A STATISTICAL ANALYSIS OF APPROACH WINDS AT CAPACITY-RESTRICTED AIRPORTS *

Glenn H. Perras
Timothy J. Dasey
Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02420-9185

Introduction

Many major airports in the U.S. rely on simultaneous approaches to closely-spaced parallel (CSP) runways to maintain a high airport acceptance rate. During Visual Meteorological Conditions (VMC), aircraft are able to utilize both runways by making side-by-side landings and are able to meet the demands of heavy volume. However, when conditions deteriorate to marginal-VMC or Instrument Meteorological Conditions (IMC), side-by-side approaches are not possible due to the inherent safety concerns associated with lowered ceilings and visibilities. This situation is severely limiting to an airport's capacity and can create large delays and increased costs. Various ideas have been suggested that would facilitate the simultaneous use of CSP runways during low ceiling and visibility (LCV) conditions at capacity-restricted airports.

This report addresses the specific scenario of a pair of approaching aircraft being staggered by some longitudinal distance. This situation alleviates the collision hazard presented by LCV conditions, but also introduces the hazard of a wake vortex encounter, particularly if the following aircraft is downwind of the leading aircraft. This situation is illustrated in Figure 1.
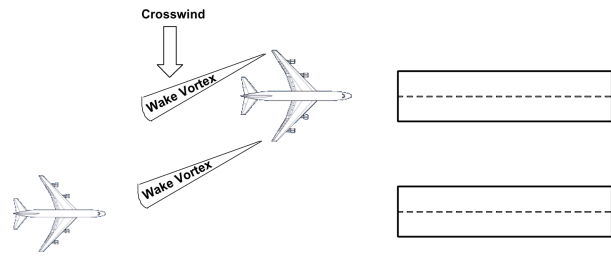

Figure 1. Wake turbulence encounters are possible in parallel approaches.

Since ambient wind speed and direction are the most important factors when considering the possibility of a lateral wake vortex encounter, wind behavior around airports with CSP runways needs to be well understood before simultaneous approaches during restrictive weather could ever be used in an operational setting.

This paper presents a statistical analysis of wind behavior for several major airports with CSP runways by using aircraft wind observations. Specifically, speed and direction characteristics of headwinds and crosswinds are examined, as well as correlations between the two wind components with respect to each other and with respect to altitude. The resulting data should prove useful for Monte Carlo simulations of new CSP approach procedures.

For this study, there were six major airports of particular interest. They were San Francisco (SFO), Newark (EWR), Philadelphia (PHL), Seattle (SEA), Boston (BOS), and St. Louis (STL). These airports are useful to study because they all have CSP runways that severely restrict capacity during LCV conditions. All of these airports could benefit greatly from an operational, simultaneous-approach procedure. Unfortunately, there were not enough data available for STL to

produce meaningful statistics, so the results were excluded from this report.

Table 1 summarizes several important factors when considering the possible benefit of a simultaneous approach procedure for the airports of interest. The number of annual operations and average rate of delay were obtained from the Federal Aviation Administration [1]. The %LCV refers to the percentage of time that the airport experiences cloud ceilings lower than 4500 feet and visibilities less than 7 miles as reported by hourly surface observations produced by the National Weather Service.

Table 1. Airport Runway and Delay Statistics

Airport	Parallel Runways	Sepa-ration (ft.)	1999 Annual Ops.	1999 Delay/ 1000 Ops.	% LCV
SFO	28R/28L	751	441,606	48.0	26.51
BOS	4L/4R	1495	502,822	29.8	24.95
EWR	22L/22R	948	463,000	78.9	22.47
PHL	27L/27R	1401	480,279	30.2	26.30
SEA	16L/16R	797	433,832	18.4	34.20

MDCRS Data Processing and Analysis Techniques

MDCRS Background Information

Due to their relative spatial and temporal density compared to any other available data source near the ground, wind observations from the Meteorological Data Collection and Reporting System (MDCRS) are a resource for producing statistical results for wind behavior over a given airport for lower altitudes. MDCRS is the only source of routine wind information above the surface at all of these airports. These data are what were used for the airports included in this study.

