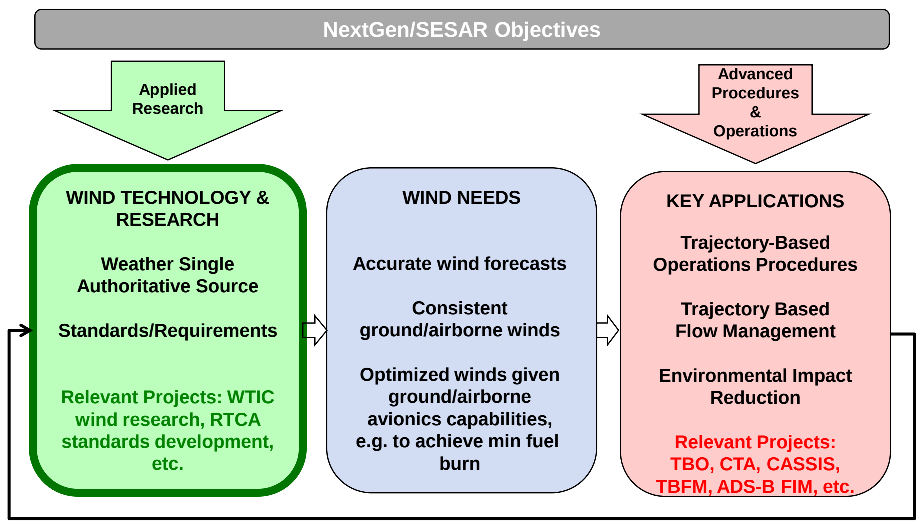

Figure 1: Wind Information Supporting NextGen Applications

This paper describes the foundational assessment of wind technology and research (shown on the left of the figure) to help address these needs and map them to benefits from the NextGen/SESAR applications they enable. In the initial phase of the work, a Wind Information Analysis Framework has been developed: a simplified version of the framework is shown in Figure 2. It contains elements of:

- **Wind Scenario** to represent the range of operational wind scenarios of relevance to the application being studied and the characteristics of different wind information forecast capabilities, such as the accuracy of the forecast relative to the actual wind field experienced.

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- **Future ATC Application** to represent the characteristics of the air traffic environment for the application of interest, such as specifics of the procedures, infrastructure, demand levels, equipage, etc. under NextGen or SESAR.
- **Aircraft/FMS Simulation** to represent the behavior of the aircraft, engine, autopilot and FMS in the context of the wind scenario and NextGen 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 NextGen application(s) 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)

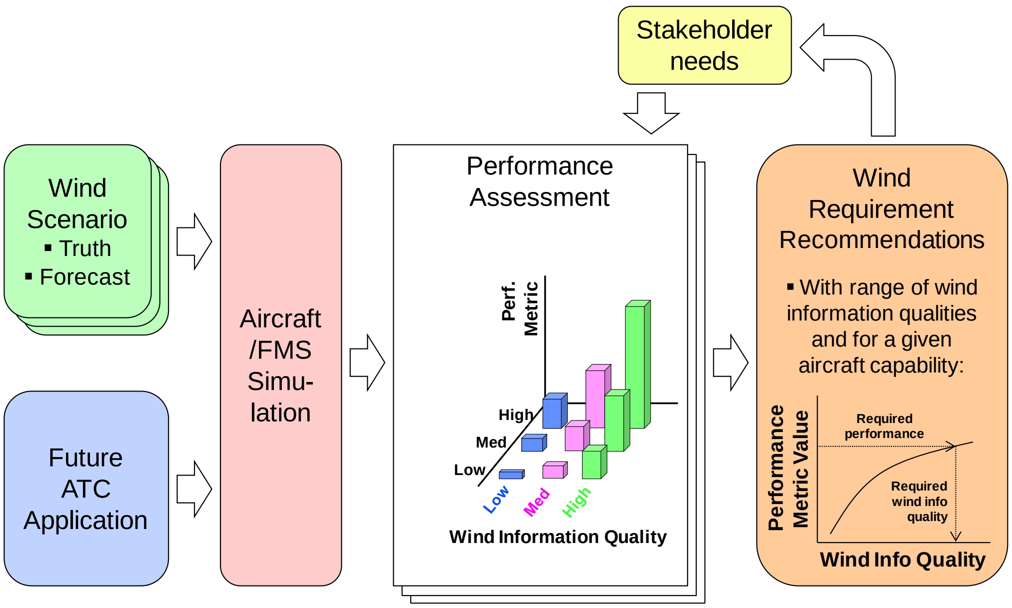

Figure 2: Generic Wind Information Analysis Framework

This generic framework is designed to be flexible and scalable to a broad range of future air traffic control (ATC) application envisioned under programs such as NextGen or SESAR. However, in order to provide focus to the first phase of this effort, the current application under consideration is four-dimensional trajectory based operations (4D-TBO or Controlled Time of Arrival (CTA)). The next section provides background for the 4D-TBO application and highlights the relevance of accurate wind information. Section III then describes how the Wind Information Analysis Framework elements are being tailored for this application. Section IV discusses the key sources of wind error that are being tracked in this work for the 4D-TBO application and preliminary simulation results from the 4D-TBO-tailored framework are presented in Section V which show the impacts of these different wind sources. Conclusions and next steps are then presented in the final section.

II. Four-Dimensional Trajectory-Based Operations (4D-TBO) Background

4D-TBO involving latitude, longitude, altitude and time-based elements is one of the fundamental capabilities required under NextGen and SESAR. 4D-TBO should enable a number of important procedures to be implemented that improve efficiency while maintaining airport capacity, such as Optimized Profile Descents (OPD), Oceanic Tailored Arrivals and 3D Path Arrival Management (3D-PAM). One concept of operations for 4D-TBO is illustrated in Figure 3 and 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 at the various waypoints in Figure 3) to manage traffic flows as efficiently as possible. These time targets could be sent to individual aircraft, which are then responsible for managing their trajectory in a manner consistent with the 4D clearance, either through manual speed control or via “Required Time of Arrival” (RTA) functionality of an FMS. In prior analyses and flight trials, one major determinant of the benefits achievable from a given 4D-TBO procedure was found to be the accuracy and temporal/spatial resolution of the wind information available to the ground and airborne FMSs which are creating and managing compliance to the time targets respectively. For example, even modest biases in the wind models used by the FMS 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 [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 and aircraft performance assumptions being used by the ground and airborne systems [2,3]. The various manifestations of wind information and aircraft performance elements across the 4D-TBO domains are illustrated by the green and blue elements respectively in Figure 3. The performance of the FMS is seen to be a key component of “aircraft capability” identified in the analysis framework for the 4D-TBO application.

