Project Report
ATC-439

Wind Information Requirements for NextGen Operations Phase 5 Report

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16. Abstract

NextGen applications with time-based control elements, such as required time of arrival (RTA) at a meter fix under 4D trajectory-based operations (4D-TBO)/time of arrival control (TOAC) procedures or assigned spacing goal between aircraft under Interval Management (IM) procedures, are subject to the quality of the atmospheric forecast utilized by participating aircraft. The work described in this report summarizes the major activities conducted in the current phase of this program which builds upon prior work. The major objectives were:

1. Support RTCA Special Committee-206 Aeronautical Information and Meteorological Data Link Services and co-chair a sub-group responsible for developing the document "Guidance for Data Linking Forecast and Real-Time Wind Information to Aircraft."
2. Analyze the performance of publically available forecast as compared to in-situ reported atmospheric conditions, specifically comparing Global Forecast System (GFS) and High Resolution Rapid Refresh (HRRR) forecast data to recorded in-flight weather Meteorological Data Collection and Reporting System (MDCRS) data.
3. Analyze current and future Flight Management Systems (FMSs) to conduct operations at significantly lower altitudes than previous studies.
4. Evaluate potential sources of aircraft-derived winds to better support 4D-TBO activities.
5. Provide recommendations for high-value future work.

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EXECUTIVE SUMMARY

NextGen applications with time-based control elements, such as required time of arrival (RTA) at a meter fix under 4D trajectory-based operations (4D-TBO)/time of arrival control (TOAC) procedures or assigned spacing goal between aircraft under Interval Management (IM) procedures, are subject to the quality of the atmospheric forecast utilized by participating aircraft. The work described in this report summarizes the major activities conducted in the current phase of this program which builds upon prior work. The major objectives were:

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5. Provide recommendations for high-value future work.

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1. INTRODUCTION

1.1 MOTIVATION

Several NextGen applications depend on access to forecasted wind data, such as Required Time of Arrival (RTA) at a meter fix under 4D trajectory-based operations (4D-TBO)/time of arrival control (TOAC) procedures or compliance to an assigned spacing goal (ASG) between aircraft under Interval Management (IM) procedures. Each must develop a representation of the winds along their routes in order to develop and execute reasonable speed profiles to achieve their timing goals with acceptable adherence.

The particulars for both an RTA and an IM operation would be specified and delivered to aircraft as a type of clearance by the Airspace Service Provider (ASP). In the United States, this would be the FAA's Air Traffic Control (ATC) system. By accepting a clearance, the crew and aircraft are responsible for meeting the terms of the clearance, including spatial or temporal constraints defined therein. This is the expectation by the ASP in order to establish and maintain the scheduling and separation strategies that it is currently executing. Knowing that performances of these operations are dependent on knowledge of future wind conditions along each aircraft's route, it is in the best interest of the ASP to be certain that the participating aircraft have sufficient forecast information to successfully conduct their clearance to the associated performance standard. A key question is what level of forecast information quality (generally speaking in terms of accuracy, resolution, and timeliness) is required to successfully perform these types of operation? The answers to those questions could be used by the ASP and the stakeholder community in general to determine what minimum forecast quality must be available to aircraft to adhere to their clearances so the ASP can confidently execute their control strategy and whether ASPs need to provide such information to the aircraft.

Figure 1 illustrates how wind information is used by ATC on the ground to develop time targets for use in a 4D-TBO procedure. Wind information in the aircraft is used by the Flight Management System (FMS) or other avionics to manage the aircraft trajectory to these targets. The performance of the procedure is typically measured as a mean and 95% spread of RTA or IM performance error at the meter fix. Note that the mean error may be zero or slightly offset. Target performance is likely to be specified as a maximum allowable performance error expected for a given fraction of operations, for example +/- *x* seconds 95% of the time [1]. Any errors in the aircraft wind information relative to the truth winds actually flown through can potentially degrade the performance of the procedure. Unacceptable performance could be mitigated by improving wind information in the aircraft, for example by using higher accuracy wind forecast models to generate wind inputs for the ground or airborne systems, updating wind information more frequently, or increasing the resolution of the forecast model in the relevant avionics system.

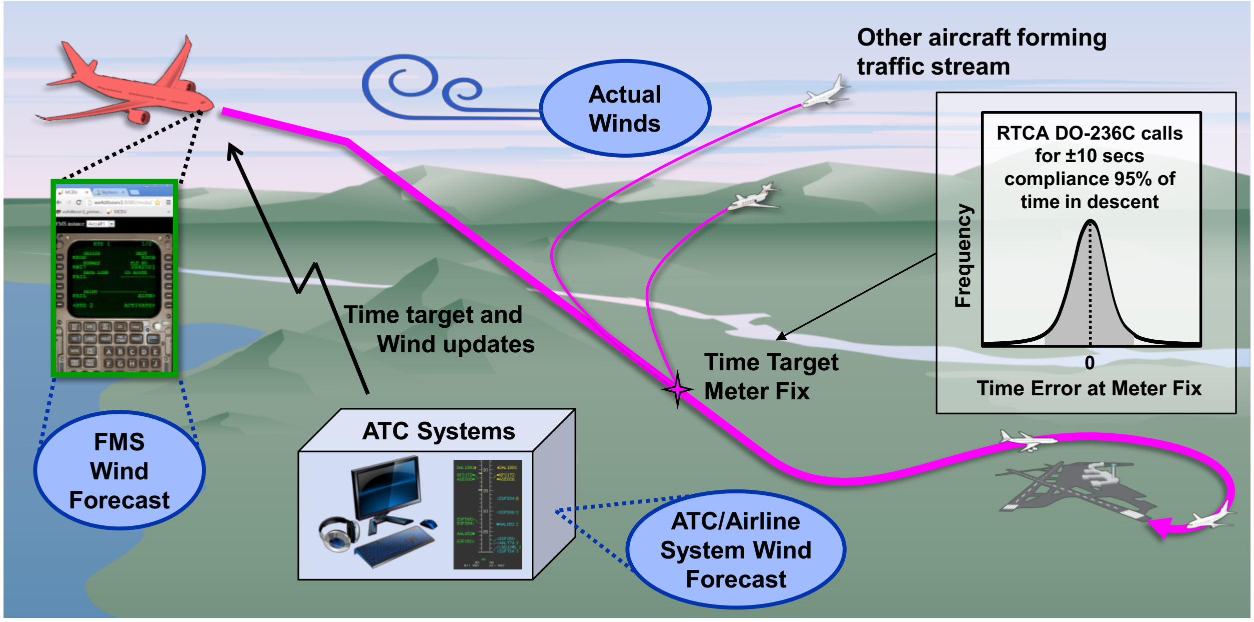


Figure 1. Focal elements relevant to 4D-TBO operations.

1.2 SUMMARY OF PRIOR WORK

In Phase 1 of this work (corresponding to FY12), a generic Wind Information Analysis Framework (WIAF) was developed to explore wind information needs across a range of NextGen applications. The framework was applied to a 4D-TBO scenario to act as a "proof-of-concept" of its use. It illustrated that even simplified executions of its elements could yield interesting and complex results which could be of high value in determining how 4D-TBO performance varies with wind information quality. Phase 2 of the work (largely corresponding to FY13) built upon this foundation by using refined and expanded applications of the Wind Information Analysis Framework. It included tasks to (1) increase modeling fidelity and explore more complex 4D-TBO procedures; (2) expand the set of wind forecast scenarios and metrics; (3) assess performance of 4D-TBO with realistic future FMS wind-handling enhancements; and (4) expand the focus applications to include Interval Management (IM), both Ground-based Interval Management (GIM) and Flight-deck Interval Management (FIM). It also undertook extensive assessment of wind information quality metrics, as well as the performance of a range of wind forecast models used by aviation stakeholders in the US and overseas. Principal outcomes from Phase 3 of this work included (1) analysis of the impact of wind information on 4D-TBO and IM performance of synthetic routes in synthetic environments; (2) analysis of various publically available wind information products available for use in the wind implications process flow diagram, and (3) example case studies of implications of different wind forecast error limits on 4D-TBO and IM trade-spaces. Phase 4 of this work included: (1) significant expansion of the capabilities of the WIAF and development of the Meteorological and Flight

Information Database (MAFID). This allowed for in-flight recorded wind and temperature conditions to be applied to simulated aircraft to replicate actual flights, including the use of the original flight's assigned route; (2) analysis of the High Resolution Rapid Refresh (HRRR) forecast model accuracy in comparisons to in-flight recorded meteorological conditions as reported by the Meteorological Data Collection and Reporting System (MDCRS); (3) support of RTCA Special Committees' needs, in particular co-chairing a sub-group of SC-206 Aeronautical Information and Meteorological Datalink Service; and (4) determining if augmented FMS wind-handling capabilities, i.e., 9 versus 4 descent forecast levels, provided a meaningful improvement in RTA performance. Full details of all this work can be found in [2-7].

1.3 CURRENT RESEARCH ACTIVITIES AND DOCUMENT OUTLINE

The Phase 5 work summarized in this report builds on the outcomes of earlier phases of work with a focus on further research and logistical and managerial support for RTCA-related activities. The sections of the report are organized as follows:

- **Section 2** summarizes the activities and outcomes of the support provided for RTCA Special Committee 206.

- **Section 3** presents analysis of the publically available forecast models GFS and HRRR and aircraft-derived atmospheric measurements which builds upon prior work and tailors the analysis for the current objectives.

- **Section 4** describes initial findings in the application of a currently available and a future enhanced FMS in conducting RTA operations to low altitude meter fixes. Both the current and future FMS were augmented to permit operations at speeds and configurations normally outside their RTA operating range.

- **Section 5** summarizes activities related to the availability and creation of aircraft-derived meteorological observations from existing FAA surveillance systems to augment existing wind information sources. In particular, this section discusses the use of MIT Lincoln Laboratory's (MIT LL's) facilities to interrogate for and collect Mode Select (Mode-S) Enhanced Surveillance (EHS) data from which aircraft-derived winds can be determined.

- **Section 6** presents a summary of the report and recommends next steps to refine and extend this work.

2. SUPPORT OF RTCA SPECIAL COMMITTEES

2.1 INTRODUCTION

As part of this program, MIT LL played a principal role in recent RTCA SC-206 (Aeronautical Information and Meteorological Data Link Services) activities as co-chair of Sub-Group 7 (SG-7) established, as per the terms of reference for SC-206, to develop the document “Guidance for Data Linking Forecast and Real-Time Wind Information to Aircraft.” The purpose for this document, herein referred to as the Wind Guidance Document, is to provide critical information required for decision making by relevant stakeholders (e.g., FAA, airlines, avionics manufactures, and standards organizations) and other RTCA Special Committees.

The administrative and managerial support activities as co-chair, while time-consuming and fundamental for the delivery goal, will not be discussed in this document. The status of the Wind Guidance Document will be discussed at the end of this section.

There were three principal application areas analyzed for the development of the Wind Guidance Document with respect to forecasted wind information. These were: Wake Turbulence Mitigation, IM and RTA. MIT LL led and conducted the RTA research to support RTCA SC-206/SG-7 goals. In the remainder of this section, we will present the research, analysis, and findings on this topic area.

2.2 RESEARCH HYPOTHESES

The results of research conducted in Phase 4 of this program (reported in [7]) provided information that helped SG-7 members establish specific RTA-related research questions pertinent to the Wind Guidance Document. The main areas of interest to the stakeholders in this community were the impact to 4D-TBO performance of: (1) use of higher-fidelity numerical weather prediction models for planning procedures; (2) use of higher-fidelity representations of winds in the FMS; (3) impacts of speed constraints on existing RNAV procedures. The hypotheses used to capture these issues were established in concert with SG-7 activities and evolved into the four listed in Table 1.

TABLE 1

RTA-Related Hypotheses Developed with RTCA SC-206/SG-7

ID	Hypothesis
H-1	The use of the High Resolution Rapid Refresh (HRRR) model as the forecast source will provide an increased percentage of flights achieving the RTA Performance Goal relative to using Global Forecast System (GFS) as a forecast source.

H-2	The use of truth data as the forecast source will provide an increased percentage of flights achieving the RTA Performance Goal relative to using HRRR as a forecast source.
H-3	Increasing the number of (equally distributed) Descent Forecast Levels (DFLs) in the FMS increases the percentage of flights that achieve the RTA Performance Goal.
H-4	Routes with speed constraints along the approach that precede or are applied at the RTA fix location will have a lower percentage of flights achieving the RTA Performance Goal relative to routes that have no speed constraints.

These were not the only hypotheses of relevance to the group or the only that were developed. However, they were designated as the most appropriate to test given the understanding of limitations of existing technical systems and the limited time available to complete the Wind Guidance Document.

The augmentations made in Phase 4 of this work to the Wind Information Analysis Framework (WIAF), including the development of the Meteorological and Flight Information Database (MAFID) and the Aircraft Reported Atmospheric Model (ARAM), directly led to making the evaluations of these hypotheses possible. See [7] for more details on these improvements.

As in earlier work, we use an RTA performance goal that an aircraft should arrive within 10 seconds of its assigned constraint time at the specified RTA fix. We define the aggregated RTA performance goal as meeting the RTA performance goal 95% or more of RTA operation attempts. This performance goal is motivated by criteria specified in RTCA DO-236C Change 1/EUROCAE ED-75, herein referred to as DO-236CC1 [8].

2.3 FORECAST INFORMATION TYPES

In Phase 4 of this work, RTA performance was evaluated using publically available HRRR forecasts and the Aircraft Reported Atmospheric Model (ARAM) developed for that effort. The latter is considered “truth” data or a “perfect forecast” for both previous and current work. In this phase, we add evaluations using the forecasts from the publically available Global Forecast System (GFS). GFS, as its name implies, provides gridded data for all of Earth with similar pressure/elevation coverage of that provided by HRRR but with a significantly coarser spacing and temporal updates (see Table 2). The consideration to evaluate GFS as a forecast source is operationally relevant as its use is widespread for flight planning purposes. Eight out of nine surveyed major United States’ airline and air transport carriers directly use GFS for flight planning and provisioning of forecasts to their aircraft as documented in the Wind Guidance Document. None of the surveyed organizations currently use HRRR in their operations.

TABLE 2

Meteorological Forecast Model Characteristics

Model	Domain	Horizontal Resolution	Update Period	Output Forecast Interval/Horizon
GFS	Global	0.5°	6 hrs	3 hrs/240 hrs
HRRR	CONUS	3 km	1 hr	1 hr

2.4 RESULTS OF CONTRIBUTIONS TO RTCA

The results of the MIT LL-led analysis of these hypotheses are fully documented in the RTCA Wind Guidance Document and the relevant excerpts of that document are included below. Note that this document is **RTCA Program Management Committee approved: This is an excerpt from RTCA, Inc. SC-206 and used with permission.**

5 REQUIRED TIME OF ARRIVAL

5.1 Overview

4D TBO is an ATM concept based on the premise that planned trajectories in both space and time are agreed upon by all parties prior to execution and that meaningful changes to estimated trajectories are shared amongst affected parties. The required accuracy and level of control (constraints) on a trajectory are subject to the circumstance of the operation and the needs of the airspace, which the flight will traverse. This is true for both spatial and temporal constraints.

In the 4D TBO concept, individual flight trajectories may be adjusted by ground-based traffic synchronization systems to allow orderly, safe, and efficient flow of air traffic. The synchronization may be applied or updated as a time constraint in a clearance provided to the flight crew. [16] An example of a time constraint is a particular time in the future when a flight is assigned to arrive within a specified temporal tolerance, δt, at a specified waypoint on a flight path.

If a flight crew believes that the aircraft can be flown such that it can arrive within the specified (or negotiated) time constraint ± δt, and accepts the clearance, they would typically employ the Time of Arrival Control (TOAC) capability of an onboard FMS to adjust the speed and vertical profile for the remainder of the clearance to arrive within the time constraint ± δt. This capability is often referred to as RTA. The term RTA in this document shall refer to both the capability and the specific time the aircraft is to cross an explicit navigational fix. This fix is known as the RTA fix. The crew would only accept the clearance if the time constraint ± δt fell within the range of the presented achievable arrival times as estimated by the RTA logic in the FMS.

In this section, we will evaluate the effect of forecast wind information on the ability of RTA systems to achieve reasonably specified time constraints. In particular, we will discuss the performance of RTA systems when attempting to achieve a time constraint, assigned during cruise and associated with a waypoint that is well into an aircraft's descent.

Because of the many degrees of freedom in the characteristics of a MET forecast (latitude/longitude, altitude, future time, wind components, temperature, etc.), it is nearly impossible to define a single meaningful metric that corresponds to a forecasting system's overall performance. As such, this evaluation will not address any particular errors in the forecasts provided to the aircraft. Instead, we evaluate meeting the aggregated RTA Performance Goal in terms of trade spaces identified in Section 5.4.

Note: *The performance goals presented in this analysis were motivated by performance goals and requirements specified in RTCA DO-236C Change 1/EUROCAE ED-75, but are not equivalent since some of the scenarios studied were more demanding than that to which the standard requires robustness. In particular, some of the scenarios have wind errors* *greater than 10 knots, speed constraints applicable longer than 40 miles, and time constraints active longer than 40 minutes of flight time.*

5.2 Impact of Winds on Trajectory Estimation

In the case of un-accelerated flight, the ground speed and direction of an aircraft is the result of the vector sum of the aircraft's true airspeed and direction and that of any horizontal winds (see Figure 5-1). This effect is well understood and is accounted for in critical operations of a flight. These include flight planning, accounting for forecasted winds on a trajectory with planned airspeeds to estimate the required fuel for a flight, and flight monitoring, where the crew and or onboard equipment monitor flight progression and fuel usage to ensure there will be sufficient fuel to safely complete the planned flight.

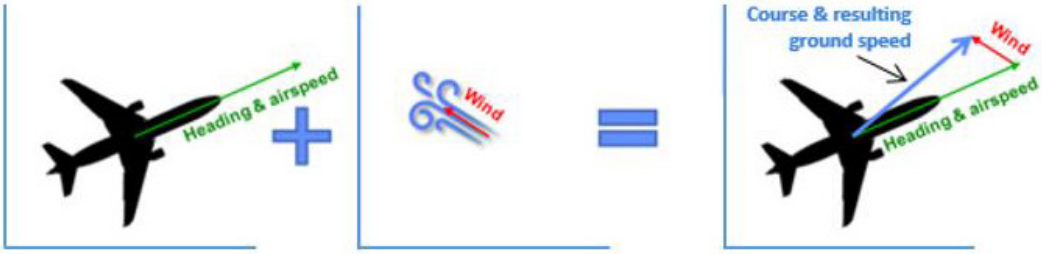


Figure 5-1: When Maintaining a Flight Path Laterally, an Aircraft's Ground Speed is a Vector Sum of True Airspeed and Wind Vectors

The temporal accuracy of a predicted trajectory is principally subject to the accuracy of the aircraft performance model, the future adherence to planned speeds along the route, and the accuracy of the forecasted MET conditions along the route at the time the aircraft is predicted to pass through that particular region. Estimates of ground speeds are derived from the future aircraft speeds and wind conditions, which are then used to generate estimates of times at future positions along the route.

