U.S. Department
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Summary Results from Long-Term Wake Turbulence Measurements at San Francisco International Airport

July 2004

The data processing details as well many of the analyses results shown herein are very specific to the SFO SOIA Concept development. In particular, there is increasing evidence that the NGE/IGE wake transport and decay characteristics from 28R to 28L are affected by sea-air interface, whereas transport and decay from 28L to 28R are more consistent with the previous measurements under similar range of aircraft altitude and aircraft sizes in an urban environment. The results presented here combined all the transport data from both runways and would therefore represent a conservative analysis for SFO SOIA. On the data processing side, parameters have been optimized to minimize false tracks within the SFO SOIA time frame of interest. Within these factors, additional data analysis were performed beyond the present report to better match the wind, ceiling and procedure details in SFO SOIA, and those results have not been reflected in this summary report, which presents more of a global view of the data collected. Consequently, the data shown in this report should not be generalized to other wake turbulence concepts without the proper understanding of these details.

February 28, 2010

For Further Information, Please Contact Either FAA Wake Turbulence Program or USDOT Volpe Center

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16. Abstract

This report summarizes the results of an extensive wake turbulence data collection program at the San Francisco International Airport (SFO). Most of the landings at SFO are conducted on closely spaced parallel runways that are spaced 750 feet between centerlines (runways 28R and 28L). The purpose of the measurement program was to provide data to support the safety assessment of future enhancements to the Simultaneous Offset Instrument Approach procedure that permits continued use of both runways in deteriorating weather. The data collection was focused on wake behavior in the critical near-ground region where a wake encounter might be most hazardous. Limited measurements were also made at a glide slope altitude of about 530 feet to confirm prior results.

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Executive Summary

This report summarizes the results of an extensive wake turbulence data collection program at the San Francisco International Airport (SFO). Most of the landings at SFO are conducted on closely spaced parallel runways (CSPRs) that are spaced 750 feet between centerlines (runways 28R and 28L). The purpose of the measurement program was to provide data to support the safety assessment of future enhancements to the Simultaneous Offset Instrument Approach (SOIA) procedure that permits continued use of both runways in deteriorating weather. The data collection was focused on wake behavior in the near-ground region where a wake encounter might be most hazardous. Limited measurements were also made at a glide slope altitude of about 530 feet to confirm prior results. The specific objective was to more accurately measure wake vortex behavior to refine FAA flight procedure development and analysis tools. These tools will be used to develop safety and procedural requirements for closely spaced parallel runway operations.

During the time period from March 2000 to October 2002, wake turbulence data were collected for over 0.26 million landing aircraft near the thresholds of Runways 28L and 28R where the glide slope height is approximately 65 feet. The wake turbulence data were taken over all seasons and all weather conditions, 24 hours per day, 7 days per week unless there was an operational problem with the equipment. The data set includes wake turbulence measurements from Small, Large, B-757, and Heavy category aircraft and represents the largest database for wake turbulence collected to date at any U.S. airport.

The SOIA procedure, as currently designed for SFO, will be used when the cross-runway component of the total wind is 10 knots or less. “SOIA conditions” at SFO typically occur in the morning or late evening and are often characterized by a fog or marine layer with low cloud ceilings and light surface winds. Stronger winds typically occur in the afternoon after the fog or marine layer has burned off and visibility and cloud ceiling conditions would support visual approach operations. Accordingly, the wake data were analyzed and categorized relative to the cross-runway component of the total wind, as measured by the Automated Surface Observing System (ASOS), to better correlate wake transport and decay times to conditions when SOIA operations would be conducted.

The vortex wake data support the conclusion that when the stagger between aircraft on adjacent approach courses is relatively small (approximately 1 nm for an approach speed of 130 kts), it is not possible for the wake from one aircraft to be blown by the wind into the path of the other aircraft quickly enough to create a hazard. The data are consistent with typical observed aircraft pairings during current SFO visual approach operations as well as proposed SOIA operations.

The data support the following general conclusions:

- Only a small fraction of wakes generated near the ground ever reach the adjacent runway under any conditions.

- Wake transport times are determined largely by the cross-runway component of the total wind, i.e., wakes consistently required longer to reach the adjacent runway during low cross-runway-component wind conditions.

- Wakes from Heavy category aircraft are more likely to reach the adjacent runway than wakes from smaller aircraft.

- Although the wake data for this report were collected exclusively at SFO, they have potentially broader applicability to other CSPR airports as well.

The data processing details as well many of the analyses results shown herein are very specific to the SFO SOIA Concept development. In particular, there is increasing evidence that the NGE/IGE wake transport and decay characteristics from 28R to 28L are affected by sea-air interface, whereas transport and decay from 28L to 28R are more consistent with the previous measurements under similar range of aircraft altitude and aircraft sizes in an urban environment. The results presented here combined all the transport data from both runways and would therefore represent a conservative analysis for SFO SOIA. On the data processing side, parameters have been optimized to minimize false tracks within the SFO SOIA time frame of interest. Within these factors, additional data analysis were performed beyond the present report to better match the wind, ceiling and procedure details in SFO SOIA, and those results have not been reflected in this summary report, which presents more of a global view of the data collected. Consequently, the data shown in this report should not be generalized to other wake turbulence concepts without the proper understanding of these details.