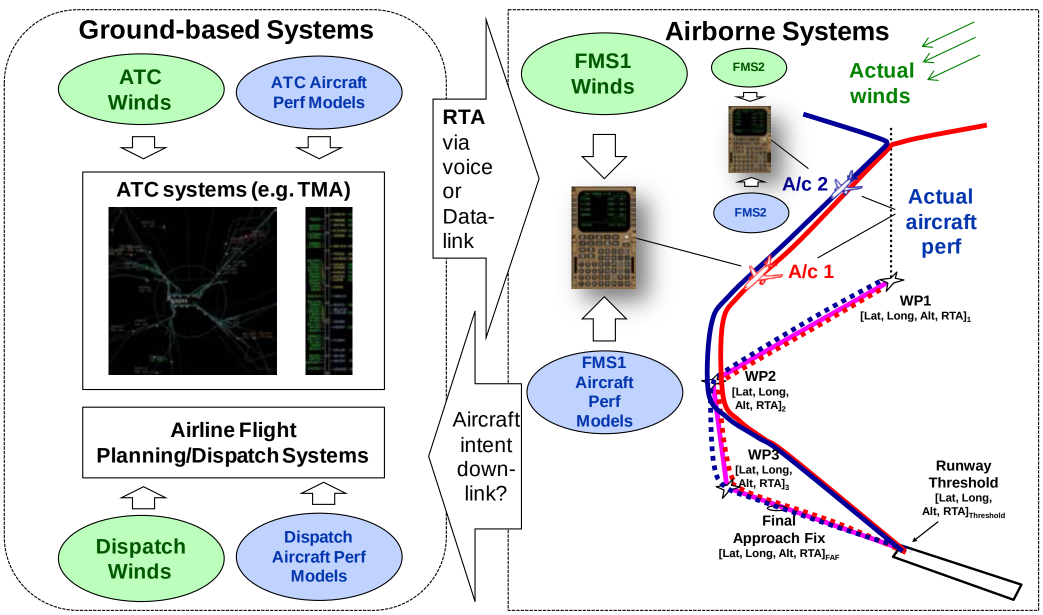

Figure 3: Four Dimensional Trajectory-Based Operations Concept

The Wind Information Analysis Framework is being tailored to establish quantitative requirements for wind diagnosis and forecasting capabilities to deliver different levels of 4D-TBO benefits, as described in the next section. Note that a key intent of the framework is addressing stakeholder needs: in the context of 4D-TBO this work may be used to support the creation of guidance such as concepts of operations, time-based performance requirements, weather Single Authoritative Source content definitions, etc.

III. Adaptation of Generic Wind Information Analysis Framework to 4D-TBO Applications

In order to exercise the analysis framework for this application, scenarios and representations of each element of the framework are required. In the current phases of the work, simplified versions of each of the elements are being applied to limited wind and 4D-TBO scenarios to examine the issues discussed above. These limited scenarios and simplified models are appropriate for the initial stages of the work to act as “proof-of-concept” to help refine the framework and to promote discussions with the sponsor and stakeholders regarding the type of outputs which would be of value. However, once this has been established, higher fidelity implementations of the key framework elements are required to ensure the accuracy and validity of the wind information requirement recommendations. Efforts based on these higher fidelity models will be presented in future publications. A summary of the variant of the analysis framework used for results presented in this paper is shown in Figure 4 and then the implementation of each block is described in turn.

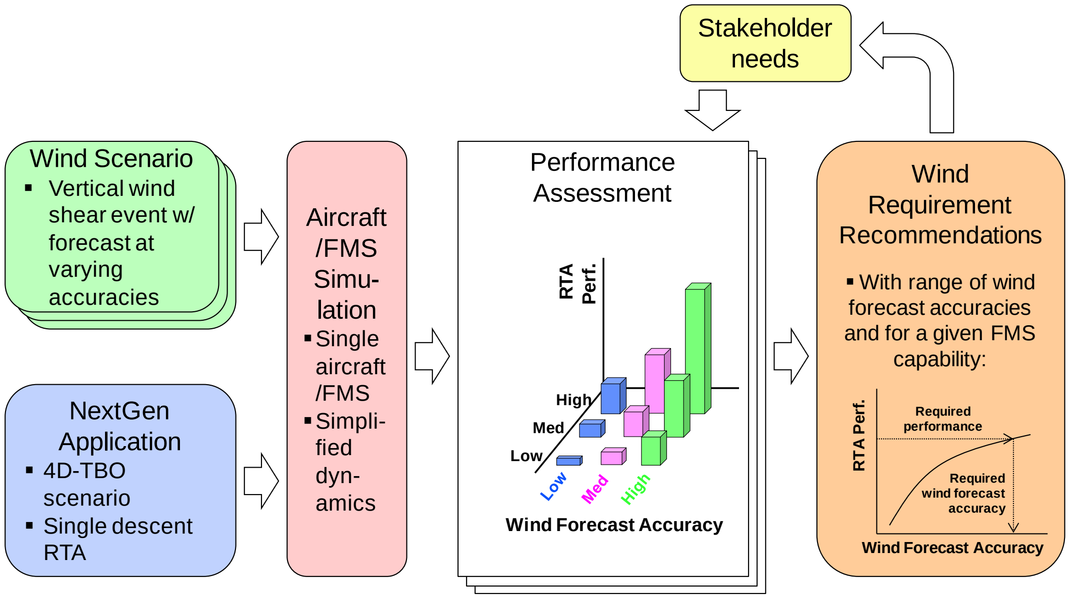

Figure 4: Initial 4D-TBO Application of Wind Information Analysis Framework

A. Wind Scenario

A study wind scenario was required which was representative of conditions occurring relatively frequently in the air transportation system and which is challenging from a 4D-TBO benefits delivery perspective. Candidate wind scenario options considered for this study included:

- 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
- Vertical shear of horizontal wind (significant change in wind vector with altitude) of varying vertical location & 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 inappropriate for capturing important effects of varying spatio-temporal resolutions which define various forecasting approaches (discussed below). The lateral boundary case was considered useful for investigating effects of varying horizontal forecast model resolution and update rates, but it was considered difficult to find real-world cases of surface fronts that did not have vertical wind shear. The vertical shear case was found to be 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 is presented in Figure 5. Note the large change in wind direction between 9,900 ft and the ground and the variation of the location of the direction change with altitude.

