Project Report
ATC-444

Wind Information Requirements For NextGen Applications Phase 7 Report

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16. Abstract

This report details the Required Time of Arrival (RTA) performance of B757 aircraft arriving at various meter fixes across a range of altitudes from 33,000' down to 3,000' above ground level (AGL). The system tested demonstrated less than ±10 second arrival error in at least 95% of flights at meter fixes down to 7,000' AGL regardless of the forecast quality provided. Below 7,000' AGL, RTA performance significantly degraded demonstrating around 80% compliance under the best forecast and operating conditions. This report also provides a comprehensive lexicon of aviation and air traffic control related "wind" terms.

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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 Goals between aircraft under Interval Management (IM) procedures, are affected by 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 as directed by the sponsor and which builds upon prior work.

This report documents the progress made in the following objective areas:

1. Analyze current and future Flight Management Systems (FMSs) to conduct RTA operations to significantly lower meter fix altitudes than previous studies. This report compares performance results for replicated flights at typical Arrival Fix altitudes to those which flew to the lower altitudes associated with fixes located at the end of Standard Terminal Arrival Routes (STARs). Additionally this report presents performance data of RTA operations as a function of the presence of speed constraints and four different descent forecast selection techniques.

2. Development of a lexicon of wind-related terms applicable to various domains. These domains include, but are not limited to, air traffic control, airline operations, and aviating.

3. 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 Federal Aviation Administration's (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 confident 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 operations to different altitudes? The answers to those questions could be used by the ASP and the stakeholder community in general to determine what the 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. A second key question is are there characteristics in a route such as speed constraints that affect the performance of these operations? This question reflects on design and operational considerations in particular with regards to using RTA capabilities in conjunction with aircraft conducting IM operations, as well as a stream of aircraft where there is mixed equipage.

Figure 1 illustrates how wind information is used by ATC automation systems on the ground to develop a time target at a meter fix for use in a 4D-TBO procedure. Wind forecast 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 error at the meter fix, where the RTA error is the difference between the target time and the achieved time. 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 ±10 seconds 95% of the time [1]. Any errors in the wind information used by the ATC or aircraft automation systems 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 automation, 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.

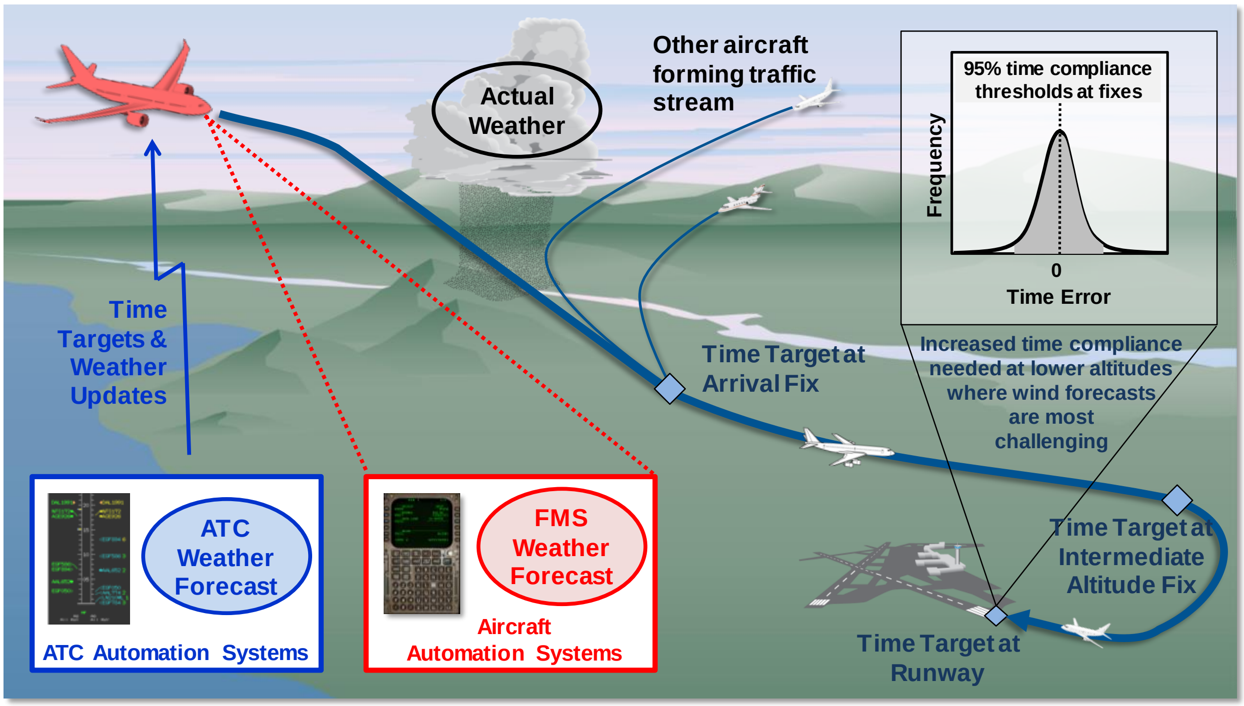

Figure 1. Focal elements relevant to Winds in 4D-TBO.

1.2 SUMMARY OF PRIOR WORK

In Phase 1 of this work [2][3][4], 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 [5] 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 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 [6] 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 [7] 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 Radio Technical Commission for Aeronautics (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 (DFLs), provided a meaningful improvement in RTA performance.

Phase 5 activities and products included: (1) the development and publication of the RTCA publication DO-369, "Guidance for Data Linking Forecast and Real-Time Wind Information to Aircraft" [8]; (2) analysis and characterization of HRRR and Global Forecast System (GFS) numerical weather prediction models; (3) augmentation of WIAF to conduct RTA operations to lower altitudes with preliminary results; (4) initial deployment of a Mode S Enhanced Surveillance (EHS) interrogation system to derive wind and temperature conditions experienced by equipped aircraft in real-time as a potential new source of empirical data of relevance to 4D-TBO. Full description of this work is available in [9].

Phase 6 activities included: (1) descriptions of program activities in support of RTCA Special Committee 206; (2) analysis of the National Aeronautics and Space Administration's (NASA) Air Traffic Management (ATM) Technology Demonstration-1 (ATD-1) and FAA's Four Dimensional Trajectories (4DT) Demonstration and their usefulness towards informing wind requirements for datalink; (3) a summary of enhanced and new methods for identifying flights for replication [10].

1.3 CURRENT RESEARCH ACTIVITIES AND DOCUMENT OUTLINE

The Phase 7 work summarized in this report builds on the outcomes of earlier phases of work with a focus on the experimentation and performance analysis of low-altitude RTA operations and the study and creation of a wind lexicon. The sections of the report are organized as follows:

- **Section 2** summarizes the performance analysis of RTA operations to lower altitudes.
- **Section 3** presents the results on the development of a lexicon on wind information related terms.
- **Section 4** presents a summary of the report and recommends next steps to refine and extend this work.

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2. LOW-ALTITUDE RTA OPERATIONS PERFORMANCE

2.1 INTRODUCTION

An initial effort to evaluate RTA operations to low altitudes was begun in Phase 5 of this program [9]. The activity was started in response to multiple stakeholders, RTCA, National Air Traffic Controllers Association (NATCA), and FAA, expressing strong interest in conducting future RTA operations to lower meter fix altitudes. Some stakeholders suggested conducting operations to as low as the runway threshold. Research on RTA performance to such low altitude (and hence slow airspeed) conditions had not been performed to date, nor was there an FMS readily available designed to operate in those conditions. Thus, Phase 5 involved the acquisition of a modified Honeywell Pegasus FMS with changes to permit continued RTA operation to low altitudes and speeds. The modifications removed restrictions in the existing research FMS that stopped RTA operation from functioning when the airspeed decreased to below 205 kt, or if any flaps were deployed. The modifications also expanded the lower limit on RTA target speeds from a hard coded value of 250 kt to a user-adjustable value, which in these experiments was 150 kt.

Unlike previous work, which replicated flights to meter fixes such that meter fix crossing altitudes would be near 10,000 ft Mean Sea Level (MSL), the goal of this task was to evaluate low altitude performance by placing RTA fix locations specified as the Initial Approach Fix (IAF) and Final Approach Fix (FAF), the later which is at or below 2,000 ft Above Ground Level (AGL). For reasons described later in this document, conducting correctly controlled flights to these fix locations were not technically possible due to erroneous FMS behaviors. Instead, flights were replicated by assigning RTAs at meter fix locations associated with arrival fixes (ARR) as well as to the last waypoint on the flight plan's Standard Terminal Arrival Route (STAR), which provided the lowest tested RTA fix crossing altitudes with values as low as 3,000 ft AGL.

2.2 MODELING APPROACH

A modeling infrastructure from previous iterations of this work (e.g., see [10]) has been expanded to support this work. The analysis infrastructure is made up of two major components: the MAFID and the AircrafT Operations Modeling System (ATOMS).

MAFID contains a collection of databases and web services. These databases contain years of historical operational data from the National Airspace System (NAS) ranging from 2016 to present day. Data includes Traffic Flow Management System (TFMS) track and flight plan data, Airport Surface Detection Equipment - Model X (ASDE-X) track data, MDCRS atmospheric data (e.g., winds and temperatures measured in situ by the aircraft), Coded Instrument Flight Procedures (CIFPs), and historical weather forecasts from models including the HRRR and GFS). The web services provide the capabilities to request and fuse historical track, flight plan and associated meteorological data, forecasts relevant at the time of the operation, historical CIFP data, and route decoding amongst other services. The capabilities of these databases and services permit the selection and qualification of flights to replicate the circumstances of actual historical flights, in addition to permitting the generation of the required data to conduct the simulations of the flights to test alternate flight operations relevant to the study objectives.

ATOMS is a distributed modeling and simulation system that includes a 6 Degree Of Freedom (6-DOF) dynamic aircraft model of a B757-200. Multiple avionics system for this aircraft relevant to the study are also simulated, including the autopilot, autothrottle, mode control panel, Multifunction Computer Display Unit (MCDU), FMS and other major components. The engine model was developed from recorded flight data under various conditions with specific effort to accurately model thrusting and fuel consumption at idle and near idle conditions as this greatly affects descent performance. Since limited access to autothrottle input/output data from recorded flight data was available, the autothrottle system response for both Mach and Calibrated Air Speed (CAS) control was developed from recorded data taken from a FAA Level D qualified Full Flight Simulator (FFS) for the B757-200. A pilot model incorporates context sensitive observation and response delays, such as when and how much to deploy speed brakes if the current CAS exceeds the target value and the FMS indicates a "drag required" message via the MCDU. A software representation of a physical Honeywell Pegasus FMS for a B757 running in a Honeywell virtual machine was utilized in this system. The operational flight code of the FMS was modified in support of our experiments to provide capabilities beyond those of the operational FMS. These included:

- The ability to perform closed-loop speed control during RTA operation in all phases of flight (not just cruise)

- The ability to perform RTA operations to lower altitudes and speeds than normally permitted by the FMS (previously RTA operations were disabled if any flaps are deployed or at speeds below 205 kt)

- An expansion of the number of DFLs from four to nine

- The ability to specify forecast temperature as part of each descent forecast

2.3 REPLICABLE FLIGHT IDENTIFICATION

MAFID and ATOMS were used to identify and replicate actual flights which met certain specific qualification criteria. One of the major efforts to support flight replications to FAFs as originally planned was to collect and identify original flights from the beginning of February 2016 through June 2018 that both closely tracked their flight plan and had associated wind and temperature measurements from the cruise phase of flight until after the flight passed its FAF. This period represents the period when all the required input data was available to the analysis system. Wind and temperature data used for this analysis were from aircraft participating in the MDCRS, which is about 20% of the commercial fleet. There is an uneven distribution of participating airlines and locations so certain aerodromes will have more (often considerably more) candidate flights than other sites. More details on MDCRS characteristics and availability is presented in ATC-439 [9].

As part of the process to expand the number of candidate flights, which was listed in the 10’s of flights in the previous phase of this program, special route processing was developed and performed [9] to account for flight plan amendments. More than 50% of flights had their route amended and without accounting for changes, many flights were disqualified because their track data did not match their original route used for candidate qualification. This process meaningfully increased the number of flights that passed the track qualification component of the candidate identification process, making new flights available for matching to available MDRCS data.

To continue the growth of candidate flights, the method developed in Phase 6 [10] to expand the available number of MDCRS routes was also applied to the data. This effort increased the number of MDCRS flights by up to 200% of which a small percentage matched to both the track qualified flights and had sufficient weather data for replication of the flight.

Even with the increased number of candidate tracked flights, only a small number of fully qualified flights were identified. This is in part due to the difficulty in associating the data from MDCRS flights to the flight with track and flight plan data. The association is normally done thanks to a mapping of encrypted tail numbers and the actual tail number, but this was found to be frequently inaccurate. It was therefore necessary to conduct our own identification of MDCRS data to tail and flight number in order to continue to increase the candidate flight count. This involved matching MDCRS track data to TFMS and ASDE-X reported track data. The effort identified two errors in the MDCRS data being provided to the public. The first being that the time stamps of all weather reports were being truncated to the minute, National Oceanic and Atmospheric Administration (NOAA) has since confirmed this finding and intended to remedy it in its next MDCRS processing release, and the second being that some MDCRS data that is fabricated is being reported as sensed and valid is also being generated and released.

An example of this behavior is shown in Figure 2. The plot is somewhat busy as it is taken from our TFMS-MDCRS Flight Associating Tool and not designed as a presentation tool. Multiple tracks from various flights to KJFK are shown along with a single set of MDCRS data (black circles) which is actually associated with the indicated track. Red circles are drawn around reports that are considered valid reports. The linearly interpolated points are clearly plotted along straight lines between actual measurements. This is very clear by the cutting of the corners in the bottom half of the figure and at the very end of the track where the actual aircraft flew a downwind, semi-circular base leg and a final leg while the MDCRS data is indicating doing straight from the base leg to the end of the track data close to the airport surface.

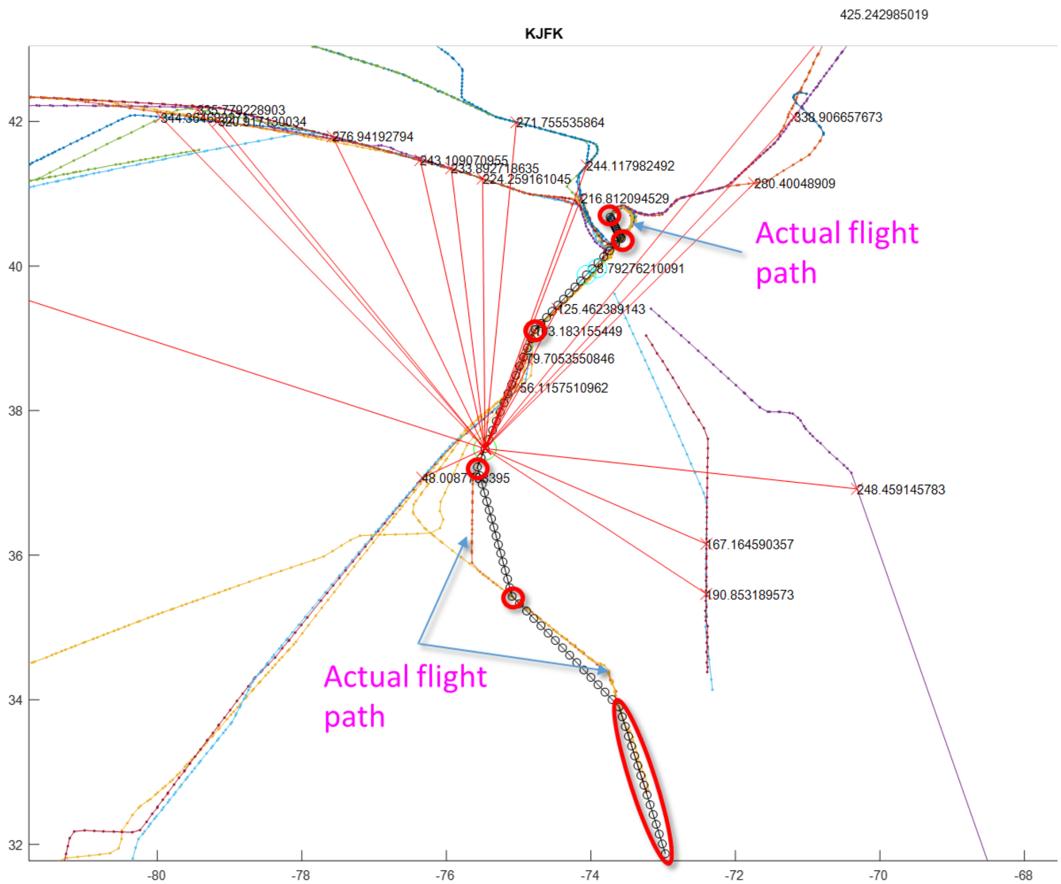


Figure 2. Questionable MDCRS data. Multiple tracks shown as line connected points. Black circles are MDCRS reports. Points encircled in red are considered valid reports. Remainder appear to be linearly interpolated from true measurements without indication as such in MDCRS data.

Another validation step involved an assessment of the quantity and quality of valid MDCRS weather reports for wind and temperature for the replicated cruise to descent portions of the flight. The validation criteria is different depending on the phase of flight. For cruise, the criteria is time-based and there must be valid reports with no greater than 8 minutes between samples. The criteria for descent is more complicated and is a function of altitude. A piecewise spacing criteria is specified which requires tight vertical spacing of reports as the altitude decreases. The altitude dependent thresholds were developed with contributions from meteorologists, pilots and subject matter experts to establish sampling minimums for modeling wind shears. The altitude dependent differential thresholds are plotted as the solid line in the left plot of Figure 3. For example, above 33,000 ft MSL, the observations may be spaced as far apart as 3,200 ft vertically. At 5,000 ft MSL, the observations must be spaced less than 1,500 ft apart. Exceeding the spacing criteria anywhere along the descent disqualifies the flight for replication as we believe the atmosphere conditions may not be correctly represented with significant gaps in the profile.

