Large-Scale Data Analysis for Characterization of the Effect of Wind Forecast Errors on ETAs

Sai Vaddi[1], Prasenjit Sengupta[2], Monish Tandale[3]
Optimal Synthesis Inc., Los Altos, CA, 94022

John E. Robinson III[4]
NASA Ames Research Center., Moffett Field, CA, 94035

This paper deals with the characterization of wind forecast errors and evaluates their impact on times of arrival. The specific wind forecast product analyzed in this paper is the Rapid Update Cycle (RUC) 1-hr forecast with 40km resolution. The RUC forecast data is compared to the data recorded by the aircraft using the Aircraft Communications Addressing and Reporting System (ACARS). The data is compared for the complete year 2011, 200nmi around the Phoenix International Airport (PHX). The paper describes two metrics: (i) wind magnitude metric, and (ii) wind uncertainty metrics. These metrics are in turn defined in terms of the effect the wind has on the Estimated Time of Arrival (ETA). Both metrics are computed for all the hourly forecasts between 6am to 10pm in the year 2011. The work illustrates the seasonal dependence of wind and wind uncertainty. It serves as the basis for selecting test days for NextGen concept evaluations in simulations.

I. Introduction

NASA and the FAA have been involved in extensive efforts to develop advanced concepts, technologies, and procedures for the Next Generation Air Transportation System (NextGen)[1]. The objective of these research efforts has been to improve the capacity, efficiency, and safety in the next-generation National Airspace System (NAS). Improvements can come in the form of more accurate and autonomous onboard navigational capabilities based on the Global Positioning System, more accurate surveillance capabilities such as Automatic Dependent Surveillance-Broadcast, advanced communication capabilities such as datalink, improved vehicle designs, and improved air-traffic operations realized through advanced automation systems. A significant portion of the NextGen research is aimed at (i) developing ground-side automation systems to assist controllers in strategic planning operations, (ii) developing controller decision support tools to separate and space the traffic, and (iii) developing flight-deck-side automation to assist pilots in accomplishing airborne merging and spacing operations.

Reference 2 describes a concept for future high-density terminal air traffic operations that has been developed by the Airspace Super Density Operations (ASDO) researchers at NASA Ames Research Center. The concept described in Ref. 2 includes five core automation capabilities: 1) Extended Terminal Area Routing, 2) Precision Scheduling Along Routes, 3) Merging and Spacing, 4) Tactical Separation, and 5) Off-Nominal Recovery. The first two capabilities are strategic planning tools and the remaining three are tactical decision support tools.

Successful implementation of precision scheduling requires an understanding of the following:

1. What is the range of flight times feasible for an aircraft to transit between two points along its flight path (e.g., Top of Descent to a Meterfix & Meterfix to Runway)?
2. What is the accuracy with which an aircraft can realize a Scheduled Time of Arrival (STA)?
3. What is the accuracy with which an aircraft can maintain self-separation with respect to a leading aircraft?

The feasible flight time depends on the following:

- Aircraft performance characteristics
- Cruise and descent speeds selected by the Flight Management System (FMS)

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[1] Senior Research Scientist, 95 First Street, AIAA Member.
[2] Research Scientist, 95 First Street, AIAA Senior Member.
[3] Senior Research Scientist, 95 First Street, AIAA Member.
[4] Lead Engineer for Airspace Technology Demonstration #1, AIAA Associate Fellow.

- Terminal area route geometry
- Atmospheric conditions such as temperature and winds

The Time-of-Arrival (TOA) accuracy and self-separation accuracy depend on the following:

- Uncertainty associated with the atmospheric predictions.
- Advisories from ground-side controllers assisted by automation tools such as Controller Managed Spacing[7] (CMS).
- Current-day and NextGen FMS automation capabilities such as the Required Time of Arrival (RTA) feature of FMS.

Current work focuses on the TOA uncertainty resulting due to the uncertainty associated with wind predictions. The work specifically focuses on Phoenix International Airport (PHX). National Oceanic and Atmospheric Administration's (NOAA's) RUC-40 1-hour wind forecast product is used. The forecasts are compared with the truth data obtained from ACARS. The data is further described in Section II. The PHX terminal airspace used for analysis is described in Section III. Definitions of the wind magnitude and wind uncertainty metrics are provided in Section IV. Finally, the data analysis results are presented in Section V.

II. Data Sources

The wind uncertainty is basically defined as the deviation between the actual (truth) wind and the predicted (forecasted) wind. Therefore, one way to model the probability distribution associated with the deviations is to study the statistical properties a large number of actual observed deviations. This requires the following data: (i) actual wind data and (ii) forecast wind data. In this research wind data obtained from ACARS is used as the truth data and the Rapid Update Cycle (RUC) wind data obtained from NOAA is used as the forecast data.

A. ACARS Data

Many commercial aircraft operating today are equipped with sensors that can provide real-time weather observations (primarily winds and temperatures) via radio downlinks. The Meteorological Assimilation Data Ingest System's (MADIS)[5] automated aircraft dataset provides ACARS[6] data obtained from many U.S. airlines. Each participating aircraft provides the position and wind information $(\tau, \lambda, h, t, W_N, W_E)$ at approximately one-minute intervals. Since this data is obtained from actual aircraft flying through the airspace the ACARS data is in general not available for any arbitrary location and time. It is only available for those spatial locations and times that the aircraft actually traveled. Moreover, all aircraft do not necessarily report this data. However, a large amount of historical data is available to characterize the statistics of the wind uncertainty. Figure 1 shows sample trajectories of aircraft operating in the PHX terminal area that reported wind data using ACARS.