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. There are also many different measures of wind information quality for any given application and scenario, such as forecast horizon; spatial domain; vertical extent; horizontal extent; spatial resolution and temporal resolution. The characteristics of some of the key forecast models against a number of performance measures are presented in full in the Appendix, but Table 1 summarizes their performance against a common measure of Root Meat Square Error (RMSE), which is widely used in the domain to represent forecast accuracy. It is seen that models of increasing spatial resolution have decreasing wind forecast error as measured against the RMSE metric. The wind modelling of the chosen vertical wind shear scenario includes wind errors which are representative of the current and possible future wind forecasting technologies in order to explore the benefits impacts of improved forecast data.

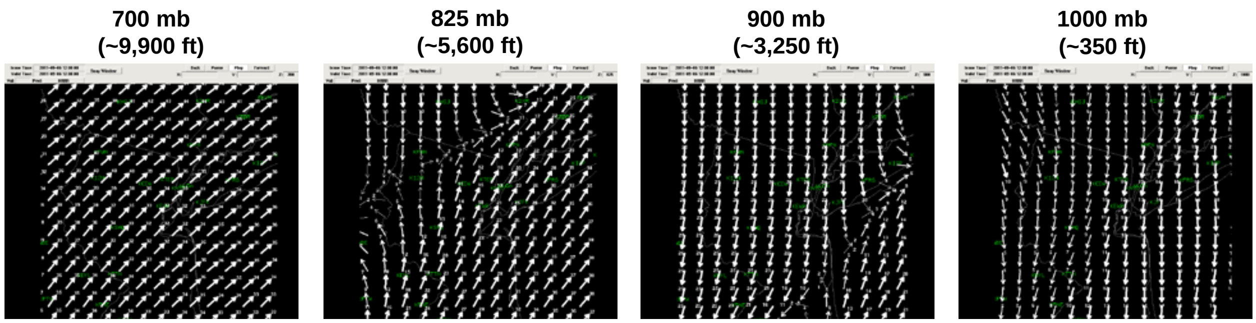

Figure 5: Sample Vertical Wind Shear Scenario (HRRR model analysis winds are shown)

Table 1: Key Wind Forecast Model Summary

Forecast Model	Horizontal Resolution	Reported RMS Vector Error	Comments	Reference
Rapid Update Cycle (RUC)	60 km	12 kts	Prior operational model	[5]
	40 km	9-11 kts	Prior operational model Errors aggregated over all (0-6 hr) forecast times	[7]
	13 km	8-10 kts (< 25 kft) 10-11 kts (25-50 kft)	Recent prior operational NOAA/NCEP model Used by TMA, ITWS Errors for 3-hr forecast	[6]
Rapid Refresh	13 km	7-10 kts (< 25 kft) 10-11 kts (25-50 kft)	Current operational NCEP model (Spring 2012) Errors for 3-hr forecast	[6]
North Atlantic European Model (NAE)	12 km	7-8 kts	Current operational European model. Will be replaced by upgraded Global Model in 2012 Estimated from component error graphs	[8]
ITWS TWINDS	10 km	7-9 kts	This was a pre-operational research configuration. No Doppler winds included. Current ITWS TWINDS has 1- and 4-km resolutions.	[5]
WAFTAGE	5 km	6 kts	Used for 3 years; CDA studies at Stockholm, 2009 MINT support Estimated from component error graphs	[8]
High Resolution Rapid Refresh (HRRR)	3 km	8-10 below 25 kft 10-12 @ 25-45 kft	Experimental, widely used (AWC, FAA Cmd Ctr, NCAR CoSPA) Errors are for 6-hr forecast	[4]

B. ATC Scenario

The ATC scenario component of the framework captures the specifics of the ATC environment within which the 4D-TBO procedures are being flown. This could include details on demand levels, aircraft and equipage types and procedures representative of current and future operations. The descent phase of flight has been seen to be of particular interest in current 4D-TBO studies and is also especially challenging from a vertical wind shear forecasting perspective. Therefore, the ATC scenario being explored in the initial stages of this work focus on a generic procedure from Top of Descent (TOD) with a target time at an intermediate metering fix at entry to the terminal area (approximately 10,000 ft). This is consistent with flight trials recently conducted in Europe [2] and also currently underway in the US [3]. The scenario may be expanded to include more complex procedure profiles and/or a larger number of time control points during the descent as appropriate as this effort progresses.

C. 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 is required. Aircraft elements modelled in this study include aircraft dynamics, engine performance, autopilot and FMS behaviors in order to model the behavior of the aircraft with a given RTA in the context of the chosen wind scenario. Each one of these elements could be modelled with a range of fidelities for any given aircraft/FMS configuration (e.g. for the FMS, from a simple MATLAB-based models capturing first-order behaviors to re-hosting of actual FMS logic). The approach being pursued in this work is to develop a modular architecture which can support different levels of model fidelity as the work matures and for different needs. In the results presented in this paper, simple models of each element described above for a typical commercial aircraft/FMS configuration were employed and which provided sufficient fidelity to prove initial utility of the framework.

D. Performance Assessment

A variety of benefits metrics 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 performance (e.g. the percentage of time a given RTA is achieved within a certain time window) 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, and then the work is likely to evolve to more integrated metrics in the future. The key performance outputs from existing RTA studies in US 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 at the meter fix, as illustrated conceptually Figure 6. 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 performance at the meter fix. This is illustrated at the right side of Figure 6.