Figure 3 presents an example flight showing the reports' altitudes as a function of the altitude differential between reports and the distance from the end of track. In this case, this flight has sufficient vertical sampling such that all the reports stay within the piecewise spacing limit.

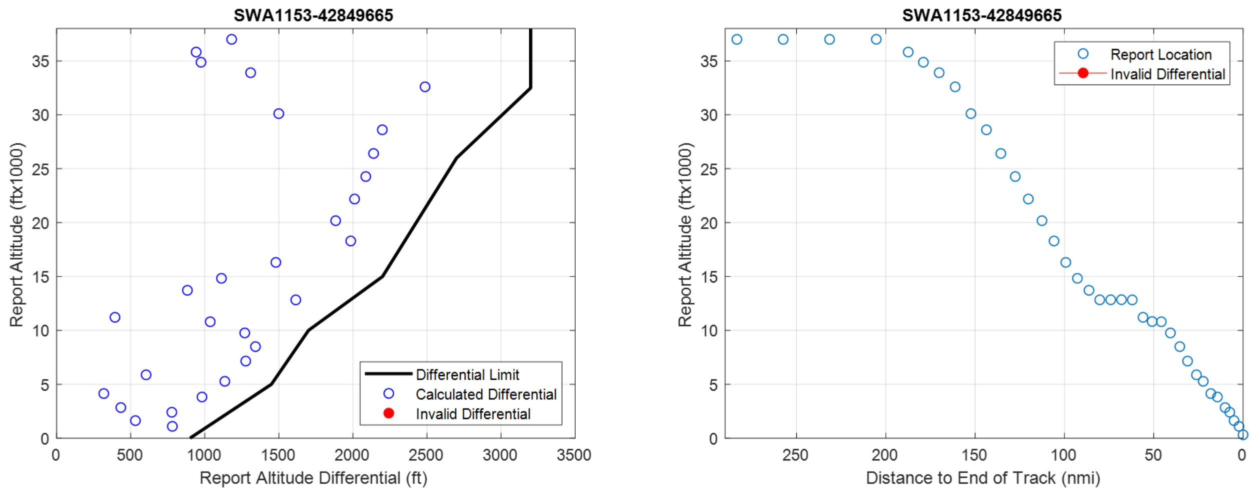


Figure 3. Valid MDRCS reports for a given flight. The report altitude versus the difference in altitudes between reports and the piecewise acceptance criteria is shown in the left plot.

A different flight and its MDCRS reported altitudes of valid data and differentials are given in Figure 4. In this instance we see two locations during the descent where the vertical spacing of valid reports exceeds the altitude dependent differential limit. Thus, this flight could not be used for replicating a flight even if its track data had passed the track qualification stage.

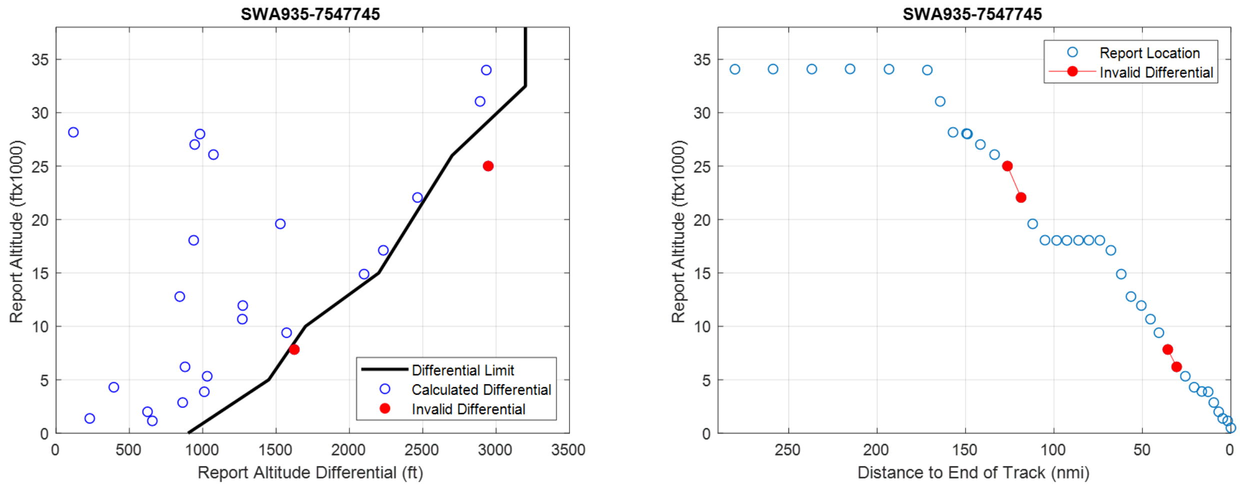


Figure 4. Valid MDRCS reports for a given flight. The report altitude versus the difference in altitudes between reports and the piecewise acceptance criteria is shown in the left plot. Red-filled circles show reports where the acceptance criteria was exceeded.

As a result of all these qualification criteria, the number of qualified flights used in this analysis was approximately 200 from an original dataset containing 28 million flights. A shakedown of the ATOMS simulation system was conducted to evaluate the distributed systems operations including augmentation of the pilot model and the newly developed autothrottle systems which was optimized and shown to significantly outperform the previously used autopilot and closely match the behaviors of the real B757 system across various altitudes and speeds.

A collection of the scenarios specifically for flights to the FAF were performed, monitored and evaluated. Initial results were very promising save for a number of outlying results that illustrated significantly poorer RTA performance than the remainder of the group, typically arriving very late. A series of investigations ensued to determine the characteristics of the problem. For example, were there specific elements or properties defined in the route that correlated to the group's poor results, was the FMS programming automation functioning correctly, were the measurements of time errors incorrect, etc. The evaluation extended into analysis of flights with the meter fix specified as the IAF and unfortunately the

The following three figures demonstrates the errant behavior for a flight programmed with the RTA fix specified as the FAF for the RNAV (GPS) Instrument Approach Procedure (IAP) for runway 33R into KBWI. In Figure 5 the aircraft is just passing the last waypoint on the STAR, named HOOOK. At this point, the FMS is indicating a meter fix arrival errors of 7 seconds, which is 1 second out of the programmed tolerance. At this point in time, the FMS thinks, and is indicating that, it is performing very well.

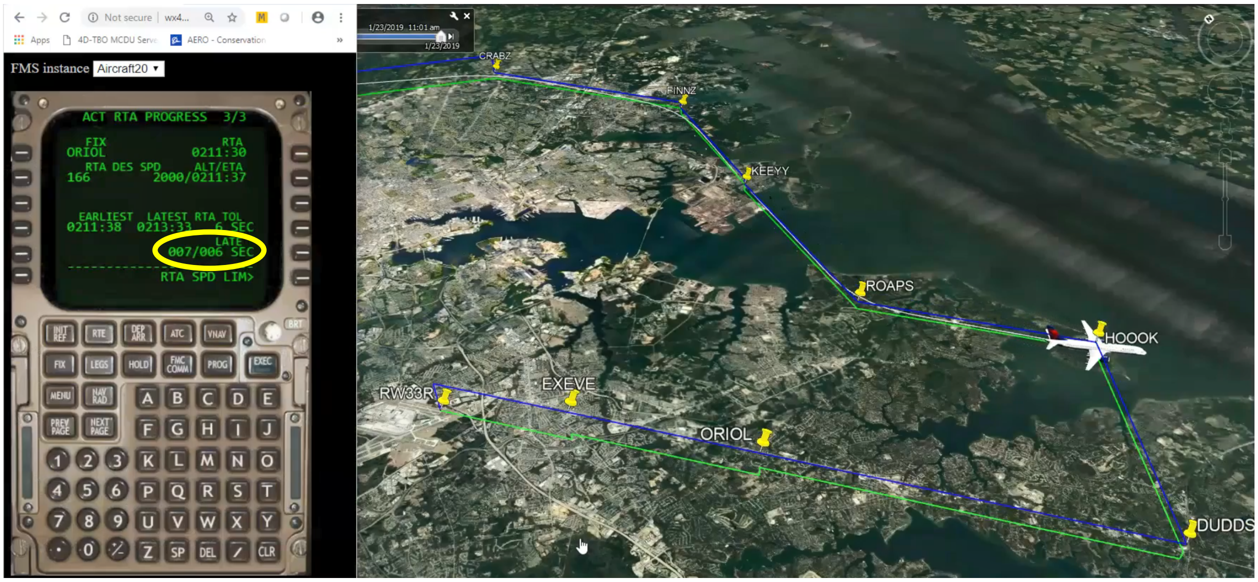


Figure 5. Time synchronized FMS RTA display and aircraft position. Aircraft shown at HOOOK which is the last waypoint in the STAR. The FMS indicates a 7 second (late) RTA error estimate (circled in yellow) for its arrival at ORIOL.

As the aircraft passed the last waypoint on the STAR, the estimated RTA time error started to grow at a very rapid rate. Only 45 seconds after passing HOOOK, the error grew by 10 seconds to a 17 second error, as shown in Figure 6. The error continued to grow for the next 30 seconds, adding 25 seconds of error in that period. See Figure 7.

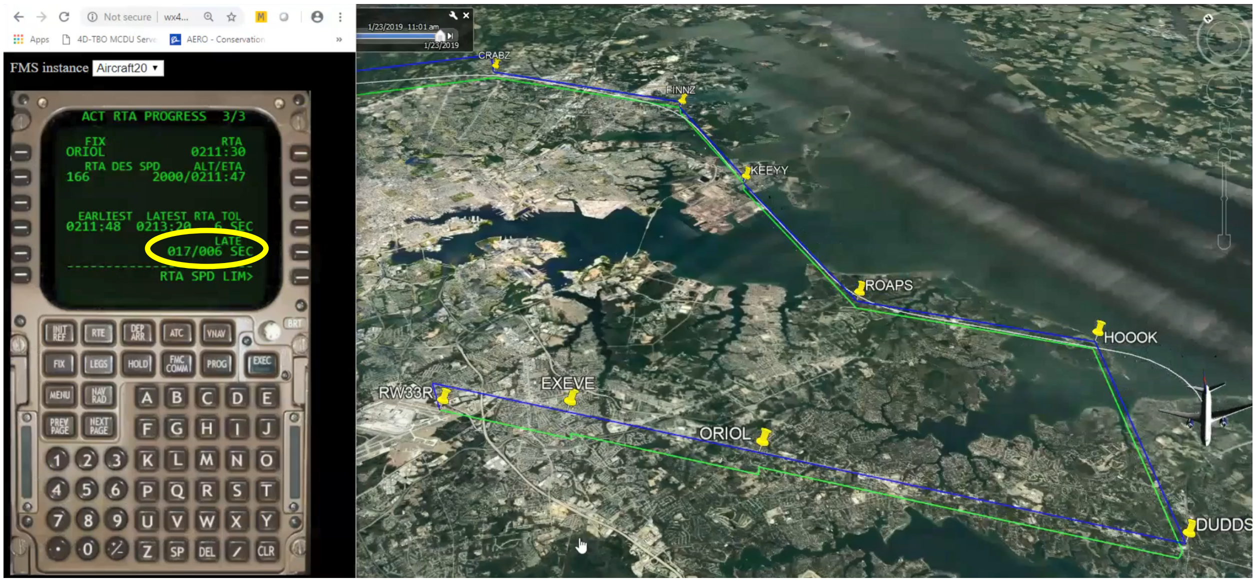


Figure 6. Time synchronized FMS RTA display and aircraft position. Aircraft shown at position 45 seconds after passing HOOOK. The FMS indicates a 17 second (late) RTA error estimate (circled in yellow) for its arrival at ORIOL.

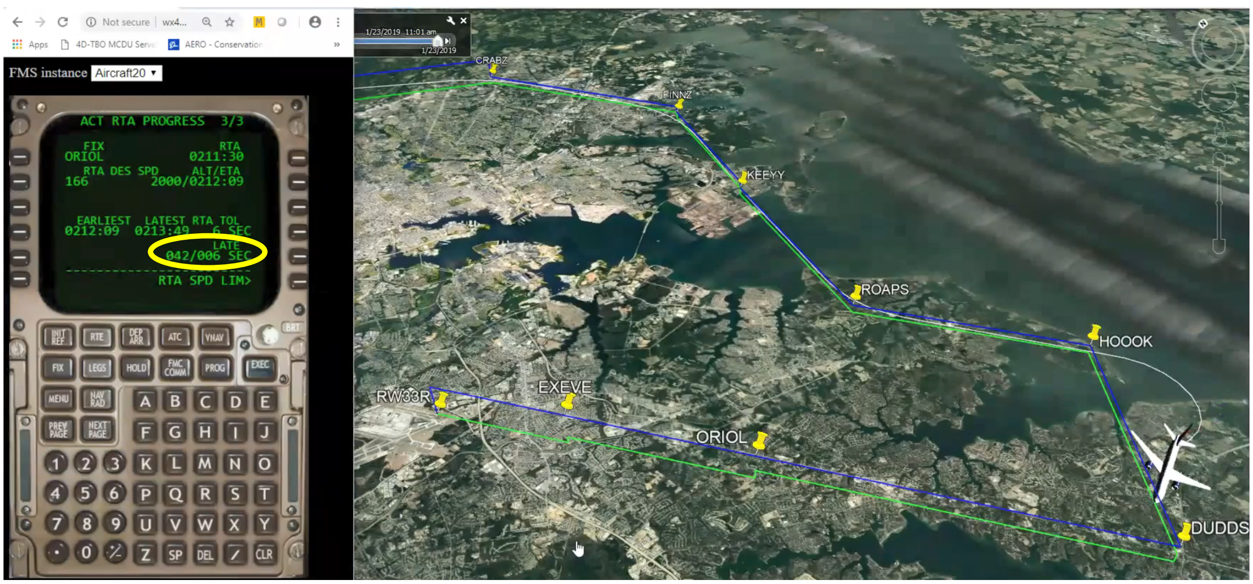


Figure 7. Time synchronized FMS RTA display and aircraft position. Aircraft shown at position 75 seconds after passing HOOOK. The FMS indicates a 42 second (late) RTA error estimate (circled in yellow) for its arrival at ORIOL.

75 second after passing HOOOK the Estimated Time of Arrival (ETA) error stabilized. This estimated error remained essentially fixed until crossing the assigned fix at ORIOL which it did with about 42 seconds of actual error. The observation taken from this is that up until reaching HOOOK, the FMS did not appear to be aware of the correct path to be flown between HOOOK and DUDDS. Once realized, it accurately predicted its arrival error, but as we will discuss later, the aircraft was too close to its RTA fix to make any speed adjustment to address the lateness of its arrival.

These conditions, where it appears that the FMS fails to account for parts of the length of certain leg segments were only observed when either the IAF or the FAF was selected as the RTA fix. The behavior was not observed on all routes, but was observed consistently on many. The behavior is independent of the destination airport such that only some route combinations to an airport produce the error and other do not.

One workaround tested was to insert an additional waypoint after the last waypoint of the STAR and prior to the IAP transition fix or IAF. The additional waypoint was placed 0.1 nmi along the track leading to the last waypoint of the STAR. In a number of flights this somehow circumvented the problem and the FMS performed as expected repeatedly. Unfortunately this only corrected a small set of routes and there was no way to predict which those would be. Because of the real time cost of execution, an exhaustive search to all the potential routes and conditions that would cause the erroneous behavior was not undertaken. Sufficient evidence that a large percentage of candidate routes for flight replication generated the erroneous behavior that it was required to abandon the effort to conduct simulation to the IAF and FAF. This eliminated one of the initial goals to conduct RTA operations to altitudes approaching 1,500 AGL. The remaining alternative was to conduct tests with metering fixes placed at common metering fix locations as well as the last waypoint of the final definition of the route's STAR. As will be seen later, this approach was advantageous as it provided a large set of measured meter fix crossing altitudes ranging from 32,000 ft AGL down to 3,000 ft AGL, the later which is comparable to the IAF altitudes observed at many airports.

2.4 TEST VARIABLES

The simulation system was used to re-fly the actual flights under sets of different conditions. The following specific conditions were controlled in the experiments to evaluate performance as a function of these test variables.

2.4.1 Meter fix location: Waypoint Corresponding to STAR Name or End of STAR (EOS)

For a given flight, the crossing altitudes of two hypothetical metering fixes were evaluated and both were a function of the STAR on the assigned route of flight. The higher altitude meter fix was selected as the point associated with the name of the STAR. For example, if an aircraft was arriving at KDEN on the ZPLYN3 STAR, ZPLYN would be one of the assigned fixes. We consider the name of the STAR as a proxy for a typical Terminal Radar Approach Control (TRACON) arrival fix and hence in this paper these fixes are referred to as "ARR". The second and lower altitude meter fix location corresponded to the last fix of the STAR (hence End of STAR or "EOS"). The actual crossing altitudes were subject to the desired vertical profile calculated and flown by the FMS.

2.4.2 Number of DFLs: 3 or 9

Typical FMSs have the ability to enter forecasted winds along the descent at three to five different altitudes. The FMS system used in this study was a manufacturer-modified Honeywell Pegasus FMS which could have up to nine levels in descent. In this study, either three or nine DFLs were populated. The presumption being that a greater the number of DFLs provides a more accurate representation of the forecasted wind profiles relative to the actual environment.