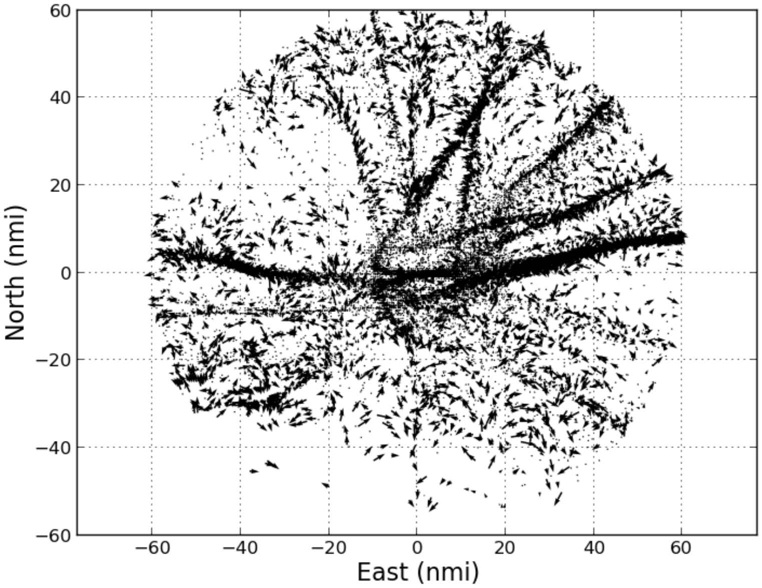

Figure 1. Sample Trajectories of ACARS Equipped Aircraft in the PHX Terminal Area

B. RUC Data

The National Oceanic and Atmosphere Administration (NOAA) provides wind and atmospheric predictions for the entire United States. These forecasts could be obtained through a weather product referred to as Rapid Update Cycle (RUC)[3]. RUC is an operational weather prediction system covering North America that updates on a hourly basis. It consists of a numerical forecast model and an analysis/assimilation system to initialize that model. RUC provides 1-18 hour forecasts, updated hourly using a 40-km horizontal resolution and 50 vertical levels. It provides the predicted North and East components of the wind. Unlike the ACARS data, RUC data is available over a much larger grid of spatial locations. Under the current research a bilinear interpolation scheme has been implemented to compute the wind predictions for spatial locations that do not exactly match the grid points.

Although the current paper focuses on wind modeling it should be noted that approach is applicable to other atmospheric data such as temperature and pressure. In that context it is worth noting that both ACARS and RUC provide temperature and pressure data as well.

III.   PHX Terminal Airspace

Figure 2 shows the PHX terminal airspace used in the current paper. Table 1 lists the combinations of RNAV STARs, fixes, and the runways that were used for the study. The selected en route transitions were for the longest route from each direction. Runways 08 and 26 were used to represent the other parallel runways at PHX – Runways 07L/07R and 25L/25R.

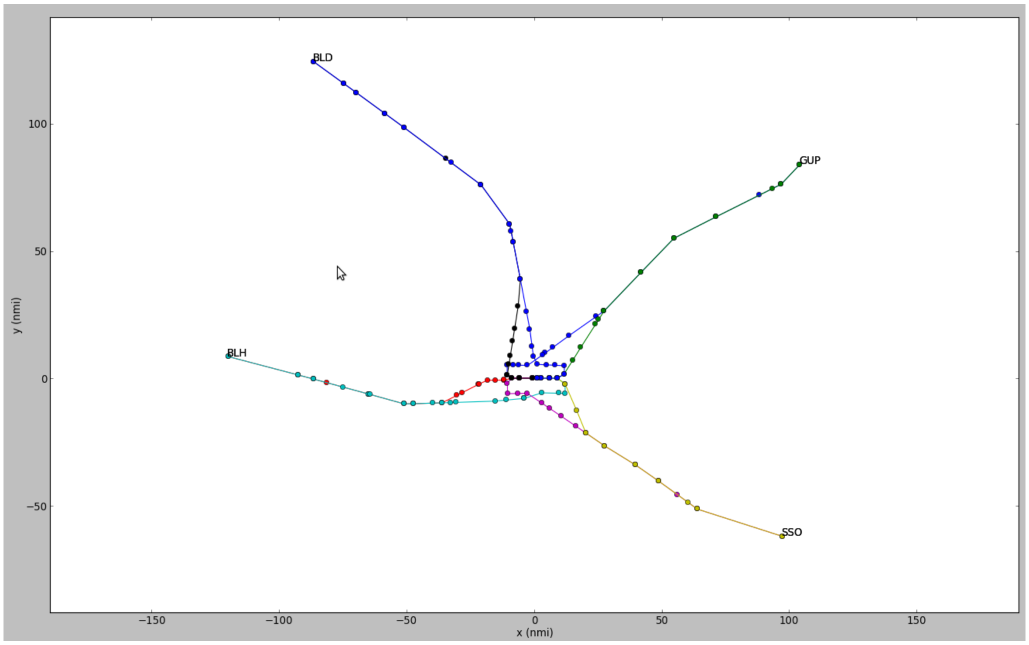

Figure 2. PHX Airspace

Table 1. PHS STARs, Fixes, and Runway Combinations

S. NO	STAR	FIX	RUNWAY
1	GEELA6	BLH	08
2	GEELA6	BLH	26
3	MAIER5	BLD	08
4	MAIER5	BLD	26
5	KOOLY4	SSO	08
6	KOOLY4	SSO	26
7	EAGUL5	GUP	08
8	EAGUL5	GUP	26

IV. Definition of Wind Metrics

The current section defines the wind magnitude and wind uncertainty metrics used in the current paper. These metrics are a function of the Estimated Time of Arrival along each route. Therefore, it is important to first identify the methodology used to compute the ETA.

