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Wind Information Requirements to Support Four Dimensional Trajectory-Based Operations[*]

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Accurate wind information is required to support some of the key applications envisioned for future air traffic concepts. A Wind Information Analysis Framework is described to assess wind information needs for different applications. The framework is 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 limitations 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 determine wind information requirements are provided.

I. Introduction

ACCURATE wind information is of fundamental importance to some 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 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 needs and the delivery of benefits from the future applications. A Wind Information Analysis Framework is developed in this work to address this need, as shown on the left side of Figure 1. The framework is described in the next section, followed by its application for a sample 4D-TBO application to illustrate its utility in Section 3. Section 4 interprets the findings in terms of how they help determine wind information needs for future air traffic control applications.

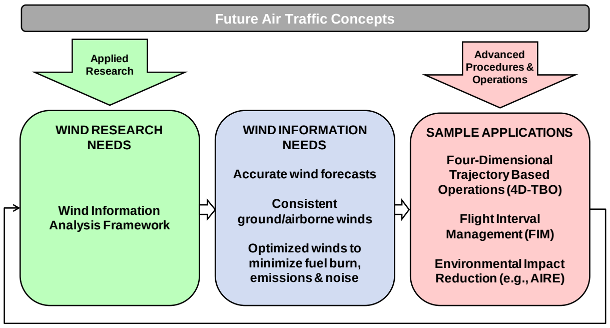

Figure 1: Wind Information Supporting NextGen Applications

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II. Wind Information Analysis Framework

A Wind Information Analysis Framework has been developed as 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 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, etc.
- **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 role of stakeholders in determining appropriate choices in the other framework elements, e.g., in terms of what performance metrics are of value to them or to support the creation of guidance or requirements documents.

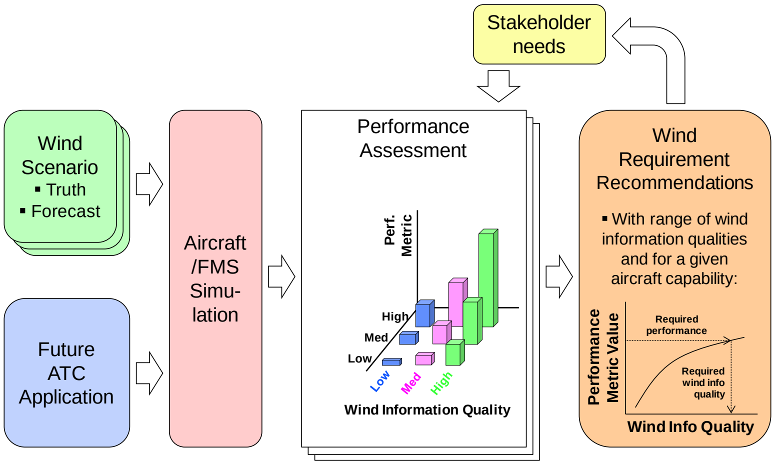


Figure 2: Generic Wind Information Analysis Framework

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 is applied in this paper to a simple 4D-TBO application, as described next.

III. Four-Dimensional Trajectory-Based Operations (4D-TBO) Application

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 3. 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 3) to manage traffic flows as efficiently as possible. These time targets are sent to individual aircraft, which are then responsible for managing their trajectory to achieve the time target at the meter fixes through 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 and airborne FMSs which are creating and managing compliance to the time targets respectively.

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 [1,2]. 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 3.

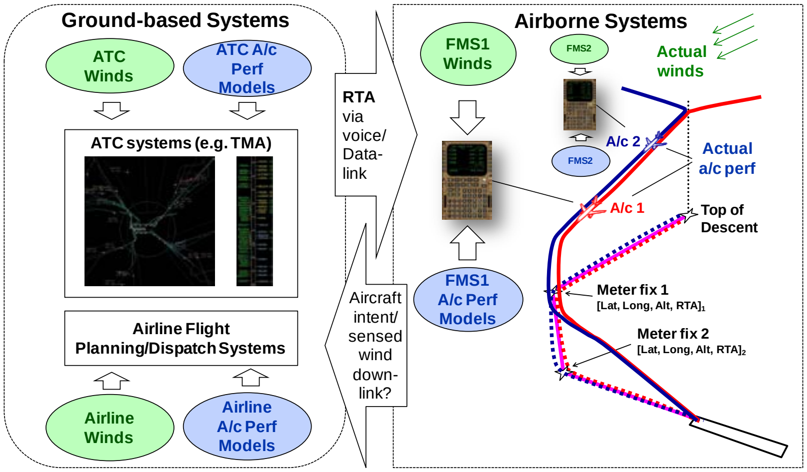


Figure 3: Four Dimensional Trajectory-Based Operations Concept

In this paper, the Wind Information Analysis Framework is tailored to the 4D-TBO application as shown in Figure 4. The implementation of each block is described in turn next.