2.4.3 Descent Forecast Sampling Technique: Top of Descent (TOD) or Optimized

As reported in DO-369, of the 13 major air transport and airlines surveyed, just over half select wind forecast data from over a single location: the top of descent (TOD) of the aircraft’s estimated trajectory. This technique was used as one of the DFL selection methodologies. As applied in this work, the TOD selection technique took the forecasted winds at three and nine equidistant altitudes. The spacing equated to the altitude difference between the cruise altitude and the destination altitude divided by the number of DFLs plus 1.

The second technique used for DFL selection optimizes the selection of forecast data along the descent trajectory, both spatially and temporal, to minimize the error between the winds estimated at each altitude in the forecast that intersects the trajectory and a linearly interpolated representation of the forecast based on the three or nine DFL altitudes selected. A greedy optimization algorithm was used in this process, removing the altitude with the least effect on the optimized cost until the number of DFLs remaining equaled three or nine as appropriate. The number of forecast levels available depends on the forecast source and the range of altitudes from cruise to destination. The optimized DFL selection technique is presumed and demonstrated in this work to be a more accurate way of representing the atmosphere to be experienced. The GFS wind, temperature, and surface pressure products were used in this work. The forecast age used in this study depended on the actual time of the replicated flight, the RTA assignment time and the schedule and publication time of GFS products. The first GFS forecast products are not typically available until approximately 2.75 hours after the model run has started which occur at 0, 6, 12, and 18z. Presuming zero time to consume and process the forecast data, the age of the forecasts could range from 2.75 to 8.75 hours old. Cruise wind forecasts were only provided for the cruise altitude.

2.4.4 Speed Constraints: STAR Speed Constraints Included or Unconstrained

Part of the selection process required that the STAR of each replicated flight had at least one speed constraint. The removal of speed constraints was expected to have a significant positive impact on RTA performance (as was shown in DO-369) because speed constraints limit the range of speed control authority of the closed-loop RTA system.

2.5 TEST DESCRIPTION

In order to explore the key research questions regarding RTA performance to low altitude meter fixes, the analysis infrastructure was exercised for a set of operationally-relevant scenarios involving flights conducting a cruise and descent operation to a meter fix with an RTA assigned. The scenarios were set up using the definitions presented in Table 1. Before a flight could be a candidate for replication, it underwent a series of qualification tests described earlier. Track data were used to identify the arrival runway, the likely IAP flown, and if the flight deviated or was vectored an unreasonable distance from the assigned route. The atmosphere that was applied to the simulated aircraft during flight replication was based on spatio-temporal weather reports from the given aircraft via MDCRS. Aircraft that did not report MDCRS data were not considered as candidates. Not all aircraft report MDCRS data equally so an additional qualification step was applied to ensure sufficient weather data was available to reasonably describe the atmosphere during the replicated portion of the flight. The qualification also required that there was available and valid sensed weather data up to at least the FAF on the IAP in case these same flights were to be replicated with RTA fixes assigned at the FAF in future research. In addition to qualifying flight and atmospheric data, all the required ancillary data to support the replication also had to be available in MAFID. These included having the temporally associated GFS forecasts, CIFPs and FMS navigational databases. An additional qualification requirement was that a candidate route's STAR had at least one waypoint with a speed constraint, as the presence or lack (via removal) of speed constraints was one of the degrees of freedom evaluated.

Based on all the qualification criteria, the arrivals of 101 actual flights among 11 airports were replicated in this study as shown in Table 2. As a function of the four test variables, each with two conditions, a total of 1616 flights were replicated. For each replicated flight, the modeled ATC procedure assigned a route-dependent RTA fix when the simulated aircraft was at a theoretical freeze horizon 230 nmi from the destination airport. Flight crews were assumed to be cognizant that RTA operations were taking place on their route and had an expectation of when the RTA procedure would begin. In preparation for the upcoming operation, the simulated flight crew performed a weather request update to their virtualized flight operations center approximately 10 minutes prior to arriving at the freeze horizon. In these simulations, that occurred at 340 nmi radially from the destination. Upon arrival at the freeze horizon, the RTA fix was delivered to the flight crew and entered into the FMS. A theoretical exchange took place between ATC and the crew who reported the earliest and latest achievable arrival times calculated by the FMS. The crew was assigned and accepted a Controlled Time of Arrival (CTA) from ATC that equated to the earliest arrival time plus 25% of the timespan between the two reported times at the assigned RTA fix. The variations in the definitions of the STARs seen in this experiment and the fixes taken from these STARs, ARR and EOS, provided a large range of RTA fix crossing altitudes which were observed to range from 2,600 to 32,000 ft AGL. Note, in this work, AGL refers to the barometric altitude of the aircraft minus the destination airport altitude. This reference is used to normalize the observed meter fix crossing altitudes as it was found that overall RTA performance is more associated with AGL than barometric altitude. Thus the performance of flights to relatively high airports such as KDEN, with an airport elevation of 5434 ft MSL, can be aggregated with flights to the other airports in this study which were all at lower elevations.

Table 1

Scenario Definition Parameters

Simulation Component	Parameter	Value
Aircraft	Aircraft Type	B757-200
	Gross Weight	170,000 lbs
	Zero Fuel Weight	150,000 lbs
	Cost Index	50
	RTA Tolerance	6 seconds
Forecast	Source	Global Forecast System
	Age	>3 hours
	Update Condition	60 nmi prior to RTA assignment Locations
Trajectory	RTA Assignment Distance	230 nmi radially from destination
	Initial Aircraft Starting Point	60 nmi prior to RTA assignment location

Table 2

Replicated Flight Destination Distribution

Airport	Number of Replicated Flights
KPHX	19
KDEN	16
KBWI	15
KHOU	15
KSEA	11
KATL	9
KMEM	5
KSTL	4
KSFO	3
KLAX	2
KMSP	2

2.6 RESULTS

Examples of trajectory profiles from replicated flights and RTA fix crossing conditions and timing errors for the 11 flights bound for KSEA are shown in Figure 8. The results in the figure correspond to the case where the RTA fix location was assigned to the last waypoint on the STAR (EOS), the speed constraints were left in place, three DFLs were used and the selection process for the DFLs was sampled over the estimated TOD location. Recall that last set of waypoints on a STAR are often dependent on the IAP selected and any transition fix selected. In this work, the programmed IAP was always an RNAV GPS type using the appropriate transition fix if it was part of the route as identified in the qualification process [7].

The upper left plot in Figure 8 presents the headwinds that the replicated flights experienced during the simulations. Headwinds have a significant effect on timing performance if unaccounted for and we see in this figure a broad range of wind conditions amongst the experiments.

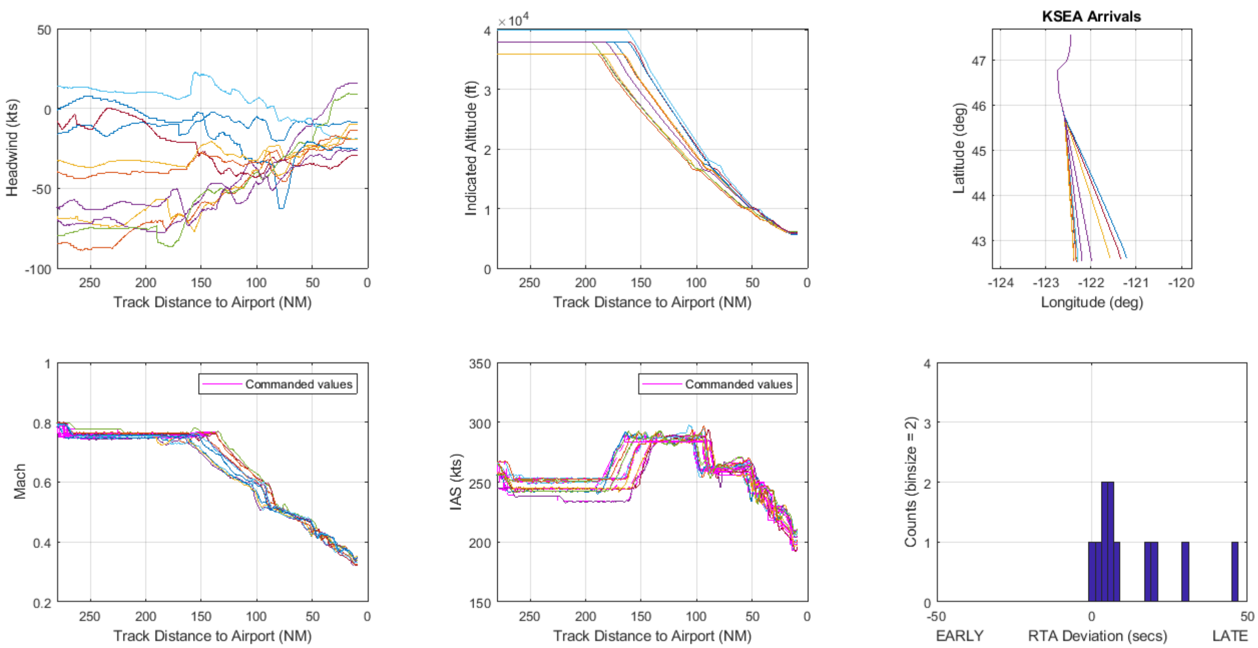


Figure 8. Sample results for KSEA flights (EOS fix location, 3 DFLs, TOD FMS winds).

The vertical and lateral profiles of these replicated flights are seen in the upper center and upper right plots respectively. The flown Mach and CAS are shown in the lower-left and lower-center plots. The FMS commanded Mach and or CAS, when active, are shown in magenta. The resulting RTA error performance is shown at the bottom right, and shows late RTA compliance varying from 0 to 50 seconds.

By comparison, Figure 9 shows the same replicated flights to the same RTA fix but using nine DFLs and wind selection via the optimized selection approach based on the estimated descent trajectories. Increasing the number of DFLs and using a more accurate method to identify winds is seen to result in smaller RTA errors: the maximum error is approximately +26 seconds and a greater concentration of errors closer to zero.

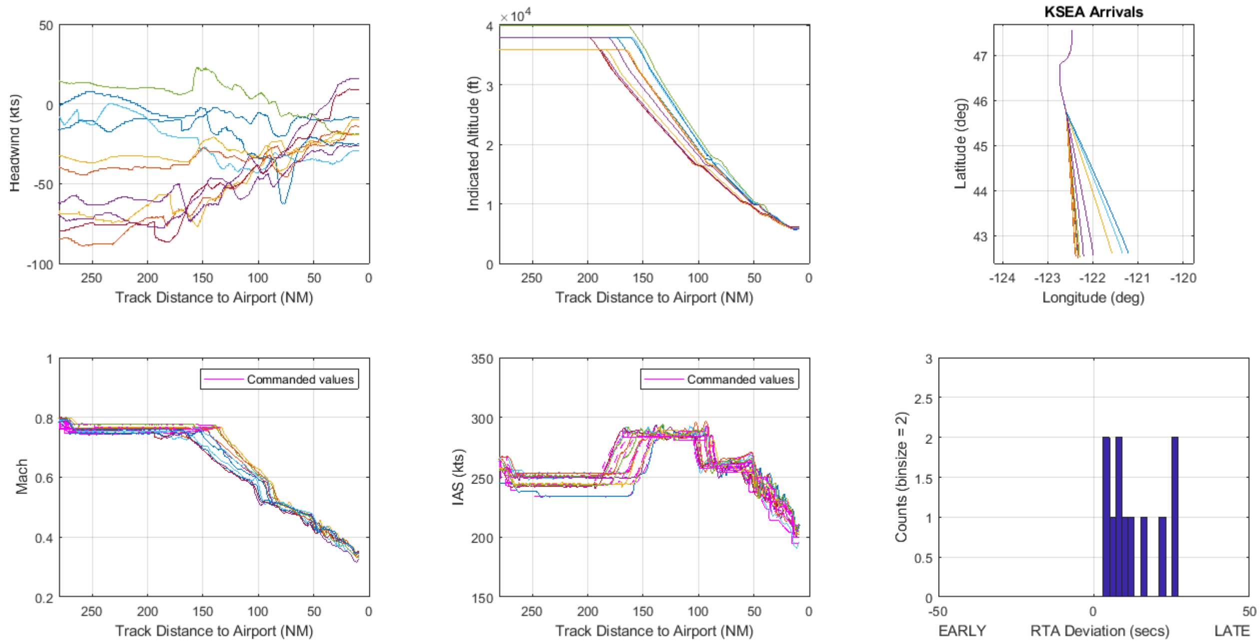


Figure 9. Sample results for KSEA flights (EOS fix location, 9 DFLs, optimized FMS winds).

Figure 10 plots the RTA performance results as a function of meter fix crossing altitude for all the replicated flight for the case where speed constraints were maintained on the STARs. These results comprise 808 individual results based on applying the 3 remaining test variables; number of DFLs, selection of wind estimates for the DFLs, and location of the RTA fix. As stated above, the AGL RTA fix crossing altitude was used when comparing RTA performance. When plotting the altitude at which the RTA fix was crossed relative to the RTA error for the flight, there appear clear groupings in crossing altitudes as well as performance. No correlation between crossing altitude and RTA error is evident above 7,000 ft AGL. However, there is a clear distinction on RTA error variance when differentiating the crossing altitudes into two ranges. That is, crossing altitudes above 7,000 ft AGL or between 3,000 and 7,000 ft AGL. In the latter, one can visually see that the RTA errors in that group have both a greater range and a greater variance.

The same distinction can be seen when repeating the flights with the speed constraints removed from the routes, as shown in Figure 11. Again, there is a clear partitioning of performance above and below 7,000 ft AGL. As expected, by having the speed constraints removed, the overall range and variance of RTA errors of both groups are reduced under this test condition yet the lower altitude group still has a greater range and variance.

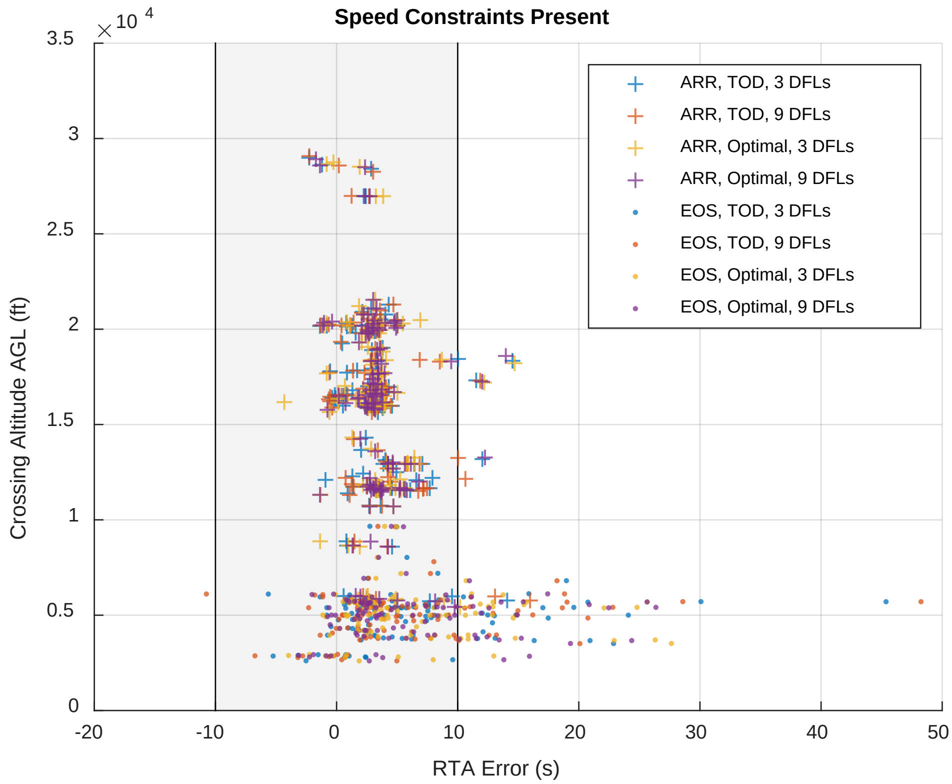


Figure 10. Meter fix crossing altitudes versus RTA time errors with STAR speed constraints (positive is late, shaded area spans ±10 second RTA error).

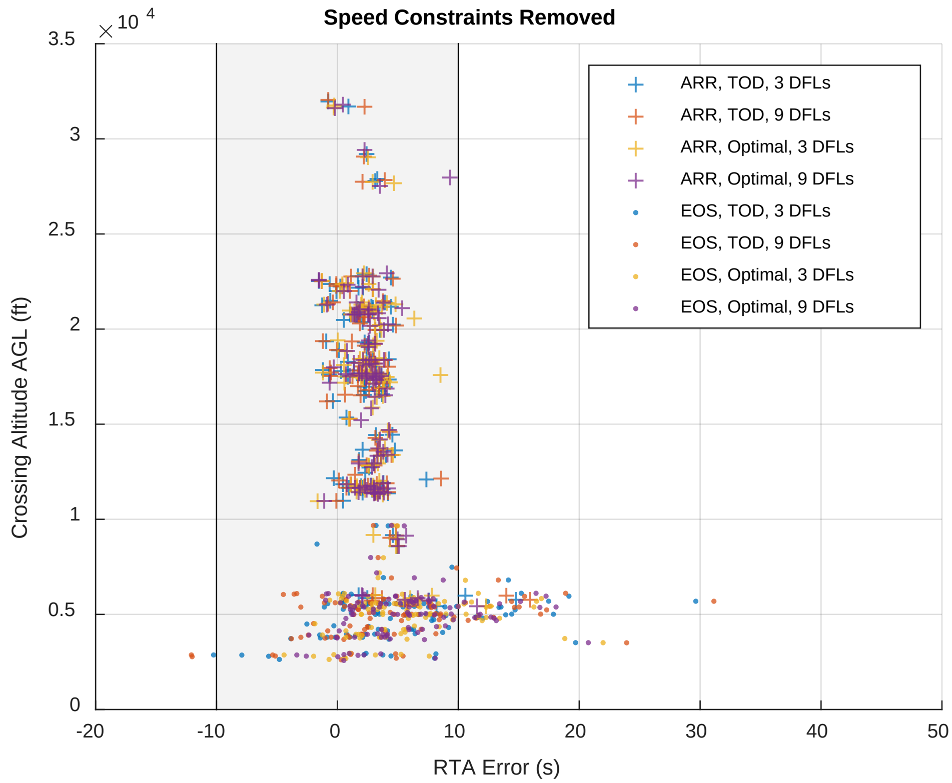


Figure 11. Meter fix crossing altitudes versus RTA time errors without STAR speed constraints (positive is late, shaded area spans ±10 second RTA error).