Foreword

The authors of this summary report integrated various draft writeups on the San Francisco wake turbulence tests. Drafts prepared by D. C. Burnham, F. Y. Wang, G. C. Greene, and D. P. Delisi were used to create this summary. The data retrieval efforts of M. Soares and H. Wassaf and discussions with J. Tittsworth are hereby acknowledged. The San Francisco test program yielded a wealth of data on the behavior of aircraft wake vortices near the ground and will be described in a comprehensive technical report. This summary report was prepared to document the results of the test program that contribute to the safety analysis of the proposed Simultaneous Offset Instrument Approach procedure.

This project could not have been successfully completed without the cooperation and help of several groups working at SFO. Particular thanks to Paul Candelaire, FAA Facilities Manager, and his group who helped establish connectivity from the test site trailer to the Air Traffic Control tower. Other groups and individuals who contributed to success include: Trig McCoy, Operations Manager; Dennis Reed, Operations Coordinator for Airfield Construction; Jim Chui and Hugo Tupac, Civil Engineering Facilities Operations & Maintenance; Scott Speers, Assistant Tower Chief; David Ong, Aircraft Noise Abatement Department; and Petullia Mandrell, FAA Airports District Office.

The data processing details as well many of the analyses results shown herein are very specific to the SFO SOIA Concept development. In particular, there is increasing evidence that the NGE/IGE wake transport and decay characteristics from 28R to 28L are affected by sea-air interface, whereas transport and decay from 28L to 28R are more consistent with the previous measurements under similar range of aircraft altitude and aircraft sizes in an urban environment. The results presented here combined all the transport data from both runways and would therefore represent a conservative analysis for SFO SOIA. On the data processing side, parameters have been optimized to minimize false tracks within the SFO SOIA time frame of interest. Within these factors, additional data analysis were performed beyond the present report to better match the wind, ceiling and procedure details in SFO SOIA, and those results have not been reflected in this summary report, which presents more of a global view of the data collected. Consequently, the data shown in this report should not be generalized to other wake turbulence concepts without the proper understanding of these details.

Table of Contents

List of Tables

List of Figures

Acronyms

AFS	Flight Standards Service
AGL	Above Ground Level
ASOS	Automated Surface Observing System
CSPR	Closely Spaced Parallel Runways
CW	Crosswind Component
DME	Distance Measuring Equipment
FAA	Federal Aviation Administration
GS	Glide Slope
HW	Headwind Component
IFR	Instrument Flight Rules
IGE	In Ground Effect
IMC	Instrument Meteorological Conditions
LDA	Localizer type Directional Aid
MAP	Missed Approach Point
OGE	Out of Ground Effect
SFO	San Francisco International Airport
SOIA	Simultaneous Offset Instrument Approach
TAMIS	Total Airport Management Information System
TERPS	Terminal Instrument Procedures
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WL	Windline

Introduction

Parallel runways spaced closer than 4300 feet between centerlines are termed closely spaced parallel runways or CSPRs. In good weather, airports routinely conduct simultaneous visual operations on CSPRs spaced as close as 700 feet apart. In bad weather, or poor visibility when visual operations are not possible, use of CSPRs less than 2500 feet apart is restricted to the equivalent of having a single runway. This effective reduction from two runways to one has a strong effect on air traffic delays at many of the busiest airports. The potential hazard of wake turbulence is one of the factors limiting the application of new technologies and procedures for all-weather use of CSPRs. Under some weather conditions, it is possible for the wake turbulence generated by an aircraft on one runway to be blown by the wind into the path of an aircraft approaching a nearby parallel runway.

The standard visual approach method for avoiding wake turbulence is to fly above the flight path of the preceding aircraft and avoid the region behind, below, and downwind. An equally effective method, which is appropriate for CSPRs, is to pair aircraft so that they are landing side-by-side or nearly so. In this case, it is not possible for the wake turbulence to be blown to the adjacent runway quickly enough to create a hazard for the other aircraft. Extending this side-by-side visual approach procedure for more general use requires a data driven assessment of the conditions under which wake turbulence will not pose a safety concern.

New procedures, such as SOIA (Simultaneous Offset Instrument Approach), are designed to allow the use of both runways in lower ceilings and visibility conditions than currently practiced. One of the constraints on implementing these new procedures is the possibility of an encounter with wake turbulence that may have been blown by the wind from the adjacent parallel runway.[1] Under most conditions, wake turbulence descends below the flight path of the aircraft that generated it and does not pose a hazard for following aircraft on the same glide slope or (depending on runway stagger) on nearby runways. However, near the ground, wakes can no longer descend and, therefore, may pose a greater likelihood of a wake encounter than at higher altitudes. In addition, a wake encounter near the ground may be more serious due to the lack of altitude for recovery. Therefore, an extensive database for wake turbulence behavior near the ground is required for a safety assessment of new CSPR procedures.