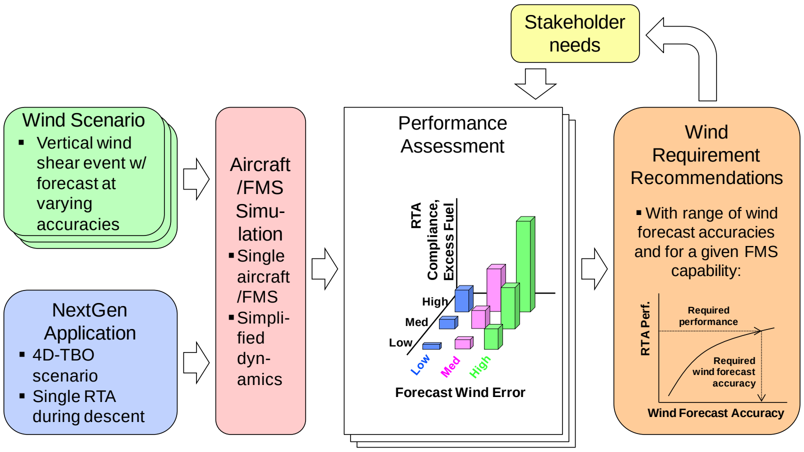


Figure 4: Initial 4D-TBO Application of Wind Information Analysis Framework

A. Wind Scenario

A 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; 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 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 difficult to find real-world cases of surface fronts that did not have associated 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 that caused major challenges from an ATC perspective is presented in Figure 5. 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 n mi x 400 n mi 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.

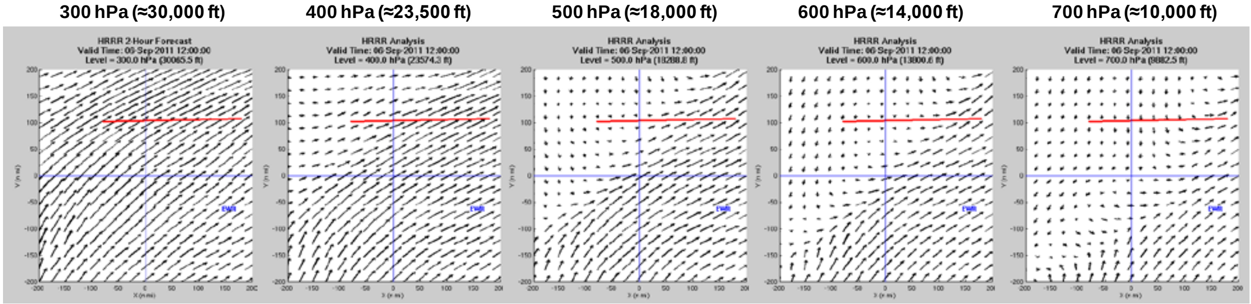


Figure 5: Sample Vertical Wind Shear Scenario (New York area, 9/6/2011)

B. ATC Scenario

The ATC scenario 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 of the work reported in this paper, a single narrow-body aircraft flying a straight-line trajectory with a meter fix at the end was modelled. The wind field was that illustrated in Figure 5 and the trajectory was intentionally located so that it encountered the lateral boundary of the wind shear (shown in red in Figure 5). For simplicity, a constant altitude flight profile was assumed in this work, with the altitude chosen to force a large wind shift part-way through the flight profile.

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, subsequent work will explore a generic procedure from Top of Descent (TOD) with a target time at a single intermediate metering fix at entry to the terminal area (approximately 10,000 ft). This is consistent with flight trials recently conducted in Europe [1] and also currently underway in the US [2].

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. Models of the aircraft dynamics, engine performance, autopilot and FMS are needed to represent 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 model 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 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) [4]. The FMS model was based on a feedback control representation of an aircraft controlling to an RTA, as shown in Figure 6. The RTA is compared to the 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.