In each of these two figures, a late arrival bias can also be seen. This is consistent with previous research findings [11][12]. The mean RTA error for the higher altitude group is 3.3 and 2.5 seconds for the speed constrained and unconstrained respectively. For the lower group, the means shift to 6.1 and 5.8 seconds respectively. Note that the RTA arrival tolerance in the FMS was set to 6 seconds in these experiments; the smallest value available. Per the manufacturer, the FMS will not try to adjust the scheduled target speeds if the estimated RTA arrival error is within the pre-set tolerance.

Several different correlations were also evaluated to see what other scenario conditions could be influencing the results. These included comparing the RTA errors as a function of integrated aircraft banking greater than 10 degrees, the integrated forecast error along the descent, various integrated weighted forecast error along the descent, and integrated speed errors. Absolute values were used for each integrated parameter. Forecast error was defined as the vector root mean square (VRMS) of the instantaneous difference between the wind applied to the aircraft and the linear-spatial interpolated forecast provided to the FMS. Forecast errors during descent were interpolated as a function of altitude instead of spatial distance used during cruise. No correlations were apparent in these evaluations.

An analysis of RTA errors versus the mean VRMS wind forecast error during the descent phase of each flight was also performed. The calculated values of mean VRMS wind forecast error plotted versus RTA error are presented in Figure 12 for speed constrained flights and Figure 13 for unconstrained flights. We see in these plots that, on multiple occasions, extreme wind forecast errors do not generate increased RTA errors and that there is again no evident direct correlation between wind forecast error and RTA error. It is possible that errors elsewhere in the system, such as FMS trajectory errors or opposing forecast errors themselves could produce a net zero effect on arrival error. Granted, there are a limited number of flights with mean VRMS wind forecast error values greater than 15 kt and it would be difficult to state there could be no correlation at all. Ample data are however available of flights having between 0 and 15 kt mean VRMS error. In this region, we still see no correlation but there is an increase in the probability of increased RTA error as a function of increased mean VRMS error. In other words, the greater the forecast error, the greater the chance of larger RTA errors.

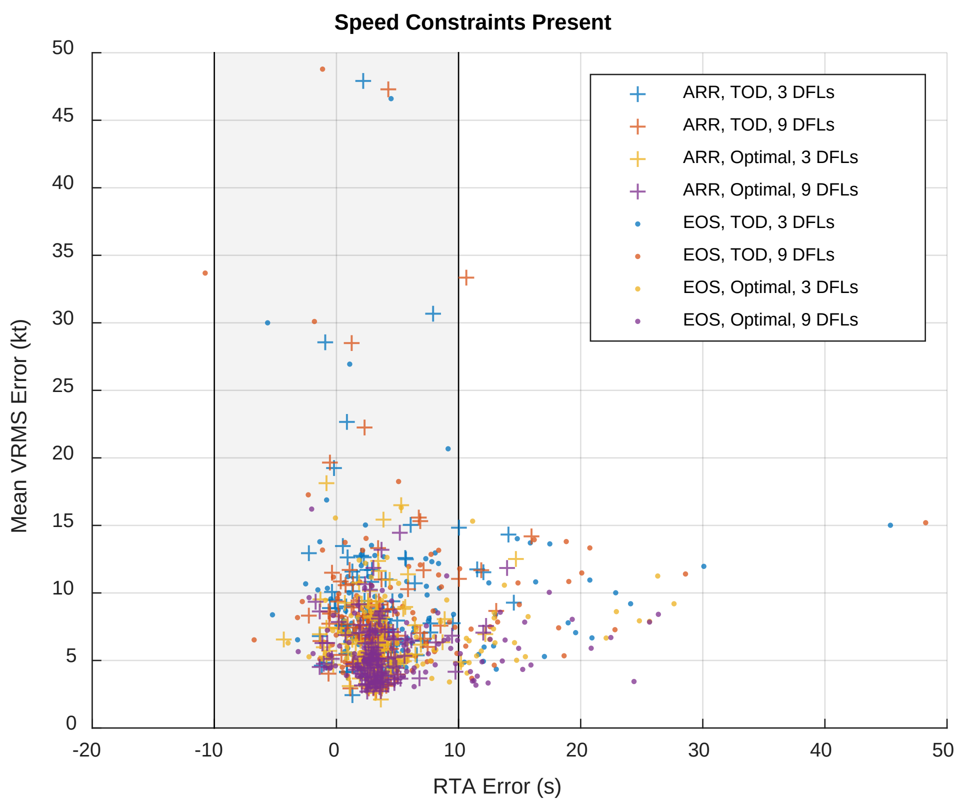


Figure 12. Mean VRMS wind forecast error versus RTA time errors with STAR speed constraints (positive is late, shaded area spans ±10 second RTA error).

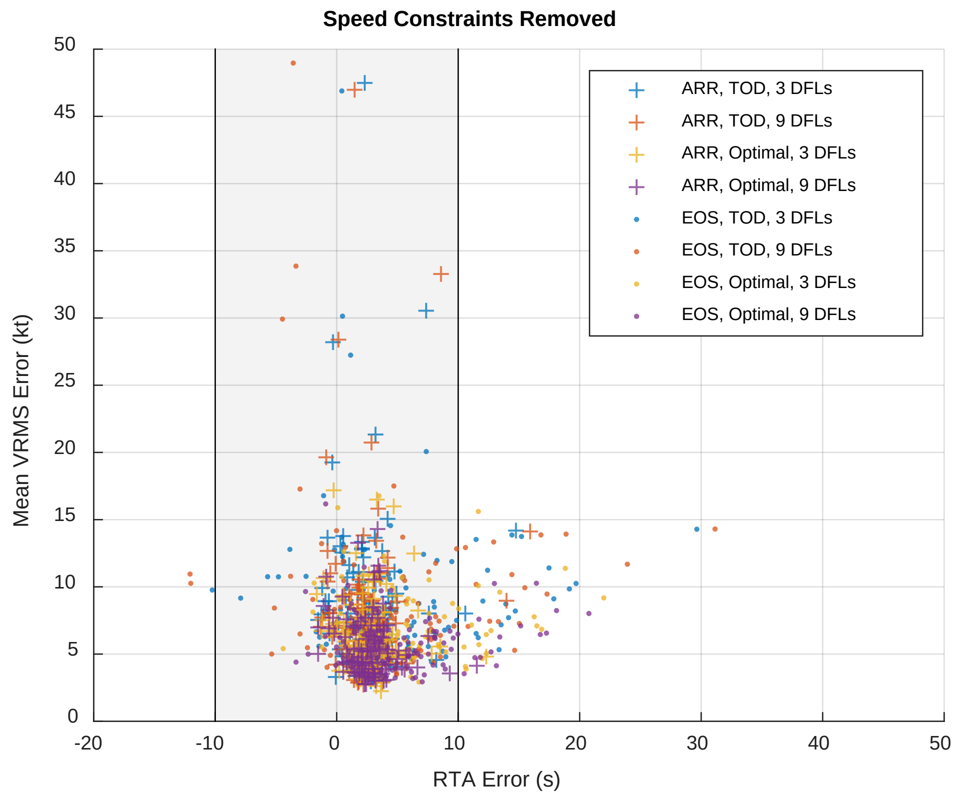


Figure 13. Mean VRMS wind forecast error versus RTA time errors without STAR speed constraints (positive is late, shaded area spans ±10 second RTA error).

To further explore the effect of forecast error and in consideration of the RTA performance requirement of 95% of flights achieving less than or equal to a ±10 second RTA error performance specified in DO-236C [1], we evaluate the percentage of flights that arrive within ±10 seconds of assigned RTA time as a function of forecast error. The data are the aggregated results for all the test conditions that affect forecast accuracy. Figure 14 and Figure 15 show the results separated into the two meter fix crossing altitude ranges (above and below 7,000 ft AGL) and with and without speed constraints respectively. In Figure 14 we can see in aggregate a decrease in overall performance with increased forecast errors for flights arriving below 7,000 ft AGL for both speed constrained and unconstrained groups.

In Figure 15, unlike the lower altitude group, for flights crossing at meter fix altitudes above 7,000 ft AGL there appears to be an effect of forecast accuracy only if speed constraints are present.

Evaluating the estimation approach of the descent forecast winds provided to the FMS, i.e., the number of DFLs or selecting forecasts from over the TOD or optimally along the descent trajectory, as expected, in Figure 16 we see a clear correlation of forecast accuracy and approach: 9 DFLs have better performance than 3, and optimized wind selection is better than selecting winds over TOD. The most striking difference occurs as a function of technique where the optimally estimated forecasts significantly reduces both the mean VRMS wind forecast error and the variance. The potential accuracy of any given technique is still dependent on the accuracy of the forecast source, which in these cases is GFS.

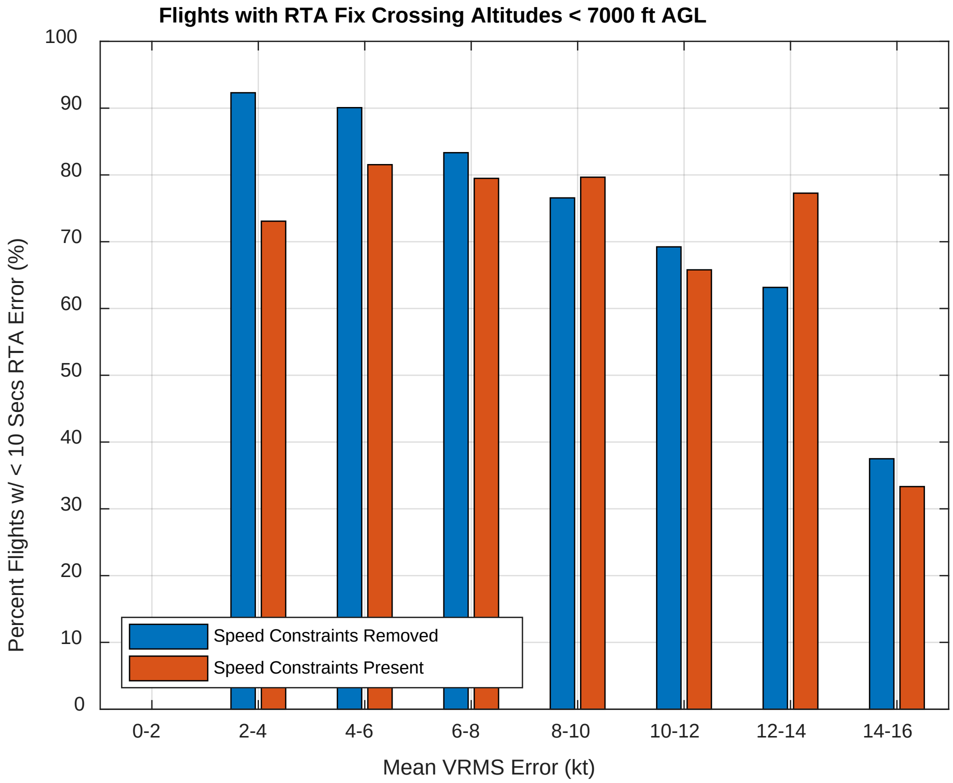


Figure 14. Percentage of flights with less than ±10s RTA error as a function of actual mean VRMS wind forecast error for meter fix altitudes below 7,000 ft AGL.

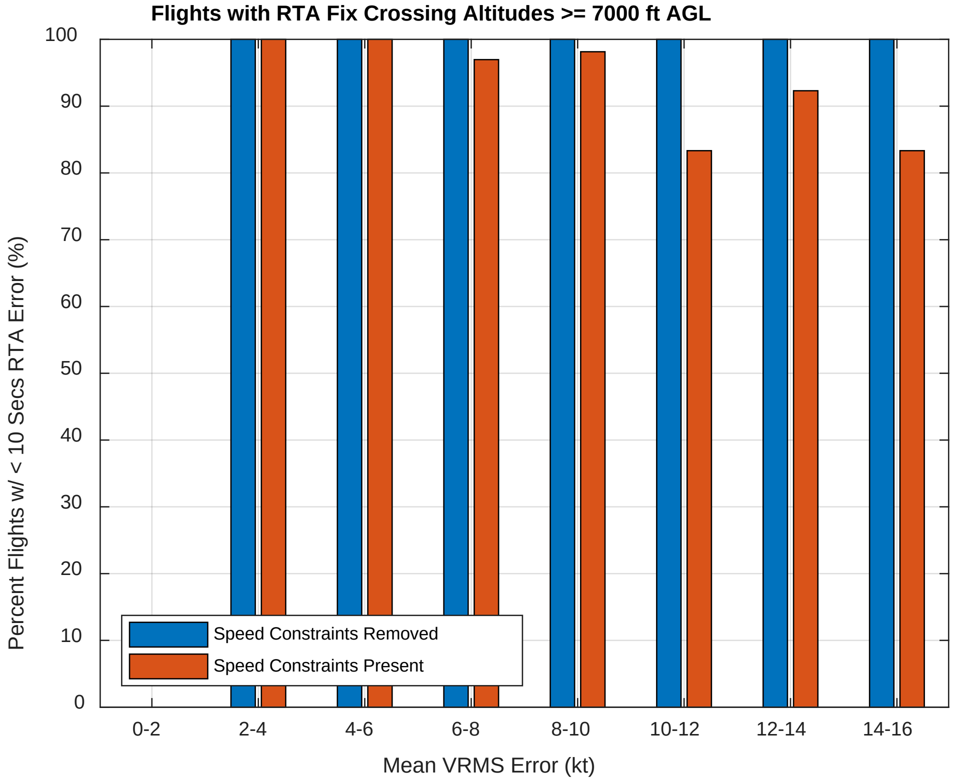


Figure 15. Percentage of flights with less than ±10s RTA Error as a function of actual mean VRMS wind forecast error for meter fix altitudes at or above 7,000 ft AGL.

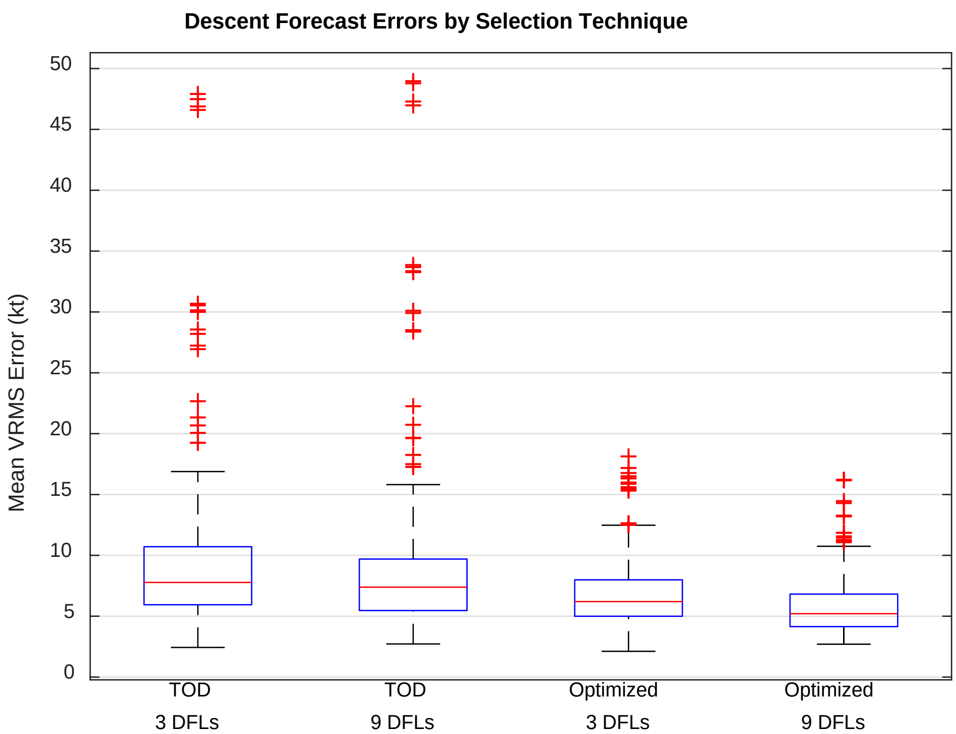


Figure 16. Descent wind forecast errors (mean VRMS) as a function of wind selection technique.

The RTA performance comparison in terms of arriving with ±10 second error as a function of each of the test variables are presented in the tables below, one for each meter fix crossing altitude group.