Nearly 50,000 MDCRS observations are provided by commercial aircraft every day over the U.S. [2]. These observations are relayed to the ground via the Aircraft Communications, Addressing, and Reporting System (ACARS), which is operated by Aeronautical Radio, Inc. (ARINC). These data are also processed, quality-controlled, and archived at the Forecast System Laboratory (FSL) [3].

The variables recorded in each MDCRS observation are latitude, longitude, altitude, time, temperature, wind direction, and wind speed. The wind observations are determined by the difference between the motion vector of the aircraft with respect to the earth, provided by the onboard inertial navigation system (INS), and the motion vector of the aircraft with respect to the air. This vector is calculated from the total airspeed measurement and heading measurement [3]. Observations are made roughly every five to six minutes at cruising altitudes and often more frequently at lower altitudes, especially during take-off [2].

MDCRS wind observations are considered to be fairly accurate when compared to other data sources. In a MDCRS versus rawindsonde collocation study [4], an rms vector difference of 3.8 m/s was reported. Much of this can be accounted for by a small sampling period relative to the mean wind and by wind variability. In an ACARS-only collocation study [3], an rms vector error of 1.8 m/s was reported.

MDCRS Variables

From the national database of MDCRS observations provided by FSL, a three-year span of reports were used for this study—from January 1997 through December 1999. The following variables were used:

- Latitude/longitude (hundredths of degree)
- Time (nearest minute)
- Pressure (tenth of millibar, converted from kPa)
- Altitude (tenths of meter)
- Wind direction (nearest degree true-north)
- Wind speed (hundredth of meter/second, converted to knots)

Observations that were flagged as erroneous by the quality-control procedures run by FSL were not used in this study.

MDCRS Altitude Correction

The altitudes reported by MDCRS observations assume a standard atmosphere between the ground and the aircraft pressure level.

This can introduce significant errors in altitude readings since the atmosphere rarely matches all standard conditions. In an effort to compensate for this error, hourly surface observations recorded by the National Weather Service (NWS) at each of the airports in this study were used to replace the standard assumed values with measured values. The recorded surface pressure and ambient temperature were used in conjunction with the MDCRS pressure at flight level to recalculate a more accurate altitude using the hydrostatic equation.

Hourly wind observations were not always available to correct the MDCRS altitudes. In these cases, the altitudes were simply left as reported. This could potentially introduce some error into the results where wind observations with uncorrected altitudes are being compared with observations that were corrected. However, since only relatively low altitudes were of interest in this study, the difference between corrected and uncorrected altitudes is not very large. One millibar of pressure difference would lead to an average altitude error of around 5.5 feet. Observed surface pressures rarely exceed 40 millibars above or below the standard atmospheric pressure.

Headwind and Crosswind Calculation

The next step towards making the MDCRS wind data more useful was to break the wind vectors into positive and negative headwind and crosswind components. A positive headwind is simply the conventional headwind. A tailwind originates from the negative direction. A positive crosswind refers to a wind originating from the right of the aircraft and a negative crosswind is from the left. All components were calculated with respect to the true-north heading of the most frequently used configuration for the parallel runways of interest at each airport. However, since runway configurations can shift frequently due to changing wind directions, the headwind and crosswind statistics generated for each airport are valid only for the specified configuration. It is understood that the presence of moderate or strong tailwinds would indicate the use of a different runway configuration, but the statistics generated are helpful in determining how often the specific configuration of interest is employed.

Altitude and Position Restrictions

MDCRS observations taken at or below 5000 feet above ground level were used in this study. The data were grouped into bins of 1000 feet to ensure that there would be enough observations in each layer to generate meaningful statistics. Also, in an effort to ensure a sufficient amount of data, wind observations taken within 1 degree latitude and 1 degree longitude from the airport of interest were included in the data set. This led to the inclusion of some observations from aircraft which were operating at other nearby airports, but it was determined that this had very little impact on the results.

Even using these liberal methods of data acceptance, some of the airports of interest yielded a relatively small amount of data considering the three-year sample that was used. The smaller amounts of data are most likely due to a lack of flights into and out of the airport by airlines participating in the MDCRS observation effort.