D. Performance Assessment

The performance assessment of the aircraft flying in the context of the wind and ATC scenario discussed above was conducted in terms of how appropriate performance metric dependent variables varied as a function of appropriate independent variables.

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.

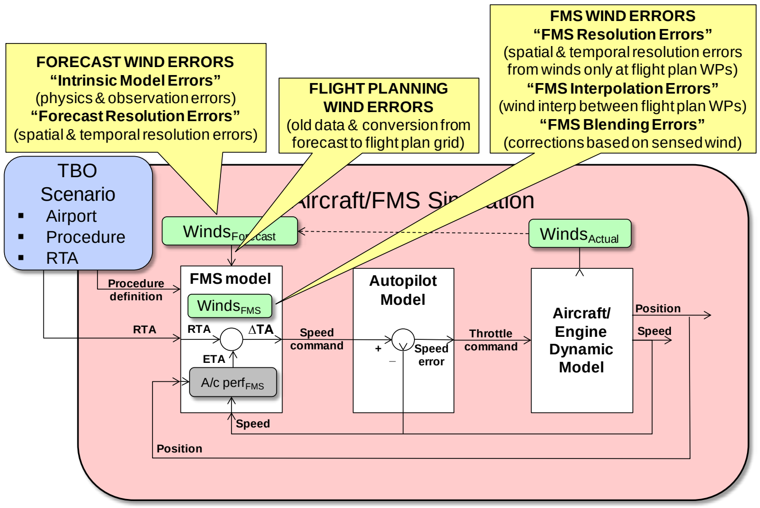


Figure 6: Aircraft Modeling and Key Wind Error Sources of Relevance to 4D-TBO Applications

Figure 6 identifies the sources of possible wind errors in the context of the aircraft control system representation in terms of Forecast Wind Errors, ATC/Airline Wind Errors and FMS Wind Errors:

- **Forecast Wind Errors** include intrinsic and resolution errors. 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 modelled 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 the vertical wind shear scenario).
- **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)

and vertical spatial resolution dictated by the number of input 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 resolution errors on top of the Forecast 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 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 interpolation errors also add to Forecast Wind 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. 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.

In order to quantify how much each of these error sources may introduce, a detailed assessment of current forecast models was undertaken. 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 performance of some of the key forecast models is presented in Table 1 relative to Root Meat Square Error (RMSE), which is widely used in the domain to represent forecast accuracy.

Table 1: Key Wind Forecast Model Summary

Forecast Model	Horizontal Resolution	Forecast Wind Error (RMS Vector Error)	Comments	Ref.
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.	[6]
	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.	[7]
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.	[7]
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 2- and 10-km internal grid 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	[9]

From Table 1 it is seen that models of increasing spatial resolution have decreasing wind forecast error against the RMSE metric and hence we can conclude the forecast errors typically fall in the range of 5-12 kts RMSE. 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, so it was assumed in this study that they had a similar range to the forecast errors discussed above. 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 5-25 kts RMSE. 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 5-25 kts RMSE range. Future work intends to quantify FMS Wind Errors more explicitly.

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, 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 error at the meter fix, as illustrated conceptually Figure 7. 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 7. The RTA compliance error used in this work represents the time interval around the ETA which contains 95% of the flights, so a larger compliance error would imply a wider RTA compliance distribution.

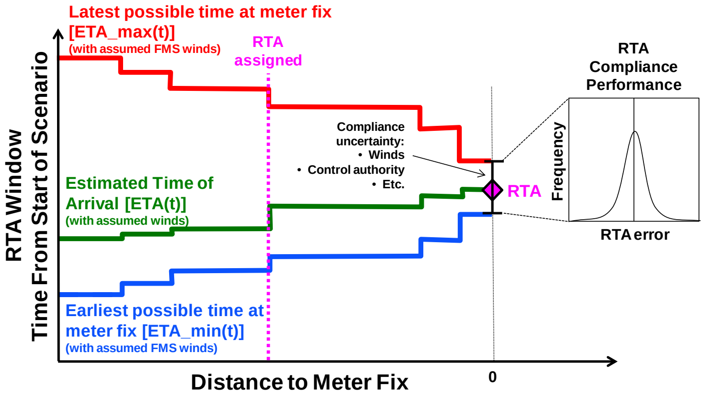


Figure 7: 4D-TBO RTA Window and RTA Compliance Performance Metrics

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 burn, which could be a problem in 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 modelling previously described.