Table 3

RTA Performance for Flights Crossing Meter Fix Above 7,000 ft AGL

Number of flights per = 99		RTA Performance (% Flights < ±10s Error)	
DFL Forecast Technique	**Number of DFLs**	**Speed Constraints Present**	**Speed Constraints Removed**
TOD	3	96	100
TOD	9	97	100
Optimized	3	98	100
Optimized	9	97	100

Table 4

RTA Performance for Flights Crossing Meter Fix Below 7,000 ft AGL

Number of flights per = 103		RTA Performance (% Flights < ±10s Error)	
DFL Forecast Technique	**Number of DFLs**	**Speed Constraints Present**	**Speed Constraints Removed**
TOD	3	79	81
TOD	9	79	82
Optimized	3	76	82
Optimized	9	78	83

As evident in Table 3, regardless of the descent forecast selection technique, number of DFLs employed, or presence/absence of speed constraints on the arrival procedures, the overall performance for flights crossing their meter fix at altitudes of 7,000 ft AGL or higher meet the desired performance that 95% of operations have less than 10 second RTA error. It should be noted that the test conditions for performance as specified in DO-236C are not equivalent to those used in this study and, in particular, were not created for operations covering the range of crossing altitudes observed in this work. The performance for flights crossing their meter fix altitudes below 7,000 ft AGL did not perform as well as the higher altitude group as shown in Table 4. Under what would be considered the best conditions in this study, i.e., applying the optimal descent forecast selection technique, 9 DFLs, and removing speed constraints, only 85% of flights arrived within ±10 seconds of their assigned RTA times. Performance was reduced further if speed constraints remained in place.

2.7 CONCLUSIONS

In this work, we evaluated the effects of meter fix crossing altitude, forecast quality (number of DFLs, selection technique of DFLs), and the effects of speed constraints on RTA performance for 1616 replicated revenue flights. The distribution of RTA fix crossing altitudes ranged from approximately 32,000 ft AGL down to approximately 3,000 ft AGL. Three particular factors appear to have the greatest effect on aggregated RTA performance. The principal driver of RTA performance was the meter fix crossing altitude. The second most important driver was seen to be the presence of speed constraints on the STAR, followed by the descent forecast accuracy.

The RTA errors results as a function of crossing altitudes in these experiments grouped nicely into two categories: above 7,000 ft AGL or below. Flights descending to RTA fix in the upper category had little difficulty in meeting the 95% performance goal of arriving within ±10 seconds of the assigned time. In contrast, the performance in the lower group was lower, just exceeding 85% using the highest quality forecast data and with STAR speed constraints removed.

The data are clear that, in the aggregate, decreased descent forecast accuracy does have a negative impact on overall RTA performance especially for the low altitude grouping. Thus, it is clear that in order to maximize the potential RTA performance, operations should be conducted with both speed constraints removed from the route and with the best possible FMS wind forecast. The lower the expected RTA meter fix crossing altitude, the more relevant is the descent forecast wind accuracy.

The significant degradation of RTA performance for flights with meter fixes below 7,000 ft AGL indicates there are factors affecting performance other than forecast and speed constraints. An analysis of speed tracking showed that for many flights that ended up with significant meter fix crossing errors, they were tracking the target speeds provided by the FMS with very little error. This has been observed even when the FMS is indicating a significant crossing error on a non-speed constrained route. We therefore suspect that the principal reasons for larger RTA errors in many of these cases is due to erroneous trajectory estimation. The manufacturer of the FMS used in this study states that this model FMS turns off RTA speed adjustments once the aircraft is within 10 nmi of the meter fix. Speed control remains closed-loop but the target speed schedule for the remainder of the flight is fixed and not adjusted for timing errors. For flights to the lower altitude meter fixes, where target speeds are already low and decreasing, it may take several minutes to cover the reaming 10 nmi allowing for the integration of significant time errors. For reference, in this study, meter fix crossing speeds for EOS flights ranged from 170 to 260 kt. Initial flaps deployment would begin at around 205 kt subject to the pilot model.

The certified version of the FMS used in this study was not originally designed for RTA operations at the lower altitudes and corresponding lower speeds flown in this work though it was modified to do so. It is possible that the internal aircraft performance model is just not appropriate without modification for this domain. The maneuvering and flaps deployment models in the FMS, for example, may be different than actual capabilities and performance though model errors in these areas could possibly be remedied with continuous closed-loop control on timing errors.

Despite these potential challenges, the results in this section strongly indicate real performance limitations to conducting RTA procedures with low altitude meter fixes. Given the ultimate 4D-TBO paradigm envisions high accuracy delivery of aircraft (e.g., to tolerance of a few seconds) to meter fixes all the way down to the runway threshold, it is important that further studies of this type are conducted. Such work should determine the temporal accuracies of RTA trajectories of a range of FMS and aircraft combinations and other factors, such as route design, that may affect individual RTA performance.

3. WIND INFORMATION LEXICON STUDY

3.1 INTRODUCTION

A wind lexicon study was conducted to catalog wind information utilized and communicated between air traffic control, air traffic managers, aviation meteorologists, airlines, and pilots. They often refer to winds using different terminology and definitions. Different terms may be used for the same wind information (e.g., “gridded winds”, “model winds”, “3D winds”), identical terms may be used for different wind data in different application contexts (e.g., “Winds Aloft”), or terms may be used for wind information sources that are conceptual, but do not actually exist (e.g., “ATC winds”, “common winds”, “FAA winds”). For Phase 7 of our work, Lincoln Laboratory was tasked with formalizing the definitions, lexicon, and other characteristics of ATC Winds, Common Winds and other sources of wind information utilized and communicated throughout the NAS.

The following sections describe the sources that were analyzed to capture the wind lexicon, some specific examples where significant ambiguous or overloaded terminology usage were found, and the results of the lexicon analysis, including a “glossary” of terms and definitions.

3.2 STUDY SOURCES

A variety of sources were utilized to capture the terminology and contextual usage of wind information:

3.2.1 Publications

- Journals, conference proceedings, organization meeting publications
- Standards and procedures documents; FAA, National Weather Service (NWS), World Meteorological Organization (WMO), and International Civil Aviation Organization (ICAO)
- Published on online glossaries
- FAA NextGen planning documents
- Web sites

3.2.2 National Traffic Management Logs (NTML) and Strategic Planning Team (SPT) logs

Lincoln Laboratory maintains an internal searchable database containing information from FAA NTML and SPT discussions. NTMLs contain logs of Traffic Management Initiatives (TMI) and operational decision-making discussions across the NAS. Strategic Planning Team telephone conferences between FAA air traffic control and management personnel and system stakeholders such as airlines, general aviation organizations, military, and NAV Canada are conducted several times a day. Lincoln Laboratory monitors the telecons and enters notes from the discussions into the database. The database was mined to extract phrases where winds were being discussed. Figure 17 shows some example excerpts of wind-related comments obtained from the NTMLs.

2/11/2018 16:49 LGA WIND CAUSING COMPRESSION ON FINAL

5/28/2018 23:25 ATL IMC ARR:08L/09R/10 DEP:8R/9L AAR(Strat/Dyn):110/98 ADJ:OTHER ADR:104 RMK: TILS APPROACHES WITH REDUCED AAR DUE TO WIND SHEAR AND GUST FRONT FORECAST AT THE AIRPORT. (updated at 2300 by A80) - LNK: ATL

8/8/2018 18:38 ... WX: LAX: NIDS WIND SENSOR REPORTING 10008G20KT

1/1/2017 18:27 Shift Summary: DAY SHIFT; LIFR ACROSS I90. T STORMS ALONG LA COAST EXTENDING INTO GULF CAUSED CLOSURE OF M345. SUPPORTING SKI COUNTRY MMUN AND WIND ROUTES TO EWR JFK. IAH WEST ARR 80 HOU EAST ARR 24 ESP ATL - LNK: IAH

5/23/2017 14:56 BOS DCC CALLED BOS, A90, ZBW TO DISCUSS OUTLOOK....TOWER IS CONCERNED WITH WIND ALOFT AND POSSIBLE INCREASE MILEAGE ON FINAL TO ALLOW RWY EXITING FOR TAILWIND.

Figure 17. Examples of wind references in NTML logs.

3.2.3 User Interviews and Surveys

In order to capture the verbal wind lexicon, interviews and surveys of operational users and researchers were conducted via email, telephone, and in-person meetings. A web-based online survey of wind information communication and usage was explored, but not conducted because the time required to distribute and process the survey fell outside of the study timeframe.

The following is a summary of the organizations, positions, and personnel that were consulted for this study:

Air Traffic Controllers and Managers

- John F. Kennedy International Airport (JFK) Tower Manager
- Former New York TRACON (N90) Traffic Management Officer
- Supervisory Traffic Management Coordinator (STMC) at ZAU Air Route Traffic Control Center (ARTCC)
- Dane County Regional Airport (MSN) Tower Manager and Controllers

Pilots and Flight Instructors

Commercial, military, and general aviation pilots and flight instructors were consulted for their use and communication of wind information for flight planning, navigation, and flight safety. These included:

- American Airlines pilot
- Delta Airlines pilot
- United Express (and former military) pilot
- Air National Guard Director of Operations
- Flight instructor for General Aviation (GA) pilots and Unmanned Aerial Vehicle (UAV) operators
- Medical transport helicopter pilot

Airlines

- Southwest Airlines Network Operations Center meteorologist
- Jet Blue System Operations Director
- Jet Blue Air Traffic Services Manager

FAA Supporting Meteorologists

- ATC System Command Center (ATCSCC) National Aviation Meteorologist (NAM)
- Certified Weather Observer at MSN airport

Subject Matter Experts

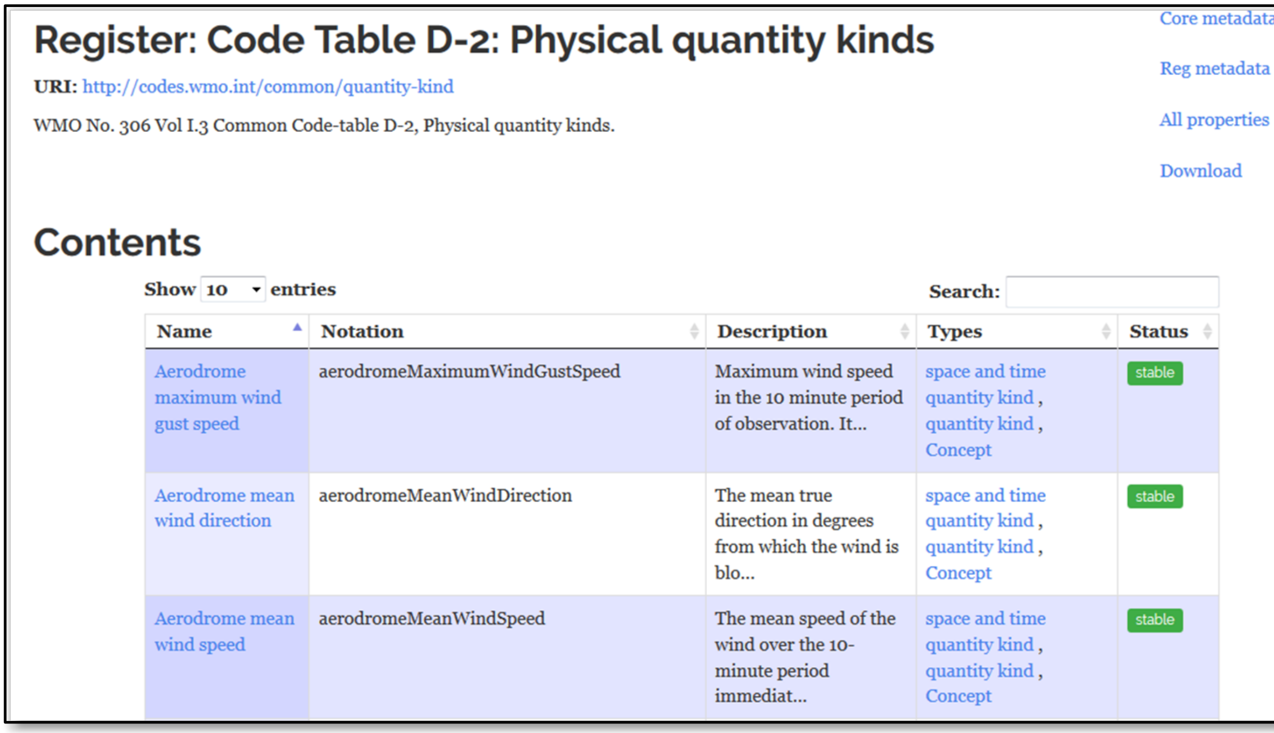
- MIT Lincoln Laboratory trainers and monitors for FAA Integrated Terminal Weather System (ITWS), Corridor Integrated Weather System (CIWS), and Consolidated Storm Prediction for Aviation (CoSPA) system users

3.2.4 Digital and Coded Weather Data Format Descriptions and Registries

Digital and Traditional Alphanumeric Coded (TAC) weather data formats containing wind data variables and codes are another source of wind lexicon. Published data from numerical weather prediction models such as NOAA's GFS, Rapid Refresh (RAP), and HRRR models contain 3D and 2D grids of wind variables utilizing standard variable names and codes that can be found in on-line registries such as the Climate and Forecast Standard Name Table [13](see Figure 18) and WMO codes [14](see Figure 19).

Standard Name	Canonical Units	AMIP	GRIB
number_of_days_with_wind_speed_above_threshold	1		
radius_of_tropical_cyclone_maximum_sustained_wind_speed	m		
tendency_of_wind_speed_due_to_convection	m s-2		
tendency_of_wind_speed_due_to_gravity_wave_drag	m s-2		
tropical_cyclone_maximum_sustained_wind_speed	m s-1		
wind_speed Speed is the magnitude of velocity. Wind is defined as a two-dimensional (horizontal) air velocity vector, with no vertical component. (Vertical motion in the atmosphere has the standard name upward_air_velocity.) The wind speed is the magnitude of the wind velocity.	m s-1		32
wind_speed_of_gust Speed is the magnitude of velocity. Wind is defined as a two-dimensional (horizontal) air velocity vector, with no vertical component. (Vertical motion in the atmosphere has the standard name upward_air_velocity.) The wind speed is the magnitude of the wind velocity. A gust is a sudden brief period of high wind speed. In an observed timeseries of wind speed, the gust wind speed can be indicated by a cell_methods of maximum for the time-interval. In an atmospheric model which has a parametrised calculation of gustiness, the gust wind speed may be separately diagnosed from the wind speed.	m s-1		
wind_speed_shear Speed is the magnitude of velocity. Wind is defined as a two-dimensional (horizontal) air velocity vector, with no vertical component. (Vertical motion in the atmosphere has the standard name upward_air_velocity.) The wind speed is the magnitude of the wind velocity. Wind speed shear is the derivative of wind speed with respect to height.	s-1		N136

Figure 18. Examples of wind definitions in Climate and Forecast (CF) Standard Names table.



Register: Code Table D-2: Physical quantity kinds

URI: http://codes.wmo.int/common/quantity-kind

WMO No. 306 Vol I.3 Common Code-table D-2, Physical quantity kinds.

Core metadata
Reg metadata
All properties
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Contents

Show 10 **entries** **Search:**

Name	Notation	Description	Types	Status
Aerodrome maximum wind gust speed	aerodromeMaximumWindGustSpeed	Maximum wind speed in the 10 minute period of observation. It...	space and time quantity kind , quantity kind , Concept	stable
Aerodrome mean wind direction	aerodromeMeanWindDirection	The mean true direction in degrees from which the wind is blo...	space and time quantity kind , quantity kind , Concept	stable
Aerodrome mean wind speed	aerodromeMeanWindSpeed	The mean speed of the wind over the 10-minute period immediat...	space and time quantity kind , quantity kind , Concept	stable

Figure 19. Examples of wind definitions in WMO code registry.

Standardized units of measure for expressing wind quantities can be found in the Unified Code for Units of Measure (UCUM)[15]. Figure 20 shows a table of international customary unit definitions from UCUM. The columns labeled "c/s" and "c/i" contain the respective case sensitive and case insensitive symbols used to represent the unit given in the name column.

name	kind of quantity	c/s	c/i	M	definition value	definition unit
inch	length	[in_i]	[IN_I]	no	2.54	cm
foot	length	[ft_i]	[FT_I]	no	12	[in_i]
yard	length	[yd_i]	[YD_I]	no	3	[ft_i]
mile	length	[mi_i]	[MI_I]	no	5280	[ft_i]
fathom	depth of water	[fth_i]	[FTH_I]	no	6	[ft_i]
nautical mile	length	[nmi_i]	[NMI_I]	no	1852	m
knot	velocity	[kn_i]	[KN_I]	no	1	[nmi_i]/h
square inch	area	[sin_i]	[SIN_I]	no	1	[in_i]2
square foot	area	[sft_i]	[SFT_I]	no	1	[ft_i]2
square yard	area	[syd_i]	[SYD_I]	no	1	[yd_i]2
cubic inch	volume	[cin_i]	[CIN_I]	no	1	[in_i]3
cubic foot	volume	[cft_i]	[CFT_I]	no	1	[ft_i]3
cubic yard	volume	[cyd_i]	[CYD_I]	no	1	[yd_i]3
board foot	volume	[bf_i]	[BF_I]	no	144	[in_i]3
cord	volume	[cr_i]	[CR_I]	no	128	[ft_i]3
mil	length	[mil_i]	[MIL_I]	no	1×10^{-3}	[in_i]
circular mil	area	[cml_i]	[CML_I]	no	1	[pi]/4.[mil_i]2
hand	height of horses	[hd_i]	[HD_I]	no	4	[in_i]

Figure 20. Examples of international customary unit definitions from Unified Code for Units of Measure (UCUM).

3.2.5 Wind Sources for FAA Decision Support Tools

The communication of wind information between air traffic controllers or air traffic managers and pilots and airlines often arises through use of automated FAA Decision Support Tools (DSTs). Many of these DSTs utilize underlying weather sensor systems or numerical weather prediction models together with airport configurations and flight route parameters to provide wind shear warnings, provide departure scheduling, analyze routes, predict trajectories, etc. Table 5 summarizes the underlying wind information sources associated with commonly utilized DSTs.