It should be noted here that we specified forecasted MET conditions and not just forecasted winds. Though winds are the principal factor in influencing the actual ground speeds, errors of predicted ground speeds are affected by errors in both forecasted winds and forecasted temperatures.

For instance, an aircraft with a planned cruise speed of 0.8 Mach at an altitude of flight level (FL) 350, a forecasted temperature error of 1 °C equates to a true airspeed error of approximately 1 knot. See Section B.4 for additional context.

5.2.1 Secondary factors

A secondary factor affecting the temporal accuracy of a predicted trajectory comes from sensing errors from aircraft instrumentation.

Allowable measurement errors of calibrated airspeeds (derived from pressure ratios) and static air temperatures (derived from air temperature measurements adjusted for ram heating effects) negatively affect the calculated true airspeed and calculated Mach number.

There are two resulting effects. First, maintaining an erroneous indicated speed (Mach or calibrated airspeed) by itself adversely affects adhering to planned speeds. Secondly, estimates of local winds are negatively affected because they are derived from the calculated true airspeed and estimates of the ground speed and track (usually from inertial or global positioning system sources). In addition to speed errors, aircraft heading errors are also compounding factors in estimating current local wind conditions. [8, 13]

Estimates of local winds are often blended with forecasted winds as part of the trajectory estimation process. Methodologies for blending estimates of local winds with forecasted winds in FMSs differ amongst manufacturers and FMS models and are considered proprietary information. See RTCA DO-361/EUROCAE ED-236, Section C.2.2.3.3 for an example of wind blending.

5.3 Required Time of Arrival Operations

When an aircraft's FMS is conducting an RTA operation, it is flying a speed and vertical profile that was developed to arrive at the RTA fix at the time entered into the FMS, i.e., the RTA ± a programmable tolerance. The RTA value ± the programmable tolerance is called the RTA target window.

As with other operations, the FMS continuously updates its estimated trajectory based on the currently sensed conditions and the forecasted environment. The principal difference from normal operations is that a new speed and vertical profile for the remainder of the route, up to the RTA fix, will typically be created and applied if the Estimated Time of Arrival (ETA) at the RTA fix is outside the RTA target window.

A variety of speed profiles can be created that would provide a solution such that the ETA at the RTA fix satisfies the constraint time given that the aircraft has sufficient speed authority. The nominal solution that is usually sought considers efficient and safe operation as well as the effect of altitude and speed constraints defined along the route. The specific algorithm for calculating updated speed profiles in a particular FMS is considered proprietary to each manufacturer. Each algorithm likely considers other operational factors, such as user-defined speed limits, to produce a speed profile that attempts to maximize the probability of arriving at the RTA fix within the RTA target window.

There can be occasions when the FMS system estimates that it can no longer arrive at the RTA fix within the RTA target window. If this condition is determined, the crew is alerted with an UNABLE RTA message. The system will continue to attempt to achieve the programmed RTA and it is entirely possible that later in the flight, the system could determine that the RTA has become achievable again. If the system cannot achieve the RTA, then the crew needs to communicate to ATC their inability to meet the constraint, and ATC can determine if a new time or speed clearance is needed.

5.4 Trade Spaces

Three trade spaces were considered in the analysis to illuminate their effect on RTA performance. These trade spaces were chosen because they are readily modifiable elements of the system as a whole and can be evaluated individually to provide insights regarding current and near-term RTA operations.

5.4.1 Trade Space 1 – Forecast Source

The varying of the forecast source is a proxy for varying forecast quality in a generalized sense. Certain forecast systems are considered to be more accurate than others and there is an expectation that a more accurate forecast will provide improved performance for all types of spatial-temporal related operations.

Two publicly available MET models were used as sources for forecast information. These two forecast models, GFS and HRRR (see Table 3-1), allow for the evaluation of a widely leveraged system and a newer and theoretically more accurate system. In addition to testing forecasts, truth data (Meteorological Data Collection and Reporting System (MDCRS) aircraft MET data) was also used to simulate a third "perfect" forecast. This allowed for the testing of what might be considered the best possible circumstance, where the future conditions are perfectly known.

Note: *In this section, truth data refers to MET information sampled from MDCRS flight data used to represent the atmospheric conditions replicated during the flights as a forecast source.*

5.4.2 Trade Space 2 – Number of Descent Forecast Levels

Another trade space, which is related to but is independent of forecast quality, includes the quantity and location of sampled forecast values that are used to represent an expected wind profile along the flight path. As this analysis was concerned with RTA occurring during descents, the predicted wind profile for the descent phase of flight is of particular interest. The number of DFLs equally spaced between the cruise and destination altitudes and sampled along the predicted descent path was varied from 0 through 9 to evaluate the RTA performance sensitivity to the number of DFLs needed to adequately describe the wind profile along the descent path. If one or more DFLs were used, their separation in altitudes equaled the cruise altitude minus the destination altitude, both rounded to one thousand feet, divided by the number of DFLs plus one. Predicted temperatures at each of the DFLs were also provided with the wind forecasts as the FMS used in this work was capable of accepting this information.

5.4.3 Trade Space 3 – Presence of Speed Constraints

Due to the limiting effect of en route speed constraints on the speed control authority of a participating aircraft, it is recommended in RTCA DO-236C Change 1/EUROCAE ED-75 to not apply speed constraints on a route prior to the location of an RTA fix. Regardless of the recommendation, it is currently a requirement that an RTA system respect any speed constraint if present on a route. Many STARs today define one or more speed constraints to aid ATC management of separation for arrivals.

5.5 Hypotheses to Test

Based on the three trade spaces to be evaluated, the following hypotheses were developed with respect to the RTA Performance Goal:

- The use of HRRR as the forecast source will provide an increased percentage of flights achieving the RTA Performance Goal relative to using GFS as a forecast source.
- The use of truth data as the forecast source will provide an increased percentage of flights achieving the RTA Performance Goal relative to using HRRR as a forecast source.
- Increasing the number of (equally distributed) DFLs increases the percentage of flights that achieve the RTA Performance Goal.
- Routes with speed constraints along the approach that precede or are applied at the RTA fix location will have a lower percentage of flights achieving the RTA Performance Goal relative to routes that have no speed constraints.

5.6 Approach and Analysis

The goal of this activity was to most directly evaluate the effect of forecasted winds on the aggregated RTA Performance Goal and how representative RTA systems could perform in the NAS. An approach was taken that performed simulations that replicated actual flights utilizing recorded wind and temperature data to reproduce the atmospheric conditions experienced on each flight.

There are two major advantages to this simulation approach. The first advantage lies with the use of the recorded flight data measured along a flight path. Replicated flights, as described in detail in Appendix B, flew the same routes as the reporting aircraft and the measured MET conditions were applied to the simulated aircraft as it flew the same regions in space. This approach provides an accurate reproduction of the atmospheric dynamics experienced by the aircraft.

Note: *Each replicated flight was a flight reporting MDCRS data. The data contains information on aircraft position, wind speed and direction, pressure, and temperature.*

Information is updated every seven minutes en route and every minute during the descent phase of flight.

A second advantage is that operationally appropriate forecasts can be used in the simulations and these forecasts would include any system and modeling errors that were inherent and applicable to a particular flight. The location and magnitude of forecast errors along the trajectory would be the actual forecast errors and would not be contrived.

Several hundred randomly sampled flights destined for 10 Class B airports that occurred between February 1 and July 8, 2016 were replicated. These flights incorporated 213 unique route clearances and encompassed 32 different STARs.

The flight data utilized were geographically and temporally dispersed. This sampling gave a broad representation of the many atmospheric conditions experienced in flights. However, as realistic as this approach is, it does not guarantee that the most extreme cases of atmospheric conditions, and more pertinently, the most extreme cases of forecast error over this period, are included in the flights analyzed.

5.6.1 Performance Metric

The RTA metric is the percentage of all the replicated flights under a specified test condition where the absolute value of the RTA TE was less than or equal to 10 seconds. This metric was motivated by the analysis approach criteria specified in RTCA DO-236C Change 1/EUROCAE ED-75.

5.7 Research Results

There were 330 flights identified as candidates for replicating in simulation per the qualification requirements specified in Section B.1. The distribution of qualified flights was uneven amongst airports evaluated (see Table 5-1). Of the 330 flights, 54 were on routes that had no speed constraints prior to the RTA fix. All of these 54 were for flights into three airports Hartsfield – Jackson Atlanta International Airport (KATL), Baltimore/Washington International Thurgood Marshall Airport (KBWI), and KEWR. Of the 27 flights to KBWI, 16 of the flights were speed-constrained.

Table 5-1: **Total of Qualified and Replicated Flights from 5-Month Evaluation Period (February 1, 2016 through July 8, 2016)**

Destination Airport	Replicated Flights
KATL*	34
KBOS	40
KBWI†	27
KDEN	67
KEWR*	9
KHOU	16
KLAX	28
KMEM	64
KPHX	34
KSFO	11
Total	**330**

Note: *An * in Table 5-1 indicates that no flights to the airport flew speed-constrained routes. A † indicates some flights to the airport, 16 of the 27 replicated in this case, flew speed-constrained routes. No annotation indicates that all the flights to the airport flew speed-constrained routes.*

The assigned time value of a particular RTA is different for each flight and is specified subject to the method described in Section B.3.3. RTA TE is defined in this work as the actual time of arrival when crossing the RTA fix minus the assigned RTA. A value greater than zero indicates the flight arrived late crossing the RTA fix after the time constraint. Negative values indicate it arrived early. RTA TE is used to specify an individual flight's RTA performance and is used in calculating the performance metric (see Section 5.6.1).

Figure 5-2 presents example histograms of RTA TEs for all 276 replicated flights whose routes had one or more speed constraints, but only for a subset of the conditions tested as indicated. These histograms represent the general characteristic that is seen amongst all of the results when forecast data are provided. The most evident trait is the tendency for the aircraft to arrive late relative to the assigned RTA. On average, the aircraft system as tested arrived at the RTA fix about 5 seconds late as presented in Figure 5-2.

The general form of the histogram is non-Gaussian with an increased area right-side tail, which also lends towards an increased late bias. The spread of the histogram, as is the standard deviations of the RTA TEs, is an indicator of the consistency of the performance of the system.

There is also a trend that the standard deviation of RTA TE decreases with an increasing number of DFLs utilized, which is the expected behavior. That is, it was expected that the more forecast information provided for the descent, the better the onboard systems could predict and maintain their trajectory assuming the forecasts are GFS and HRRR forecast models.

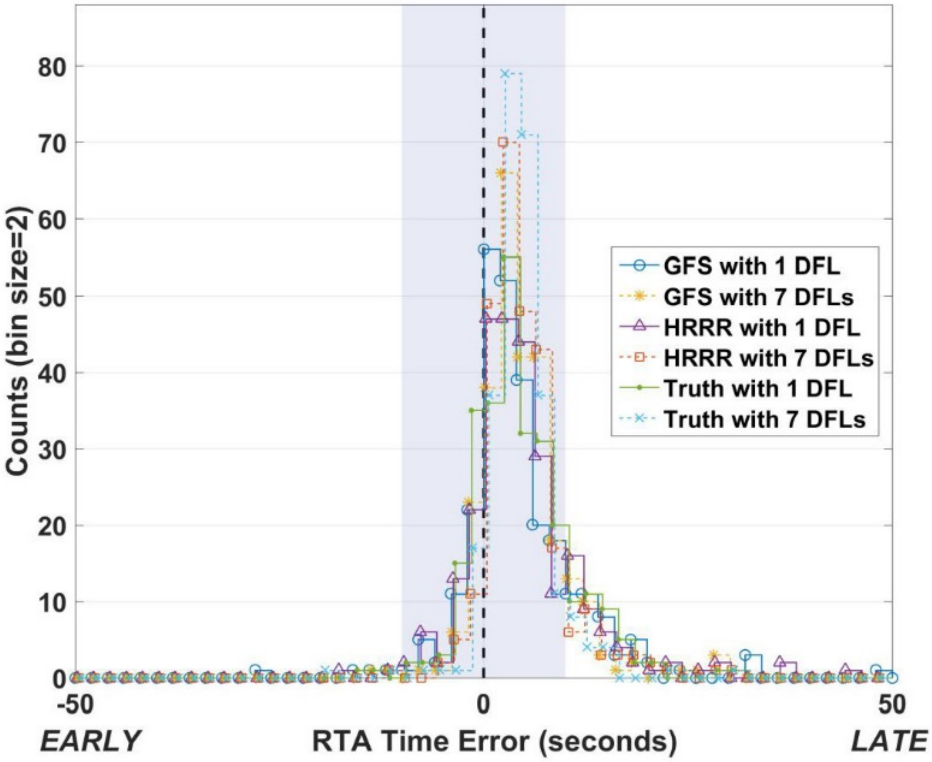


Figure 5-2: Examples of RTA TE Histogram for all 276 Replicated Flights with Speed Constraints Present on Their Routes with Varying Forecast Source and Number of DFLs. Histogram Shapes Are Consistent When Using 1 or More DFLs

Table 5-2 provides a complete breakdown of biases and standard deviations on RTA TE for the conditions tested. Table 5-3 lists the means of the absolute values for the RTA TE for completeness. The first row of Table 5-2 and Table 5-3 presents the performance when forecast information is not provided for either cruise or descent. The principal comparison here is between the speed constrained versus unconstrained. The mean errors on RTA TE (biases) are not great in magnitude, but the standard deviations are relatively large even in the absence of speed constraints. There is no surprise in the magnitudes of the standard deviations given that these flights did experience winds, routinely greater than 100 knots during cruise for which they had no forewarning. Interestingly, the standard deviation of the RTA TE of the group of flights that did not have speed constraints was slightly less than half that of the speed-constrained cases; 34 seconds versus 59 seconds respectively. This significant level of reduction in standard deviation under the two test conditions is seen throughout the remaining test conditions as well.

The provision of forecast information at cruise levels (row 2 in Table 5-2) had a significant effect on performance, reducing all standard deviations by over 66%. The biases are also significantly reduced, but since the standard deviations are still significantly larger than the biases, the key indicator of delivery performance at this point is still the standard deviations.

With the application of just 1 DFL, there is a noticeable reduction in the standard deviations of RTA TE, reducing the values by about 50% from the cruise forecast only cases. With 2 or more DFLs, both the biases and standard deviations have begun to approach their lowest values for any greater number of DFLs used.

Table 5-2: Means and Standard Deviations of RTA TE for Replicated Flights

		Bias (Std Dev) seconds					
Inputs		With Speed Constraints (N=276)			Without Speed Constraints (N=54)		
No Forecast		8.8 (58.7)			3.1 (33.9)		
Cruise Forecast	# DFLs	Forecast Source			Forecast Source		
		GFS	HRRR	Truth	GFS	HRRR	Truth
Yes	0	3.8 (15.8)	4.8 (18.8)	4.8 (18.7)	0.9 (6.6)	2.5 (11.5)	0.9 (6.0)
Yes	1	4.7 (7.3)	5.2 (9.5)	5.0 (10.5)	2.0 (3.2)	2.0 (4.3)	1.8 (4.1)
Yes	2	4.9 (5.8)	5.0 (6.0)	4.5 (5.9)	2.2 (2.2)	2.1 (2.7)	2.1 (2.5)
Yes	3	4.8 (5.6)	4.6 (5.2)	4.3 (4.7)	1.9 (2.5)	1.9 (2.7)	2.0 (2.9)
Yes	4	5.0 (5.5)	4.7 (5.1)	4.1 (4.3)	2.2 (2.6)	2.0 (2.6)	2.4 (2.9)
Yes	5	4.9 (5.6)	4.8 (5.3)	4.1 (3.9)	2.2 (2.8)	2.3 (2.6)	2.2 (2.6)
Yes	6	5.0 (5.3)	5.0 (5.0)	4.4 (3.4)	2.2 (2.6)	2.2 (2.8)	2.2 (2.1)
Yes	7	5.0 (5.5)	5.0 (4.9)	4.3 (4.1)	2.3 (2.7)	2.1 (2.6)	2.2 (2.6)
Yes	8	5.0 (5.4)	4.9 (4.9)	4.2 (3.4)	2.4 (2.9)	2.2 (2.7)	2.4 (2.4)
Yes	9	4.9 (5.2)	4.9 (4.9)	4.1 (3.7)	2.3 (2.6)	2.2 (2.6)	2.4 (2.2)

Table 5-3: Means of the Absolute Value of RTA TE for Replicated Flights

		Mean of |Time Error| seconds					
		With Speed Constraints (N=276)			Without Speed Constraints (N=54)		
Inputs							
No Forecast		43.7			22.6		
Cruise Forecast	# DFLs	Forecast Source			Forecast Source		
		GFS	HRRR	Truth	GFS	HRRR	Truth
Yes	0	10.3	11.5	11.4	4.8	6.0	4.5
Yes	1	5.9	6.4	6.0	2.8	3.2	3.0
Yes	2	5.7	5.6	5.0	2.5	2.8	2.7
Yes	3	5.4	5.1	4.9	2.5	2.5	2.5
Yes	4	5.6	5.2	4.5	2.7	2.6	2.8
Yes	5	5.5	5.3	4.5	2.7	2.8	2.6
Yes	6	5.6	5.4	4.7	2.6	2.7	2.4
Yes	7	5.5	5.3	4.7	2.8	2.7	2.5
Yes	8	5.5	5.2	4.5	2.8	2.7	2.6
Yes	9	5.5	5.3	4.4	2.6	2.6	2.7

The coloration in Table 5-4 is used as a visual aid to distinguish realms that the aggregated RTA performance (percent of attempts) is equal to or within ±10 seconds: green ≥ 95%, 95% > yellow ≥ 90%, and red < 90%.

Table 5-4: Percentage of Replicated Flights Whose RTA TE ≤ ±10 Seconds

		Flights Meeting RTA Performance Goal (%)					
		With Speed Constraints (N=276)			Without Speed Constraints (N=54)		
Inputs							
No Forecast		🔴 24.5			🔴 47.2		
Cruise Forecast	# DFLs	Forecast Source			Forecast Source		
		GFS	HRRR	Truth	GFS	HRRR	Truth
Yes	0	🔴 65.5	🔴 63.4	🔴 64.9	🔴 83.3	🔴 83.3	🔴 87.0
Yes	1	🔴 82.2	🔴 82.0	🔴 84.0	🟢 98.2	🟡 90.7	🟢 96.3
Yes	2	🔴 85.8	🔴 86.9	🟡 91.6	🟢 100.0	🟢 100.0	🟢 100.0
Yes	3	🔴 86.1	🔴 88.4	🔴 89.5	🟢 100.0	🟢 100.0	🟢 98.2
Yes	4	🔴 86.6	🔴 88.7	🟡 90.6	🟢 98.2	🟢 100.0	🟢 98.2
Yes	5	🔴 89.5	🟡 90.2	🟡 93.8	🟢 98.2	🟢 100.0	🟢 100.0
Yes	6	🔴 87.3	🔴 88.7	🟡 93.1	🟢 98.2	🟢 100.0	🟢 98.2
Yes	7	🔴 86.5	🔴 89.1	🟡 92.7	🟢 100.0	🟢 100.0	🟢 98.2
Yes	8	🔴 88.6	🟡 91.2	🟡 94.9	🟢 98.2	🟢 98.2	🟢 100.0
Yes	9	🔴 87.6	🟡 90.6	🟡 94.6	🟢 100.0	🟢 98.2	🟢 100.0

For flights with speed constraints, the performance varied as a function of forecast source. The analysis shows that there is in general an increase in performance when using HRRR as the forecast source as compared to using GFS in most cases. There is also a performance increase when using truth data as compared to HRRR forecast data. When the results are separated along the trade space of with and without speed constraints along the routes, the performances are strikingly different. The first observation of note is that when speed constraints exist, the aggregated RTA Performance Goal in this analysis could not be met under the conditions tested, regardless of the source or quantity of forecast information provided, including when truth data was provided as a forecast.