Exceedance Probability

The first parameter calculated for each wind component was the probability that either the headwind or crosswind would exceed a particular value at any given time, hereafter referred to as exceedance probability. These values were calculated by dividing the number of observations that exceed the given value by the total number of observations. Exceedance probabilities were calculated for headwind and crosswind speeds for one-knot intervals in a range spanning from –20 to +20 knots. It must be noted that the probabilities calculated for the negative values of the range represent an observation exceeding that value in magnitude in the negative direction (i.e., a stronger tailwind or negative crosswind).

Probabilities were also calculated from wind observations taken strictly during LCV times. As previously noted, LCV is defined to be cloud ceilings less than 4500 feet and/or visibilities less than 7 miles. The presence of these conditions was determined by using the NWS hourly surface observations. The exceedance probability values are very useful in determining general characteristics of wind behavior at each of the airports.

Headwind and Crosswind Comparisons

To assess the dependence between headwind and crosswind values, probabilites were determined for all possible headwind and crosswind pairings over a range from –20 knots to +20 knots for each wind component. Plots were made which displayed the probability of each possible pairing over the entire data set. Conditional probabilities for each headwind and crosswind pair were also computed and the results were plotted. To further quantify the results of all these plots, correlation coefficients were calculated between the headwind and crosswind values for each airport.

Headwinds and Crosswinds with Altitude

Hourly means of both headwind and crosswind values from each 1000-foot layer were computed to compare the correlation of winds with altitude. The hourly means were used in order to minimize the influence of wind variability.

In this study, adjacent altitude layers were compared to determine headwind or crosswind relationships with respect to altitude. Conditional probabilities for each headwind and crosswind pair between adjacent altitude layers were computed and plots were created to illustrate the results. Correlation coefficients were also calculated from these data.

Wind Analysis Results

Exceedance Probability Results

Although results were generated for several airports, only those for SFO will be presented in this report. The author may be contacted if results from other airports are desired.

Figure 2 shows headwind exceedance probabilities for the entire SFO data set. It can be easily seen that there is a high probability of experiencing a strong positive headwind when landing on runways 28R or 28L. There also tends to be little directional or speed shear with altitude as shown by the similarity between each 1000-foot layer. The results for LCV times are presented in Figure 3 and show very few differences from Figure 2. The one exception is that a little more

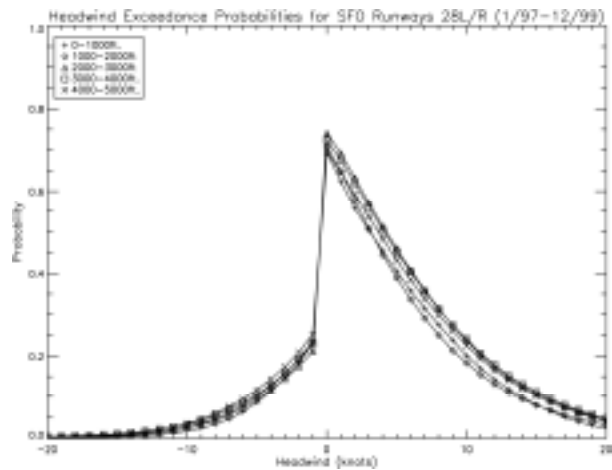shear with altitude seems possible since the probabilities between layers are a bit more widely-spaced.

Figure 2. Headwind Exceedance Probabilites for SFO.
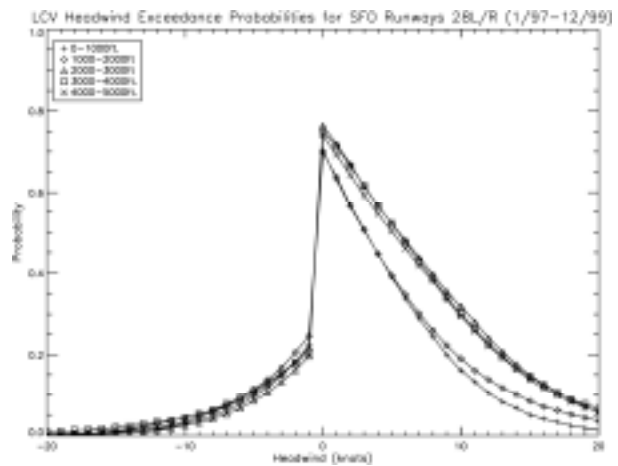

Figure 3. LCV Headwind Exceedance Probabilities for SFO.