Table 5

Wind Sources for FAA Decision Support Tools and Systems

DST/ System	Description	Where Used	Wind Source(s)	How Wind Used	Update Rate	Forecast Steps
TBFM	Time-Based Flow Management (Subsumes TMA)	ATCSCC, ARTCCs, TRACONs, & ATCTs. Initially 28 core + 13 non-core airports as of 11/30/2017 [16]	RAP 40 km [8]	Trajectory prediction Departure scheduling	Hourly	1 hour
TMA	Traffic Management Advisor	ARTCCs	RUP 13 km [17]	Route analyzer, trajectory synthesizer [18]	Hourly	1 hour
TSAS	Terminal Sequencing and Spacing	Initially DEN in Dec. 2020, then ATL in Dec, 2021. LAX in 2022. [19]	RAP 40 km [8][19]	Trajectory prediction. Part of TBFM	Hourly	1 hour
GIM-S	Ground Based Interval Management - Spacing	ZAB (PHX), ZDV (PHX, DEN), ZSE (SEA) [16]	RAP 40 km [8]	Trajectory prediction and ETA to time targets	Hourly	1 hour
ERAM/ EDST	En Route Automation Modernization/ ERAM Decision Support Tool (aka, En Route Decision Support Tool)	ARTCCs	RAP 40 km [8][20][21]	Trajectory estimation, route planning	Hourly	1 hour
ATOP	Advanced Technologies & Oceanic Procedures	Oceanic ATC facilities: Anchorage FIR, Guam CERAP, Oakland Oceanic, NY Oceanic	GFS [16]	Oceanic traffic management and route planning [22]	6 Hours	3 hours
FDP2000	Flight Data Processor - 2000	Alaska ARTCC (ZAN)	NAM 11.25 km [16][20]	Trajectory estimation, route planning	6 Hours	3 hours
TDWR	Terminal Doppler Weather Radar	45 major airports	TDWR, LLWAS	Wind shear warnings, runway configuration (wind shifts, terminal wind profiles)	60 sec	N/A
WSP	Weather Systems Processor	34 medium traffic airports	ASR-9, LLWAS	Wind shear warnings, runway configuration (wind shifts)	30 sec	N/A
ITWS	Integrated Terminal Weather System	49 airports and TRACONs	TDWR, LLWAS	Wind shear warnings, runway configuration (wind shifts, terminal wind profiles)	60 sec	N/A

3.3 WIND LEXICON EXAMPLES

This section presents discussions of the lexicon associated with four different references to wind information for which significant ambiguity in the lexicon were uncovered.

3.3.1 ATC Winds and Common Winds

The terms "ATC winds" [23][24] and "common winds" [24] have recently been used in association with NextGen 4D-TBO Advanced Interval Management (A-IM) concepts. In reports we examined and in discussions with researchers, we found that so-called "common winds" for A-IM are not a specific wind data source, but rather a conceptual single common source of winds aloft data (actual source to be determined) that are to be provided to both ground-based and flight deck automation systems. The underlying (but questionable) assumption is that a single, common source of current and forecast wind information is needed on both sides of the A-IM procedure in order to successfully meet the ASG at Achieve-By Points (ABT) within acceptable error limits by accurately accounting for current and expected wind effects on the own ship and target aircraft.

Descriptions and discussions of A-IM concepts and performance also specified "ATC winds" as the source and provider of the common winds. Again, this is conceptual, as FAA does not create its own wind aloft forecasts or a service to provide them. In a recent telephone discussion with A-IM researchers, we learned that "ATC winds" has been deprecated in favor of a different wind source called "ATS (Air Traffic Service) winds". While this more generalized term disassociates it from necessarily being an FAA service, it is still conceptual and it is not known at this time what its requirements are.

3.3.2 Winds Aloft

"Winds Aloft" is a heavily overloaded term in the wind lexicon having many variations in its terminology and meanings. Pilots and air traffic controllers speak of "winds aloft" when referring to current or expected winds along an aircraft's flight altitude and location. Synonyms include "winds at altitude", "upper level winds", or "upper winds". The following are some examples of sources of "winds aloft".

FB Winds

"Winds aloft" often refers to a wind forecast product produced by NOAA's Aviation Weather Center known as the "Wind and Temperature Aloft Forecast" or "FB Winds" (see https://aviationweather.gov/windtemp). "FB" is part of the WMO product identifier (e.g., "FBUS31 KWNO 091956"). It provides forecast winds and temperatures at selected locations and altitudes in coded text or graphical formats. It is produced every 6 hours and forecasts are valid for 7, 9, or 12-hour forecast time periods, and is frequently utilized for flight planning by commercial and GA pilots.

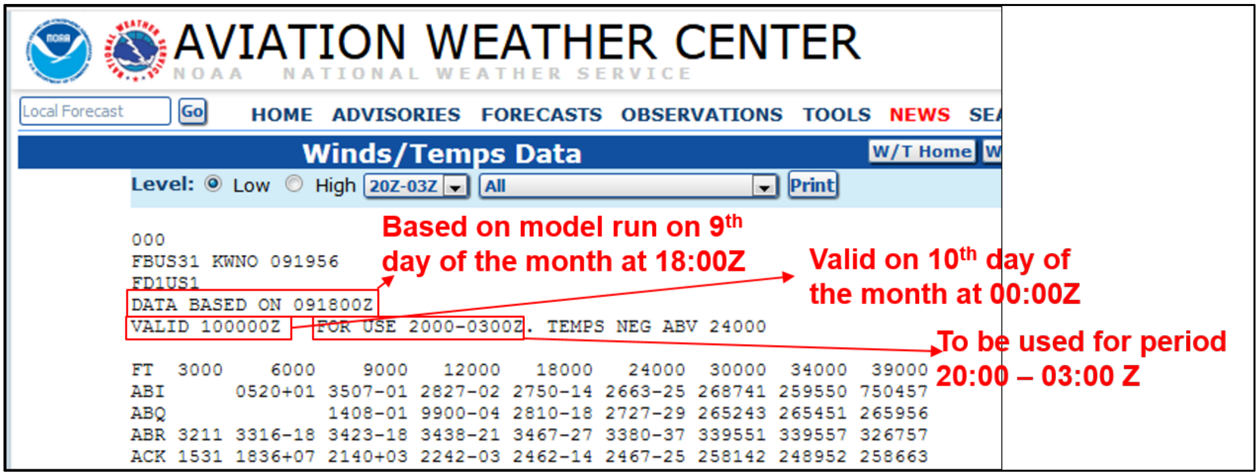

Figure 21. Excerpt of FBWinds Text Bulletin from NOAA Aviation Weather Center.

The FB Winds product is sometimes misinterpreted by pilots, especially with regard to the forecast valid times (as evident by numerous publications attempting to explain it). Whereas numerical weather prediction models provide time-sequences of forecasts valid at discrete look-ahead times (e.g., +1, +2, +3 hours in the future), the FB Winds forecasts are valid for a broad time period in the future as given by the "FOR USE" indicator in the bulletin. While sufficient for general strategic flight planning, it is a poor choice for NextGen applications such as 4D-TBO where more temporally precise knowledge of the winds are needed to generate and achieve time targets under rapidly changing weather conditions.

Numerical Weather Prediction Model Winds

Diagnostic and forecast winds produced by numerical weather prediction models are also a common source of "winds aloft". The New York Center Weather Service Unit (CWSU) produces a Strategic Planning Aid (SPA) website for the N90 TRACON at https://www.weather.gov/zny/n90. One of the selections in the SPA is the "Winds Aloft", which provides a time series of forecast vertical wind profiles for the selected airport location. The source of these winds aloft is the NOAA RAP model, which updates hourly with 1-hour forecast time steps (Figure 22).

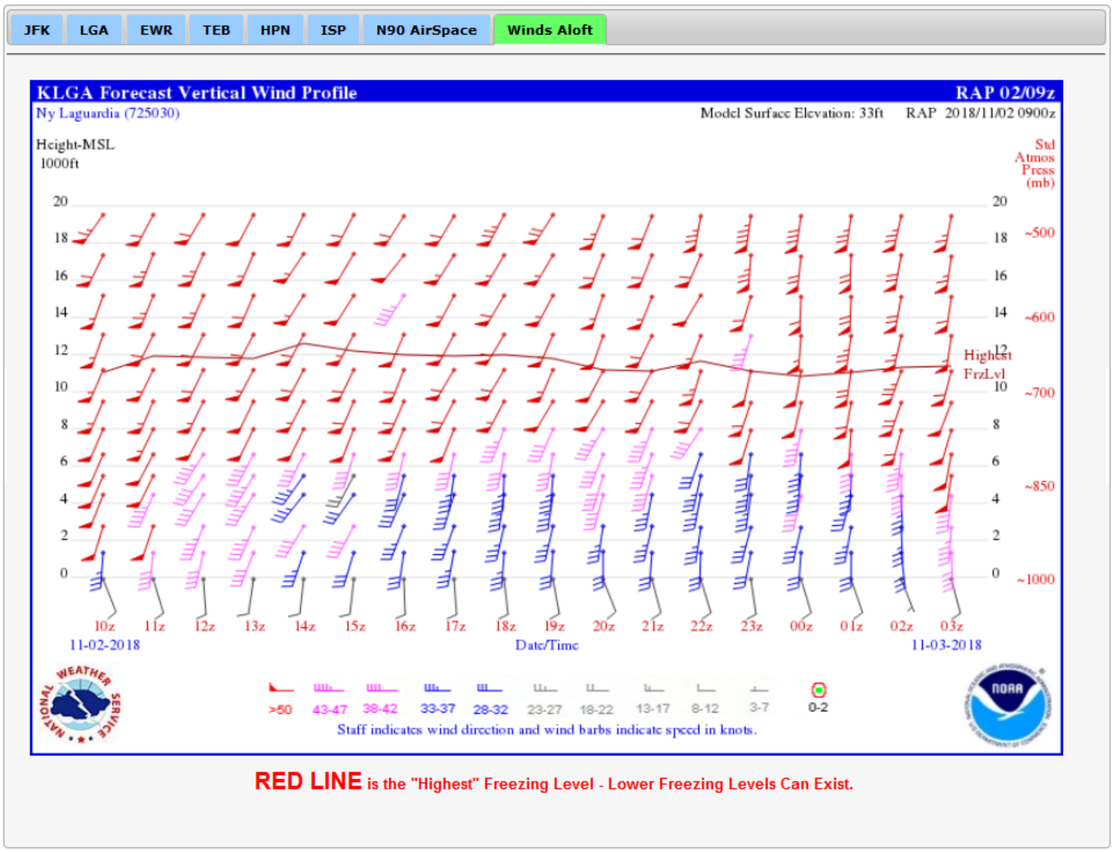

Figure 22. "Winds Aloft" display of RAP model winds from the N90 SPA tool.

The WMO Statement of Guidance for Aeronautical Meteorology [25] recommends use of the World Area Forecast System (WAFS) model for "upper winds" for en route flight planning. The WAFS model is updated every 6 hours and is produced at two forecast centers: UK Met Office and NOAA (see Figure 23).

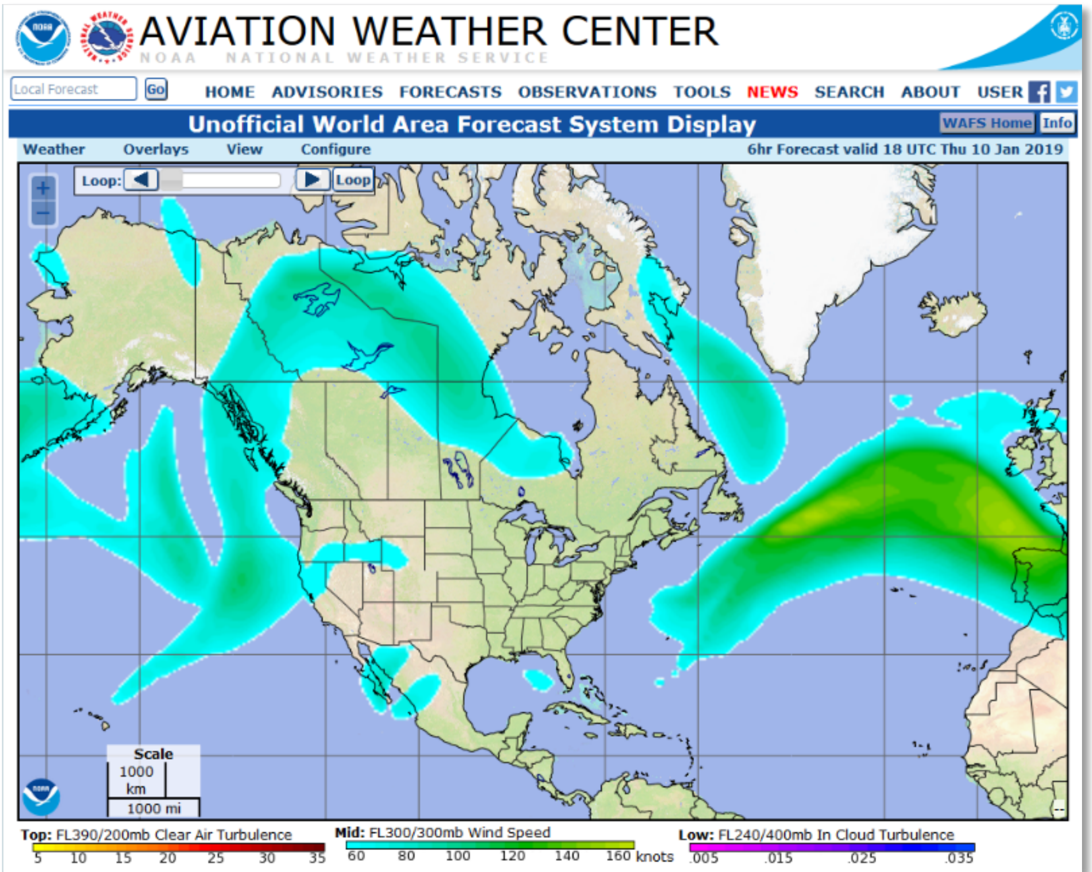

Figure 23. Example WAFS winds display from NOAA AWC.

Terminal Wind Profiles

Another source of wind information referred to as "winds aloft" is the Terminal Wind Profiles product generated by the FAA ITWS. It provides current wind directions and speeds at selected locations and altitudes surrounding an airport in a tabular graphical display. It is utilized by airport traffic managers and controllers. In addition to "winds aloft", it is also referred to as "capture box winds" and "upper level winds". Figure 24 shows an example ITWS Terminal Winds Profile display showing wind profiles for four location surrounding Philadelphia International Airport (PHL) (BUNTS, TERRIE, AIRPORT, MAZIE, and VCN). Each profile has rows with three columns of numbers. The first column is the altitude of the wind observation in hundreds of feet above mean sea level. The second column is the wind direction in degrees, and the third column is the wind speed in knots.

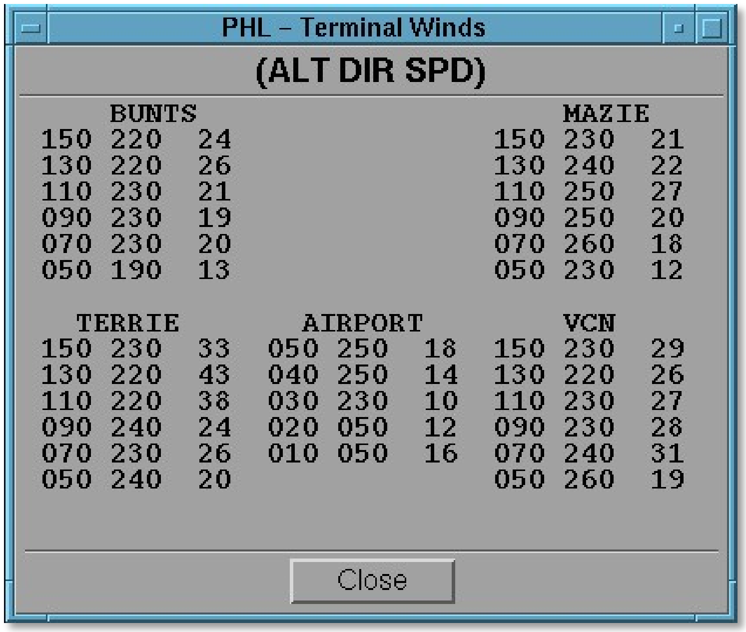

Figure 24. ITWS Terminal Winds Profile Display.

3.3.3 Compression

Compression of an air traffic stream typically refers to a situation where reduced in-trail spacing of aircraft occur due to increasing headwinds along a flight path. When an aircraft encounters an increasing headwind, its ground speed decreases. An aircraft following the slowing aircraft on the same flight path will have a higher ground speed than the aircraft ahead of it, resulting in reduced separation between the two.

Compression is frequently mentioned in NTML logs and Strategic Planning Telecons (SPT), often in context of setting an Airport Arrival Rate (AAR) for an airport. Figure 25 from Reiche, et.al. [26] plots the average annual number of days where wind compression was noted as an air traffic impact in NTML during the period 2009-2011. Note that the three NY airports, Newark Liberty International Airport (EWR), JFK, and LaGuardia Airport (LGA), have the highest number of days where compression was reported (nearly 70 days over the 3-year period analyzed).