5.8 Summary of Results

This analysis was conducted in consideration of TOAC in the NAS in the near to mid-term. The evaluation used existing STARs, publicly available forecast systems, and a FMS system that could emulate the capabilities of current and future systems. There were 330 unique flights that were replicated under 31 test conditions producing 10,230 performance results for statistical evaluation.

The analysis shows that there is an increase in performance when using HRRR as the forecast source as compared to using GFS. There is also a performance increase when using truth data as compared to HRRR forecast data. These performance improvements as a function of forecast source are only seen for the speed-constrained cases. In unconstrained flights, the aggregated RTA Performance Goal was achieved principally 100% of the time using 2 or more DFLs regardless of the forecast source used. Thus, the first two hypotheses were proven true only for the speed-constrained cases.

The analysis indicates that there is a significant improvement in the aggregated RTA Performance Goal as the systems increase from using 0 to 2 DFLs. The simulations show that little improvement, if any, is seen by using more than 2 DFLs with the exception on speed-constrained routes. Thus, the third hypothesis is not proven.

There is a clear distinction in aggregated performance when comparing the routes with or without speed constraints. Unconstrained cases outperformed constrained cases and with the exception of the condition of 1 DFL and HRRR as the forecast source, would have met the 95% performance goal with only one or more DFLs. Thus, hypothesis four has been proven.

5.9 Caveats

There are some caveats to consider in this analysis that limit the scope of the results, as seen in the list below:

- limited to descents to ~10,000 ft,

- single airframe,
- single FMS logic,
- auto throttle in simulation has lower performance than certified system,
- does not consider optimization of DFL selection,
- does not consider effect of temperature forecasts though temperature forecasts were provided wherever a wind forecast was provided,
- does not consider fuel usage, and
- does not consider comfort of flight.

5.10 Operational Wind Recommendations

Based on the analysis, the following recommendations have been developed to maximize RTA performance:

- Time constraints should be given higher priority over speed constraints.

  Note 1: *In light of IM operations, the time constraints should be given priority over the published speed constraints within a tolerance of the speed constraints. An example of a tolerance is defined in RTCA DO-361/EUROCAE ED-236 (Section 2.2.4.4.4).*

- In absence of giving priority to time constraints, apply the RTA fix prior to the location of the first speed constraint on the route.

  Note 2: *Per Table 5-4, in the aggregate, flights without speed constraints significantly outperformed flights with speed constraints.*

- Use or create the wind forecast source(s) that provides the best performance for the intended operation.
  - There is room for improvement in publicly available forecast models. The analysis in this document shows that performance is measurably improved on speed-constrained routes when using truth data as forecasts (reduced bias, reduced standard deviations, and increased aggregated RTA performance).

- If choosing between either GFS or HRRR as the wind forecast source for the operation, use HRRR as the forecast source instead of GFS.

  Note 3: *For 2 or more DFLs, no meaningful difference in the aggregated RTA Performance Goal was seen for flights without speed constraints regardless of the forecast source used; however, for all tests of the speed-constrained flights that utilized decent forecasts, those using HRRR outperformed those using GFS.*

- Always provide wind forecasts at cruise waypoints.
- For flights without speed constraints on their routes, use at least 2 DFLs for acceptable performance.
- For flights with speed constraints on their routes, use 5 or more DFLs.

Note 4: *Based on interpretation of the aggregated RTA performance of speed-constrained flights, the use of an increasing number of DFLs, up to 5, consistently improved performance compared to the use of fewer DFLs. The use of more than 5 DFLs did not improve performance further. This is in contrast to the non-speed-constrained flights where the use of 2 DFLs practically maximized performance.*

APPENDIX B REQUIRED TIME OF ARRIVAL SIMULATION DETAILS

B.1 Identification of Candidate Flights

The simulation approach entails the reproduction of flights that occurred in the NAS, with the addition of an RTA added to their clearance. The MDCRS reported MET data from the original flights, are applied to the simulated aircraft as it passes through the same regions in space as the original flight.

Not all of the surveyed NAS flights can be used in these experiments. Strict qualification criteria are applied to maximize the assurance that the conditions observed and the methods by which the aircraft were flown can be faithfully reproduced by automation. For instance, many of these criteria are designed to ensure that a qualifying flight was most likely flown by the FMS during the area of interest, as it was in the simulations. The qualification parameters described below, when applied, resulted in the rejection of over 99% of NAS flights evaluated over the five-month observation period starting February 1, 2016 through July 8, 2016.

Surveillance data for each flight is provided by Traffic Flow Management System and MDCRS track data. The track data are broken into segments where the flight both remained on its assigned route (±4 NM) as defined in its departure clearance and had a complete set of MDCRS data sampled over the same period. A given segment must have had its beginning location further than 280 NM radially from the destination and its ending location occur after its assigned RTA fix location.

The assigned route must also have a fix where the aircraft is expected to cross at an altitude between 10,000 and 15,000 feet. A flight does not qualify if its assigned route had any future clearances (e.g., EXPECT …), which are found on many STARs. This is because we cannot be certain if any of these values were programmed into the FMS.

The track data must also have demonstrated a continuous cruise altitude (±1000 feet) prior to the observed TOD location.

For this work, 247 individual flights from the 5-month observation period were replicated. Table B-1 lists the elements of 128 routes flown, which were unique if looking at the STAR transition through the remainder of the programmed flight, i.e., the origin and route to the STAR transition were ignored. The table also lists the specific RTA fix assigned on each route as well as indicating if one or more speed constraints existed on the route.

Table B-1: List of Unique Routes from the STAR Transition to the Destination That Were Utilized in this Work

Destination	STAR Transition	STAR	IAP Transition	IAP	RTA Fix	Speed Constrained
KATL	MOL	DIRTY3	BOYKN	ILS26L	HAARY	No

Destination	STAR Transition	STAR	IAP Transition	IAP	RTA Fix	Speed Constrained
	MOL	DIRTY3		ILS28	HAARY	No
	MOL	DIRTY3	MMCAP	ILS27R	HAARY	No
	MOL	DIRTY3	PRMAN	ILS28	HAARY	No
	FLASK	DIRTY3	BOYKN	ILS26L	HAARY	No
	FLASK	DIRTY3	PRMAN	ILS28	HAARY	No
	MOL	DIRTY3	HAINZ	ILS26R	HAARY	No
	MOL	DIRTY3	ROMMM	ILS27L	HAARY	No
	FLASK	DIRTY3	MMCAP	ILS27R	HAARY	No
	MEM	KOLTT1	AAKAY	ILS09L	KOLTT	No
	MEM	KOLTT1		ILS10	KOLTT	No
	BNA	KOLTT1		ILS10	KOLTT	No
	MEM	KOLTT1	DEWHY	ILS10	KOLTT	No
	PAYTN	WARRR1	DEWHY	ILS10	WARRR	No
	PAYTN	WARRR1		RNV09R	WARRR	No
KBOS	TRUIZ	QUABN3		ILS22L	QUABN	Yes
	TRUIZ	QUABN3		RNV04R	QUABN	Yes
	TRUIZ	QUABN3		ILS27	QUABN	Yes
	TRUIZ	QUABN3	BENNN	ILS33L	QUABN	Yes
	TRUIZ	QUABN3		ILS04R	QUABN	Yes
	TRUIZ	QUABN3		ILS33L	QUABN	Yes
	TRUIZ	QUABN3	NOLEY	ILS22L	QUABN	Yes
	TRUIZ	QUABN3		RNV32	QUABN	Yes
	TRUIZ	QUABN3		RNV33L	QUABN	Yes
	TRUIZ	QUABN3		RNV22L	QUABN	Yes
KBWI	THHMP	RAVNN6		ILS10	CAPKO	Yes
	THHMP	RAVNN6		RNV33R	CAPKO	Yes
	BKW	RAVNN6		ILS10	CAPKO	No
	BKW	RAVNN6	JANNS	ILS33L	CAPKO	No
	THHMP	RAVNN6	JANNS	ILS33L	CAPKO	Yes
	THHMP	RAVNN6		RNVY15R	CAPKO	Yes
	BKW	RAVNN6		ILS33L	CAPKO	No
	BKW	RAVNN6		RNVY28	CAPKO	No
	THHMP	RAVNN6		ILS33L	CAPKO	No
KDEN	ONL	ANCHR3		ILS35R	DOGGG	Yes
	HALEN	BOSSS2	BOSSS	ILS35R	BOSSS	Yes
	ZIGEE	BOSSS2	BOSSS	ILS35R	BOSSS	Yes
	WOLLF	CREDE3		ILS16L	CLFFF	Yes
	WOLLF	CREDE3		ILS16R	CLFFF	Yes

Destination	STAR Transition	STAR	IAP Transition	IAP	RTA Fix	Speed Constrained
	WOLLF	CREDE3		RNVY16R	CLFFF	Yes
	GWEDO	FRNCH3		ILS34L	HIMOM	Yes
	EKR	FRNCH3		ILS35L	HIMOM	Yes
	CHE	FRNCH3		ILS34L	HIMOM	Yes
	OATHE	JAGGR3		ILS16L	QWIKE	Yes
	OATHE	JAGGR3		ILS17L	QWIKE	Yes
	KIISS	JAGGR3		ILS16L	QWIKE	Yes
	KIISS	JAGGR3		ILS17R	QWIKE	Yes
	KIISS	JAGGR3		ILS17L	QWIKE	Yes
	CHE	KAILE2		ILS16L	KAILE	Yes
	CHE	KAILE2		RNVY16L	KAILE	Yes
	HSI	KOHOE3		ILS35R	DOGGG	Yes
	OBH	KOHOE3		RNVY35R	DOGGG	Yes
	SPAWN	KOHOE3		RNVY35R	DOGGG	Yes
	HSI	KOHOE3		ILS35L	DOGGG	Yes
	SPAWN	KOHOE3		ILS35L	DOGGG	Yes
	SPAWN	KOHOE3		ILS35R	DOGGG	Yes
	OBH	KOHOE3		ILS35R	DOGGG	Yes
	OURAY	LDORA2	LDORA	ILS35L	LDORA	Yes
	OURAY	PEEKK3		ILS16L	CLFFF	Yes
	OATHE	PURRL2		ILS35L	ROCCS	Yes
	SPAWN	WAHUU2		ILS16L	LIPKE	Yes
	OBH	WAHUU2		ILS16L	LIPKE	Yes
	SPAWN	WAHUU2		RNVY16L	LIPKE	Yes
	HALEN	ZPLYN3		ILS16L	QWIKE	Yes
KEWR	FAK	PHLBO3		RNV04L	SOMTO	No
	GVE	PHLBO3		ILS22L	SOMTO	No
	GVE	PHLBO3	KILMA	ILS04L	SOMTO	No
	FAK	PHLBO3		ILS04L	SOMTO	No
	GVE	PHLBO3		ILS04L	SOMTO	No
KHOU	SAT	BELLR2		ILS12R	HNTRR	Yes
	AEX	WAPPL2		ILS12R	SWWAA	Yes
	SWB	WAPPL2		ILS12R	SWWAA	Yes
	SWB	WAPPL2		RNV22	SWWAA	Yes
KLAX	PGS	RIIVR2	RIIVR	ILS25L	LUVYN	Yes
	PGS	RIIVR2	RIIVR	RNVY25L	LUVYN	Yes
	PGS	RIIVR2	RIIVR	RNVY24R	SKOLL	Yes
	TNP	SEAVU2	SEAVU	RNV25R	BCOVE	Yes

Destination	STAR Transition	STAR	IAP Transition	IAP	RTA Fix	Speed Constrained
	TNP	SEAVU2	SEAVU	RNVY25L	LUVYN	Yes
	TNP	SEAVU2	SEAVU	ILS25L	LUVYN	Yes
	TNP	SEAVU2	SEAVU	ILS24R	SKOLL	Yes
KMEM	BWG	BLUZZ1		ILS18L	COPEN	Yes
	BWG	BLUZZ1		ILS18R	COPEN	Yes
	BWG	BLUZZ1	COVIM	ILS27	COPEN	Yes
	BWG	BLUZZ1		ILS18C	COPEN	Yes
	BWG	BLUZZ1		ILS36L	MRCEL	Yes
	BWG	BLUZZ1		RNV36L	MRCEL	Yes
	BWG	BLUZZ1		ILS36C	MRCEL	Yes
	PXV	BLUZZ1	WSTON	ILS36L	MRCEL	Yes
	BWG	BLUZZ1	WSTON	ILS36L	MRCEL	Yes
	RZC	BRBBQ1		RNV36L	BEERT	Yes
	RZC	BRBBQ1		ILS36L	BEERT	Yes
	WHOLL	BRBBQ1		ILS36L	BEERT	Yes
	WHOLL	BRBBQ1		RNV36L	BEERT	Yes
	WHOLL	BRBBQ1	WSTON	ILS36L	BEERT	Yes
	WHOLL	BRBBQ1		ILS18C	JAMLA	Yes
	RZC	BRBBQ1		ILS18C	JAMLA	Yes
	FSM	BRBBQ1		ILS18C	JAMLA	Yes
	RZC	BRBBQ1		ILS18L	JAMLA	Yes
	RZC	BRBBQ1		ILS18R	JAMLA	Yes
	ELD	HOBRK1		ILS18C	JAMEA	Yes
	LIT	HOBRK1		ILS18L	JAMEA	Yes
	ELD	HOBRK1		ILS36L	ROCAB	Yes
	LIT	HOBRK1		ILS36L	ROCAB	Yes
	NMANN	HYTHR1		ILS09	ROBYE	Yes
	ZOKER	MONAA2	COVIM	ILS27	LOHNI	Yes
	MATCN	MONAA2	COVIM	ILS27	LOHNI	Yes
	WASER	VANZE1		ILS36C	FASOP	Yes
	TALLO	VANZE1		ILS36C	FASOP	Yes
	WASER	VANZE1		ILS36R	FASOP	Yes
KPHX	TENTS	BRUSR1		ILS25L	ANNTI	Yes
	TENTS	BRUSR1		ILS08	BDWIL	Yes
	TENTS	BRUSR1		ILS07L	BDWIL	Yes
	WOTRO	BRUSR1		ILS07L	BDWIL	Yes
	ZUN	EAGUL6		RNVY08	QUENY	Yes
	ZUN	EAGUL6		ILS07L	QUENY	Yes

Destination	STAR Transition	STAR	IAP Transition	IAP	RTA Fix	Speed Constrained
	GUP	EAGUL6		ILS07L	QUENY	Yes
	GUP	EAGUL6		RNVY07L	QUENY	Yes
	GUP	EAGUL6		RNVY07R	QUENY	Yes
	GUP	EAGUL6		RNVY08	QUENY	Yes
	DRRVR	PINNG1		ILS07L	DDUKE	Yes
	DRRVR	PINNG1		RNVY07L	DDUKE	Yes
	DRRVR	PINNG1		ILS25L	PAAAR	Yes
	DRRVR	PINNG1		RNVY25L	PAAAR	Yes
KSFO	INYOE	DYAMD2		ILS28L	CEDES	Yes
	INYOE	DYAMD2	ANETE	RNVX28R	CEDES	Yes
	INYOE	DYAMD2		ILS28R	CEDES	Yes
	INYOE	DYAMD2		RNVX28R	CEDES	Yes
	INYOE	DYAMD2	ARCHI	ILS28R	CEDES	Yes

B.2 Pilot Model

Correct simulation of qualified flights required the incorporation of a reactive pilot agent. This agent employs a heuristic model to emulate several actions an actual pilot might conduct during a typical flight. The agent possesses the ability to react to speed errors during descent and react to FMS indicated DRAG REQUIRED messages and dynamically set the altitude correction (“baro” setting) to the field station pressure when transitioning out of Class A airspace. Additional behaviors implemented included the setting of appropriate flap positions and lowering gear during the appropriate stage and condition of flight. The circumstances of when and how the pilot agent responds to the various conditions were developed with the aid of an active B757 captain with over 20,000 hours of flight time experience.

In brief, the pilot agent would deploy spoilers up to 75% to slow the aircraft during idle or near idle descents if observing that the target airspeed was greater than a certain amount for a certain period of time. Spoilers might be raised, lowered, or stowed depending on the response of the system. The reactiveness in terms of delay, thresholds, release hysteresis, and other related parameters varied as a function of flight state. Typically, the reactivity of the pilot agent increased as altitude decreased.

The pilot agent’s reactions to DRAG REQUIRED message is similar, but does not equate to the behaviors for the use of spoilers as a function of speed errors. The DRAG REQUIRED message may be presented under various circumstances by the FMS and not just to reduce speed. It may be presented in order to maintain a certain descent profile even if the current indicated airspeed is lower than the target airspeed and the throttles are not at idle.

The application of a pilot agent to set the destination station pressure in the Kollsman window at the appropriate stage of flight captures a condition that is often overlooked in many simulations. It is particularly important in Vertical Navigation descents because if the station pressure is anything other than 29.92 in-Hg, a discontinuity in the vertical descent profile is created. This discontinuity may be hundreds of feet and the aircraft will have to correct accordingly and as such there is an effect on the overall performance of the system.

B.3 Summary of Simulation Approach

A single airframe model (B757-200) and modified FMS system (Honeywell Pegasus) was used for all flight simulations. At the beginning of each scenario, the aircraft are configured identically in terms of payload and fuel quantities and distributions. The FMSs are programmed identically (e.g., same cost function) save for the route and any forecasted MET data.

The FMS system itself is an extension of certified flight software, which was modified for research and compiled for the target avionics hardware. Unlike the certified Pegasus FMS, this system is capable of performing closed-loop speed control through all phases of flight if an RTA is active. Additionally, this FMS allowed for the programming of up to nine DFLs, which included the ability to specifying both the forecasted wind and temperature at each DFL.

At the beginning of each scenario, the simulated aircraft is placed at its flown cruise altitude and on its route at least 280 NM radially from its destination. The date and time at the start of each simulation equates to the date and time when the actual aircraft passed the same location on that route. The aircraft is programmed with the flight plan from its clearance and follows the route with the autopilot and autothrottle systems activated using FMS guidance. All components of the system run in real-time.