Figure 4 shows a nearly equal distribution of positive and negative crosswind probabilities during all weather conditions at SFO. Crosswinds also look to be light in either direction given the steep decline in probability values with increasing wind magnitude. During LCV times in Figure 5, there tends to be a higher probability of negative crosswinds than during all conditions.
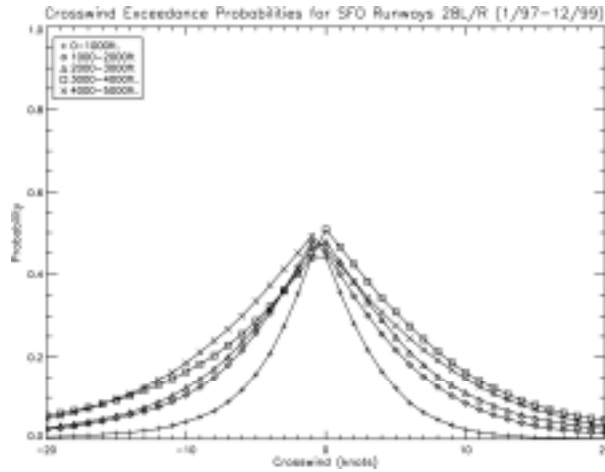
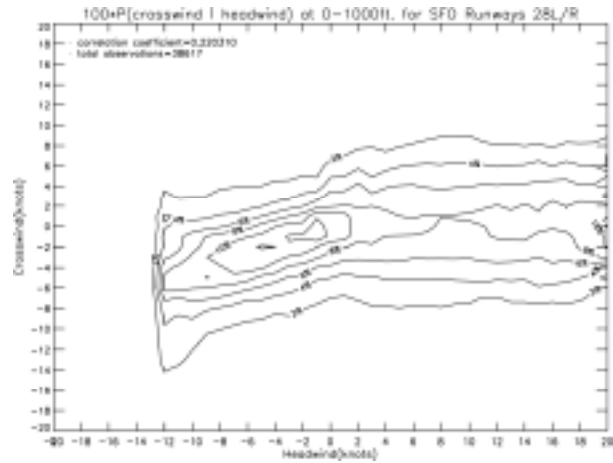**Figure 4. Crosswind Exceedance Probabilities for SFO.**

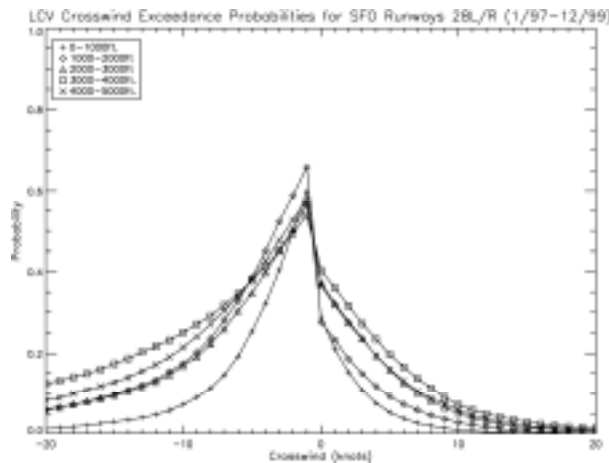**Figure 6. Conditional Crosswind Probabilites for SFO.**

Figure 5. LCV Crosswind Exceedance Probabilites for SFO.