E. Wind/FMS Requirements Recommendations

Variations of the dependent variables with the independent variables allow an analysis of the key relationships of interest in this study. For example, the Performance Assessment block of Figure 4 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 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 performance metrics to increase with higher forecast and FMS wind errors, but the relative and absolute magnitude of the performance variation with each 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.

IV. Results

A. Model Set-Up

The current aircraft/FMS model is coded in MATLAB and flies the scenario trajectory using BADA performance assumptions and flying through the real-world wind case detailed above. 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. The truth wind data based on the HRRR 0-hour forecast are used for computing actual time-of-flight per each segment in between control points.

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 418 kts constant TAS (consistent with BADA nominal speed for cruise at FL210) 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 is the Forecast Wind Error.

The FMS model makes 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 are used at each control point to determine the *estimated* time-of-flight (ETA) to the meter fix and correct the airspeed to attempt to meet the RTA. The difference between the FMS wind and the truth wind is the sum of the Forecast Wind Error and the FMS Wind Error. 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 forecast wind and FMS wind errors are generated for every control point using normal distributions with the noise value in knots being equal to a single standard deviation. The simulated FMS currently does not perform blending; its error, thus, represents agglomerated error terms. Every sample of the error characteristics generates a new FMS error instance.

Based on the wind model assessment presented in Table 1, the best wind forecast models have an RMSE $\approx$ 5 kts, while older, coarser models have an RMSE $\approx$ 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.

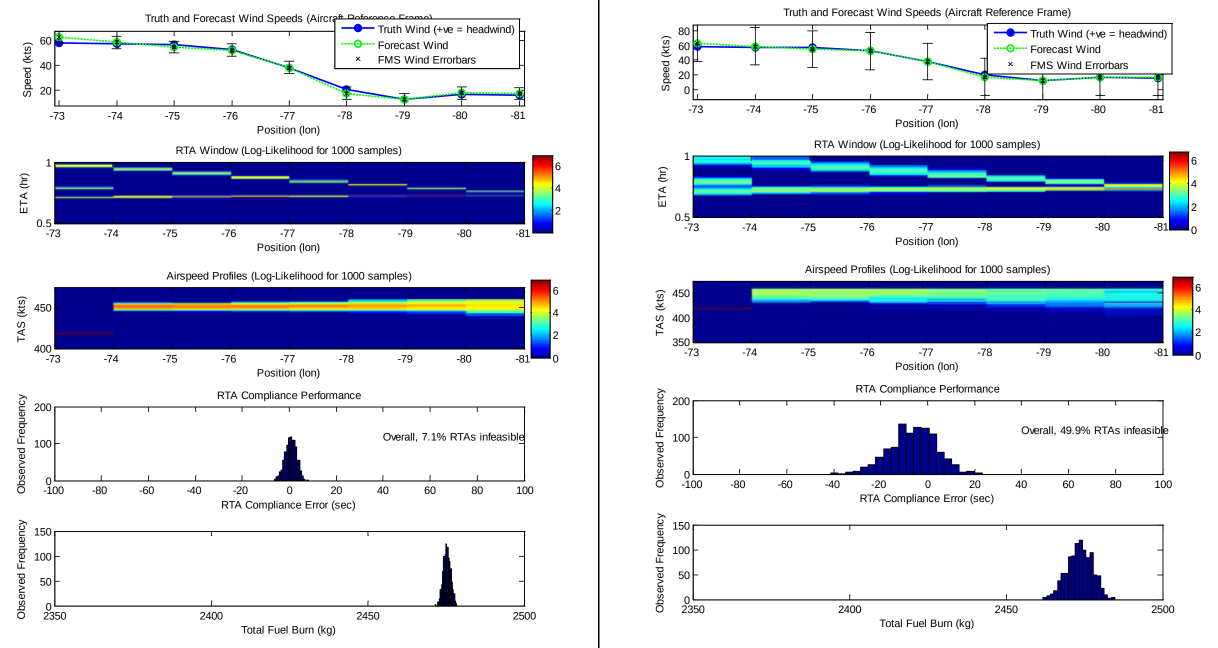
The sections that follow present results from the Monte Carlo simulations for a variety of cases to showcase the insights that can be gained from the use of the analysis framework.