It was presumed that the flight crew would be aware of the approximate location of the RTA freeze horizon and would be expecting an RTA clearance. It was established as a procedure that the simulated crew would request for (or a ground system would push) updated forecast data approximately 10 minutes prior to the aircraft reaching the RTA freeze horizon.

With the aircraft en route, forecast information (wind and temperature) are programmed into the FMS for the remainder of the route. Forecast information for cruise waypoints is only provided at the current cruise altitude. Forecast information for descents is provided at the particular altitudes associated with the scenarios where that altitude intercepts the predicted descent trajectory. Forecast information is part of the trade spaces under evaluation so the number of DFLs in the descent forecasts and the presence of cruise forecasts are specified as part of the experiment (see Figure B-1).

B.3.1 Required Time of Arrival Freeze Horizon

An artificial freeze horizon, an artificial line in space established by ATC, where once crossed, the sequencing and scheduling of arriving aircraft to a destination become fixed, for setting the RTA was located 230 NM from radially each destination (see Figure B-1). This distance emulates where ATC might establish a freeze horizon for sequencing and scheduling arriving aircraft to a destination. The RTA fix and target time are programmed into the FMS and executed, i.e., the close-loop TOAC is activated, when crossing this artificial horizon.

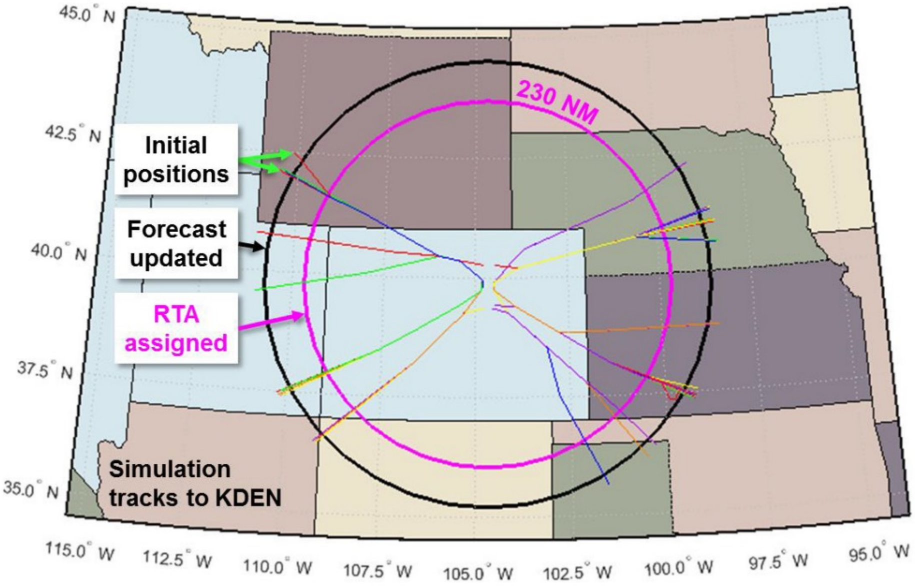


Figure B-1: Examples of Simulated Flight Tracks into KDEN. Aircraft are Initially Positioned in Cruise About 280 NM from the Destination. A Forecast, Which May Be No Different from the Pre-Departure Forecast Depending on Source and Actual Time of Update is Provided Approximately 10 Minutes Prior to Assigning the RTA Fix and Time Constraint. The Tracks in the Figure End at the Assigned RTA Fix

B.3.2 Forecast Data Description

Two publically available forecast models were used in the evaluation and reported flight data was used to represent a third "perfect" forecast. The two forecast models, GFS and HRRR are available to the public via the NOAA's National Centers for Environmental Prediction data distribution service. They are available for download via file transfer protocol or hypertext transfer protocol (see Table B-2). Both GFS and HRRR data were collected in real-time from operational sources and archived with appropriate timing information. This permits the system to identify the forecasts that were available at the historical times of replicated flights.

Table B-2: **Meteorological Forecast Model Characteristics Used in This Analysis**

Model	Domain	Hoizontal Resolution	Update Period	Output Forecast Interval/Horizon
GFS	Global	°0.5	6 hrs	3 hrs / 240 hrs
HRRR	CONUS	3 km	1 hr	1 hr/18 hrs

The age of a forecast model output set, defined as the time difference between the current (wall clock) time and the model cycle time, is a concern because forecast accuracy has been shown to degrade with increasing look-ahead times. [14] The greater the age of a forecast set, the greater the associated forecast look-ahead time from that set is needed in order to match a desired valid time in the future. Operationally, the minimum possible age of a forecast set depends on the particular forecast source/system and includes the time needed to assimilate observation data, compute the forecast products, and transport as necessary the produced products to a distribution service. We shall call the accumulation of these times relative to the model cycle time the "minimum forecast production delay."

For the current operational GFS, the minimum forecast production delay is approximately 3.5 hours. For a given GFS forecast set, the first two look-ahead forecast products available are valid for +0 and +3 hours relative to the model cycle time. Thus, because it takes a minimum of 3.5 hours for the products to be available, both of these forecasts are valid for times that will have already passed. The +6-hour forecast is the first of the individual forecasts in a GFS forecast set that would refer to a future time (see Figure B-2).

For GFS products, the successive forecast look-ahead times at +9 hours, +12 hours, etc., are usually available at the distribution site within 1 minute from the time the preceding forecast is available. The last forecast, for +240 hours, is usually not available until approximately 4.5 hours after the model cycle time.

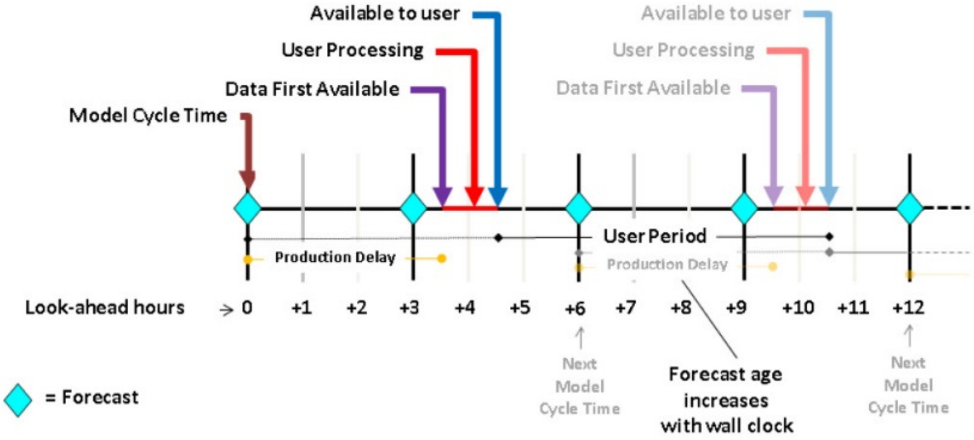


Figure B-2: **GFS Timeline. Available Only Four Times a Day and Latent in Delivery, Depending on When Sampling Forecast as a User, the Age of the Forecast Can Vary from 4.5 to 10.5 Hours Old**

Unlike GFS, which issues forecast sets once every 6 hours, the HRRR model produces forecast sets once every hour. It also produces forecasts at hourly look-ahead intervals from the model cycle time out to +18 hours. For the current operational HRRR, the minimum forecast production delay is approximately 55 minutes with succeeding hourly forecast look-heads for the given forecast set usually available at the distribution site less than three minutes from the time the preceding forecast is available. Thus, the +1-hour forecast is the first HRRR product that is available for a future time, albeit its valid time may only be several minutes into the future.

Before data derived from these forecasts could reach an onboard system in an aircraft, there are additional delays that occur. These include the transport of the forecast data from the distribution site to a user's system and the processing of the forecast for incorporation into the user's systems such as flight planning tools.

We optimistically specified in this work that this period of user delay would take 1 hour and also incorporated any transport delay to the aircraft. Therefore, the minimum "age" of a forecast set shall be the minimum forecast production delay plus the user delay. For GFS, this will then be 4.5 hours and for HRRR, 1 hour and 55 minutes.

Since these studies emulated actual flights including replicating the dates and times which they were flying, the final age of a forecast delivered to an aircraft depended on when the aircraft requested a forecast update during its replicated wall clock time relative to the forecast that could have been available at the time. The maximum age of a forecast that could be sent to the aircraft equals the minimum age plus the period between each forecast set. For GFS, that is 4.5 + 6 hours, thus, equaling 10.5 hours. For HRRR, the maximum age is 2 hour 55 minutes.

B.3.3 Required Time of Arrival Fix Location

The RTA fix that was specified depended on the route the aircraft was flying. The fix selected was chosen as the first fix that would likely be crossed at an altitude of around 10,000 ft based on the performance of the aircraft and any altitude constraints as specified by the STAR and instrument approach procedure selected for the approach. The "agreed" time constraint that the aircraft was to cross the fix was the earliest possible time as estimated by the FMS plus 25% of the span between the earliest and latest estimated times rounded to the nearest 1/10th of a minute. It should be noted that in the FMS system employed in these experiments, the RTA can only be set with the resolution to 1/10th of a minute. The earliest and latest ETA values were computed without any uncertainty margin applied as reported on this FMS. Only flights that crossed the RTA fix between 9000 and 12,000 ft were included in the analysis.

B.4 Temperature Effect on True Airspeed

The effect of a 1°C temperature error on estimation of true airspeed while flying at a constant Mach speed can be demonstrated by the following set of equations:

Standard temperature in the troposphere (h) = 15 - 0.0019812*h(ft) °C

Speed of sound (T) = $1.94384\ (\frac{kts}{\frac{m}{s}}) * \sqrt{1.4 * 286.9(\frac{J}{kg}K) * (273.15K + T(°\mathrm{C}))}$ knots

True airspeed (TAS) = Mach (M) * speed of sound

M = 0.8

Standard temperature at FL350 ≅ -54 °C

TAS (-54°C) = 461.37 kts

TAS (-55°C) = 460.31 kts

Thus, a 1°C difference in the estimate of temperature when flying at M = 0.8 at FL350 equates to an approximate 1 knot error in true airspeed.

3. ANALYSIS OF WIND INFORMATION

3.1 INTRODUCTION

Phase 3 of this work [6] examined the forecast accuracy of operational U.S. numerical weather prediction models used by ATC and airlines' flight planning departments. The models evaluated were the Global Forecast System (GFS), Rapid Refresh (RAP), and High Resolution Rapid Refresh (HRRR). The source of "truth" winds for comparison against the model forecast winds was the HRRR zero-hour analysis winds. The RMS vector error between the forecasts and the HRRR truth winds was the chosen metric. The RMS vector errors were computed through three-dimensional sampling and aggregational averaging over a 10-month period within four volumes centered over San Francisco International Airport (SFO), Phoenix Sky Harbor International Airport (PHX), Chicago O'Hare International Airport (ORD), and New York Newark Liberty International Airport (EWR).

In Phase 4 of this work [7], we performed an extended and complementary assessment of wind forecast model performance wherein forecast model performance was evaluated along actual flight trajectories using aircraft meteorological data reports from the Meteorological Data Collection and Reporting System (MDCRS) as the source of truth winds for comparisons against the forecasts. Recall that aircraft-derived winds are considered superior representations of true conditions compared to 0-hour forecasts which are often used but tend to filter out high frequency spatial and temporal wind features. The Phase 4 research focused on assessment of HRRR 0–6 hour forecast model performance versus MDCRS.

In Phase 5, we have extended the trajectory-based performance analysis to the GFS model since that model continues to be commonly used by ATC and stakeholders. In addition, we extended the HRRR performance assessment to cover the 7–12 hour forecast look-aheads for comparisons against the GFS 0–12 hour forecast results. The following sections present the results of the trajectory-based GFS performance and contrast these results with the extended HRRR trajectory-based performance results as well as comparisons of the trajectory-based analyses against the volumetric HRRR truth-based analyses conducted in Phase 3.

3.2 DATA SOURCES

3.2.1 MDCRS

MDCRS aircraft observations are collected, processed, and archived by NOAA Global Systems Division (GSD), and are made publically available through the Meteorological Assimilation Data Ingest System (MADIS). More than 100,000 meteorological reports per day from more than 4,000 aircraft are available over the Contiguous United States (CONUS) from the MDCRS system [9]. Figure 2 shows an example of MDCRS data coverage for a single day (1 February 2016). On this day, there were nearly 125,000 aircraft observations over the CONUS.

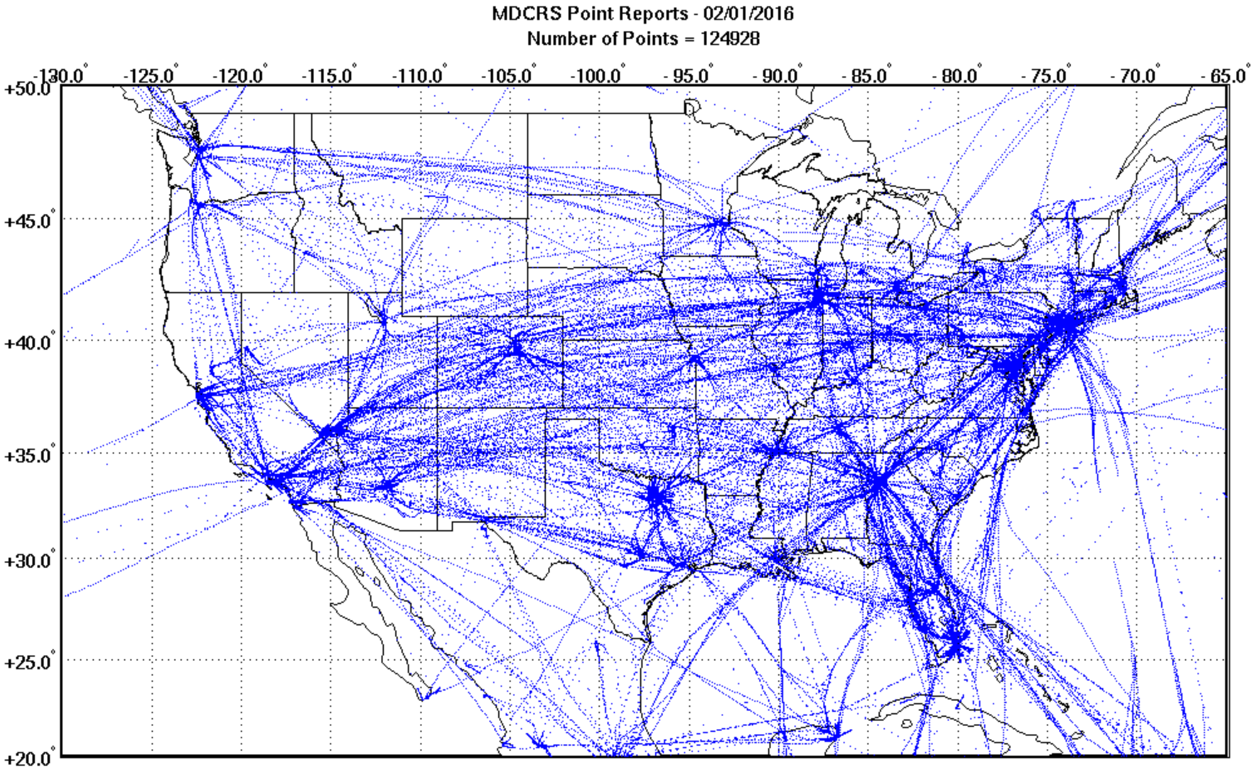


Figure 2. Example MDCRS report coverage over CONUS.

The aircraft reports include position information (latitude, longitude, pressure altitude), time, meteorological variables (temperature, wind speed and direction, etc.), and quality flags for each of the variables. MADIS performs a number of post-processing temporal and positional consistency quality checks prior to storage in their database. Each report contains a "roll flag" field that may or may not be populated, and indicates when the aircraft is maneuvering (turning, banking) such that the associated data report may be unreliable. In our analysis dataset, we found that only 12% of the reports had roll flag information present, with 95% of the reports with available roll flags identified as “good” quality (roll ≤ 5 degrees), and 5% of the available roll flags as “bad” quality (roll > 5 degrees). Given the paucity of available roll flag information, we only rejected aircraft reports on the basis of the roll flag if the information was present and indicated bad roll quality.

Aircraft reports are generally provided at varying nominal update frequencies depending on the phase of flight. Table 3lists the nominal update frequencies by phase of flight.

TABLE 3

Nominal MDCRS Report Update Rates

Flight Phase	Report Update Rate
Take-Off	**6–90 seconds**
Departure	**20–510 seconds**
En-Route	**3 minutes if below 465 hPa (~20,000 ft)** **7 minutes if above 465 hPa** **1 minutes if icing conditions are present**
Approach	**60 seconds**

MADIS aircraft data are provided in two formats: points and profiles. The points data contain all of the available reports without any associations or organization to specific flights. The profile data are a subset of the points data that groups the points by flights for arrivals and departures only, but do not include reports from cruise segments. We found that not all available arrival and departure segments were represented in the MADIS profile data, and reports from cruise altitudes were needed for our study, so we performed our own track associations from the point data using the encrypted tail numbers available with each aircraft report together with spatial and temporal proximity logic. Figure 3 shows 3D and 2D plots of individual points and resulting associated tracks for a single day over the ORD region.

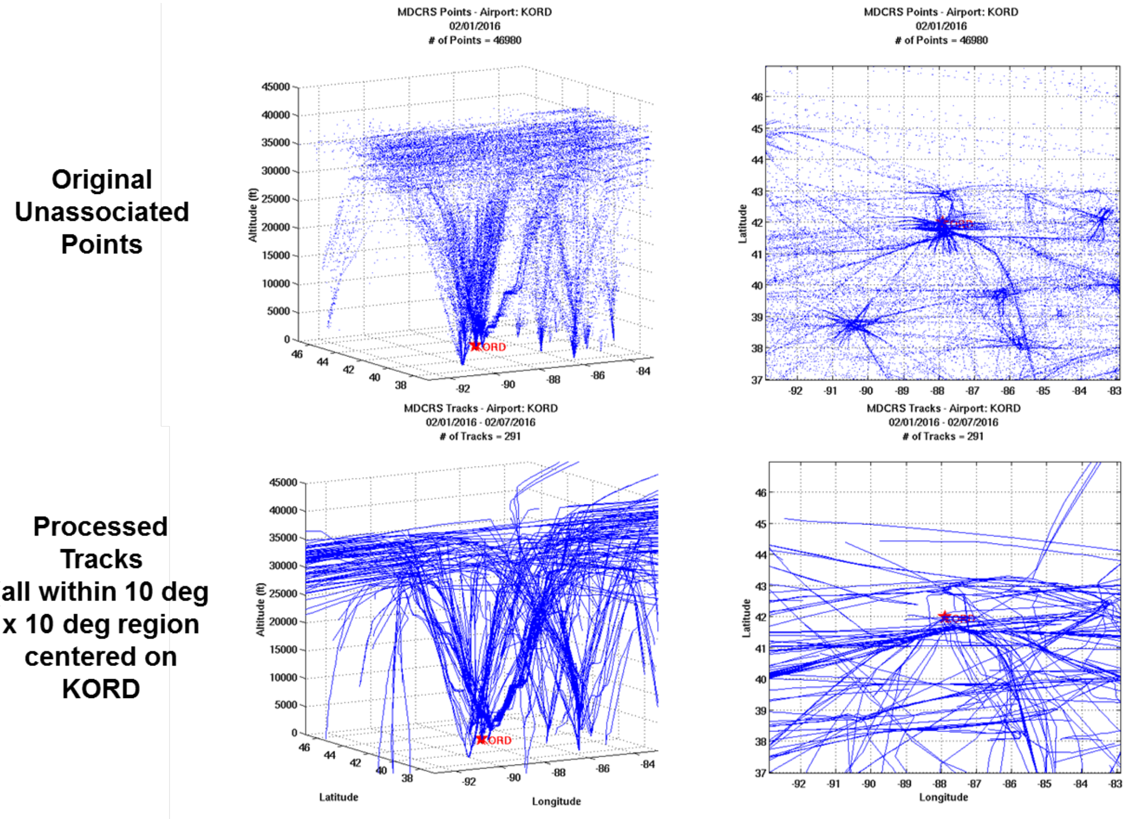


Figure 3. 3D (left) and 2D (right) views of unassociated MDCRS points (top) and resulting tracks (bottom) after track association. Data are from descents into the ORD region on Feb. 1, 2016.