A. ETA Computation

The following common piece-wise linear speed profile is used along all the STARs:

- 280KIAS farther than 200NM
- 270KIAS at 80NM
- 240KIAS at 40NM
- 140KIAS at 0NM

This speed profile was formulated as a reasonable approximation of the published speed constraints and standard operating procedures at PHX. In between the speeds are interpolated. The following approach is used to compute the ETA along each route:

- Convert IAS to True Airspeed at Waypoints
- Interpolate for True Airspeed as a Function of Path Length between Waypoints
- Discretize Path at 3nmi Interval
- Get Winds at 3nmi Intervals. Three wind scenarios are considered:
    - Zero Wind
    - RUC Forecast Wind
    - Spatio-temporally correlated wind
- Compute Ground Speed at 3nmi Intervals
- Compute Transit-Time Over 3nmi Intervals Using

The ETA corresponding to Zero Wind scenario is represented as $ETA_{zerowind}$, the ETA corresponding to RUC forecast wind is represented as $ETA_{RUCforecast}$.

B. Wind Magnitude Metric (WMM)

The purpose of the WMM is to characterize the nominal strength of the wind, irrespective of the accuracy of the forecast. It is expected that winds affect the ETA; therefore, the stronger the wind the bigger the difference between the $ETA_{zerowind}$ and $TA_{RUCforecast}$. The difference however would be different for each route. It could make flights on some routes travel faster and flights on the opposite routes travel slower. For this work a scalar metric that encompasses all the routes is sought. The following definition satisfies the above requirements and can be applied to arbitrary number of STARs, fixes, runways:

$$WMM = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|ETA_{zerowind\_i} - ETA_{RUCforecast\_i}\right|}{ETA_{zerowind\_i}} \tag{1}$$

where n is the number of route combinations. The absolute value of the numerator prevents cancellation of wind effects on opposite routes; the normalization with the denominator treats variations along short and long routes appropriately; and the average over the number of routes prevents the expression from assuming very large values for large number of routes. The WMM could be interpreted as follows: It is the average percentage variation of ETA with respect to the zero wind ETA for a given set of STARs and runway configuration.

C. Wind Uncertainty Metrics (WUMs)

Though the WMM is computed using a wind forecast product such as RUC, it is expected to be invariant to the wind forecast product. It is expected that all wind forecast products respond to large scale changes in weather patterns. The WUM on the other hand characterizes accuracy of the wind forecast products in terms of ETA. Again, a scalar metric that encompasses all the routes is sought. Two different metrics are adopted in the current research. These metrics are based on n ETA Monte-Carlo simulations (each consisting of 5000 runs) conducted one along each route. The WUMs are based on the statistics of the ETA distributions obtained from these Monte-Carlo simulations. The ETA variation in each Monte-Carlo simulation is used as a measure of the wind uncertainty. The variation is characterized using two different approaches: (i) 90 percentile interquartile range, and (ii) standard deviation. The former is better suited for all distributions, whereas the latter is better suited for normal distributions. The WUM definitions are given below:

$$WUM_{90percentile} = \frac{1}{n}\sum_{i=1}^{n} \frac{\left|ETA_{95Percentile\_i} - ETA_{5Percentile\_i}\right|}{ETA_{zerowind\_i}} \tag{2}$$

$$WUM_{STD} = \frac{1}{n}\sum_{i=1}^{n} \frac{ETA_{STD\_i}}{ETA_{zerowind\_i}} \tag{3}$$

V. Results

Results obtained from analyzing the RUC-40 and ACARS data for the entire year of 2011 around PHX are presented in this section.

A. Variation of Wind Uncertainty with Altitude

Figure 3 shows the variation of North and East wind forecast errors as a function of altitude.