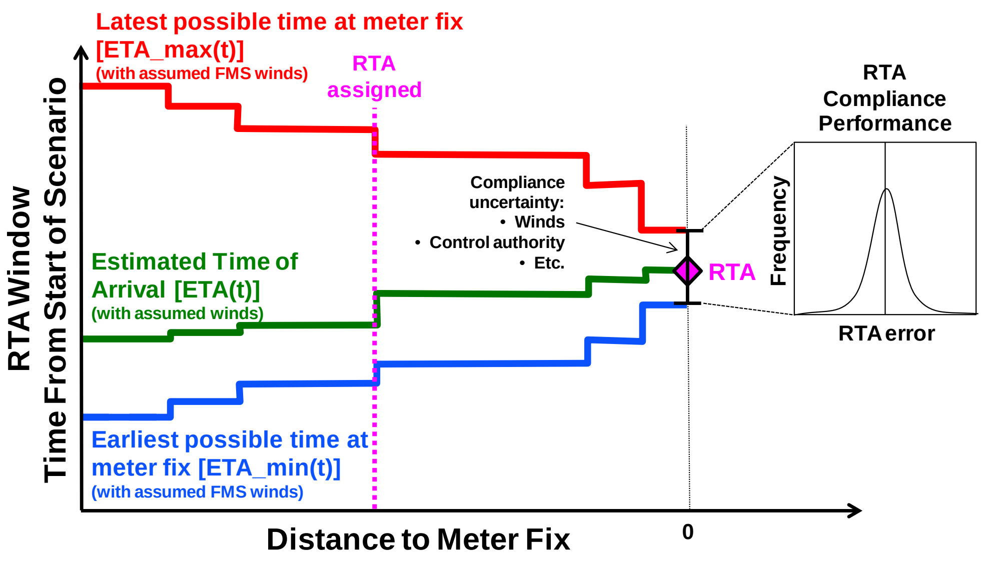

Figure 6: 4D-TBO RTA Window and RTA Compliance Performance Metrics

E. Wind/FMS Requirements Recommendations

Variations of benefits metrics with two key independent variables are illustrated in the graph in Figure 4. These are wind information quality and FMS capability. Wind information quality can be categorized in terms of "low" (e.g., based on coarse forecast models), "medium" (e.g., representing state-of-the-art today) and "high" (e.g., representing possible future wind forecasting products which may be motivated by performance requirements identified by this analysis). In terms of FMSs, the capability of the automation to support automatic RTA control is of critical importance to the study and varies significantly across the commercial aircraft fleet. "Low" capability is representative of older technology FMSs which typically provide lateral and vertical control but no automatic RTA functionality (i.e. RTA capability is only possible via manual speed control). "Medium" capability is representative of current generation FMSs which typically provide lateral, vertical and RTA control but incorporate wind information only at a limited number altitudes and only at specified waypoints. 'High" capability might represent possible future generations of FMSs which may hold potential for much more complex RTA compliance algorithms and better wind representations (e.g. more levels, gridded winds not restricted to waypoints, etc.).

It is reasonable to expect 4D-TBO benefits to increase with better wind information and more advanced FMS capabilities, but the magnitude of benefits changes with variation in the independent variables 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 to support different levels of 4D-TBO performance.

IV. Wind Error Sources Relevant to 4D-TBO Applications

The importance of wind errors to 4D-TBO performance has been introduced in the previous sections. This section provides more details on the types of wind errors of relevance to the 4D-TBO application. Figure 7 shows a feedback control representation of an aircraft controlling to an RTA which is provided to the input of the FMS (at the left of the diagram). This RTA is compared to the ETA at the meter fix which is being continuously calculated by the FMS. A wind forecast ($Winds_{Forecast}$) is used as a basis for a representation of the expected wind field in the FMS ($Winds_{FMS}$) which is used together with an aircraft performance model (A/c $perf_{FMS}$) 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 autothrottle command to the engine. This should lead to the ETA being driven towards the RTA (as long as the RTA is within the feasible region defined in Figure 6) with a time constant driven by the aircraft and engine dynamics. The sources of possible wind errors in the context of this control system representation are also illustrated in Figure 7 in terms of wind forecast errors, ATC/airline errors and FMS errors, each of which are described next.

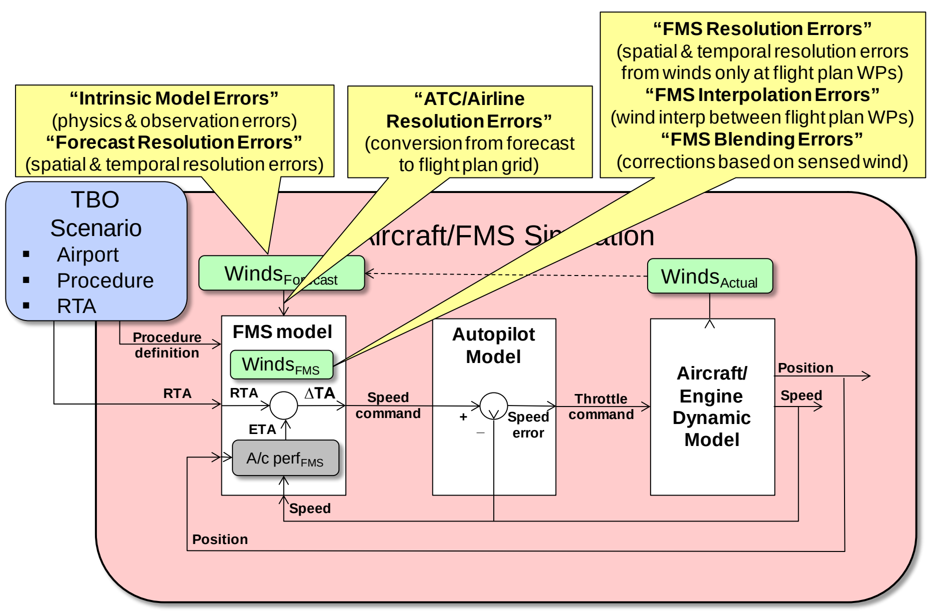

Figure 7: Key Wind Error Sources of Relevance to 4D-TBO Applications

A. Forecast Wind Errors

i. Intrinsic Model Errors

Intrinsic model error is the aggregate error that encompasses 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 modelled state of the atmosphere to increasingly differ from the actual state of the atmosphere (the "butterfly effect").

ii. Forecast Resolution Errors

Forecast resolution errors are essentially the sampling errors that arise due to 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 in scenarios where winds are changing rapidly in space or time (such as the vertical wind shear scenario). Although model spatial and temporal resolution contributes to the overall intrinsic model error, the significance of these effects is being explored separately in this study.

B. ATC/Airline Wind Errors

When airlines file a flight plan for a given flight, available wind forecast information impacts the chosen route of flight, as well as the filed altitudes and speeds. 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 those in the base wind forecast discussed above.

C. FMS Wind Errors

i. FMS Resolution Errors

Most currently operational FMSs only allow [9] wind magnitude and direction information to be entered for a limited number (typically 3-5) altitude levels 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 mile apart) and vertical spatial resolution dictated by 3-5 generic altitude levels. This down-sampling of the wind forecast information to the trajectory-based grid that can be handled by the FMS leads to additional "FMS Resolution Errors" on top of the wind forecast errors.

ii. FMS Interpolation Errors

Although current FMSs only allow wind information to be entered at the specific trajectory-referenced locations discussed above, wind estimates can be made at other locations by using interpolation algorithms. Lateral and vertical wind estimates are sometimes 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. These 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 5 would not be well represented by linear or constant interpolation) and therefore "FMS Interpolation Errors" add to wind forecast errors. In addition, if an aircraft leaves its flight plan route for any reason (e.g., air traffic control 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 (see next).

iii. FMS Blending Errors

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. Specific details on these blending algorithms are often proprietary, but in principle they are designed to correct for the other error sources identified above.