In addition to storing the position and time information of each MDCRS track sample, track-aggregated wind statistics including wind speed and headwind minima, maxima, means, and standard deviations were computed and stored with the track data in order to support subsequent qualification of tracks based on wind environment characteristics. Headwind values were computed based on along-track changes in direction between successive report locations, not actual aircraft heading information, since that information was typically absent in the MDCRS data. A tail number key file provided by NOAA to MIT LL with the authorization of Airlines for America (A4A) allowed assignment of the actual tail number to each generated track. When combined with other flight information, the actual tail numbers allow look-up and comparisons of the MDCRS-based tracks with filed flight plans.

The processed MDCRS tracks are stored in a database table for additional processing and analysis. As of this writing, the MDCRS tracks database presently contains over 2.5 million tracks from 1 January 2015 through 31 January 2017, and continues to be updated as additional MDCRS data are acquired.

3.2.2 High Resolution Rapid Refresh (HRRR)

The HRRR model is an hourly updating, 3 km horizontal resolution, CONUS domain numerical weather prediction model produced by NOAA/NCEP. The HRRR updates hourly and provides hourly forecast grid sequences of meteorological variables with look-aheads from 0 to 15 hours. For our analyses, we obtained and processed the pressure vertical coordinate files having 25 hPa vertical resolution extending from 1000 hPa to 50 hPa (approximately 360–67,500 ft under ISA conditions). Two dimensional surface variables such as surface pressure, wind, and temperature are also included in the pressure coordinate data files.

3.2.3 Global Forecast System (GFS)

The GFS model is run by the NOAA/NCEP every 6 hours and produces forecast grid sequences of meteorological variables at 3-hour look-aheads for the 0-to-192-hour (8-day) forecast range. For our analyses, we processed the 0.5 degree latitude-longitude, pressure vertical coordinate files having 25 hPa vertical resolution extending from 1000 hPa to 50 hPa.

3.3 ANALYSIS METHODOLOGY

3.3.1 Geographical Coverage

In order to assess forecast capabilities across different geographic wind environments, HRRR and GFS wind forecast comparisons were made over four separate 400 NM x 400 NM regions centered on San Francisco (SFO), Phoenix (PHX), Chicago (ORD), and Newark (EWR) airports as shown in Figure 4. The SFO region provides a relatively “benign” west coast environment dominated by high pressure, low wind speeds, and infrequent wind shear. The PHX region represents an arid climate, and is also a relatively benign wind environment, but has more occurrences of sub-tropical jet stream winds due to its southerly latitude. The ORD region typifies an upper mid-western climate with a good mix of convective summer and winter storms with occasional strong winds and vertical wind shear. The EWR region represents the northeast coastal environment which has a high frequency of strongly sheared wind environments (e.g., “Nor’easters”), and high winds aloft due to frequent confluence of the polar and sub-tropical jet streams.

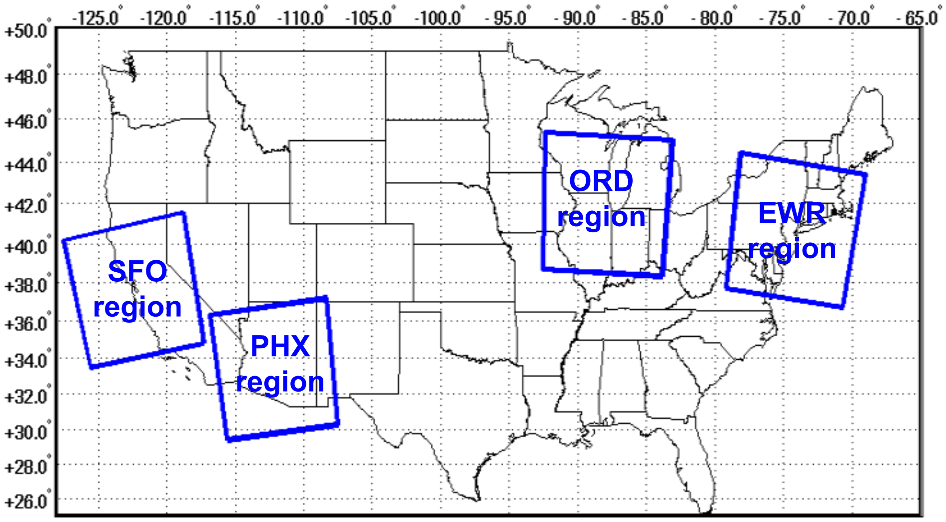


Figure 4. Regions analyzed for wind forecast model performance.

3.3.2 Analysis Period

MDCRS wind observations and matching HRRR and GFS wind forecasts from a 1-year period extending from March 1, 2015 through February 29, 2016 were compared and analyzed over the four regions for forecast model look-ahead times ranging from 0 to 12 hours.

3.3.3 Selection and Matching of MDCRS and Forecast Model Data

Candidate MDCRS Track Segment Selection

For each airport analysis region, MDCRS tracks were first pre-filtered to select candidate tracks having length of at least 200 NM and having a lowest altitude ending point within a 30 NM radius from the airport center and less than 2,000 feet above the airport altitude. An analysis segment for each candidate track was then extracted by proceeding backward from the arrival endpoint to the point of intersection of the model data partition region boundary. This resulted in arrival track segments of approximately 200 NM in length and ensured that sufficient numbers of descent samples were captured for track-based metrics and subsequent breakout of wind forecast performance statistics by altitude. Figure 5 shows an example of selected descent track segments into ORD during the period 11/12/2015 00:08:00 GMT through 11/13/2015 02:32:00 GMT.

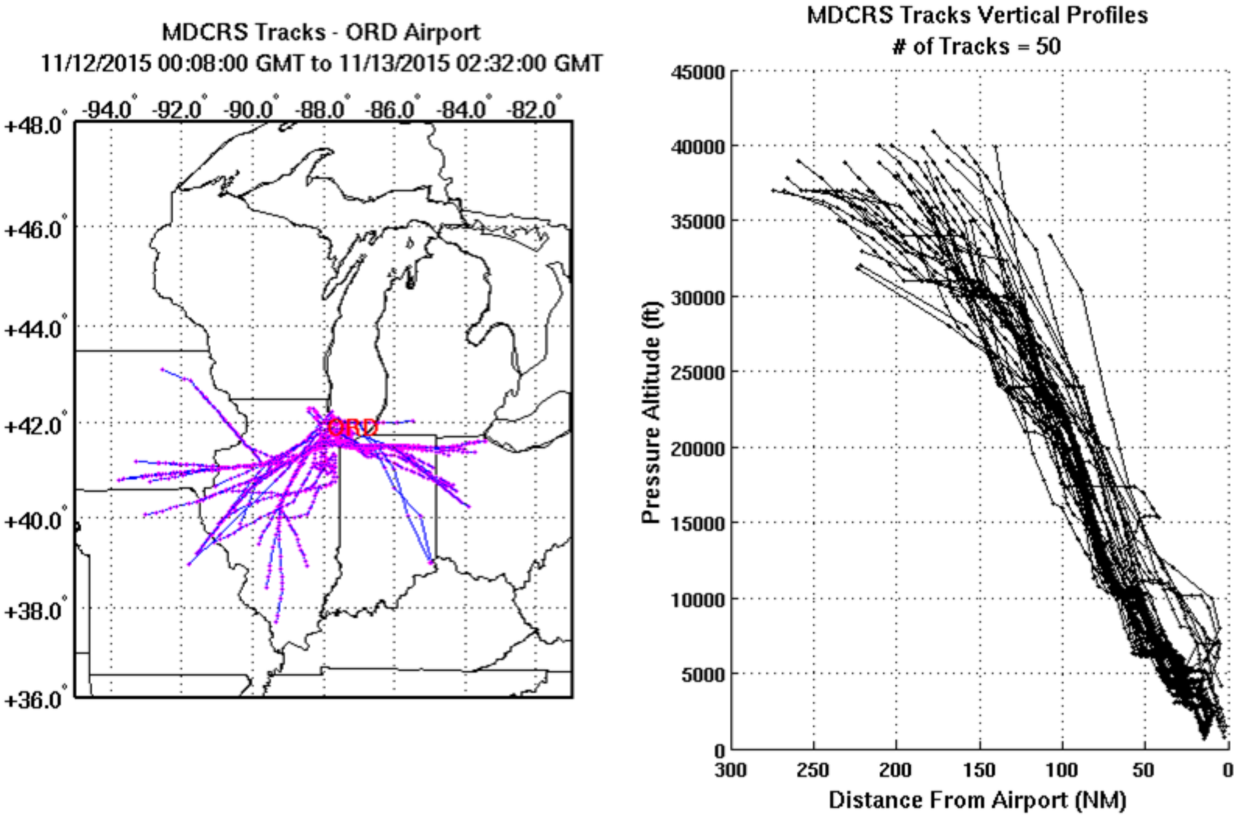


Figure 5. Example of MDCRS descent track segments. Left plot shows lateral track segment locations. Right plot shows vertical profiles of track segments.

Spatial Matching of Model Forecasts and MDCRS Observations

Model forecast data were matched horizontally to the latitude and longitude of the MDCRS observations using bilinear interpolation. Vertical interpolation of the model data to the MDCRS pressure altitudes was performed by first converting the MDCRS pressure altitudes to their equivalent U.S. Standard Atmosphere pressures and using linear interpolation in log(p) across the 25 hPa increment model pressure surfaces.

Temporal Matching of Model Forecasts and MDCRS Observations

Two methods for temporal matching of model wind forecasts with MDCRS observations are reflected in the forecast model performance analyses presented in this report: single track time matching and independent sample time matching.

a) ***Single Track Time Matching Method***

The initial temporal matching approach originally developed in Phase 4 matched MDCRS observations to model forecast times by first requiring that the final MDCRS observation of a candidate comparison track fall within plus or minus 15 minutes of an hourly forecast valid time. If an MDCRS end time match to an hourly model forecast time was found, then that same model forecast was used to compare against all of the preceding MDCRS data points in the track. This approach was used for the 0–6 hour HRRR forecast performance assessment documented in the prior Phase 4 report and is reflected in the expanded 0-12 hour HRRR forecast results presented in this report.

b) ***Independent Sample Time Matching Method***

In the course of the conducting the GFS forecast performance analysis for Phase 5, an improved temporal matching approach was developed. Rather than accepting or rejecting an entire track's samples based on the arrival end point time being within 15 minutes of model forecast valid hour and matching all of the track's samples to the same forecast valid time, each MDCRS sample's time was examined independently, and if the MDCRS sample time fell within the 15 minute time window of the hour, it was selected for comparisons against all available combinations of model forecast run cycle times and forecast look-ahead times valid for that hour. Compared to the single track time matching approach, this approach provides more precise matching of model forecasts to MDCRS samples, especially at MDCRS track segment points most distant from the end point, which may have times as much as 45 minutes earlier than the track segment end point time. HRRR forecast comparisons against MDCRS using this improved temporal matching approach are presently being processed, but the results were not yet available for analysis at the time of this report. Therefore, the HRRR results shown in this report are still based on the single track time matching approach. Updated HRRR performance results based on the independent sample time matching approach will be presented in later reports.

Temporal Interpolation between Model Forecasts

There was no temporal interpolation between the hourly HRRR forecasts, but for GFS, which has a three-hour forecast look-ahead resolution, temporal interpolation was performed at the intermediate hourly intervals between the published forecast intervals (e.g., for 1, 2, 4, 5, 7, 8, 10, and 11 hour forecast look-aheads) using the time-bracketing GFS forecasts. This facilitates categorization of performance results between the two models for each of hourly forecast look-ahead times out to 12 hours.

3.3.4 Categorization of Results

Wind forecast model performance discussed in the following sections is categorized by:

- Metrics

  - RMS vector difference
  - Mean absolute headwind difference
- Forecast look-ahead time (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 hours)
- Altitude
- Location

3.4 METRICS

The following wind forecast accuracy metrics were computed between MDCRS observations and model forecasts.

3.4.1 RMS Vector Difference (RMSVD)

The root mean square vector difference is the root mean square difference applied to the magnitudes of the forecast and observed wind vector components as given by Equation (1):

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

where N is the number of forecast-observation pairs, u is the east-west component of the wind vector, v is the north-south component, and subscripts f and o refer to forecast and observed, respectively. It is one of the most commonly used metrics to quantify performance of wind forecast models.

3.4.2 Mean Absolute Error (MAE)

The mean absolute error is the average of the absolute value of the difference between the forecast (f) and the observation (o) as given by Equation (2). This metric weights positive and negative errors equally, making it a measure of total forecast error, and is used in this study for quantifying headwind component differences between the model forecasts and MDCRS observations.

$$MAE = \frac{1}{N}\sum_{n=1}^{N}\left|f_n - o_n\right| \tag{2}$$

3.4.3 Outlier Rejection

Although NOAA MADIS imposes a number of quality control factors in their post-processing of the MDCRS reports, anomalous reports can still occur due to malfunctioning aircraft sensors, problems in data recording or transmission, etc. When repeated anomalous wind observations are noticed for a given MDCRS tail number, we flagged the aircraft as “bad,” and excluded any reports from that aircraft for the analyses. We found that the RMS vector difference between pairs of aircraft reports and associated model forecasts to be a useful metric for rejecting outliers. We chose a conservative value of 200 knots as the threshold for outlier rejection, since there could be actual very large forecast differences in high gradient wind environments such as jet stream boundaries.

3.5 RESULTS

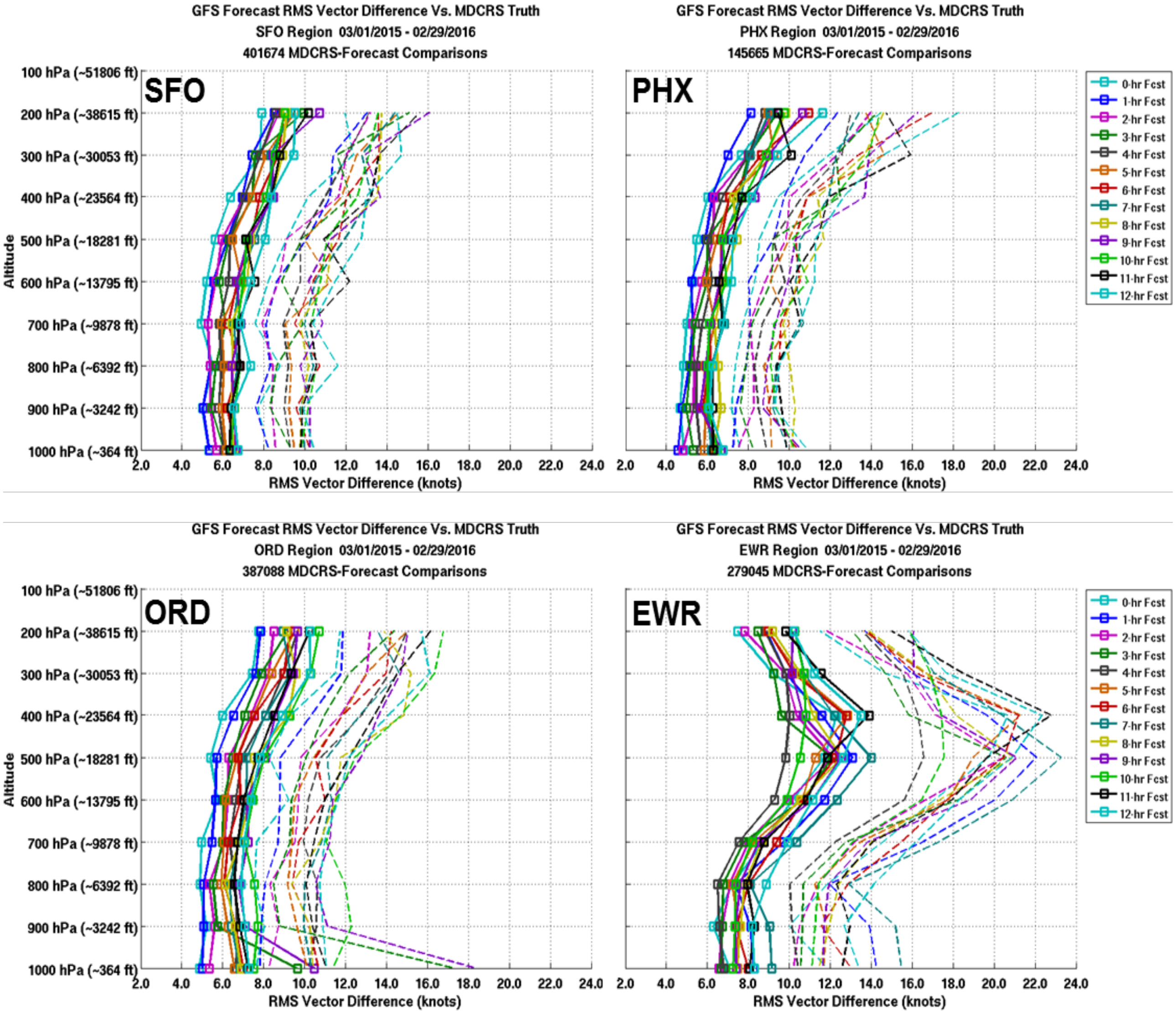
3.5.1 RMS Vector Difference (RMSVD) Analysis Results

Figure 6 and Figure 7 show the GFS and HRRR RMS vector differences, respectively, versus MDCRS truth as functions of look-ahead time and altitude for the four analysis regions. GFS forecast differences are seen to be less dependent on forecast look-ahead than HRRR as evident by the narrower spread of the difference curves. Although the GFS RMS vector differences generally tend to increase with altitude like the HRRR, the GFS differences show more variability over altitude for any given look-ahead time, and there is even some crossing of the difference curves across the look-ahead times. Some of this variability seen in the GFS statistics may be due to having significantly fewer matches of available GFS forecasts with the MDCRS samples given the 6-hourly model run cycle and 3-hour forecast look-ahead resolution of the GFS model. Compared to HRRR, there were about 75% fewer MDCRS-GFS comparison matches found over the one-year analysis period.