B. Performance with Basic RTA Assignment Strategy

Figure 8 presents the RTA window, RTA compliance performance and fuel burn metrics (previously introduced) for each combination of low (5 kts RMSE) and high (25 kts RMSE) 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. There are five 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 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. This final fuel burn plot can also easily be converted to carbon dioxide emissions performance by using the standard multiplier of 1 kg of fuel burn producing 3.16 kg of CO_2.

(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

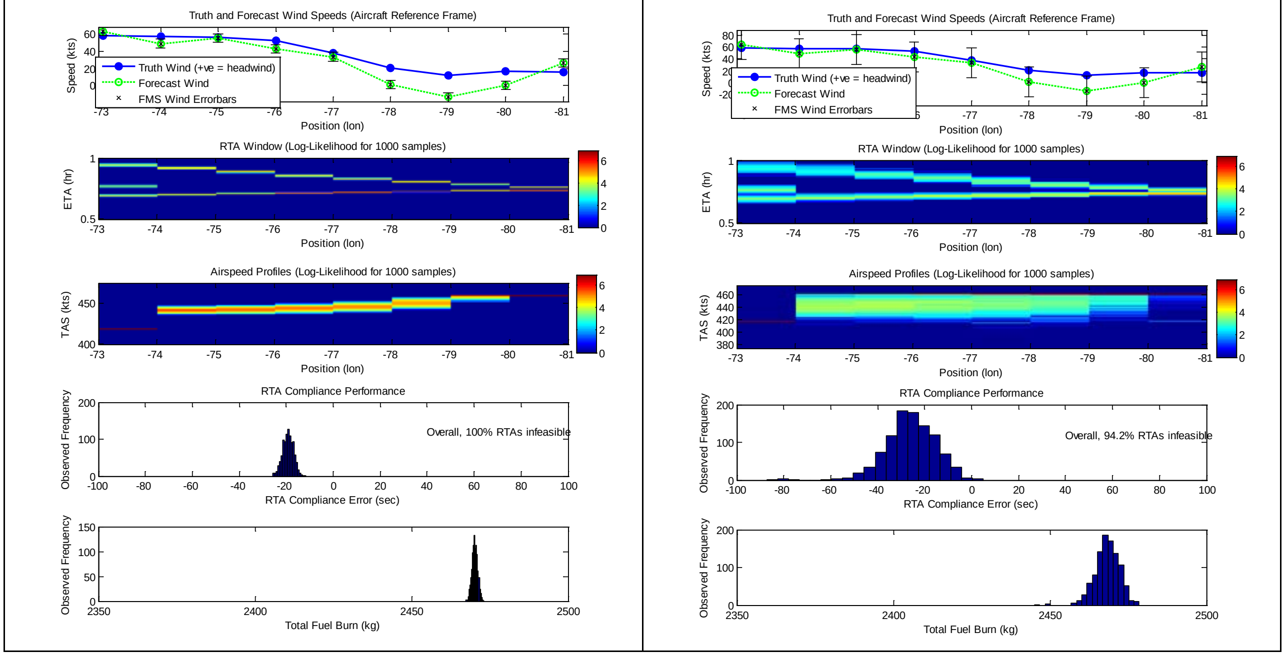


Figure 8: Sample 4D-TBO Performance Metrics for Various Forecast and FMS Wind Errors, Basic RTA Assignment Strategy

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 true wind profiles are based on the wind case presented in Figure 5 at an altitude of 20,800 ft 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 after the RTA is assigned, 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, again as expected given the small assumed errors in the model forecast and FMS winds in this scenario. Resultantly, a small fraction of the RTAs (~7%) are deemed infeasible in this scenario. RTA feasibility in our simulation is determined by whether the final ETA falls in between the times achievable by flying at either the maximum or minimum velocities. This evaluation occurs at every intermediate fix, and typically, if an RTA becomes infeasible, it is highly improbable for it switch back to being feasible.

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 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 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 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 by 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 the forecast winds. The offset in the model forecast and FMS errors relative to the truth winds is not corrected in the final trajectory step which produces as an offset in the RTA compliance error distribution. 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. For this high forecast wind error case, none of the RTAs are deemed feasible. Although the distribution does not fall within the minimum/maximum ETA bounds, it may be likely that an RTA compliance check based on time thresholds would find these feasible. We plan to evaluate a time threshold-based method in the near future.