V. Sample Results

A. Model Set-up

i. Aircraft/FMS model

The current aircraft/FMS model is coded in MATLAB. It is a simplified point kinematic system with infinite control authority for immediate reaction at every calculation and has bounded minimum and maximum indicated airspeed (IAS) of 350 kts and 450 kts respectively. For the particular wind shear scenario under evaluation, it is useful to treat the model as a 1-D airspeed control model, since we are currently concerned only with a trajectory normal to the wind shear zone in which an aircraft would experience a rapid headwind/tailwind switch.

The trajectory is defined by a starting point and a number of intermediate equidistant control points along the trajectory at which the remaining trajectory is re-evaluated to update the airspeed based on the error between observed and predicted winds aloft. A meter fix is assumed to exist at the end of the simulated trajectory and the RTA is assigned at the first trajectory re-evaluation point determined by assuming a 400 kts constant IAS with zero wind up to the meter fix. Speed corrections are made at the control points spaced at 1° longitudinal at ~40.7° latitude (~45.6 nm). The winds aloft begin as a 30 kts headwind and transition to a 30 kts tailwind from -77° to -75° longitude.

The model uses several instantiations of wind data:

- The truth wind data are used for computing time-of-flight per each segment in between control points.
- Forecast wind data are used to estimate an initial feasible RTA (taken as the mid-point of the RTA window at the assignment point for this study).
- FMS wind data are used at each control point to determine the ETA to the meter fix and correct the airspeed to attempt to meet the RTA.

Because the model computes speeds on a per-segment basis (i.e., between control points), the wind speeds are interpolated to the middle of the segment: $\mathrm{U}_{S(N,N-1)} = {(\mathrm{U}_N + \mathrm{U}_{N-1})}/{2}$, where $\mathrm{U}_{S(N,N-1)}$ is the wind speed associated with the segment bounded by N and N-1, and U_N, U_{N-1} are the values at the segment bounds.

The FMS model attempts to find and maintain a constant airspeed over the course of the trajectory to the meter fix by integrating the ground speed-based segment times for the remaining portion of the trajectory and solving for the airspeed that best matches the given RTA. In an error-free environment, this results in a truly constant airspeed, requiring no modification during flight. As errors are introduced by either the wind forecast model or the FMS wind model, the FMS must take corrective action and alter the airspeed for the remainder of the flight. Although this is a closed-loop control system, and in this simplified model of aircraft behaviour and trajectory it will not lead to compounding errors, if each individual error is sufficiently large that it takes the trajectory outside the feasible region, the end result could be an inability to meet the RTA.

The FMS/aircraft model is invoked in a Monte Carlo fashion to obtain a statistical description of the error characteristics arising from the various wind models. The next section details the errors introduced by the forecast winds model. The FMS wind errors are generated for every control point using a normal distribution with the noise value in knots being equal to a single standard deviation. Every sample of the error characteristics generates a new FMS error instance. The forecast winds remain stationary in the results presented here, although in order to explore the independent contributions of both distributions, we will sample from each error distribution for every sample in future work.

ii. Wind model

Actual and simulated wind fields are being used to quantify the effects of varying wind information quality on the performance metrics being investigated. An extensible, object-oriented modelling framework for representing 4D wind information as well as other atmospheric parameters, both simulated and actual, has been implemented using MATLAB (see Figure 8). Although it is being used for modelling winds in this application, the framework can be expanded to include other types of models and atmospheric parameters (light gray boxes and lines in the figure).

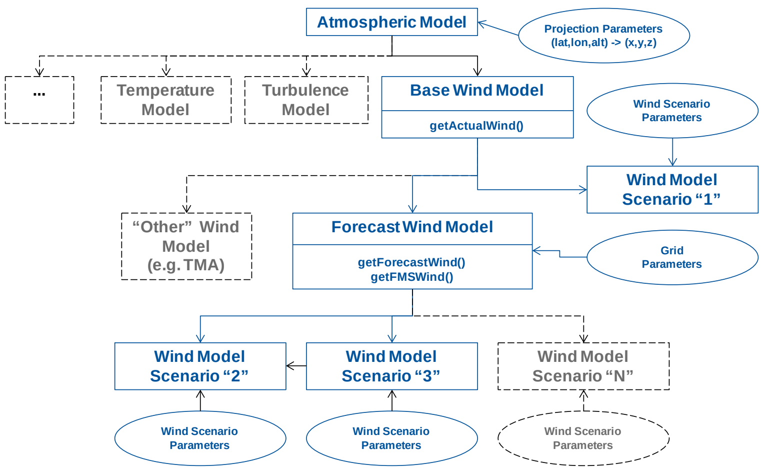

Figure 8: Wind Modelling Framework (elements in blue have been implemented)

Each wind model contains scenario-specific logic that implements parameterized continuous analytical functions for generating simulated wind values as a function of 3-D location and time. Wind values returned from calls to the analytical function, i.e., via "getActualWind()", are used in the 4D-TBO simulations to represent the actual wind that the aircraft encounters.

Figure 9 shows the wind model simulation parameters and resulting wind field for the sample results that follow. For this simple scenario, the wind speed is constant and the wind direction varies horizontally through a stationary, north-south oriented shear zone. Accordingly, the wind model parameters define the location and width of the shear zone, and the amount of linear wind direction change through the shear zone.