Table 4 and Table 5 present numerical summaries of the RMS vector differences between the model forecasts and MDCRS truth winds following aggregation over all altitudes as a function of forecast look-ahead time for GFS and HRRR, respectively. The altitude averaged GFS RMS vector differences were generally larger than the HRRR differences, with GFS differences ranging from 5.8 knots to 10.5 knots, and HRRR RMS vector differences ranging from 4.4 knots to 8.3 knots.

As noted in our prior Phase 4 report, the EWR region again has notably larger forecast differences compared to the other regions, especially at high altitudes (around 20,000–30,000 feet) where climatologically more frequent jet stream crossings occur compared to the other sites. The larger errors at EWR are seen in the GFS as well as the HRRR.

Note that these comparative results are preliminary, as the HRRR results are based on the single track time matching approach and will be revised to use the independent sample matching method that was used for the GFS analysis in a following update.



GFS Forecast RMS Vector Difference Vs. MDCRS Truth
SFO Region 03/01/2015 - 02/29/2016
401674 MDCRS-Forecast Comparisons

GFS Forecast RMS Vector Difference Vs. MDCRS Truth
PHX Region 03/01/2015 - 02/29/2016
145665 MDCRS-Forecast Comparisons

GFS Forecast RMS Vector Difference Vs. MDCRS Truth
ORD Region 03/01/2015 - 02/29/2016
387088 MDCRS-Forecast Comparisons

GFS Forecast RMS Vector Difference Vs. MDCRS Truth
EWR Region 03/01/2015 - 02/29/2016
279045 MDCRS-Forecast Comparisons

Figure 6. RMSVD (solid curves) and RMSVD plus one standard deviation (dashed curves) between GFS forecasts and MDCRS wind observations by altitude and forecast look-ahead time for SFO, PHX, ORD, and EWR airport regions (Independent Sample Time Matching approach was used).

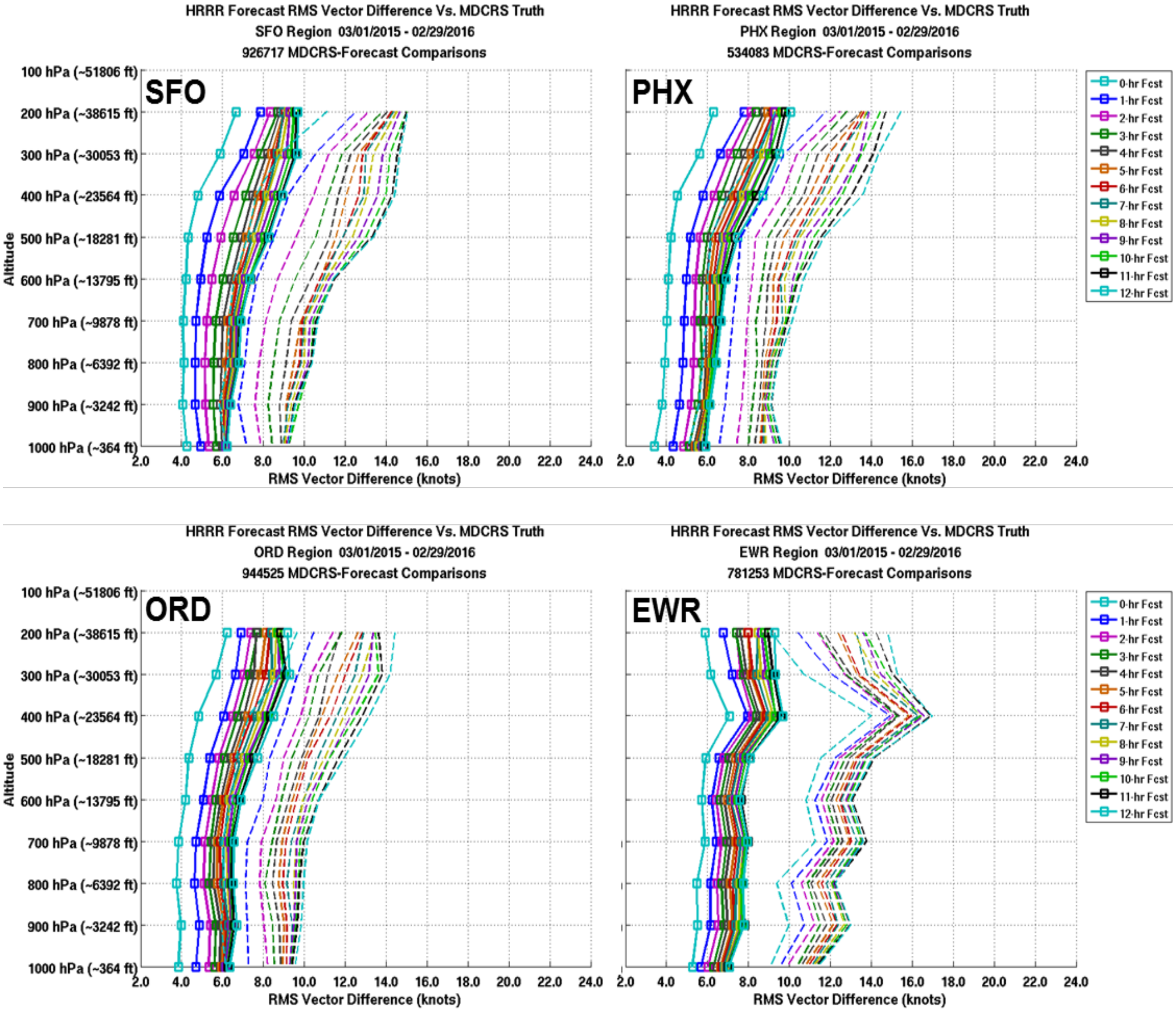


Figure 7. RMSVD (solid curves) and RMSVD plus one standard deviation (dashed curves) between HRRR forecasts and MDCRS wind observations by altitude and forecast look-ahead time for SFO, PHX, ORD, and EWR airport regions (Single Track Time Matching approach was used).

TABLE 4

GFS Forecast RMS Vector Differences (knots) vs. MDCRS Truth (Based on Sample Time Matching Method)

Airport Region	Forecast Look-Ahead (hours)												
	0	1	2	3	4	5	6	7	8	9	10	11	12
SFO	6.0	6.2	6.3	6.7	6.6	6.9	7.3	7.4	7.4	7.6	7.4	7.6	7.8
PHX	5.9	5.8	6.3	6.4	6.5	6.9	7.2	7.1	7.3	7.3	7.2	7.4	7.7
ORD	5.8	6.0	6.6	7.1	7.4	7.0	7.3	7.5	7.7	8.3	8.4	7.8	8.1
EWR	8.9	9.9	8.7	8.7	8.4	9.4	9.8	10.7	9.5	9.5	9.2	10.1	10.5

TABLE 5

HRRR Forecast RMS Vector Differences (knots) vs. MDCRS Truth (Based on Track Time Matching Method)

Airport Region	Forecast Look-Ahead (hours)												
	0	1	2	3	4	5	6	7	8	9	10	11	12
SFO	4.7	5.5	6.1	6.5	6.9	7.1	7.2	7.3	7.4	7.5	7.7	7.8	7.8
PHX	4.4	5.4	5.9	6.3	6.5	6.7	6.9	7.0	7.1	7.2	7.3	7.4	7.5
ORD	4.5	5.4	5.9	6.2	6.4	6.6	6.8	6.9	7.1	7.2	7.3	7.4	7.5
EWR	5.9	6.6	6.9	7.1	7.3	7.5	7.6	7.8	7.9	8.0	8.1	8.2	8.3

3.5.2 Headwind Difference Analysis

Figure 8 and Figure 9 show the GFS and HRRR mean absolute forecast differences, respectively, as functions of look-ahead time and altitude for the four analysis regions.

As expected due to the geometry of the calculations, headwind component forecast errors are generally less than RMS vector differences. As seen with the RMS vector difference analysis presented earlier, the GFS differences again appear to be less dependent on forecast look-ahead than HRRR, and forecast differences are larger at EWR than the other regions.

Table 6 and Table 7 present numerical summaries of the mean absolute headwind differences between the model forecasts and MDCRS truth winds aggregated over all altitudes as a function of forecast look-ahead time for GFS and HRRR, respectively. GFS headwind differences ranged from 3.2 knots to 4.7 knots, while the HRRR headwind differences ranged from 2.6 to 4.9 knots. In contrast to the RMS vector differences discussed in the previous section, the GFS headwind differences values appear to run much closer to their corresponding HRRR headwind difference values, and were generally slightly smaller than the HRRR differences. This result is unexpected, but should be considered preliminary and will be revisited pending completion of the HRRR reanalysis using the independent sample time matching method that was used for the GFS analysis.

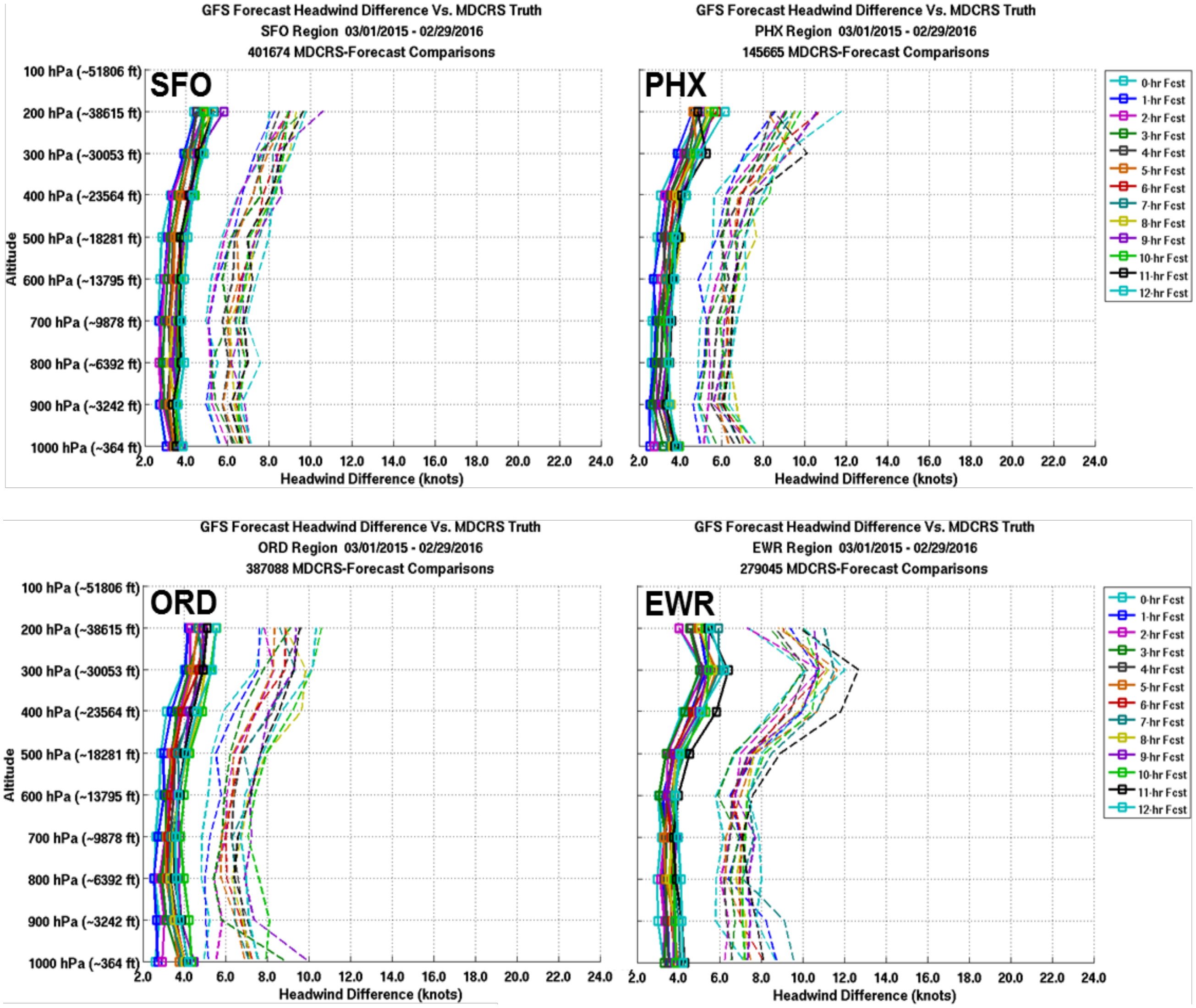


Figure 8. Mean absolute headwind forecast difference (solid curves) and mean plus one standard deviation (dashed curves) between GFS forecasts and MDCRS wind observations by altitude and forecast look-ahead time for SFO, PHX, ORD, and EWR airport regions (independent sample time matching approach was used).

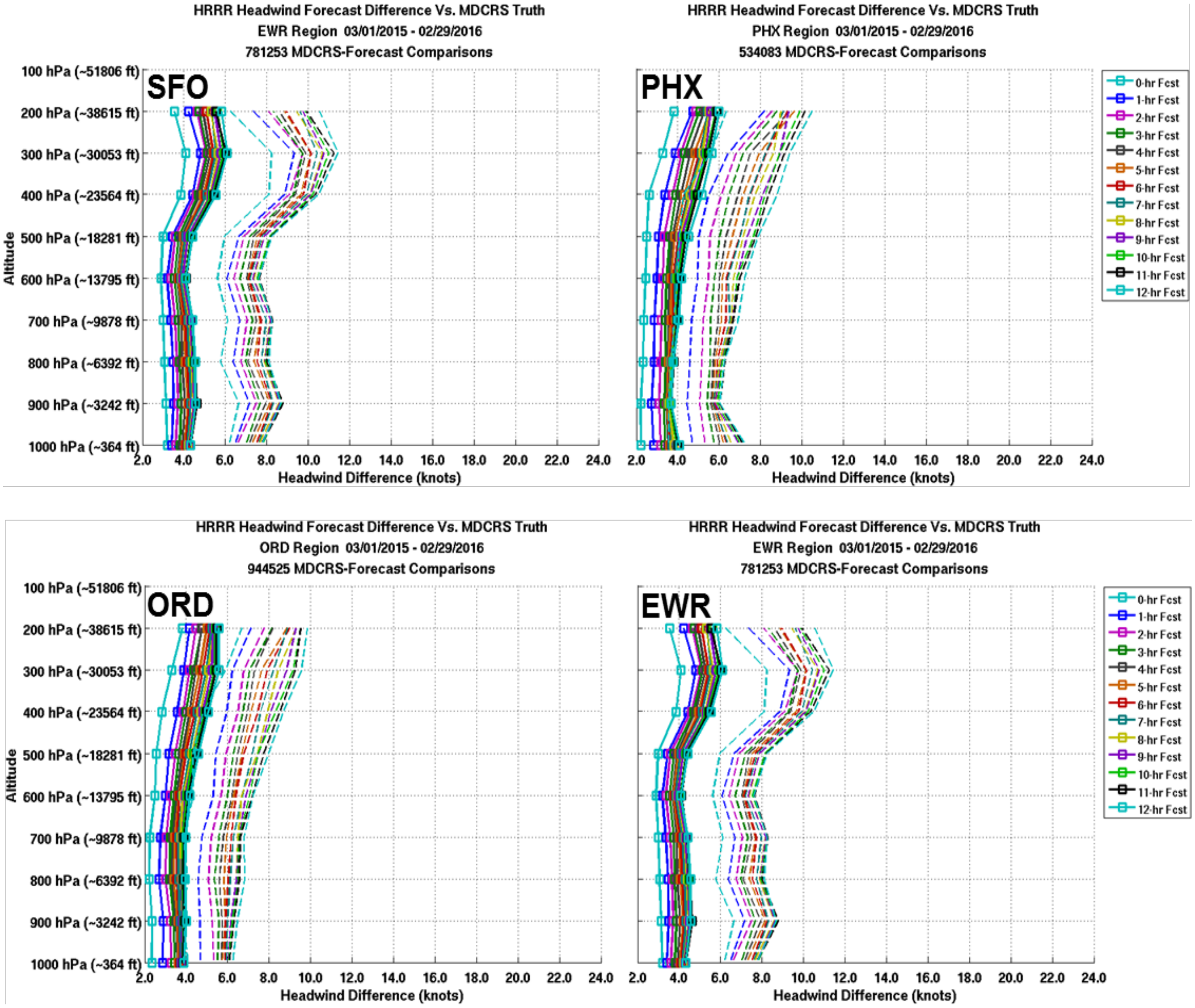


Figure 9. Mean absolute headwind forecast difference (solid curves) and mean plus one standard deviation (dashed curves) between HRRR forecasts and MDCRS wind observations by altitude and forecast look-ahead time for SFO, PHX, ORD, and EWR airport regions (single track time matching approach was used).

TABLE 6

GFS Forecast Mean Absolute Headwind Differences (knots) vs. MDCRS Truth (Based on Sample Time Matching Method)

Airport Region	Forecast Look-Ahead (hours)												
	0	1	2	3	4	5	6	7	8	9	10	11	12
SFO	3.2	3.2	3.4	3.5	3.6	3.7	3.9	3.9	4.0	4.0	4.0	4.0	4.2
PHX	3.2	3.1	3.4	3.4	3.5	3.7	3.8	3.8	4.0	4.0	3.9	4.0	4.1
ORD	3.1	3.1	3.4	3.6	3.9	3.7	3.8	3.9	4.1	4.2	4.5	4.1	4.3
EWR	3.6	4.0	3.7	3.8	3.9	4.2	4.2	4.5	4.2	4.3	4.4	4.7	4.6

TABLE 7

HRRR Forecast Mean Absolute Headwind Differences (knots) vs. MDCRS Truth (Based on Track Time Matching Method)

Airport Region	Forecast Look-Ahead (hours)												
	0	1	2	3	4	5	6	7	8	9	10	11	12
SFO	2.8	3.3	3.7	4.0	4.2	4.3	4.4	4.4	4.5	4.6	4.7	4.7	4.8
PHX	2.6	3.3	3.6	3.8	3.9	4.1	4.2	4.2	4.3	4.4	4.4	4.5	4.6
ORD	2.7	3.2	3.5	3.7	3.8	4.0	4.1	4.2	4.3	4.3	4.4	4.4	4.5
EWR	3.3	3.8	4.0	4.1	4.3	4.4	4.4	4.5	4.6	4.7	4.8	4.8	4.9

3.6 SUMMARY OF RESULTS

In the prior Phase 4 research, a trajectory-based assessment of HRRR 0–6 hour forecast model performance versus MDCRS aircraft wind observations was conducted. In the Phase 5 work described here, we extended the trajectory-based performance analysis to the GFS model. In addition, we extended the HRRR performance assessment to cover the 7–12 hour forecast look-aheads for comparisons against the GFS 0–12 hour forecast results

During the process of analyzing the GFS forecast performance, we discovered some inaccuracies in our "single track time" approach for matching model forecasts to MDCRS observations that may have resulted in some MDCRS samples inappropriately falling outside of the 30-minute time matching window for the associated hourly forecast valid time. An initial reprocessing of the GFS data has been completed using an improved independent sample time matching method, and the preliminary results are presented in this report. At the time of this writing, the HRRR versus MDCRS comparisons are still being reprocessed using the improved independent sample time matching method. Hence, the HRRR results presented in this report are based on the older "single track time" matching method and should be considered preliminary, especially when comparing against the GFS results.