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, RTA compliance and fuel burn variabilities, and the fraction of RTA infeasible, are all worse than those observed in the second set of results, with 94.2% 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, 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.

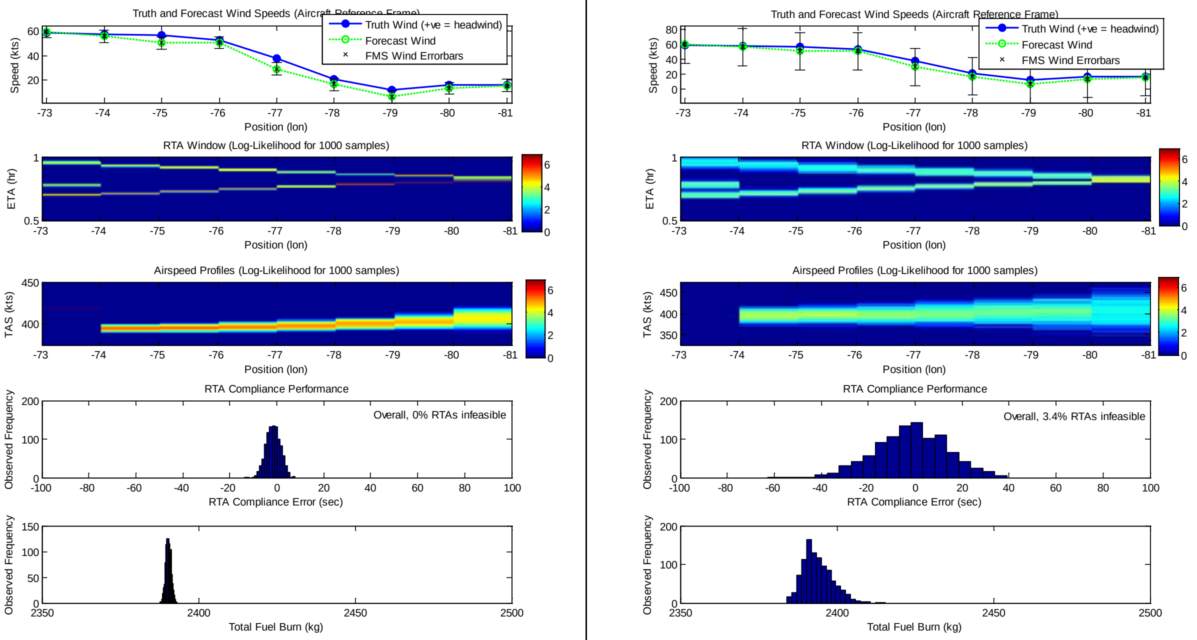
C. Performance with Advanced RTA Assignment Strategy

Figure 9 presents the same results for the case of the “advanced” RTA assignment strategy (which do account for forecast winds). The key differences from the RTA assignment strategy which does not consider forecast wind are seen in the speed profile behavior, the percentages of infeasible RTAs, as well as 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 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 TAS with respect to the starting nominal airspeed, the amount of fuel burned while following these trajectories is reduced accordingly. This may not be true for all speed reductions because of the non-linearity in the airspeed-to-fuel burned 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