Wind Field Simulation Parameters

Parameter	Value
StartWindDir	270 deg
StartWindSpd	30 knots
ShrZoneWindDirDelta	-180 deg
ShrZoneCenterX	-160000.0 m
ShrZoneWidth	160000.0 m

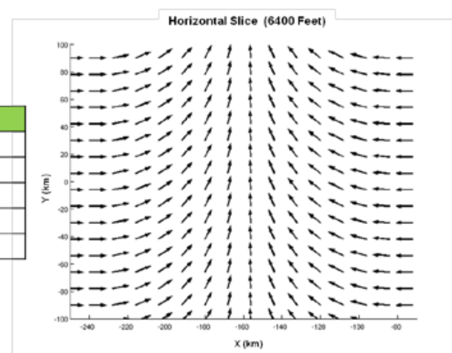

Figure 9: Simulation Parameters and Generated Wind Field
(a 2-D horizontal slice of the horizontal winds are shown at right with X and Y distances in kilometers with respect to an origin east of the displayed grid. Winds are from the west on the left, then rotating through the shear zone centered at X = -160 km, becoming easterly on the right)

In order to represent simulated or actual gridded forecast wind information such as that provided by numerical weather prediction models, the wind models also implement logic to sample the analytical wind function at varying spatial and temporal resolutions, or alternatively import actual wind model data (such as HRRR model data). Simulated intrinsic model errors (normally distributed random errors or constant wind speed and direction errors) are then superimposed on the gridded wind values. Random error fields are constructed such that they are correlated over appropriate time and length scales. Figure 10 shows examples of superimposed wind errors on a sample gridded wind field. The gridded wind models provide a "getForecastWind()" function that retrieves the gridded forecast wind value for the requested location and time. If the location is between grid points, then the function employs a specified interpolation method between neighboring points. Currently "nearest neighbor", and linear interpolation are supported.

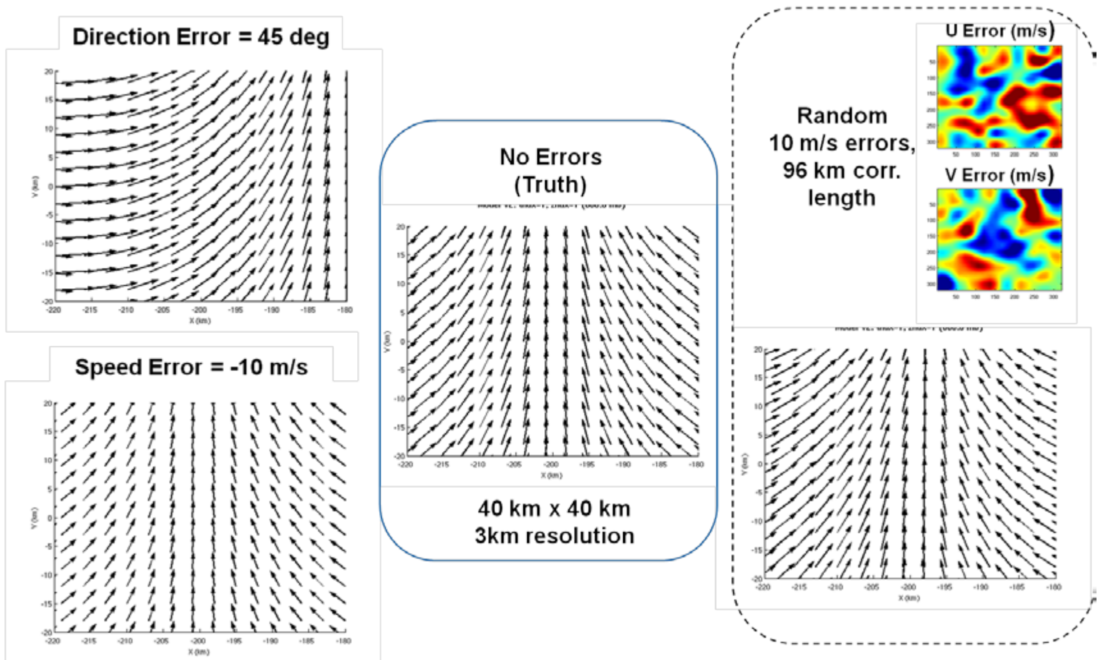

Figure 10: Examples of Simulated Wind Forecast Errors

B. RTA Window and RTA Compliance Performance for Various Forecast and FMS Wind Errors

Based on the wind model assessment presented in Table 1, the best wind forecast models have an RMSE ≈ 5 kts, while older, coarser models have an RMSE ≈ 25 kts, so these were taken as the “low” and “high” wind forecast error bounds in these results. Operational data regarding FMS errors is hard to acquire due to its proprietary nature. However, the FMS resolution and interpolation errors identified above would incrementally add to the wind forecast errors, while FMS blending has the potential to improve the wind forecast errors. As a first approximation, in these sample results the “low” and “high” FMS errors were taken to be the same as the wind forecast errors, i.e. 5 and 25 kts respectively.

Figure 11 presents the RTA window and RTA compliance performance metrics (previously introduced) for each combination of low and high forecast wind and FMS error. There are four sub-plots in each panel: the top plot presents the true wind, forecast wind and FMS wind as a function of aircraft position (longitude) along its trajectory; the second plot presents the RTA window as a function of position; the third panel presents the airspeed as a function of position; and, finally, the fourth plot shows the RTA compliance error. In each case, the RTA is assigned after the first simulated prediction step, corresponding to approximately -78° longitude on the position axis.