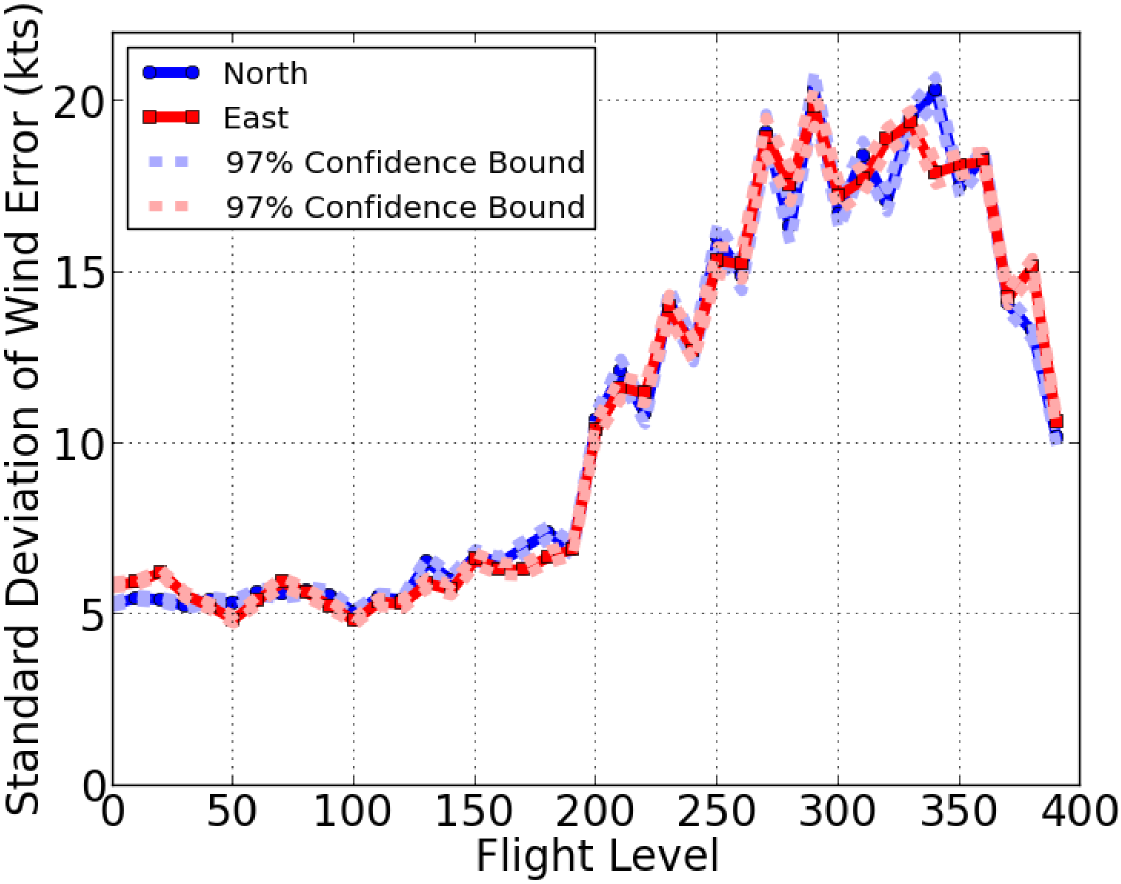

Figure 3. Variation of RUC-40 Wind Errors with Altitude

B. Spatio-Temporal Correlation in Wind Errors

At a given altitude, the standard deviation of North and East wind forecast errors at two spatially and temporally separated locations and time instants, is found to be correlated. From a physical perspective this is expected since the wind error at the same location is expected to change gradually over time, due to changes in prevailing wind. Furthermore, without spatial correlation an aircraft along a given path could experience unrealistic wind patterns such as a strong head wind immediately followed by a strong tail wind.

An example of the correlation coefficient variation with respect to relative distance and time is shown in Figure 4. A strong correlation with respect to time is found at the same physical location (relative distance = 0 nmi). The correlation with respect to relative distance at the same time (relative time = 0 min) is found to decrease exponentially. An interesting feature is the appearance of a ‘ridge’ of strong correlation along a line of relative distance / relative time. This is currently under investigation. A possible cause is the availability of ACARS data along specific approach path in the TRACON, instead of a larger, generic area.