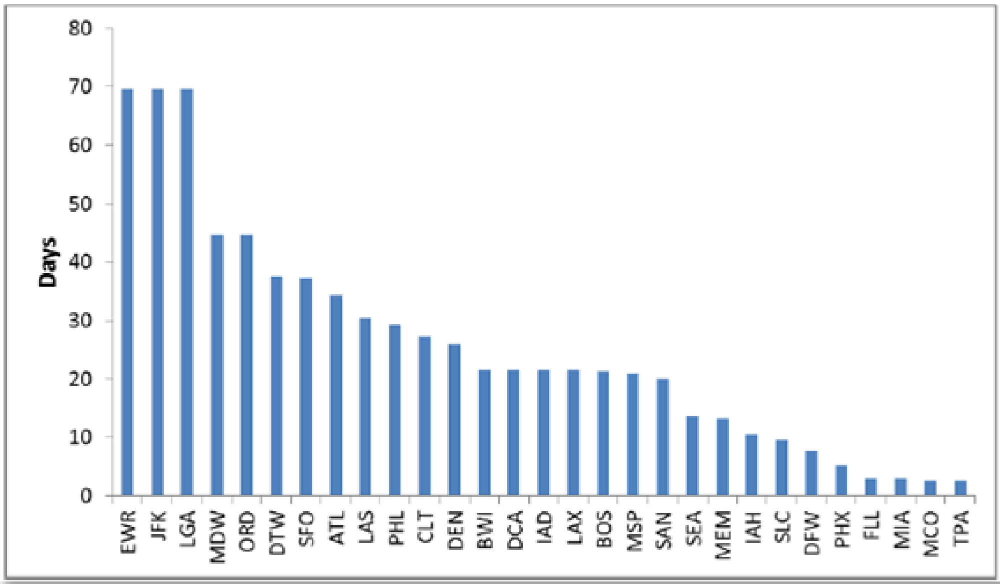

Figure 25. Average annual number of days where compression was noted in NTML during 2009-2011 (From Reiche, et.al., 2016 [26]).

Because compression is such a frequent impact to operations in New York, the N90 SPA website includes an experimental compression forecast (see Figure 26):

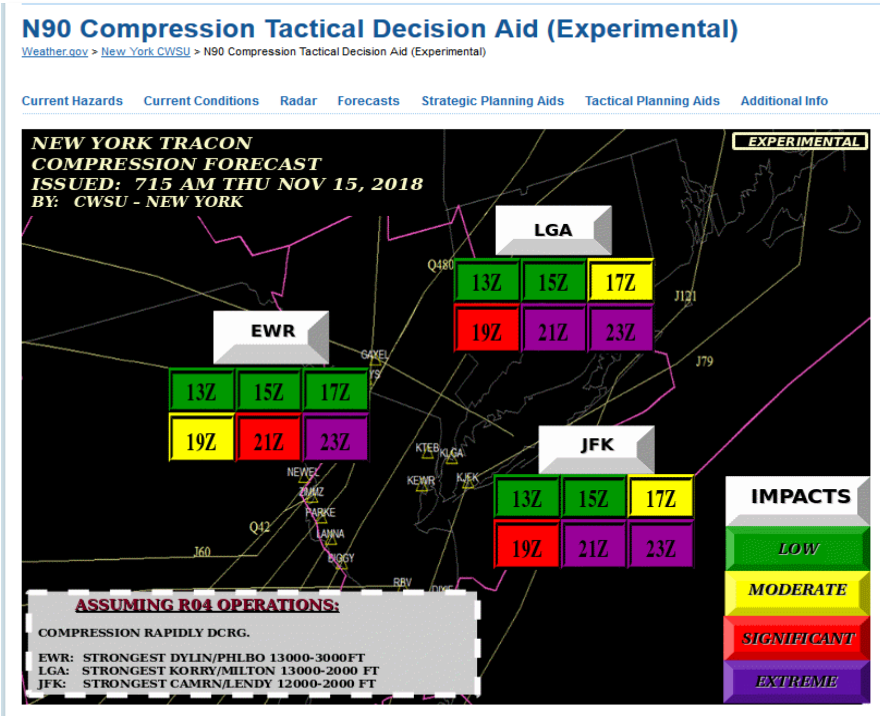

Figure 26. Example Compression Forecast from N90 SPA.

In our interviews with users and reviews of publications and websites, we found a number of variations in the compression lexicon:

- “Compression”
- “Wind compression”
- “Compression on final”
- “Compression at altitude”
- “Adaptive compression”
- “Volume compression”

The last two compression-related terms in the list above, “adaptive compression” and “volume compression”, are not wind-related, but are traffic density related terms. See Table 7 for the sources, contexts, and definitions of these terms.

3.3.4 Airport Wind

The “Airport Wind” is communicated to pilots by one of the tower controllers during departure clearance and final approach. It is intended to be “generally representative of wind conditions across the airport runway complex” [27]. The source of the airport wind report varies across facilities. Some airports have multiple wind sensors, and the choice of sensor for the airport wind is at the discretion of the local air traffic operations manager. When the airport wind is being communicated to pilots, the controller is not typically aware of what sensor is providing the wind observation. Figure 27 shows the distribution of FAA-owned wind sensors (in addition to Automated Surface Observing System/Automated Weather Observing System) across the Continental United States (CONUS), (from [27]).

For airports with wind shear detection system such as Low Level Wind Shear Alert System (LLWAS) or ITWS, the airport wind direction and speed is displayed with an “AW” designator on the top row of a Ribbon Display Terminal situated near a tower controller’s position as shown in Figure 28 [28].

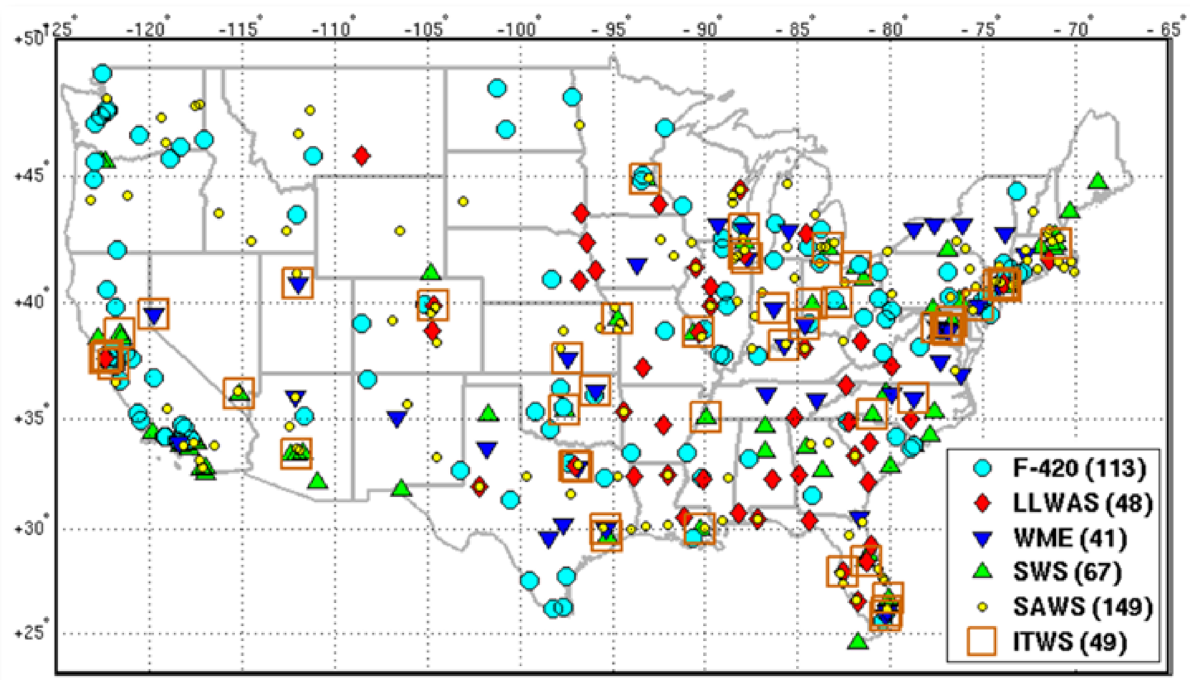

Figure 27. FAA sensor sources for providing designated airport wind.

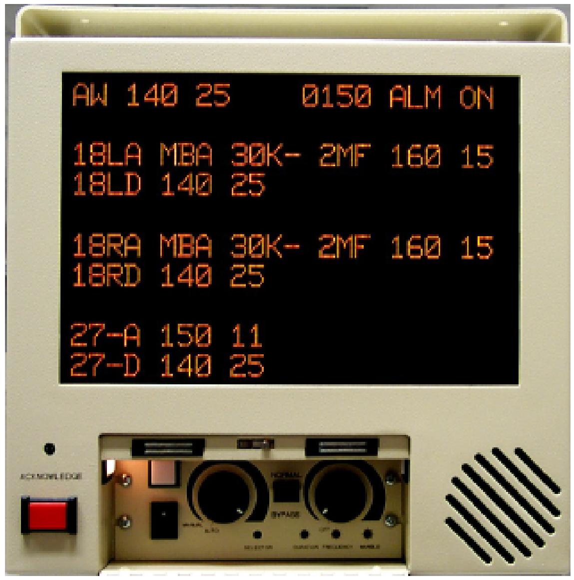

Figure 28. Controller Ribbon Display Terminal (RBDT).

3.4 WIND LEXICON GLOSSARY

In this section, we present a glossary of terms uncovered in the wind lexicon study. One or more context categories have been assigned to each lexicon term as shown in Table 6 below:

Table 6

Wind Lexicon Categories

Category	Definition
Flight Route Winds	Winds associated with flight phases, aircraft measurement, or navigation
Wind Induced Effects & Phenomena	Wind effects on aircraft performance or navigation and meteorological wind phenomena
Surface Winds	Winds associated with surface wind reports or measurements
Winds Aloft	Wind terms related to winds above the surface
Sensor Winds	Wind terms associated with sensors or sensor systems
Conceptual Winds	Wind terms that don't correspond to a specific wind observation or forecast (e.g., "Common winds")

Table 7 summarizes the wind lexicon results. Formal published definitions were not found for some terms, though it is often clear from usage context or related terms what is meant. In those cases, a proposed definition based on consultation with subject matter experts has been supplied and is noted with "[MIT LL]" following the definition.

Table 7

Wind Lexicon Summary

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
3-D wind [25]	A spatial collection or sequence of observed or forecast wind values having positions distributed in both horizontal and vertical dimensions. Numerical weather prediction models typically provide wind values projected onto a regularly spaced 3-dimensional grid. *[MIT LL]*	Winds Aloft	Flight planning, TFM		
Adaptive Compression [29]	A [traffic management] procedure that ensures all slots in a program are used by moving flights earlier to take advantage of open slots and moving open slots later. Not wind-related.	Wind Induced Effects and Phenomena	TFM	Slot compression	Compression, Compression at altitude, Compression on final, Adaptive compression, Volume compression, Wind compression
Airport Wind [27]	Observed winds generally representative of wind conditions across the aerodrome runway complex. *[MIT LL]*	Surface Winds	Pilot information	Tower winds	Surface winds, Current winds, Centerfield wind
Along track wind [30]	The along track wind forecast error (ATWFE) is defined as the along-track component of the difference between the wind forecast and the sensed wind	Flight Route Winds	4D-TBO IM		Headwind

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
ATC winds [23][24]	Air Traffic Control Winds. “A common understanding of wind conditions (ATC Winds) along an aircraft’s route of flight that is available to both the ATC automation and the flight deck automation”	Conceptual Winds	4D-TBO IM	ATS winds	ATS winds, Common winds
ATS winds [31]	Air Traffic Service Winds (replaces former “ATC winds”). A wind service used to communicate detailed winds from ATC to aircraft automation systems at specific flight levels to support Flight Interval Management operations	Conceptual Winds	4D-TBO IM	ATC winds	ATC winds, Common winds
Centerfield wind [27]	Surface winds measured at a location near the center of an aerodrome. Also known as the “airport wind”. *[MIT LL]*	Surface winds, Flight Route Winds	Pilot information	Center field wind, CF wind	Airport wind Threshold wind
Common winds [24]	A notional concept for 4D-TBO Interval Management whereby ground-based (ATC) and airborne (flight deck) navigation automation systems are presumably utilizing the same ("common") source of wind data for time target estimation. [MIT LL]	Conceptual Winds	4D-TBO IM		ATC winds, ATS winds
Compression [32][33]	The loss of horizontal separation between aircraft as a function of variations in headwind and tailwind encountered upon approach to airports. When significant enough, may require	Wind Induced Effects and Phenomena	TFM	Wind compression	Compression at altitude, Compression on final, Adaptive compression, Volume compression

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
	reduced arrival rates for the impacted airports.				
Compression at altitude [32]	Compression as aircraft are coming into merge points at high altitudes occurring outside terminal approach and generally above 6,000 feet AGL.	Wind Induced Effects and Phenomena	TFM	Compression, Wind compression	Compression, Compression on final, Adaptive compression, Volume compression
Compression on final [32]	Compression occurring on descent to final approach, generally starting 10 mi from airport, and where separation > 3 mi must be maintained.	Wind Induced Effects and Phenomena	TFM	Compression, Descent compression, Wind compression	Compression, Compression at altitude, Adaptive compression, Volume compression
Crosswind [34][35]	1. The wind component perpendicular to the longitudinal axis of a runway. 2. The wind component perpendicular to the to an aircraft's flight path *[MIT LL]*	Flight Route Winds	Runway configuration	Cross wind, Crosswind component	Headwind, Tailwind,
Crosswind threshold [34]	Maximum crosswind allowance threshold for a runway *[MIT LL]*	Flight Route Winds	Runway configuration		Crosswind
Current winds [36]	Airport Wind provided to a pilot *[MIT LL]*	Surface winds	Pilot information, Flight planning	Airport Wind, Centerfield wind	Threshold wind

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
Descent winds [37]	Forecasted winds provided to an FMS intended to represent the conditions to be experienced during an aircraft's planned descent.	Winds Aloft, Flight Route Winds	Aircraft FMS		
Doppler wind [25]	Wind measured by Doppler radar. Multiple Doppler wind measurements from at least two radars can provide accurate 3D winds within precipitating areas.	Sensor and Observation Systems	Flight planning, Trajectory prediction		
Flight level wind [35]	Aircraft derived wind condition at an aircraft's current flight altitude level. An air traffic controller working traffic in an airport tower, approach control, or en route center, may receive (or request) a pilot report that includes "flight level wind." *[MIT LL]*	Winds Aloft, Flight Route Winds	Flight planning, TFM		Upper level wind
Forecast vertical wind profile [38]	NOAA RAP model winds displayed on NY Strategic Planning Aid (SPA) Tool *[MIT LL]*	Winds Aloft	Flight planning		Wind profile, Vertical wind profile
Gust front [34][39]	The leading edge of gusty surface winds from thunderstorm downdrafts; sometimes associated with a shelf cloud or roll cloud.	Wind Induced Effects and Phenomena	Flight safety, Airport planning, Wind shear alerts		Wind shear

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
Headwind [40]	The component of atmospheric winds that acts opposite to the aircraft's flight path	Flight Route Winds	Runway configuration, Trajectory estimation	Head wind, Headwind component	Tailwind, Crosswind
ITWS winds [35][38]	Wind shear alerts and airport winds reported on ITWS ribbon display *[MIT LL]*	Surface Winds	Controller and pilot information, Flight safety		Terminal Winds, Ribbon Display Winds
Jet Stream [34][39][41]	1. Relatively strong winds concentrated in a narrow stream in the atmosphere, normally referring to horizontal, high-altitude winds. [39] 2. A high-velocity narrow stream of winds, usually found near the upper limit of the troposphere, which flows generally from west to east. [41]	Wind Induced Effects and Phenomena	Flight planning	Jetstream, JSTR (abbrev.)	Jet Streak
Jet Streak [39]	A point or area ("streak") of relative maximum wind speeds within a jet stream.	Wind Induced Effects and Phenomena	Flight planning		Jet Stream
Microburst [34][42]	1. A small downburst with outbursts of damaging winds extending 4 kilometers or less. In spite of its small horizontal scale, an intense microburst could induce wind speeds as high as 150 knots. [42]	Wind Induced Effects and Phenomena	Flight safety, Airport planning, Wind shear alerts		Wind shear

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
	2. A convective downdraft with an affected outflow area of less than 4 kilometers wide and peak winds lasting less than 5 minutes. [39]				
Mountain wave [34][39]	The wavelike effect characterized by updrafts and downdrafts that occurs above and behind a mountain range when rapidly flowing air encounters the mountain range's steep front.	Wind Induced Effects and Phenomena	Flight safety		Mountain wave turbulence
Mountain wave turbulence [34]	Turbulence associated with a mountain wave *[MIT LL]*	Wind Induced Effects and Phenomena	Flight safety		Mountain wave
NIDS wind [34]	Wind information shown on a NAS Information Display System *[MIT LL]*	Sensor and Observation Systems	Flight planning, Trajectory prediction		
Path-based wind shear [43]	Wind shear due to changes in wind speed and/or direction in a short distance along a flight path	Flight Route Winds	Flight safety, Flight planning, TFM	Path-based shear	Wind shear
Raw winds [34]	Observed surface winds reported by ASOS *[MIT LL]*	Sensor and Observation Systems	Airport runway configuration, TFM	Raw ASOS winds	

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
Ribbon Display Wind [38]	Alphanumeric display of Airport Wind (AW) and wind shear alerts on a Ribbon Display Terminal in an ATC Tower or TRACON *[MIT LL]*	Surface winds	Controller and pilot information, Flight planning, Flight safety		ITWS winds, Terminal winds
Sensed wind [30]	Wind estimated by aircraft. *[MIT LL]*	Sensor and Observation Systems	4D-TBO IM		
Surface wind [34][44]	Wind measured near ground level	Surface winds	Pilot Information		Airport wind, Current winds, Centerfield wind
Tailwind [34]	The component of atmospheric winds that acts in the direction of the aircraft's flight path *[MIT LL]*	Flight Route Winds	Runway configuration, Trajectory estimation	Tail wind, Tailwind component	Headwind, Crosswind
Terminal Winds [32][35]	ITWS product that provides wind direction and speed at selected locations and altitudes surrounding an airport. *[MIT LL]*	Winds Aloft	Flight planning, TFM	Terminal Wind Profiles, TWINDS, Capture Box Winds	ITWS Winds
Threshold wind [27][45]	Winds at or near the arrival end of runway. *[MIT LL]*	Flight Route Winds	Pilot information	Runway threshold wind	Centerfield wind