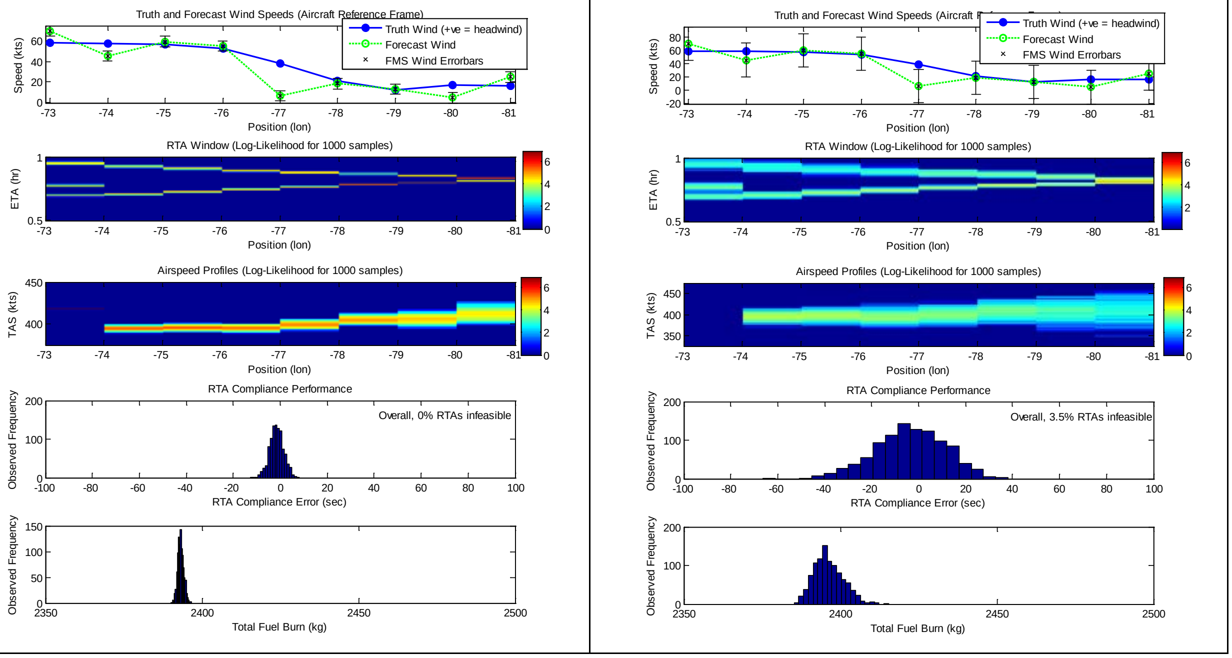


Figure 9: Sample 4D-TBO Performance Metrics for Various Forecast and FMS Wind Errors, Advanced RTA Assignment Strategy

It is noteworthy to add 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 Figures 8 and 9; additionally, this is illustrated in the following subsection.

The differences between the “basic” and “advanced” RTA assignment strategies are provided here for illustrative purposes only. Sophisticated RTA assignment algorithms may provide more benefits, e.g., assigning RTAs targeting optimal cruise velocities.

D. 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 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 10), the % infeasible RTAs and fuel burn (emissions) distribution width as a function of forecast wind error and FMS error: see Figure 11 and Figure 12.

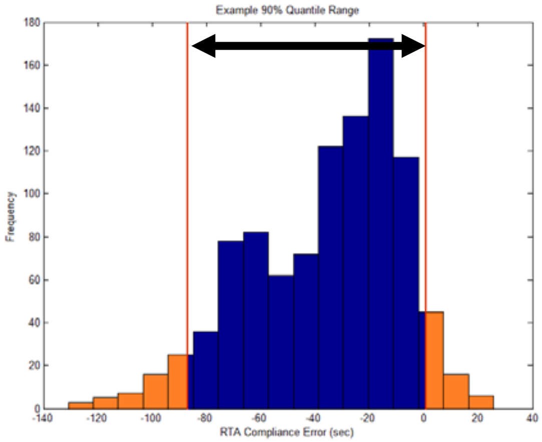


Figure 10: Example 90% Interquantile Range shown by arrow (data below 5% and above 95% are represented by light/orange color)

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 11 and Figure 12. In general, the smaller the forecast and FMS wind errors the smaller the RTA compliance interquantile range, % infeasible RTAs and fuel burn. Performance degradation is seen to be much more severe with FMS wind errors than with forecast wind 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. The RTA assignment algorithm also has a significant impact on overall performance. Using slightly more sophisticated criteria results in a large improvement in the fractions of infeasible RTAs. Fuel burn is also affected: Figure 12 shows a large difference in amount of fuel used between the basic assignment (shown as the leftmost top group of green circles) and the advanced assignment. This figure also shows the dependence of the amount of fuel burned and the width of the fuel burn 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 distribution beyond the impact of forecast error. The advanced assignment strategy varies the RTA, thus impacting the fuel burn distribution. This can be seen in the increasing sizes of the fuel burn circles as the RTA distribution width increases. Additionally, the average fuel burn slowly increases as the forecast error increases.

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 surfaces like these 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 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.