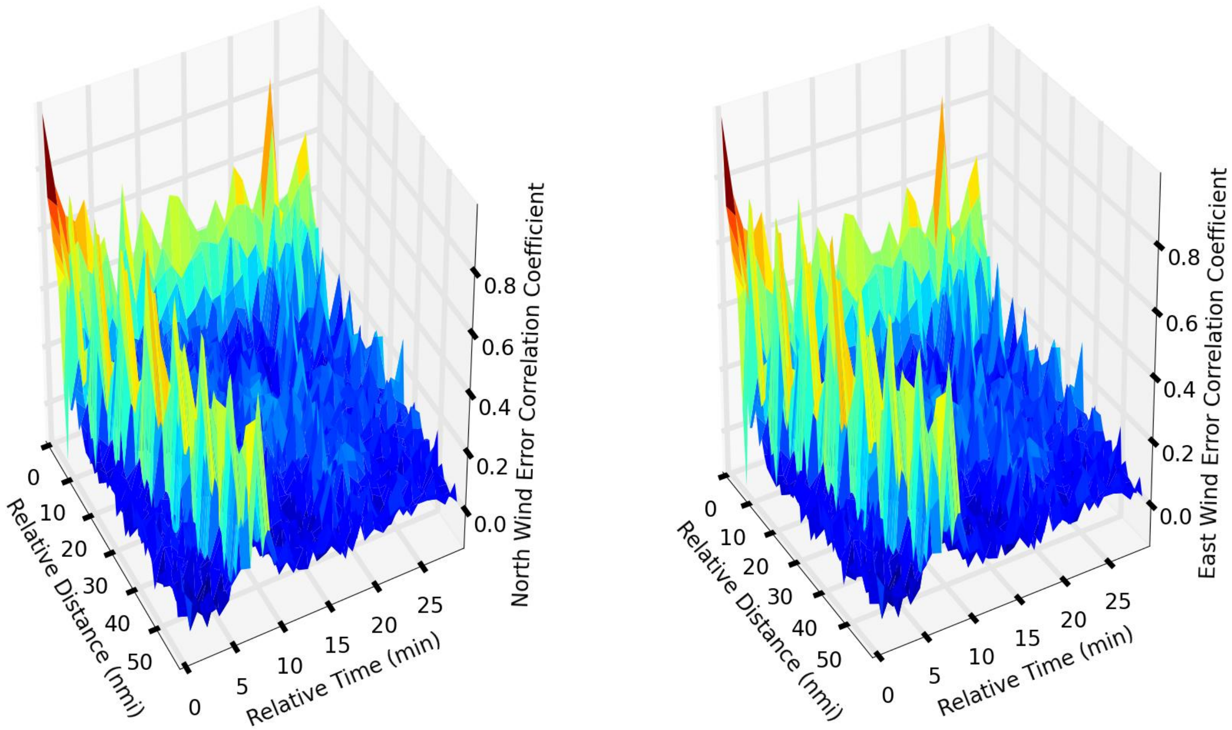

Figure 4. Spatio-Temporal Correlation of North and Wind Errors

C. Seasonal Variation of Wind Errors

Figure 5 and Figure 6 show the seasonal variation of wind errors as a function of the day of the year and altitude. The plots show that the wind forecast errors are minimum during the months of the July-September. On the other hand they seem to assume very large values during the months of January, February, April, and December.