Table 2. Correlation Coefficients Between Headwind and Crosswind Values

Airport	r 0-1000 ft.	r 1000-2000 ft.	r 2000-3000 ft.	r 3000-4000 ft	r 4000-5000 ft.
SFO	0.22	0.12	0.06	0.14	0.12
BOS	-0.10	-0.07	-0.04	-0.05	-0.01
EWR	-0.08	-0.06	-0.08	-0.03	0.02
PHL	-0.10	-0.03	0.01	-0.01	-0.01
SEA	0.09	0.43	0.45	0.38	0.34

Correlation Results

Headwind and Crosswind Comparison

In an effort to determine the relationship between headwind and crosswind components from given wind observations, contour plots were created that show the conditional probability values of each possible headwind/crosswind pair in a range from +20 to –20 knots. These plots were done for each 1000-foot layer up to 5000 feet. An example from SFO can be seen in Figure 6. The correlation coefficient(r) results between headwinds and crosswinds for each airport are summarized in Table 2.

These results show that there seems to be very little correlation between simultaneous headwind and crosswind components. However, there are some noticeable exceptions at SEA and SFO. At SEA, significantly larger correlation values are seen in all layers above 1000 feet than at any of the other airports. At SFO, the correlation coefficient value of 0.22 in the surface layer is more than twice as large as any other surface layer value for any of the other airports. However, these larger values seen at SFO and SEA are still not representative of a strong correlation.

The absence of a strong correlation between headwinds and crosswinds at each of the airports is very important when considering the use of a simulation model. Headwind and crosswind values used in any simulation may be considered independent of one another since there is very little relationship between them.

Headwinds and Crosswinds with Altitude

When determining a level of correlation between headwinds or crosswinds from adjacent altitude layers, the results are much different than when comparing headwinds and crosswinds. Figure 7 shows an example of the plots made which compare hourly mean crosswind values for adjacent altitude layers. Table 3 summarizes the correlation coefficient values calculated from the crosswind data, and Table 4 presents the results for headwinds. The headings for the columns of coefficient values in each table contain numbers representing the particular altitude layers that were compared. The layer numbers are as follows:

- 0 = 0-1000 feet
- 1 = 1000-2000 feet
- 2 = 2000-3000 feet
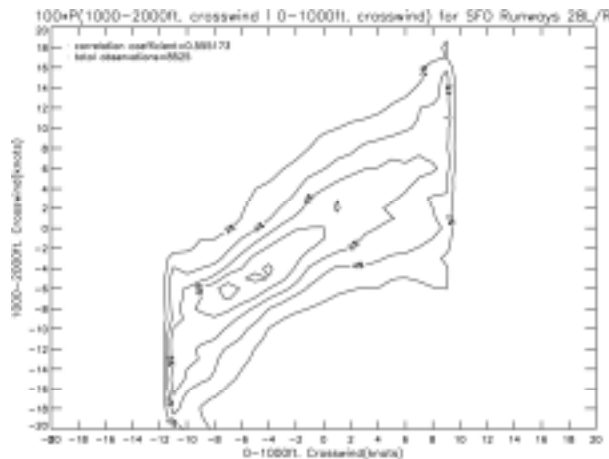- 3 = 3000-4000 feet
- 4 = 4000-5000 feet

**Figure 7. Conditional Probabilities
for Crosswinds with Altitude at SFO.**

**Table 3. Correlation Coefficients
for Crosswinds with Altitude**

Airport	r (0-1)	r (1-2)	r (2-3)	r (3-4)
SFO	0.56	0.76	0.75	0.85
BOS	0.68	0.79	0.78	0.75
EWR	0.78	0.84	0.81	0.81
PHL	0.77	0.85	0.83	0.83
SEA	0.52	0.80	0.74	0.76

It can be seen from the results of each table that there is a reasonably strong correlation between both crosswinds with altitude and headwinds with altitude at all the airports of interest. There is a noticeably weaker correlation near the surface, especially at SFO and SEA in the crosswind data. This may indicate an outside influence on winds in the lower levels, such as the local topography and its associated frictional force.

**Table 4. Correlation Coefficients
for Headwinds with Altitude**

Airport	r (0-1)	r (1-2)	r (2-3)	r (3-4)
SFO	0.65	0.69	0.77	0.80
BOS	0.72	0.83	0.76	0.80
EWR	0.75	0.83	0.83	0.83
PHL	0.80	0.85	0.81	0.81
SEA	0.80	0.86	0.77	0.81

When considering the use of a simulation model to create wind profiles along an approach path, the strong relationship between the wind components with altitude must be accounted for. In choosing a simulated headwind or crosswind value for a particular altitude, the values for subsequent altitudes must follow the relationship established by the correlation results. The values are not independent of one another.