Although there are considerable overlaps in the ranges of forecast errors seen in the two forecast models across regions, altitudes, and forecast look-aheads, there are several preliminary general conclusions that can be drawn:

1. Both GFS and HRRR forecasts exhibit the expected trends of increased forecast error with altitude and look-ahead time, but GFS results exhibited more variability in altitude.

2. GFS wind forecast errors were found to be less dependent on forecast look-ahead than HRRR. The RMS vector and headwind forecast difference curves for GFS are much closer together than for HRRR.

3. GFS wind forecast differences compared to MDCRS truth were generally found to be larger than HRRR differences for the RMS vector difference metric, but the reverse trend was found for the mean absolute headwind difference metric. This is a surprising result and needs further analysis and verification.

4. The EWR region has notably larger forecast model differences than the other three regions that were analyzed. This is consistent with prior results.

5. As expected from geometry, headwind component forecast errors were generally less than RMS vector wind forecast errors for both HRRR and GFS.

In the prior Phase 4 work, we presented an analysis of the accumulated effects of HRRR wind forecast error along trajectories employing a Mean Estimated Time-To-Fly (ETTF) difference metric. This analysis has not yet been extended for the GFS and additional 7–12 hour HRRR forecast look-aheads in this work phase, but we intend to revisit this metric in the next phase, possibly utilizing the FMS component of the Wind Information Analysis Framework (WIAF) to compute differences in ETAs given different forecast wind fields along the trajectories.

4. LOW-ALTITUDE LOW-SPEED RTA

4.1 MOTIVATION

The original expectation for the application of RTA operations was to be performed at altitudes ranging from cruise levels down to altitudes normally seen at Terminal Radar Approach Control (TRACON) entries at or near 10,000 ft MSL. A number of stakeholders, and in particular air traffic controller representatives from the National Air Traffic Controllers Association (NATCA) who have participated in RTCA work, have expressed strong interest in conducting RTA operations to lower altitudes. The majority of interest is to determine if RTA operations can maintain performance goals with RTA fix locations specified as the Initial Approach Fix (IAF) or Final Approach Fix (FAF) which is at or below 2000 ft above ground level (AGL). Some stakeholders have also expressed interest in conducting RTA operations to even lower altitudes such as the runway threshold.

To evaluate the performance in these domains, the capabilities of the FMS currently utilized in the WIAF needed to be augmented due to known limitations in the FMS RTA software.

4.2 FMS MODIFICATIONS

As part of Phase 3 work, Honeywell delivered a research variant of the Pegasus FMS which, unlike the Black-label version, had RTA capability in all phases of flight. That version of the FMS was further enhanced during Phase 4 to provide the ability to use up to 9 DFLs, in lieu of the standard 4 levels, as described in the Phase 4 report [7]. While it is true that these versions could conduct RTA operations in all phases of flight, it could not do so in all conditions of each phase. In respect to this work, the existing system stopped attempts to meet the RTA under the following conditions:

- Deployment of flaps
- Speeds below 200 knots

In the previously delivered research versions of FMS, there was a software implementation error and the user adjustable upper and lower RTA speed limits were both hardcoded and could not be changed. In this case, the lower speed limit was fixed at 250 knots which is well above normal approach speeds and thus impractical for RTAs at the IAF or lower. This implementation error, by limiting the lower RTA speed limit, coincidentally voided the existing coded logic that automatically disengages RTA control when the aircraft's airspeed is below 200 knots.

As part of Phase 5, Honeywell was again contracted to modify the research variant of the Pegasus FMS to permit RTA operations where flaps are deployed and managed speed could go below 200 knots.

Honeywell delivered a modified FMS which, amongst other changes, permits the setting of the upper and lower RTA speed limits by the user. By default, the lower RTA speed limit is 100 knots. This is a non-practical value from a safety perspective for the B757. However, the change to such a low value and other aggressive software changes to permit low speed/altitude RTA operations was performed for very practical reasons by Honeywell in terms of providing the RTA capabilities for the planned experimentation under a constrained cost and time schedule. It was not expected that this current FMS derivative would be modified with the intention to produce software ready for certification.

4.3 KNOWN ISSUES

Evaluations of the modified FMS revealed issues with the system providing speed targets after engaging the RTA operation during cruise. The particular symptom was the apparently random oscillation of speed targets which were observed to change in steps of up to 0.06 Mach. The issue was reported to Honeywell and they were able to confirm the defect.

MIT LL has identified that this behavior only appears to occur when the headwind component of the wind is greater than 85 knots and that it is also somehow coupled with the value selected for the time constraint. The specific cause for the behavior has been investigated but not yet identified by Honeywell. The reader should be advised that the RTA capabilities and its interactions with other FMS operations are very complex and it can sometimes be daunting to find the root cause of unexpected behaviors.

The oscillatory behavior appears to stop prior to the aircraft arriving at the top of descent point. To date, the oscillatory speed target behavior has not been observed in descent.

4.4 INITIAL EXPERIMENTATION

Despite these known issues, initial low-altitude trials were conducted down to the IAF on a limited set of flights and under a limited set of conditions. This would allow us to determine at least if the modified FMS was continuing to attempt the RTA through the flight regime of interest, as required, and if so, roughly how well it was performing.

It should be understood that the performance presented here may not reflect future performance. Given the known issue, there are doubts on its overall proper functioning and it cannot be certain that the speed targets profiles were necessarily the correct ones.

4.4.1 Flight Qualification

The same date bounds used in the RTCA work, February 1 through July 8, 2016, and the qualification methodology described in its section 5.4.2 of the Phase 4 final report [7], such as requiring track data to remain adjacent to the defined route, was used to qualify the flights for low-altitude RTA replications except for one difference. In lieu of having sufficient track and MDCRS data as well as remaining on course from cruise through to a manually selected RTA fix that was coincident with transitions through 10,000 ft mean sea level (MSL), these conditions now had to be met until the original flight passed the IAF on its identified approach procedure.

As shown in Table 8, only a limited number of flights were identified as qualified flights to the IAF. We do not find the reduction to 1/3 the size of the previous number of qualified flights as surprising as the lateral track tolerance for qualifying flights becomes considerably more stringent (sigmoid function) as the aircraft approaches the destination. See [7] Section 2.2.3 for more details.

TABLE 8

Total of Qualified and Replicated Flights from a Five-Month Evaluation Period (February 1, 2016 through July 8, 2016) with the Respective RTA Fix Located at the Initial Approach Fix

Destination Airport	Replicated Flights
KBOS	8
KBWI	1
KDEN	11
KHOU	4
KLAX	16
KMEM	14
KPHX	24
KSFO	6
Total	**84**

4.5 CONDITIONS OF THE EXPERIMENTS

This initial analysis considered only a limited range of conditions that were motivated by the results generated for the SC-206 Wind Guidance Document and in consideration of program schedule. These conditions were selected after review of the results presented in section 2 as most likely to present germane characteristics of results to be used to drive further testing. The principle difference was the limit on the number of DFLs tested and the selection of a single forecast source. Table 9 presents the conditions of these experiments.

TABLE 9

Test Conditions for Replicated Flights to IAF

	Independent Variable	Values Tested
Equipage	# of Descent Forecast Levels	3, 9
Wind Scenario	Data Source	GFS (age appropriate)
	Forecast Sampling Method	Equispaced along descent
	Forecast Update Condition	10 mins before RTA assignemnt
ATC Scenario	Metering Fix Position	IAF
	RTA Assignment Distance	230 NM radially from airport
	With/Without Speed Constraints	With

The rationale for the selection of 3 DFLs was that this value represented the minimum number of DFLs known to be delivered to aircraft based on the survey results conducted for the Wind Guidance Document. Specifically, this would be representing aircraft like the B737 that uses the GE/Smiths FMS, which is limited to no more than three DFLs. The selection of nine DFLs was to represent the opposite condition using the maximum amount of DFLs that could be utilized by our test platform.

The choice to first look at GFS as a forecast source was driven by the survey results, which showed that eight out of nine surveyed airlines used this as their wind source. Also, since the use of GFS as forecast also showed a minor, but real, degradation in the overall RTA performance on speed constrained routes, we thought that using GFS, along the three DFLs, would demonstrate lower-bound performance.

4.6 RESEARCH RESULTS

Figure 10 shows tracks for replicated flights into Memphis International Airport (KMEM). As with the results presented for the Wind Guidance Document, the outer black ring of Figure 10 indicates the points where their forecast information was updated and the inner magenta ring represents the point where the RTA is assigned. Unlike the experiment to 10,000 ft, a number of these flights required more complex maneuvering depending on their approach to the airport and the active runway at the time of their arrival. Figure 11 is a close-in view of Figure 10 showing some of the additional maneuvers. Though more complex, the current results when individually inspected do not show decreased RTA performance on the routes with increased maneuvers as compared to other flights into KMEM.

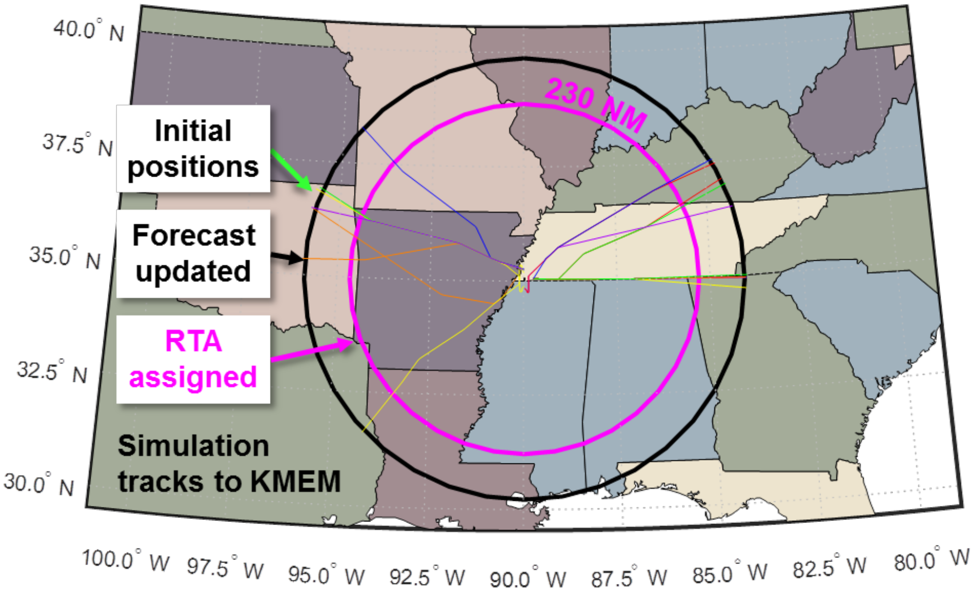


Figure 10. Examples of tracks for replicated flights into KMEM.

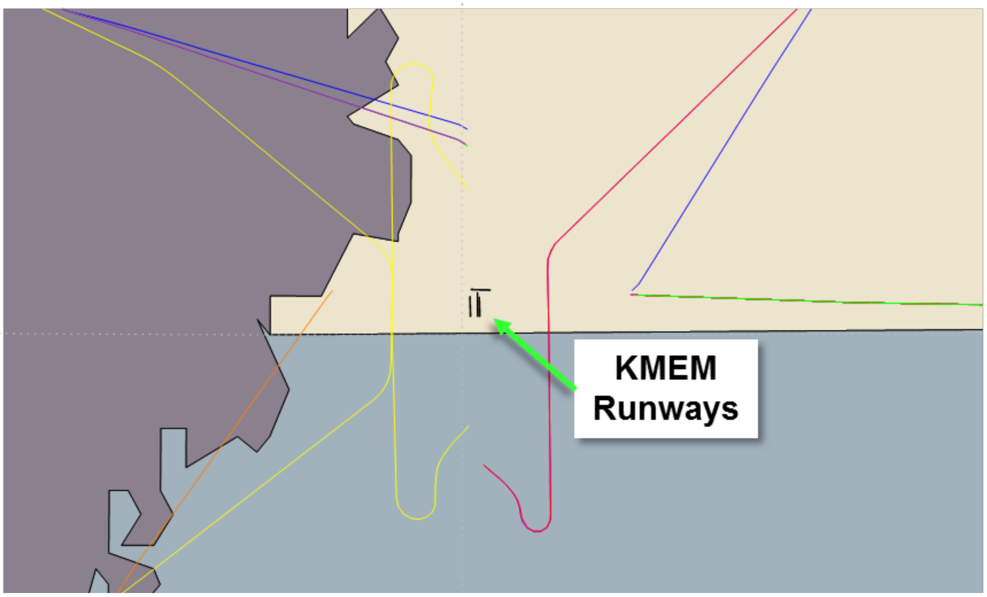


Figure 11. Close-in view of tracks of replicated flights into KMEM showing certain flights have increased maneuvering. The depicted runways at KMEM are drawn to scale.

4.7 SUMMARY OF RESULTS

There was an expectation that the aggregated performance of flights to the IAF would be lower than that for flights to 10,000 ft. The principle reasons for this are: an increase in both distance and duration under time control, expected increases in wind shear at lower altitudes, increased aircraft maneuvering as the aircraft approaches the terminal area, and the dynamic effects of aircraft configuration changes at lower speeds and altitudes (e.g., flaps and landing gear deployment). In general, we can say lower RTA TE performance was observed and so the results were not surprising in the general sense.

The standard deviations in RTA TE were larger as expected (see Table 10). The magnitude of the increase was higher than expected and is likely due to the durations of the procedures and an autothrottle system that does not perform as well as the actual system.

There was a surprising performance reversal where the replicated flight using 3 DFLs had a higher aggregated performance than of those flights using 9 DFLs (see Table 11). It is important to state that hard conclusions should not be drawn on the relatively small sample size (see Table 8) and that an expanded analysis is required in order to determine the presence or lack thereof of consistent performance under these conditions. Future work is recommended to explore these issues further.

TABLE 10

Means and Standard Deviations of RTA TE for Replicated Flights to IAF and 10,000 ft

		Bias (Std Dev) seconds With Speed constraints Forecast Source = GFS	
Inputs		Meter Fix Location	Meter Fix Location
Cruise Forecast	# DFLs	IAF (N=84)	10,000 ft (N=276)
Yes	3	4.5 (8.2)	4.8 (5.6)
Yes	9	4.6 (8.0)	4.9 (5.2)

TABLE 11

Percentage of Replicated Flights to IAF and 10,000 ft Whose RTA TE ≤ ±10 Seconds

		Flights Meeting RTA Performance Goal (%) With Speed Constraints Forecast Source = GFS	
Inputs		Meter Fix Location	Meter Fix Location
Cruise Forecast	# DFLs	IAF (N=84)	10,000 ft (N=276)
Yes	3	🔴 83.3	🔴 86.1
Yes	9	🔴 79.8	🔴 87.6

5. AIRCRAFT-DERIVED METEOROLOGICAL OBSERVATIONS USING MODE-S EHS

5.1 OVERVIEW

Current forecast models such as GFS and HRRR ingest atmospheric measurements reports from radiosondes and aircraft that participate in the Meteorological Data Collection and Reporting System (MDCRS). These aircraft-based weather observations (AbOs) are one of the most important factors in the accuracy of winds and temperature forecasts [10].

Unfortunately, these reports are often sparse (given the limited number of MDCRS flights and radiosonde launches) and delayed which ultimately limits their utility, especially to support rapid forecast modeling and/or applications that need near real-time weather data. (A detailed description of MDCRS is presented in [7] Section 3.2.1.)

Some of the limitations of MDCRS (coarse sampling per aircraft, small number of reporting aircraft, delays in observation delivery, etc.) were all motivating factors in identifying another data source that could be used to improve forecasts and potentially provide real-time observations. Two potential sources were identified, Automatic Dependent Surveillance-Contract (ADS-C) and Mode-Selective Enhanced Surveillance (Mode-S EHS). Only Mode-S EHS is discussed in this section as it could be used as a ready source to create Aircraft-derived weather Observations (AdOs) to significantly increase sampling rates and volumetric coverage.

Mode-S EHS is required equipage for scheduled flights in Europe. It is not required for operations in the NAS nor is Mode-S EHS currently used operationally by the FAA. However, the secondary surveillance systems found on the FAA’s Air Route Surveillance Radar (ARSR) and Airport Surveillance Radar (ASR) radars could be used to interrogate state information (e.g., airspeed, heading, ground speed, etc.) from appropriately equipped aircraft. These data can then be used to estimate the current wind field and air temperature where an aircraft is flying from the EHS data registers 0x50 (Track and Turn Report), and 0x60 (Heading and Speed Report). The contents of these two registers are sufficient to estimate the current wind field and air temperature where an aircraft is flying.

MIT LL is involved with the operation of three secondary radar sites in the US (White Sands, NM, Elwood, NJ, and Lexington, MA) not used in ATC operations. The latter of the three sites is located at MIT LL on Hanscom AFB and is known as the Mode-S Experimental Facility (MODSEF) and is currently configured with a 60 NM observation and interrogation range (see Figure 12). This secondary radar sits atop an Airport Surveillance RADAR-8 (ASR-8) and revolves at a rate of 12.5 rotations per minute (i.e., a 4.8 secs update rate).

Figure 12. MIT LL Mode-S Experimental Facility (MODSEF), Lexington, MA.

5.2 DATA INTERROGATION

As part of this Phase 5 effort, software and minor hardware enhancements were made to the MODSEF to permit the collection and dissemination of Mode-S EHS data. We use two standalone applications that communicate with the MODSEF in order to collect all the relevant aircraft data. The first application is responsible for collecting and reporting surveillance data from the radar. These data are delivered to the client application formatted as All Purpose Structured Eurocontrol Surveillance Information Exchange (ASTERIX) Category 048 Surveillance Data Exchange [11] and provide geographical position and altitude information along with other data. No special interrogation is required to obtain these data as the surveillance system produces these reports automatically.

A second application was developed to observe and interrogate aircraft to 1) determine if they support Mode-S EHS interrogations, 2) if so, which data registers they can transmit with populated data, and 3) if any, interrogating for those registers required to collect the state data needed to derive weather observations.

5.3 DATA COLLECTION STATUS

Currently, the surveillance and basic interrogation applications have been deployed and are operating continuously within the MODSEF. Data are being archived and live streaming is distributed within MIT LL. The live and archived data have been processed to validate message content but have not yet been used to generate instantaneous or filtered weather observations.