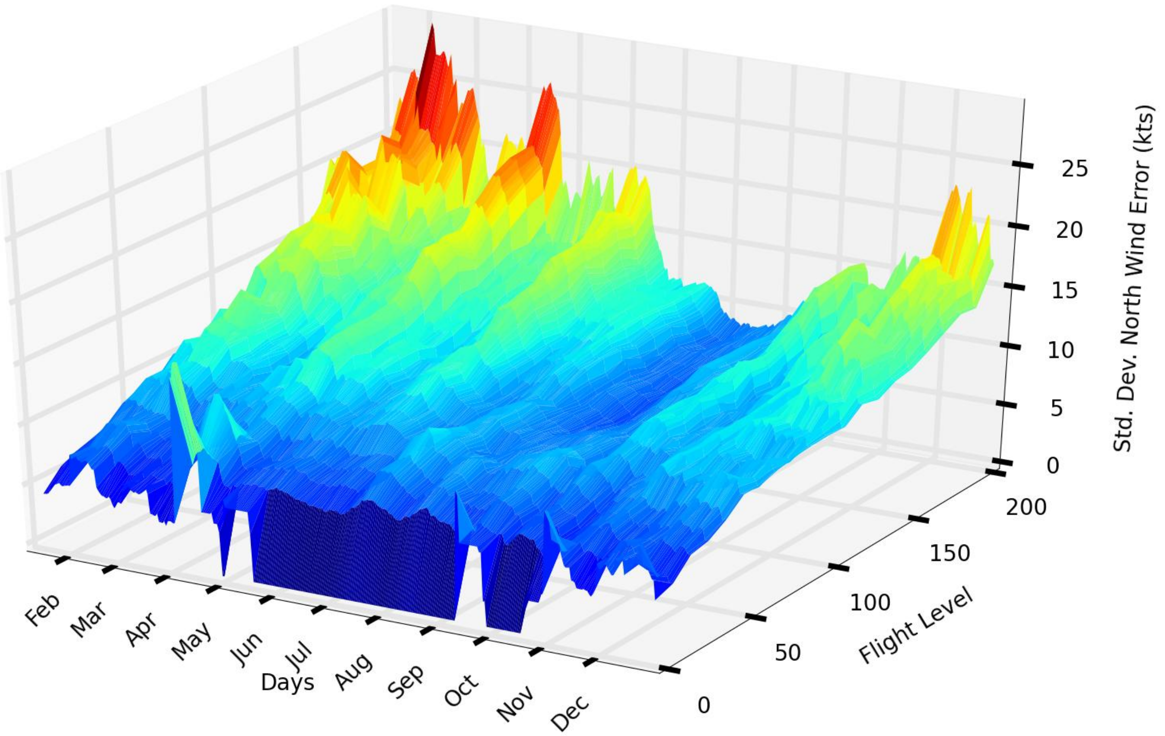

Figure 5. Seasonal Variation of North Wind Forecast Errors at PHX

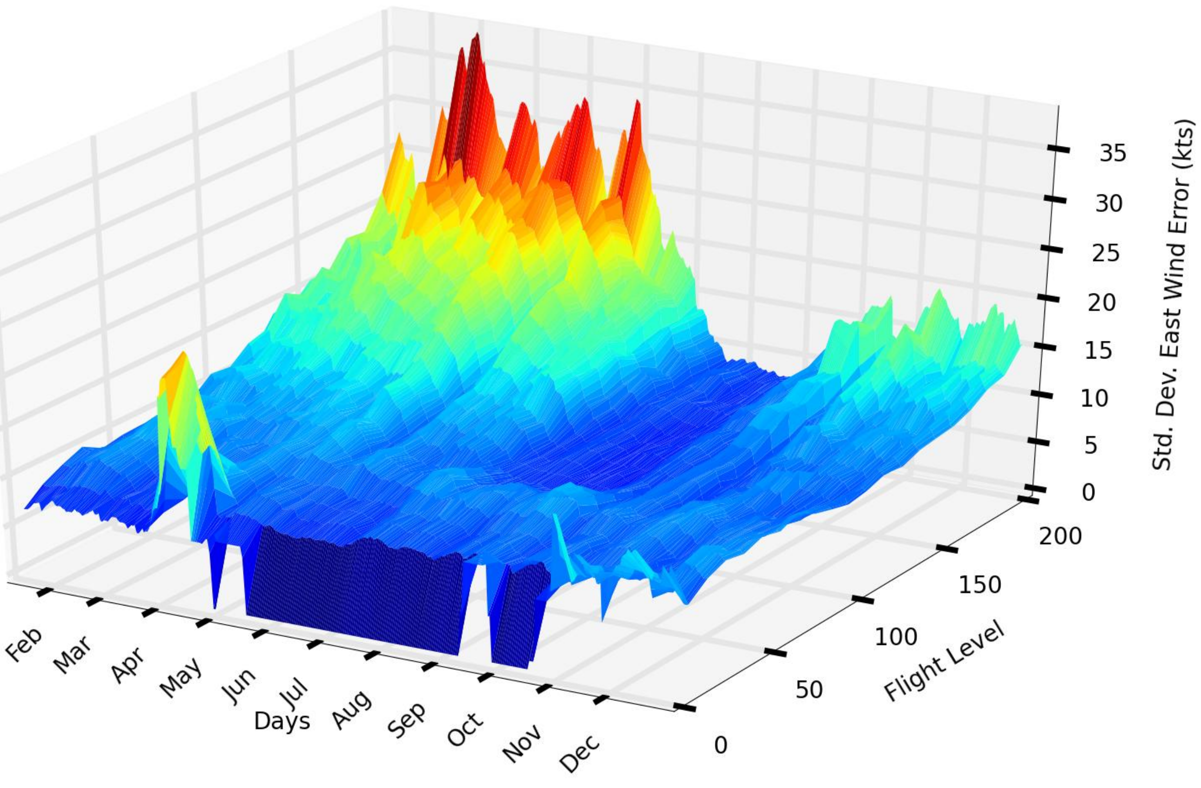

Figure 6. Seasonal Variation of East Wind Forecast Errors at PHX

D. ETA Variation Along PHX Routes

Figure 7 shows the result of a 5000 run Monte-Carlo simulation conducted using the RUC forecast corresponding to 01/17/2011, 6:00AM along the EAGUL5 route from the GUP fix to PHX Runway 08. The difference between the blue line and the red line is a measure of the wind magnitude. The spread of the cyan colored histogram is a measure of the wind uncertainty.

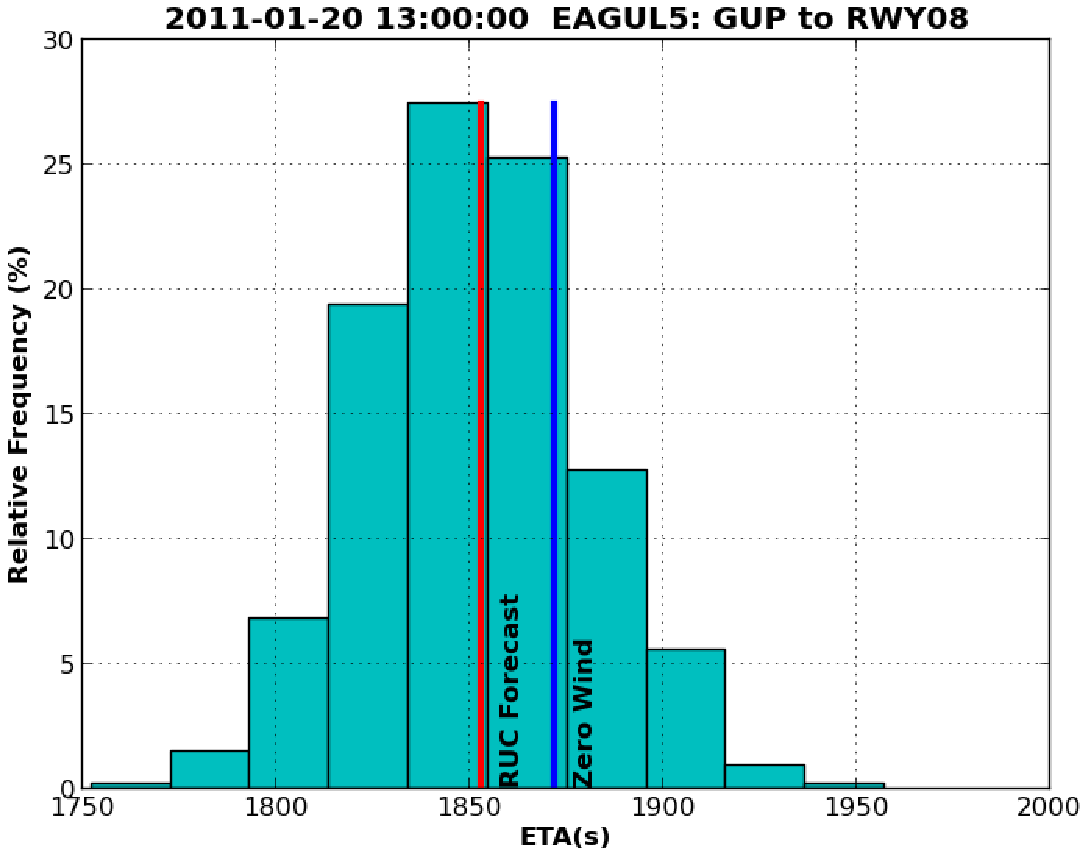

Figure 7. **Figure 7. ETA Variation Along EAGUL5 Route from GUP to PHX Runway 08**

E. Seasonal Variation of Wind Magnitude Metric

Figure 8 shows the seasonal variation of the WMM. The time series clearly shows both high frequency oscillations and low frequency variations. It indicates that the months of July-August as the ones with the lowest effect on ETA.