Critical-Crosswind Results

When considering the use of simultaneous CSP approaches, a minimum crosswind value can be calculated which would transport the wake of a leading aircraft into the flight path of a trailing aircraft. The variables needed to make this calculation are the distance between the parallel runways, the spacing between the pair of landing aircraft, the average approach speed of each aircraft, and the wing spans of each aircraft. An average critical-crosswind value was calculated for each airport, assuming a 1 nautical-mile spacing between aircraft, average approach speeds of 130 knots, and wing spans of 33 meters, which matches that of a Boeing 727. The results of these calculations are summarized in Table 5. The exceedance probability values in Table 5 refer to the probability that the critical-crosswind will be exceeded anywhere from the surface up to 5000 feet at any given time. The LCV exceedance probabilities were calculated from wind observations taken exclusively during LCV conditions. These numbers are valuable in approximating how often a simultaneous CSP

approach system could be used safely at each airport.

Table 5. Exceedance Probability Values for Critical Crosswind

Airport	Critical Crosswind (knots)	Exceedance Probability	LCV Exceedance Probability
SFO	14	0.13	0.13
BOS	30	0.06	0.05
EWR	18	0.21	0.18
PHL	28	0.05	0.06
SEA	15	0.12	0.17

The results of Table 5 are approximations for the purpose of showing the use of the crosswind statistics. Based on these approximations, a CSP approach procedure would be safe to implement the vast majority of the time at every airport studied. However, exact benefit would require a more rigorous model of the procedure. In some cases, it is clear from Table 5 that the runway configurations that were analyzed would not even be used during times of such high crosswinds.

Discussion

MDCRS observations are a very valuable data source for producing statistical analyses of wind behavior over airports. The data are temporally and spatially much more dense than any other near-ground data available. The statistics generated by the analyses performed in this study should prove very helpful to the modeling effort in support of a CSP approach procedure at any of the selected capacity-restricted airports.

The airports that were studied showed similar general qualities in wind behavior, but each had some traits specific to the airport that would be important to include in any modeling effort. All airports showed a strong correlation between both headwinds with altitude and crosswinds with altitude. However, there was very little correlation between headwind and crosswind components taken from the same wind observation.

The exceedance probability statistics generated for both headwinds and crosswinds at each airport are very useful in developing a general sense of wind behavior with respect to parallel runways of interest at these airports.

General tendencies in strength and direction of each wind component with altitude can be determined by examining the plots provided.

Based on the results from this study, the following steps should be used in constructing wind profiles for procedural or benefits models:

- Choose a crosswind surface value for a particular airport by using the crosswind probability distribution provided.
- Use the conditional probability distribution results to choose crosswinds at higher altitudes.
- Repeat steps 1 and 2 for headwinds.

When comparing the statistics generated exclusively for LCV times, some differences in wind behavior can be seen for all the airports studied. However, the differences are usually not very large. Future work may include gathering more MDCRS wind observations to increase the total amount of LCV observations. This will ensure that the results represent a longer-term climatological average.

Although MDCRS observations are a valuable resource due to their temporal and spatial availability, they are not an ideal data source due to their need for altitude correction, their seemingly random nature, and their lack of time-averaging in the measurements. An appropriate future study should evaluate the use of pencil-beam Doppler radars (EWR, BOS TDWRs) for a more robust estimate of mean approach wind statistics.

References

[1] Federal Aviation Administration Web Site, 2000, http://www.faa.gov/newsinfo.htm

[2] Forecast System Laboratory Web Site, 2000: http://acweb.fsl.noaa.gov/FAQ.html

[3] Benjamin, Stanley G., Barry E. Schwartz, Rodney E. Cole, 1999, "Accuracy of ACARS Wind and Temperature Observations Determined by Collocation." *Weather Forecasting*, 14, pp.1032-1038.

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