In a recent multi-hour sampling, well over 50% of all aircraft observed by the MODSEF were equipped with a Mode-S transponder. Of these Mode-S equipped aircraft, approximately 30% to 90% observable at any given time indicated and reported sufficient state data to derive estimates of both wind and temperature (not all aircraft are equipped and configured the same). Of these, about 5% indicated the capability to download what is known as a Meteorological Routine Air Report (MRAR). An MRAR downlink is populated with wind and temperature information, amongst other observations, as calculated onboard the aircraft, i.e., an AbO. Observations in these reports would be considered more accurate than that which would be derived from the interrogated data. This percentage of observed MRAR capable aircraft is about the same as has been reported in Europe [12].

The percentage of observed aircraft that reported sufficient data to calculate weather observations varies throughout the day but anecdotally never has been seen to be less than 25% during business hours. Figure 13 shows position reports of observed aircraft taken over a sample period of two minutes from the live stream currently produced by the MODSEF after our alterations. The magenta colored points indicate reports where weather (both wind and temperature) conditions could be estimated from the interrogated data reported by the aircraft. In this figure, the vast majority of aircraft were AdO capable. In contrast, there were zero MDCRS data reports as provided by MADIS for the same geographical region shown in Figure 13 during the same two-minute window. To see any MDCRS data in this region, we expanded the time period to 120 minutes (±60 minute around the first MODSEF sample time). Sixty-one reports from three unique aircraft were reported by MADIS and can be seen in Figure 14.

The percentage of AdO-capable aircraft depends on the number of flights in the area that are appropriately equipped and can report registers 0x50 and 0x60. The percentages reported above are in line with findings made elsewhere in the United States. In 2012, Puntin et al reported that at least 38% of the US registered civilian aircraft fleet reported these registers and 79% of the international fleet observed flying in the US supported these registers [13].The equipage trend has been positive and the overall equipage percentages have certainly increased since the report written in 2012. In a written correspondence with United Airlines, for example, they state they plan to have 100% of their fleet Mode-S EHS equipped by the year 2020.

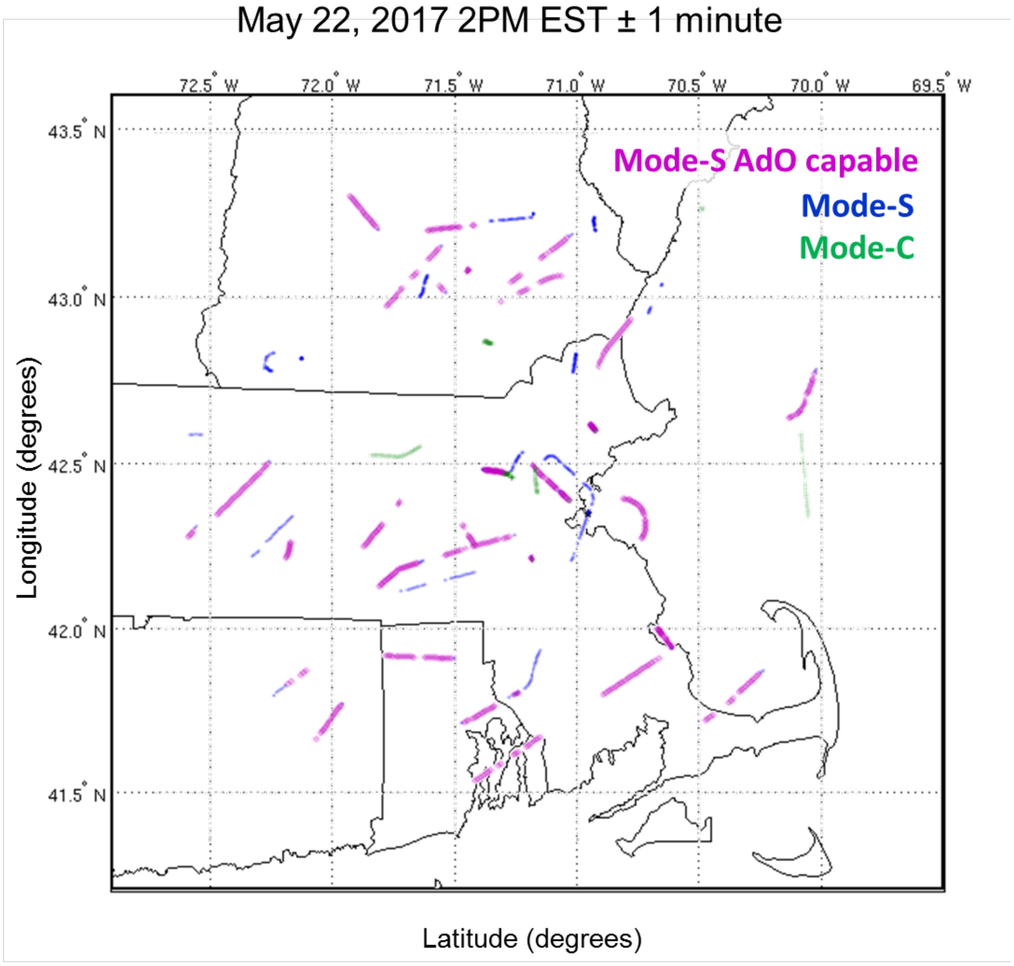


Figure 13. Two minutes of aircraft position reports taken with MODSEF. The color coding indicates aircraft transponder reporting capabilities. Green – altitude reporting only, Blue – altitude and aircraft ID reporting, Magenta – reports with data sufficient to create weather observation, i.e., each magenta point could be an estimated weather observation.

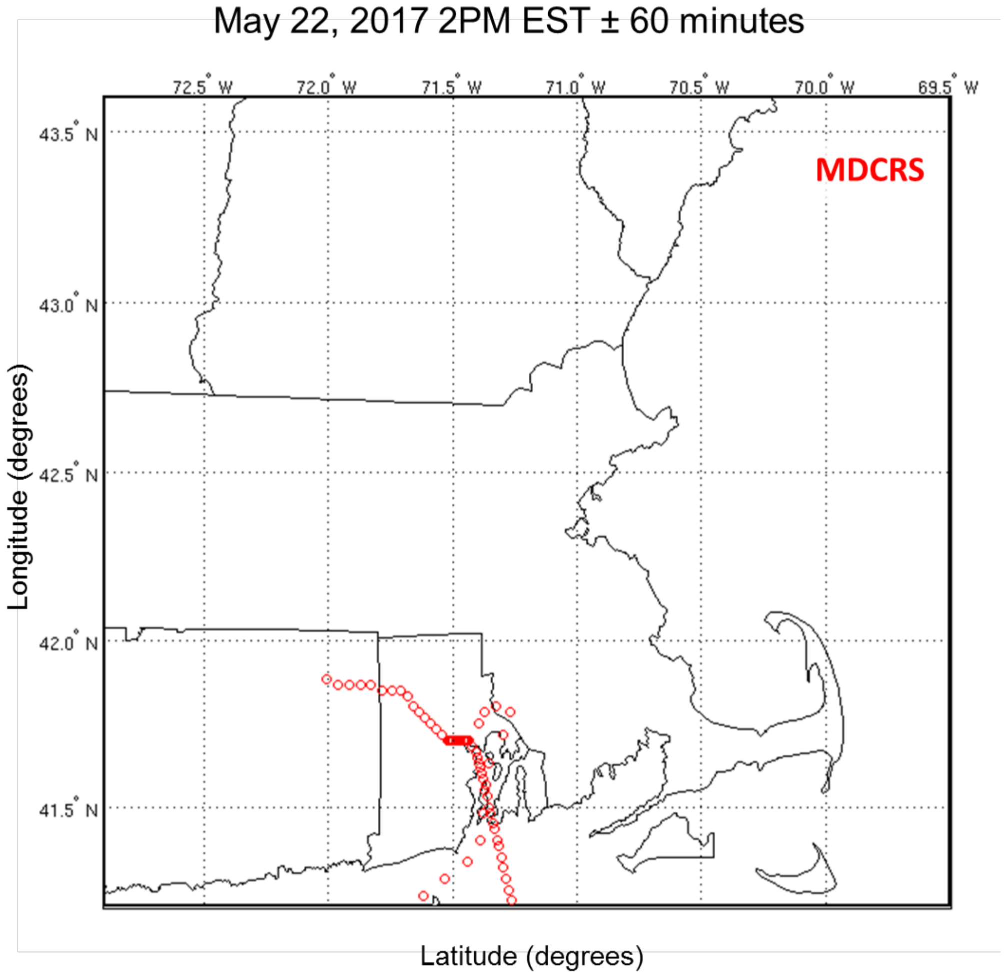


Figure 14. A 120 minute window around the sample period shown in the previous figure provided only 61 MDCRS reports for the same geographical region. To ensure all reports were available, these date were downloaded from MADIS two days after actual sample time to address delivery and processing delays.

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6. KEY FINDINGS AND RECOMMENDED NEXT STEPS

6.1 KEY FINDINGS

The results of this work have led to some important findings. With regards to the RTCA support, it appears that there is insufficient information available to fully characterize how NextGen operations such as RTA and IM will perform across the NAS. This is due in part to limited analysis in terms of breadth and quantity in one or more of the following factors:

- Geographical location
    - RTA was limited to 10 Class B airports
    - IM limited to a single simulation location Denver International Airport (KDEN)
- Modeled airframes
    - RTA analysis was conducted on a single six-degree of freedom aircraft (B757-200) model
    - IM aircraft models were three-degree of freedom models with simplified components
- Modeled avionics
    - RTA analysis was conducted on a single manufacturer-provided FMS system with a low fidelity autothrottle model
    - IM avionics were identical for all aircraft modeled with simplified avionics behavior (e.g., new speed targets were always obtained within a fixed period of time)
- Environmental conditions
    - Not all seasons were evaluated nor were explicit simulation conducted of known challenging weather days
- Selection process of forecast information for aircraft as currently performed by industry

An important finding on RTA operations is that speed constraints on procedural routes have a significant negative effect on RTA performance. The results of this study clearly show that it is nearly impossible for current system to meet the desired RTA performance goals given the current technology in

FMS logic and atmospheric forecasting accuracy when speed constraints are present. In contrast, replications of flights on routes without speed constraints have been shown to achieve nearly 100% desired performance with only a minimum amount of forecast information.

Forecast models, both GFS and HRRR, were most erroneous and variable in the New York metropolitan area (EWR) of the four model areas evaluated. This observation is similar to that reported in earlier phases of this work. It demonstrates that either the forecast models are consistently less accurate in this region or have insufficient or inaccurate initial conditions or some combinations of each. Based on the multiple comparisons of forecast data to MDCRS as truth data, it is difficult to say which forecast model (GFS or HRRR), can be considered the more accurate model when analyzed in the aggregate over an extended period of time. Operational use of HRRR forecasts as employed for the RTA analysis did show improved RTA performance in most cases when speed constraints were present on a procedural route.

The MODSEF, a secondary surveillance system located at MIT LL that is like many deployed across the US, was modified in such a way to interrogate aircraft for data germane for deriving wind and temperature observations if the aircraft was capable. Evaluations performed on data collecting by this system indicate that a significant percentage of aircraft in its region are capable of providing the data necessary to estimate wind and temperature conditions. The total number of additional reporting weather aircraft could be well over one order of magnitude greater than available through MDCRS alone.

6.2 RECOMMENDED NEXT STEPS

Based on current findings, there are a number of particular activities that we recommend be conducted in order to develop the information needed for the stakeholder community to close information gaps and for further research in new areas directly relevant to NextGen operations.

The activity of supporting SC-206 was one of the efforts that clearly led to formation of stakeholder interest and the direction of knowledge creation that was sought in order to best plan for and leverage NextGen operations. Due to constraints on this organization and others participating in the development of the Wind Guidance Document, not all areas of interest were evaluated before the finalization of the document. It was clear to those actively participating that the first release of the Wind Guidance Document would have to be amended with additional material expanding the original content. We recommend that continued support be provided to RTCA, including that of SC-206 as required, in order to help identify potential problems with existing concepts, develop solutions for recognized problems, and expand knowledge through research required for RTCA to support stakeholders' needs as required.

Work to date has generated performance trade-spaces for a limited set of aircraft/FMS types and ATC and wind scenarios. In order for the findings from the work to be more representative of a range of operating conditions, analysis should be expanded to include a broader range of wind conditions and, if possible given available resources, operational aircraft/FMS types (e.g., Boeing B737 or Airbus A320 with GE FMS). Discussions are currently underway with a major avionics supplier to explore this option.

FMS systems and ATC scenarios should be evaluated using techniques for selecting forecast information that are explicitly used by various major airline operators to identify shortfalls in industry approaches to providing forecast information.

Research performed to support RTCA has shown that under the conditions tested, the use of the "perfect" forecast outperformed both of the forecast systems evaluated. This implies that more accurate forecasts would be beneficial to RTA performance on speed constrained routes. One area in which to explore whether that could be used to either 1) support the creation of more accurate forecasts, or 2) substitute forecasts provided to FMSs with real-time observations would be the collection of aircraft-derived weather conditions. One means to do this could come from the interrogation of aircraft via secondary surveillance radar which could be used to obtain useful information from aircraft about the current state of the atmosphere. One advantage of this approach is that the update rate is high and the distribution of sounding locations, i.e., the distribution of aircraft locations, is much greater than what is achieved with the standard way of obtaining aircraft-based weather observations. Evaluation of this approach, i.e., collection, validation, utilization, could be beneficial to improving RTA performance.

As shown by the results developed in this phase of work in support of RTCA, the greatest factor on RTA performance was the presence or lack thereof of speed constraints. Evaluations of effects of these types of constraints and other procedural elements should be fully evaluated in relation to RTA performance and forecast information.

Future NextGen operations and advanced avionics may require forecast information distributed across dependent systems in a form that does not exist today. It is recommended to evaluate the system needs for data sharing and develop recommended requirements on performance of the distribution system and data content.

Further evaluation of IM trade-spaces is warranted based on Wind Guidance Document results. This activity should involve further discussions and collaboration with relevant A-IM groups at FAA and National Aeronautics and Space Administration (NASA) to identify needs for further analysis in this area. RTCA has identified limitations with existing results based on fast-time, moderate-fidelity simulations at a limited number of airports. The MIT LL WIAF could be leveraged given its higher fidelity models and capability of performing flights throughout the NAS to examine IM performance as a function of forecast quality in more expansive and realistic environments aligned with sponsor and stakeholder needs.

Phase 4 and 5 work led to the development of FMS variants with various performance enhancements relevant to 4D-TBO procedures that could be made to existing FMSs for possible implementation in the near-term. These activities were enabled by a technical collaboration with Honeywell to make modifications to the B757 Pegasus FMS. One of the latest enhancements was an FMS that can perform RTA operations to low altitudes. Analysis of low-altitude RTA operations would address stakeholders' (e.g., FAA NextGen, NATCA, etc.) interest in evaluating the potential of implementing RTA operations in this domain. This effort identifies the implications of conducting low-altitude RTA operations (e.g., with meter fixes at the initial approach fix or lower) and assess quality of wind forecast information required to achieve different performance levels. Another enhancement of potential interest is the ability to provide aircraft estimated trajectories to the ground. As part of that activity, Honeywell could make modifications to the FMS to permit the publishing of trajectory estimates from the Pegasus FMS. The accuracy of the predicted trajectories should be evaluated with respect to forecast quality and how errors in the trajectories could affect ground-based sequence and scheduling systems.

Phase 5 analysis of wind forecast information of key publically-available wind models (GFS, HRRR) against aircraft-based observations from the MDCRS system led to some surprising findings in relation to the model source and the geographical area for forecast. Further analysis should be conducted to evaluate the identified poorer forecast accuracy in the Northeast corridor in both of these forecast systems. Additional work should involve the evaluation of the predictability of forecasts accuracy so that periods and locations of likely degraded forecast performance (e.g. during frontal passages) can be operationally anticipated.

One area of development for the WIAF should be undertaking more detailed validation and verification of the simulation-based analyses conducted to date. A particular area of interest would be to improve the B757 autothrottle model based on data collected with United Airlines during Phase 4 work.

GLOSSARY

4D-TBO	4D-Trajectory Based Operations
A4A	Airlines for America
AbO	Aircraft-based weather Observations
ACARS	Aircraft Communications Addressing and Reporting System
AdO	Aircraft-derived weather Observations
ADS-C	Automatic Dependent Surveillance-Contract
AGL	Above Ground Level
ARAM	Aircraft Reported Atmospheric Model
ARSR	Air Route Surveillance Radar
ASG	Assigned Spacing Goal
ASP	Airspace Service Provider
ASR	Airport Surveillance Radar
ASR-8	Airport Surveillance RADAR-8
ASTERIX	All Purpose Structured Eurocontrol Surveillance Information Exchange
ATC	Air Traffic Control
ATM	Air Traffic Management
CONUS	Contiguous United States
DFL	Descent Forecast Level
EHS	Enhanced Surveillance
ETA	Estimated Time of Arrival
ETTF	Estimated Time-To-Fly
EWR	New York Newark Liberty International Airport
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FIM	Flight-deck Interval Management
FMS	Flight Management System
GFS	Global Forecast System
GIM	Ground-based Interval Management
GSD	NOAA Global Systems Division
HRRR	High Resolution Rapid Refresh
IAF	Initial Approach Fix
IM	Interval Management
KATL	Hartsfield-Jackson Atlanta International Airport
KBOS	Boston Logan International Airport
KBWI	Baltimore/Washington International Airport
KDEN	Denver International Airport

KEWR	Newark Liberty International Airport
KHOU	William P. Hobby Airport
KLAX	Los Angeles International Airport
KMEM	Memphis International Airport
KPHX	Phoenix Sky Harbor International Airport
KSFO	San Francisco International Airport
MADIS	Meteorological Assimilation Data Ingest System
MAE	Mean Absolute Error
MAFID	Meteorological and Flight Information Database
MDCRS	Meteorological Data Collection and Reporting System
MET	Meteorological
Meter fix	Location where aircraft is targeting to get to by the CTA/RTA is controlled to by FMS in TOAC procedures
MIT LL	Massachusetts Institute of Technology Lincoln Laboratory
Mode-S	Mode Select; Discrete Addressable Secondary Radar System With Data Link
MODSEF	Mode-S Experimental Facility
MRAR	Meteorological Routine Air Report
MSL	Mean Sea Level
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATCA	National Air Traffic Controllers Association
NOAA	National Oceanic and Atmospheric Administration
ORD	Chicago O'Hare International Airport
PHX	Phoenix Sky Harbor International Airport
RAP	Rapid Refresh
RMS	Root Mean Square
RMSVD	Root Mean Square Vector Difference
RMSVE	Root Mean Square Vector Error
RTA	Required Time of Arrival function of an FMS which manages aircraft speed in an attempt to comply with CTA at the meter fix
RTCA	Radio Technical Commission for Aeronautics
SFO	San Francisco International Airport
STAR	Standard Terminal Arrival Route
TAS	True Air Speed
TE	Time Error
TOAC	Time of Arrival Control
TOD	Top of Descent
TRACON	Terminal Radar Approach Control
WIAF	Wind Information Analysis Framework

REFERENCES

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