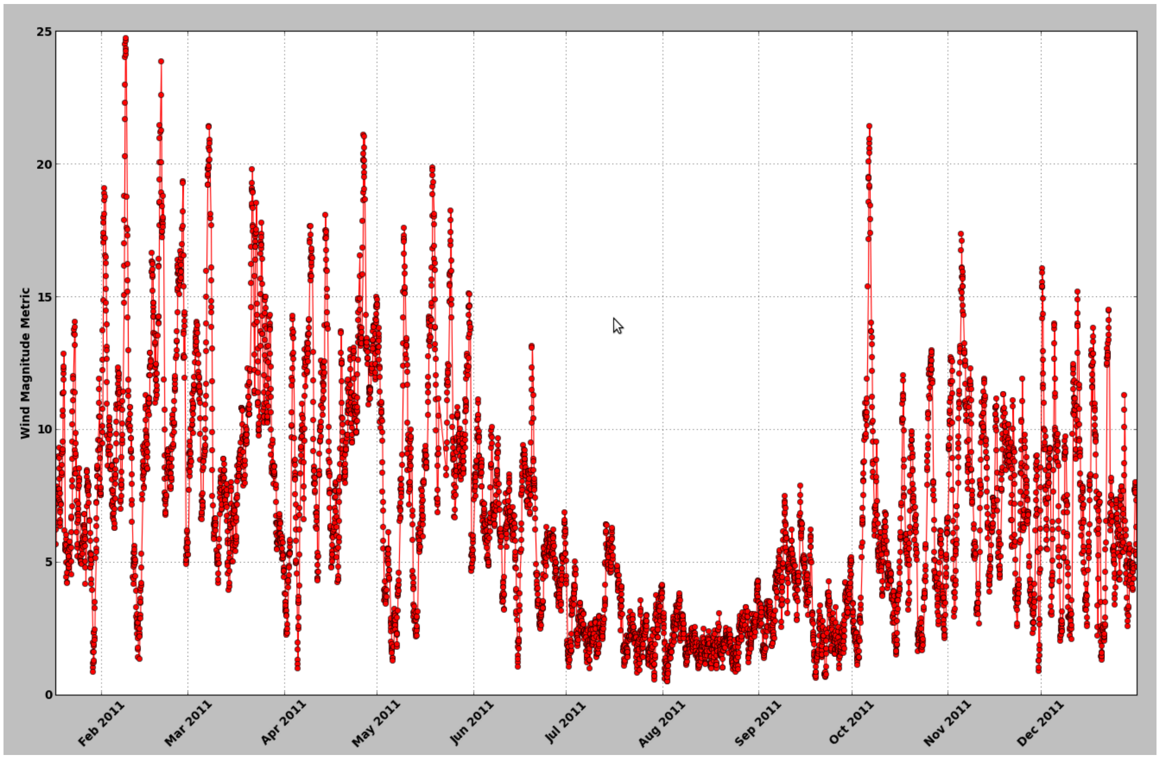

Figure 8. Seasonal Variation of Wind Magnitude Metric

F. Seasonal Variation of Wind Uncertainty Metric

Figure 9 and Figure 10 shows the seasonal variation of the WUMs based on STD and 90percentile respectively. The time series clearly shows both high frequency oscillations and low frequency variations. It indicates that the months of July-August as the ones with the lowest wind uncertainty.