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
Upper level winds [34]	Winds typically associated with the cruise phase of flight. *[MIT LL]*	Winds Aloft Flight Route Winds	Flight planning, TFM	Upper winds, Winds at altitude	Upper wind forecasts
Volume Compression [29]	Air traffic spacing compression arising due to increased air traffic density within an airspace sector or volume. Not wind-related. *[MIT LL]*	Wind Induced Effects and Phenomena	TFM		Adaptive compression, Compression, Compression at altitude, Compression on final, Adaptive compression, Volume compression, Wind compression
Wind and Temperature Aloft Forecast [46]	Computer prepared forecasts of wind direction, wind speed, and temperature at specified times, altitudes, and locations.	Winds Aloft	Flight planning	FB Winds, Forecast Winds and Temperatures Aloft, FD Winds, FB, Winds Aloft, Winds Aloft Forecast, Aviation center wind matrix, Descent winds, Winds at altitude	Winds Aloft
Wind compression [34]	Assumed same as “Compression”. Distinguishes from non-wind related compressions (e.g., “Adaptive Compression”, “Volume Compression” *[MIT LL]*	Wind Induced Effects and Phenomena	TFM	Compression	Compression, Compression at altitude, Compression on final,

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
					Adaptive compression, Volume compression
Wind gust [34][39]	Rapid fluctuations in the wind speed with a variation of 10 knots or more between peaks and lulls. The speed of the gust will be the maximum instantaneous wind speed.	Wind Induced Effects and Phenomena	Flight safety, Airport runway configuration		Gust front
Wind routes [34][36]	Dynamic RNAV transcontinental ATM routes that take advantage of favorable en route winds for W-to-E traffic coming to NY airports *[MIT LL]*	Flight Route Winds	Flight planning, TFM		
Winds for departure [35]	Wind expected or encountered during takeoff roll and through 2 nm departure *[MIT LL]*	Flight Route Winds, Surface Winds	Pilot information	Departure winds	Winds on final
Wind shear [34][41]	A change in wind speed and/or wind direction in a short distance.	Wind Induced Effects and Phenomena	Flight safety, Airport planning, Wind shear alerts	Windshear, Shear	Microburst, Gust front, Path-based wind shear

Term [Source]	Definition	Category	Context	Synonyms	Related Terms
Wind shift [34][39]	A change in wind direction of 45 degrees or more in less than 15 minutes with sustained wind speeds of 10 knots or more throughout the wind shift.	Wind Induced Effects and Phenomena	Airport planning	Windshift	Gust front
Winds on final [35]	Wind expected or encountered during final approach from 3 nm to touch-down *[MIT LL]*	Flight Route Winds, Surface Winds	Pilot information	Final approach winds	Winds for departure
WME wind [27]	Wind report from airport Wind Measuring Equipment (WME) *[MIT LL]*	Sensor and Observation Systems	Pilot information		Airport wind, Centerfield wind

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3.5 CONCLUSIONS

The wind lexicon study utilized many sources including in-person interviews of air traffic controllers and managers, pilots, airlines and aviation meteorologists, publications, standards documents and manuals, traffic management logs, online glossaries, and weather web sites. A tabulated, categorized glossary of over 60 wind terms and definitions was compiled. Where we could not find formal definitions for commonly used terms, proposed definitions were provided and noted for these.

As a precursor to the wind lexicon survey, we identified the wind data sources underlying or provided by FAA DSTs commonly used by ATC and ATM. We found that gridded wind forecasts provided by NOAA's RAP and GFS models are most commonly utilized in the FAA DSTs. Internationally, the WAFS model is a source of en route upper level wind information for pilots and airlines recommended by the WMO.

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4. KEY FINDINGS AND RECOMMENDED NEXT STEPS

4.1 KEY FINDINGS

The results of this work have led to some interesting and relevant findings. Concerning RTA performance and to the general question of the correlation of RTA timing error and forecast error, more accurate descent forecast do not guarantee reduced arrival errors on an individual flight basis but do increase the probability of smaller arrival errors. Aggregated RTA timing errors are significantly poorer for flights with meter fix altitudes below 7,000 ft AGL. Optimally sampling wind forecasts along the estimated descent trajectory provides significantly more accurate descent forecasts compared to sampling over the estimated top of descent location and using 9 DFLs compared to 3 also improves forecast accuracy regardless of the technique.

For the Pegasus FMS tested, there is a clear performance separation in RTA time arrival error between flights that arrive at their RTA fix above 7,000 ft AGL or below this value. For the higher altitude group, more than 96% of all flights, tested under any condition, arrived within ±10 second error. When speed constraints were removed from routes, 100% of flights in this group had less than ±10 second arrival error. The higher altitude group performance is still susceptible to descent forecast error if the speed constraints are left in place and for this condition there is a continued degradation in performance as the descent forecast increases. The removal of speed constraints from routes provided improvements in general and significantly reduced variance and peak timing errors.

The overall performance of the low-altitude group was significantly poorer than that of the higher group. Regardless of the test condition or forecast accuracy, this group's performance under each test condition never exceeded 85% of flights arriving with less than ±10 second timing error. Group performance in this domain was proportionally affected by the descent forecast error regardless of whether speed constraints remained in place or not. The less accurate the forecasts, the lower the group performance. It is suspected that a significant factor on the performance of the low-altitude group was caused by the Pegasus FMS ceasing closed-loop control on RTA timing errors once the aircraft is within 10 nmi of the RTA fix. In this low-altitude domain, there are often continuous reductions of speeds and the potential of flaps deployment and it is possible that the FMS does not predict these conditions well.

The wind lexicon study utilized many sources including in-person interviews, publications, standards documents and manuals, traffic management logs, online glossaries, and weather web sites. Over 60 wind-related terms were identified. In general, we did not find much confusion or ambiguities in verbal communications of wind information between ATC, airlines, and pilots. Many operational users (e.g., pilots, controllers) are insulated from details of underlying wind sensors, systems, and numerical models. Displayed information generated by DSTs and systems are communicated in accordance with policies and procedures (e.g., FAA 7110). However, we identified four wind-related terms that were frequently overloaded or ambiguous: ATC or Common Winds, Compression, Winds Aloft, and Airport Wind. Their uses and contexts were described in detail in preceding sections of this report.

4.2 RECOMMENDED NEXT STEPS

Based on current findings, to further the potential of 4D-TBO operations in particular as the concept extends to operation to lower and lower altitudes, we think additional work is required to determine the temporal accuracies of RTA trajectories of various FMS and aircraft combinations and other factors, such as route design, that may affect individual RTA performance.

Given the identified issues with MDCRS data sourced from NOAA/Meteorological Assimilation Data Ingest System (MADIS), additional work should be performed to help develop and validate data processing changes to address the publishing of un-sampled meteorological data.

The wind lexicon developed in this report is not exhaustive, and should be expanded with further research. The tabular presentation of the information also has limitations with regard to page space and ability to link together related information. Eurocontrol manages an online ATM lexicon (see https://ext.eurocontrol.int/lexicon/index.php/Main_Page) that utilizes a web-based semantic Wiki platform that would be a good model for making this wind lexicon more accessible and expandable going forward.

GLOSSARY

4DT	Four Dimensional Trajectories
4D-TBO	Four Dimensional-Trajectory Based Operations
6-DOF	6 Degree Of Freedom
AAR	Airport Arrival Rate
ABT	Achieve-By Point
AGL	Above Ground Level
A-IM	Advanced Interval Management
ARR	Arrival fixes
ARTCC	Air Route Traffic Control Center
ASDE-X	Airport Surface Detection Equipment - Model X
ASG	Assigned Spacing Goal
ASOS	Automated Surface Observing System
ASP	Airspace Service Provider
ATC	Air Traffic Control
ATCSCC	ATC System Command Center
ATCT	Air Traffic Control Tower
ATD-1	ATM Technology Demonstration-1
ATL	Hartsfield-Jackson Atlanta International Airport
ATM	Air Traffic Management
ATOMS	AircrafT Operations Modeling System
ATS	Air Traffic Service
AWOS	Automated Weather Observing System
CAS	Calibrated Air Speed
CERAP	Center Radar Approach Control
CF	Climate and Forecast
CIFP	Coded Instrument Flight Procedure
CIWS	Corridor Integrated Weather System
CONUS	Continental United States
CoSPA	Consolidated Storm Prediction for Aviation
CTA	Controlled Time of Arrival
CWSU	Center Weather Service Unit
DEN	Denver International Airport
DFL	Descent Forecast Level
DST	Decision Support Tool
EDST	En Route Decision Support Tool
EHS	Enhanced Surveillance
EOS	End of STAR

ERAM	En Route Automation Modernization
ETA	Estimated Time of Arrival
EWR	Newark Liberty International Airport
FAF	Final Approach Fix
FFS	Full Flight Simulator
FIM	Flight-deck Interval Management
FIR	Flight Information Region
FMS	Flight Management System
GA	General Aviation
GFS	Global Forecast System
GIM	Ground-based Interval Management
HRRR	High Resolution Rapid Refresh
IAF	Initial Approach Fix
IAP	Instrument Approach Procedure
ICAO	International Civil Aviation Organization
IM	Interval Management
ITWS	Integrated Terminal Weather System
JFK	John F. Kennedy International Airport
LAX	Los Angeles International Airport
LGA	LaGuardia Airport
LLWAS	Low Level Wind Shear Alert System
MADIS	Meteorological Assimilation Data Ingest System
MAFID	Meteorological and Flight Information Database
MCDU	Multifunction Computer Display Unit
MDCRS	Meteorological Data Collection and Reporting System
Meter fix	Location where aircraft is targeting to get to by the CTA/RTA is controlled to by FMS in TOAC procedures
Mode S	Mode Select; Discrete Addressable Secondary Radar System With Data Link
MSL	Mean Sea Level
MSN	Dane County Regional Airport
NAM	National Aviation Meteorologist
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATCA	National Air Traffic Controllers Association
NOAA	National Oceanic and Atmospheric Administration
NTML	National Traffic Management Log
NWS	National Weather Service
PHL	Philadelphia International Airport
PHX	Phoenix Sky Harbor International Airport
RAP	Rapid Refresh

RBDT	Ribbon Display Terminal
RNAV	Area Navigation
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
SEA	Seattle/Tacoma International Airport
SPA	Strategic Planning Aid
SPT	Strategic Planning Team
STAR	Standard Terminal Arrival Route
STMC	Supervisory Traffic Management Coordinator
TAC	Traditional Alphanumeric Coded
TBFM	Time-Based Flow Management
TFM	Traffic Flow Management
TFMS	Traffic Flow Management System
TMA	Traffic Management Advisor
TMI	Traffic Management Initiative
TOAC	Time of Arrival Control
TOD	Top of Descent
TRACON	Terminal Radar Approach Control
TSAS	Terminal Sequencing and Spacing
UAV	Unmanned Aerial Vehicle
UCUM	Unified Code for Units of Measure
VRMS	Vector Root Mean Square
WAFS	World Area Forecast System
WIAF	Wind Information Analysis Framework
WMO	World Meteorological Organization

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REFERENCES

1. “Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation,” RTCA Special Committee 227 (SC-227) Standards of Navigation Performance, Washington DC, DO-236C, September 2014.

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

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

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

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

6. Edwards, C., McPartland, M. D., Reynolds, T. G., Sandberg, M., Teller, T., Troxel, S., “Wind Information Requirements for NextGen Applications Phase 3 Final Report,” MIT Lincoln Laboratory, Project Report ATC-422, December 2014.

7. Edwards, C., Glina, Y., McPartland, M., Reynolds, T G., Troxel, S., “Wind Information Requirements for NextGen Applications Phase 4 Final Report”, MIT Lincoln Laboratory, Project Report ATC-431, March 2017.

8. “Guidance for the Usage of Data Linked Forecast and Current Wind Information in Air Traffic Management (ATM) Operations,” RTCA Special Committee 206 (SC-206) Aeronautical Information and Meteorological Data Link Services, Washington, DC, RTCA DO-369, July 2017.

9. Edwards, C., Glina, Y., McPartland, M. D., Reynolds, T. G., Troxel, S. W., “Wind Information Requirements for NextGen Operations Phase 5 Report,” MIT Lincoln Laboratory, Project Report ATC-439, 22 August 2017.

10. Edwards, C., Glina, Y., McPartland, M. D., Reynolds, T. G., Troxel, S. W., “Wind Information Requirements for NextGen Operations Phase 6 Report,” MIT Lincoln Laboratory, Project Report ATC-442, 2018.

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

12. C. Edwards, Y. Glina, J. Jones, M. McPartland, T. Reynolds & S. Troxel, “Effects of Enhancing FMS Descent Forecasts on Four Dimensional Trajectory-Based Operations Performance”, 16th AIAA Aviation Technology, Integration, and Operations Conference, Washington DC, AIAA 2016-4069, 2016.

13. Climate and Forecast (CF) Conventions, http://cfconventions.org/Data/cf-standard-names/65/build/cf-standard-name-table.html

14. WMO codes registry, https://codes.wmo.int/

15. Unified Code for Units of Measure, https://unitsofmeasure.org/ucum.html

16. FAA website, “NextGen Portfolio - Time Based Flow Management”, https://www.faa.gov/nextgen/snapshots/portfolios/?portfolioId=11

17. Robinson, M., Reynolds, H., Evans, J. E., “Traffic Management Advisor (TMA) – Weather integration”, 14th Conference on Aviation, Range, and Aerospace Meteorology (ARAM), Amer. Meteor. Soc., Atlanta, GA, Jan 2010.

18. Traffic Management Advisor (TMA), NASA, https://www.aviationsystemsdivision.arc.nasa.gov/research/foundations/tma.shtml

19. Daskalaskis, Chris, TSAS System Engineer/Project Lead, personal communication.

20. CSS-Wx/NWP Attachment J-07 NextGen Weather Description, Table C-7 “ERAM Inputs”, Aug. 16, 2018.

21. FAA Order J0 7110.65, Air Traffic Control, Chapter 13. Decision Support Tools, Section 1. ERAM Decision Support Tools (EDST), page 13-1-1.

22. "Lockheed Martin to Continue Support for FAA's Micro-EARTS, Aviation Today, https://www.aviationtoday.com/2016/05/31/lockheed-martin-to-continue-support-for-faas-micro-earts/, May 31, 2016.

23. "Advanced Interval Management Preliminary Concept of Operations", FAA report in support of RTCA Special Committee 214, Version 1.0, Mar. 27, 2014.

24. "Four Dimensional Trajectories (4DT) Demonstration", Embry-Riddle Aeronautical University, Final Report to FAA, OTA DTFAWA-08-A-00001 Task W, Version 3.0, Apr. 1, 2017.

25. WMO Statement of Guidance for Aeronautical Meteorology, January 2018.

26. Reiche, C., M. Robinson, C. Craun, and R. Bass, "Operational Shortfalls and Potential Benefits of Path-Based Wind Shear Prediction", 16th AIAA Aviation Technology, Integration, and Operations Conference, 13-17 June 2016, Washington D.C.

27. Clark, D.A., R. Ferris, D. Moradi, "Airport Wind Observations Architectural Analysis", MIT Lincoln Laboratory Project Report ATC-443, July 10, 2018.

28. Instruction Book, "Low-Level Windshear Alert System - Relocation/Sustainment (LLWAS-RS)", Type FA-14100, TI 6560.69A, U.S. DOT/FAA, 5/28/2009.

29. "Traffic Flow Management in the National Airspace System", October, 2009, FAA ATO presentation brochure, 2009-AJN-251.

30. Scharl, J., "ATD-1 Avionics Phase 2 Flight Test: Post-Flight Data Analysis Report", NASA/CR-2017-219645, July, 2017.

31. Weitz, L (MITRE) and G. Comstock (stratmach.com), Advanced Interval Management (A-IM) researchers, personal communication.

32. Former New York TRACON (N90) Operations Manager, personal communication.

33. Squires, K, M. DiSpigna, W. Scura, and G. Strassberg, D. Cleaver, "The New York Center Weather Service Unit Compression Forecast Demonstration Project", Abstract for National Weather Association 41st Annual Meeting (#NWAS16), Norfolk, VA, Sept. 10-15, 2016.

34. FAA National Traffic Management Log (NTML) entry.

35. Ferris, R., MIT Lincoln Laboratory, personal communication.

36. American Airlines (AAL) pilot.

37. "Advanced Flight Management Computer System", ARINC Characteristic 702A-3, December 15, 2006.

38. NY TRACON Weather Strategic Planning Aid (SPA), https://www.weather.gov/zny/n90

39. National Weather Service Glossary, https://w1.weather.gov/glossary/

40. Airplane Flying Handbook, FAA-H-8083-3A, US DOT/FAA Flight Standards Service, 2004.

41. Pilot's Handbook of Aeronautical Knowledge, FAA-H-8083-25B, US DOT/FAA Flight Standards Service, 2016.

42. Pilot/Controller Glossary, FAA Air Traffic Organization Policy JO 7110.65X, Oct. 12, 2017.

43. Klimenko, Victor and M. Klopfenstein, 2018, "Accuracy of New York Automated Wind Compression Tool", 98th Annual Meeting of AMS, Austin, TX, 7-11 January, 2018.

44. ICAO English Pro Aviation Glossary, referenced by Dauntless Aviation Glossary, http://dictionary.dauntless-soft.com/definitions/groundschoolfaa/

45. Armbruster, Paul, "Wind Reporting Systems in the NAS", Presentation at Friends and Partners of Aviation (FPAW) Forum, Washington, D.C., Aug. 8, 2012.

46. NOAA AWC Advisory Circular 00-45G Change 1, Oct. 2014, NWS Instruction 10-812, Oct. 25, 2016.