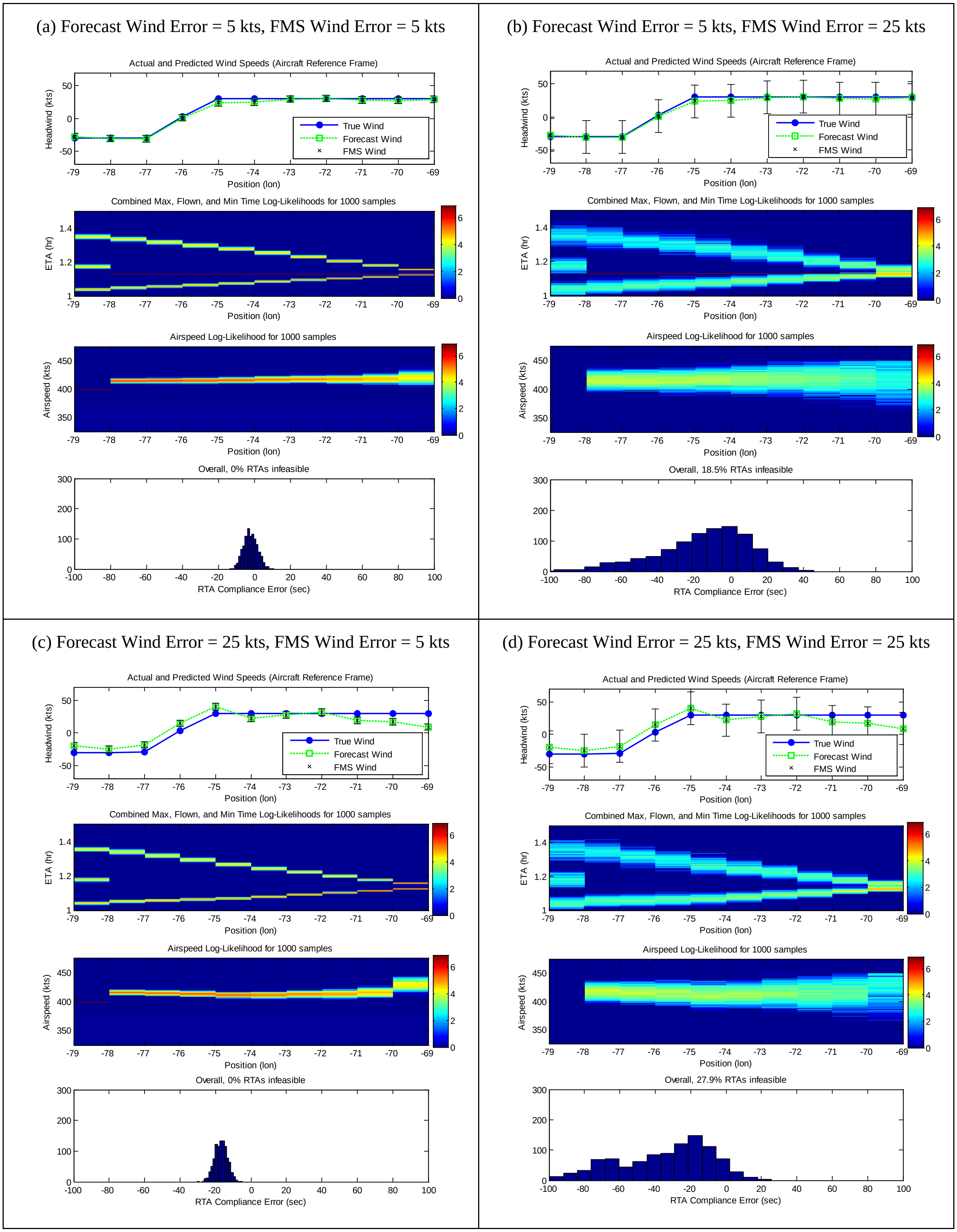

Figure 11: Sample 4D-TBO Performance Metrics for Various Forecast and FMS Wind Errors

The top left panel of results is for the case of low wind forecast errors (5 kts RMSE) and low FMS error (5 kts RMSE). The wind profiles are presented as simple headwind/tailwind components along the direction of flight with positive being a headwind in the aircraft's reference frame. The true wind profile is seen to be an initial tailwind with a smooth transition to a headwind for much of the latter part of the simulated flight. 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 400 kts IAS by default. After the RTA is assigned, there is an initial increase in airspeed which is consistent with the FMS wind expectation of a net headwind up to the meter fix. The speed variation over time is relatively small given the small wind errors, but the slight increase near the end of the profile can be explained by the fact that there is a slight negative bias in the model forecast and FMS errors relative to the truth wind at this time. Therefore, the aircraft actually experienced more of a headwind than expected, requiring a small speed increase to compensate for the wind error. Finally, the RTA compliance error is seen to be a tight distribution, again 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 RMSE) and high FMS wind error (25 kts RMSE). 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 boundaries show much greater variability, which translates into much greater speed variability and RTA compliance error compared to the previous set of results. Note, because of the high FMS errors, 18.5% of the RTAs become infeasible during the profile (i.e. outside the boundary defined by the maximum and minimum ETAs), even though the initial RTA assignment was feasible (based on a "constant 400 kts IAS, zero wind" assumption).

The bottom left set of results is for the case of high forecast wind error (25 kts RMSE) and low FMS wind error (5 kts RMSE). This is evident in the sizeable offsets between the truth and forecast wind profiles in the top plot, 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. However, the offset in the model forecast and FMS errors relative to the truth winds manifests as an offset in the RTA compliance error distribution. Because the expectation was for less of a headwind than actually experienced towards the end of the profile, the aircraft arrives on average 20 seconds late to the meter fix compared to the RTA.

The bottom right set of results is for the case of high forecast wind error (25 kts RMSE) and high FMS wind errors (25 kts RMSE), 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 and RTA compliance variabilities, and the fraction of RTA infeasible, are all worse than those observed in the second set of results, with 27.9% of the RTAs becoming infeasible. Now the RTA compliance error distribution is also offset in the negative direction similar to that observed in the third set of results. Hence it is seen that, in these sample results with the modelling 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 distribution.

The RTA assignment strategy also plays an important role in determining the fraction of feasible RTAs. If the strategy were to change from the simple zero-winds assignment at nominal airspeed (as used in the results presented in Figure 11) to a strategy involving a one-time winds forecast and using the average of the min and max ETAs at the time of RTA assignment, the percentage of infeasible RTAs drops dramatically (e.g., from 27.9% to 10.2% in the case of 25 kts RMSE wind forecast and FMS errors). This points to the fundamental importance of accurate wind forecast and aircraft performance models in the RTA assignment algorithms, for example, as would be present in the ground-based systems identified in Figure 3. These will be explored in more detail in future publications.

C. Wind Information Requirements

By parametrically varying the forecast wind and FMS wind errors from low to high values, it is possible to obtain RTA performance metric surfaces that are of value in the setting of 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 12) and the % infeasible RTAs as a function of forecast wind error and FMS error.

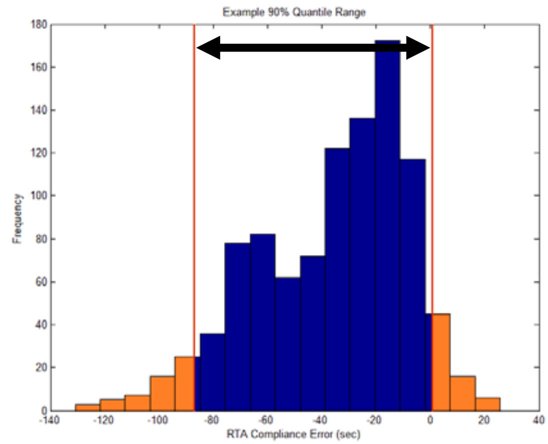

Figure 12: Example 90% Interquantile Range shown by arrow
(data below 5% and above 95% are represented by light/orange color)

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 13. In general, the smaller the interquantile range and the fewer % infeasible RTAs, the better the RTA performance. Performance degradation is seen to be much more severe with FMS wind errors than with wind forecast errors. 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.