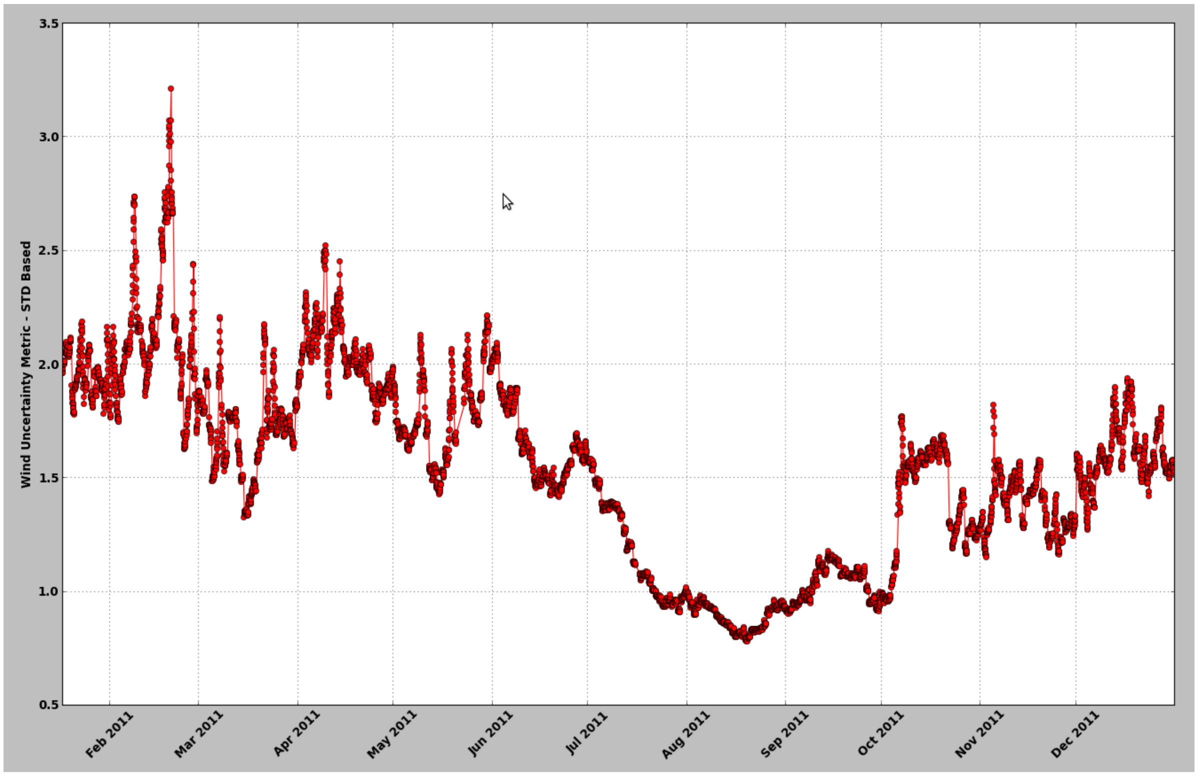

Figure 9. Seasonal Variation of Wind Uncertainty Based on STD Metric

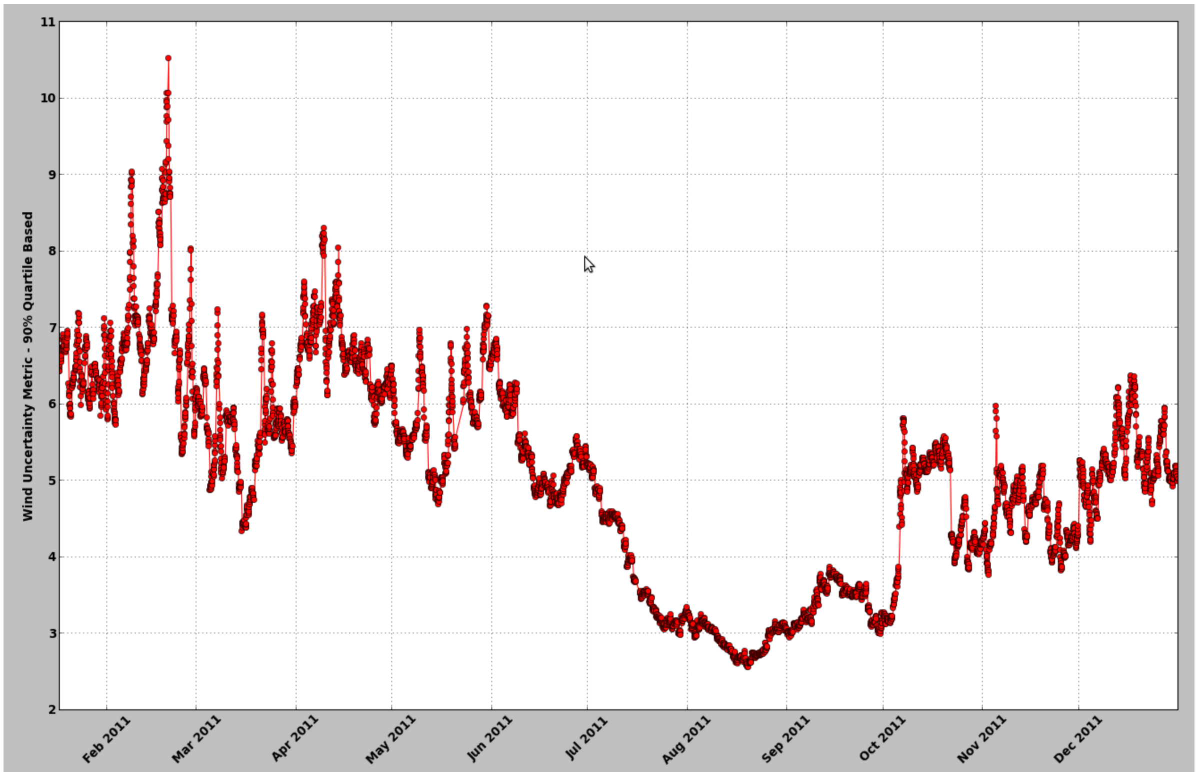

Figure 10. Seasonal Variation of Wind Uncertainty Based on 90 Percentile Metric

Conclusions

The current paper studies the effect of wind uncertainty resulting from forecast errors on the expected times of arrival. The work specifically focuses on the PHX airport, RUC-40 wind forecast product, and the year 2011. It can be concluded from the results of this paper that the wind forecast errors are: (i) dependent on the altitude, (ii) spatio-temporally correlated, and (iii) dependent on the month of the year. The wind magnitudes can cause ETA variations up to 25% when compared to the ETAs with zero wind. The wind uncertainty resulting from forecast errors can cause ETA variations up to 10% when compared to the ETA with zero wind errors. The work serves as a formal basis for evaluating the effect of wind uncertainty in evaluating NextGen concepts.

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