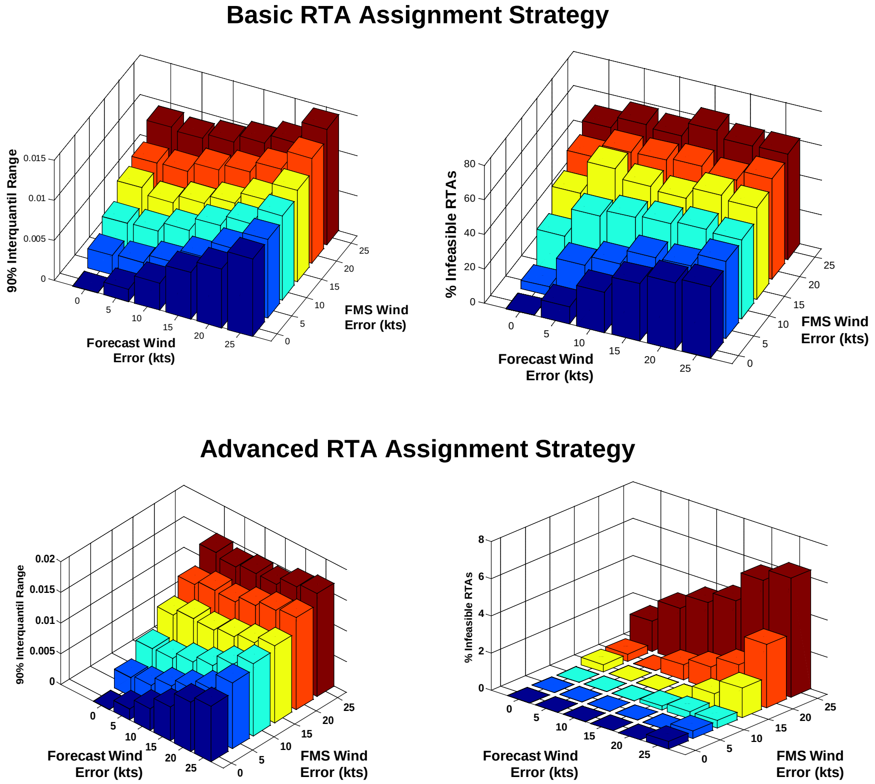


Figure 11: RTA Compliance 90% Interquantile Range (left), % Infeasible RTAs (right), and as a Function of Forecast Wind and FMS Wind Error for the Basic (top) and Advanced (Bottom) RTA Assignment Strategy

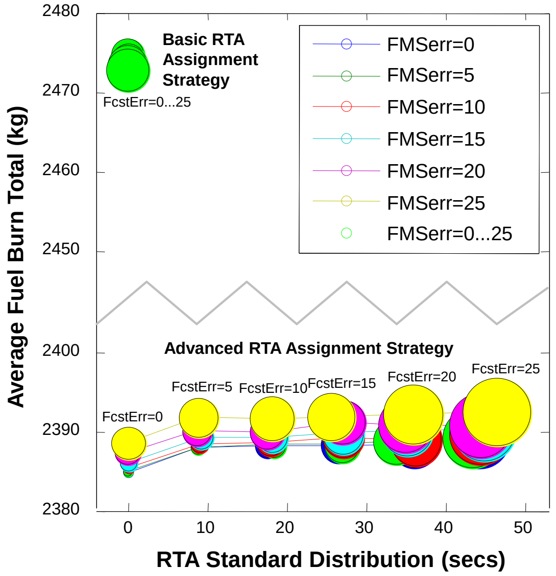


Figure 12: Fuel Burn Average and Standard Deviations for Basic (top group) and Advanced (bottom groups) Assignment Strategy

V. Conclusions & Next Steps

Many future air transportation system paradigms require access to high quality wind information. The primary objective of the current work is to quantify the relationship between wind information requirements and benefits delivery under future procedural applications. An analysis framework to achieve this objective has been described and it has been applied to a realistic 4D-TBO scenario under a challenging wind environment with representative wind error models to illustrate its utility. Next steps for this work include:

- Increasing the aircraft/FMS modelling fidelity (e.g., by using full aircraft aerodynamic/propulsion simulation and re-hosted FMS software) and exploring more complex RTA procedures (e.g., add a vertical profile element) to increase the realism and applicability of the results to stakeholder needs.
- Expanding the set of wind forecast scenarios to address 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 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, Improved TMA and/or DataComm applications.

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