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 next. However, it can be seen how, in principle, forecast wind error and FMS wind error requirements could be set from surface like this in order to achieve a given RTA compliance performance, or define what level of RTA compliance performance would be possible with different combinations of forecast and FMS wind errors. Such relationships are the primary objective of this analysis approach, and hence these sample results demonstrate the utility of the approach being pursued.

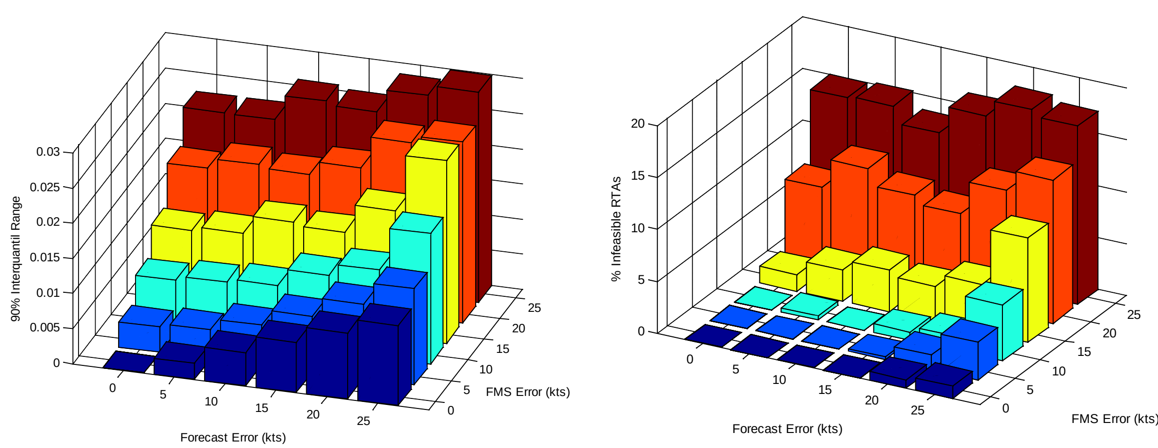

Figure 13: RTA Compliance 90% Interquantile Range (left) and % Infeasible RTAs (right)
as a Function of Forecast Wind Error and FMS Wind Error

VI. Conclusions & Next Steps

The utility of the Wind Information Analysis Framework has been demonstrated through its application for a simple 4D-TBO scenario coupled with representative wind error models. Even this simplified set of models allows significant insights to be gained which are of value to stakeholders in terms of overall behaviors. Next steps include:

- Increasing the aircraft/FMS modelling fidelity (e.g., by using full aircraft aerodynamic/propulsion simulation and re-hosted FMS software) to increase the realism and applicability of the results to stakeholder needs such as time of arrival control requirements setting.
- Developing higher resolution wind forecast models to address gaps between required performance levels and current state of the art models identified through this analysis.
- Add fuel burn as another key performance metric in the 4D-TBO analysis given there are often important trade-offs in system performance identified through parallel fuel assessments.
- Collaborating with FMS vendors to explore realistic future FMS capabilities to address some of the identified shortcoming in existing FMS capabilities, and integrating these improved algorithms into the analysis framework to analyse their impact.
- Expanding the focus applications beyond 4D-TBO, e.g. Flight Interval Management – Spacing, Improved TMA and/or DataComm applications.

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Appendix: Wind Forecast Model Summary

Model	Producer	Domain	Resolution and Update	Output Forecast Step / Horizon	Operational Status	Users
GFS	NOAA/ NCEP	Global	0-192 hrs: 25 km 204-384 hrs: 80 km Update: 6 hours	3 hrs / 192 hrs 12 hrs / 204-384 hrs	Operational	Public Domain Airlines (flight route planning) Private wx vendors Boundary conditions for RAP model
Rapid Update Cycle (RUC)*	NOAA/ NCEP	CONUS	13 km 50 levels to 50 mb Update: 1 hour	1, 3 hours/ 18 hours	Operational until March 20, 2012	NOAA (Av.Wx.Ctr, Storm Pred. Ctr) FAA (ATM, CWSUs, ITWS, TMA) Airline dispatchers Private vendors (e.g., WSI, TWC) Av. Wx. Research
Rapid Refresh (RAP)*	NOAA/ NCEP	North America	13 km 50 levels to 10 mb Update: 1 hour	1 hour 18 hours	Operational March, 2012 (Replaces RUC)	
High Resolution Rapid Refresh (HRRR)*	NOAA/ ESRL	CONUS	3 km 50 levels to 20 mb Update: 1 hour	1 hour/ 15 hours	Experimental Est. operational at NCEP in 2014	AWC, FAA Command Ctr, NCAR, CoSPA, NWP
ITWS TWINDS*	FAA, MIT LL	Terminal Area 240 x 240	4 km, 36 levels 1 km, 24 levels Update: 5 min	0 hours (diagnostic only)	Operational at 44 major US airports	ATC managers, supervisors at ATCTs, TRACONs, & ARTCCs, pilots, airline dispatch
WTMD Wind Forecast Algorithm (WFA)	MIT LL, FAA Prototype	Airport	Single point 6 levels to 1000 ft Update: 1 min	Nowcast valid for next 20 min	Prototype FAA testing at IAH, SFO, & MEM 2012-13	ATC for runway planning (parallel approach)
Terminal Aerodrome Forecast (TAF)	WFOs, UK Met Office	Airport 5 mi radius	Surface winds only Update: 6 hours	Varies 30 hours	Operational	Commercial airlines, military, GA pilots
Global	UK Met Office	1024 x 769	25 km 70 levels to ~80 km Update: 6 hours	1 hour / 144 hours	Operational Replaces NAE in 2012	Forecasters, airlines, air traffic control, private aviation met. service providers
North Atlantic European Model (NAE)*	UK Met Office	600 x 360	12 km 70 levels to ~80 km Update: 6 hours	1 hour / 48 hours	Operational Will be replaced by upgraded higher resolution Global model in 2012	
UK4	UK Met Office	UK 288 x 360	4 km 70 levels to ~40 km Update: 3 hours	3 hours / 36 hours	Current operational Becomes secondary model behind UKV in 2012	
UKV	UK Met Office	UK+ 744 x 928	Variable (1.5, 4 km) 70 levels to ~40 km Update: 3 hours	3 hours / 36 hours	Experimental Becomes main operational model for UK in 2012	
WAFTAGE*	UK Met Office	Stockholm region (relocatable)	62x70 lat-lon pts (~ 5 km) 45 levels (1000 ft intervals) Update: 1 hour (custom)	20 min 80 min	Research	In use for past 3 years; CDA studies at Stockholm, 2009 MINT support