SOIA operational procedures have been designed to eliminate the possibility of such a wake encounter and to provide both enhanced safety and runway throughput. To assess the safety of the SOIA procedure, an extensive data collection effort was undertaken at San Francisco International Airport (SFO). During the time period from March 2000 to October 2002, wake turbulence data were collected for over 0.26 million landing aircraft near the thresholds of Runways 28L and 28R where the glide slope height is approximately 65 feet. These wake turbulence data were taken over all seasons and all weather conditions, 24 hours per day and 7 days per week, unless there was an operational problem with the equipment. The data set includes wake turbulence measurements from

Small, Large, B-757, and Heavy category aircraft and represents the largest database for wake turbulence ever collected at any U.S. airport.

FAA Flight Standards (AFS-420) conducted a safety analysis[2] of the SOIA procedure, as currently designed for SFO. A crosswind limit of 10 knots on the use of SOIA was introduced as an operational limit to keep an aircraft from overshooting the turn toward Runway 28R when the wind was blowing toward Runway 28L. Therefore, all of the results presented in this report are for the SOIA-procedure-imposed 10 knots or less operational limit on the cross-runway component of the wind (unless specifically stated otherwise).

The data processing details as well many of the analyses results shown herein are very specific to the SFO SOIA Concept development. In particular, there is increasing evidence that the NGE/IGE wake transport and decay characteristics from 28R to 28L are affected by sea-air interface, whereas transport and decay from 28L to 28R are more consistent with the previous measurements under similar range of aircraft altitude and aircraft sizes in an urban environment. The results presented here combined all the transport data from both runways and would therefore represent a conservative analysis for SFO SOIA. On the data processing side, parameters have been optimized to minimize false tracks within the SFO SOIA time frame of interest. Within these factors, additional data analysis were performed beyond the present report to better match the wind, ceiling and procedure details in SFO SOIA, and those results have not been reflected in this summary report, which presents more of a global view of the data collected. Consequently, the data shown in this report should not be generalized to other wake turbulence concepts without the proper understanding of these details.

The Problem

San Francisco International Airport (SFO) operates two perpendicular sets of closely-spaced parallel runways (CSPR). The centerlines of the runways are separated by 750 feet. An aerial photograph of the parallel runways at SFO is shown in Figure 1. More than 80 percent of the time, SFO uses Runways 28L and 28R for arrivals and Runways 1L and 1R for departures. Under visual meteorological conditions (VMC), maximum airport capacity is achieved by alternating paired arrivals on 28L/28R followed by paired departures on 1L/1R. Under instrument meteorological conditions (IMC), the SFO parallel runways are treated as a single runway and simultaneous operations are not permitted; therefore, airport capacity is effectively reduced by about a factor of two. Thus, when IMC prevail, SFO experiences substantial delays.

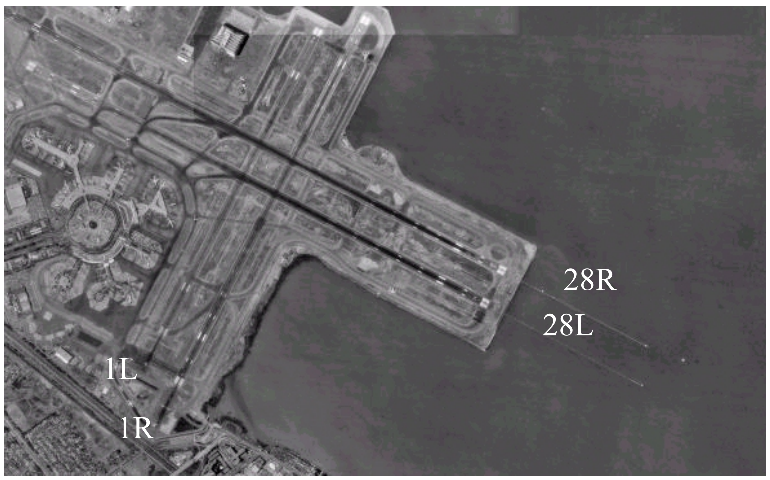


Figure 1. Aerial view of the SFO parallel runways
(Taken from United States Geological Survey).

The Proposed Solution

The means proposed for mitigating wake turbulence concerns during paired approaches to CSPR is different from that for single-runway operations. The safety of single-runway operations is ensured by imposing a sufficiently long longitudinal separation distance between consecutive arrivals for the wake turbulence from the lead aircraft to decay or depart the approach corridor. The safety of paired approaches to CSPR can be ensured by minimizing the longitudinal distance in the grouped aircraft pair. In so doing, the wake turbulence from the lead aircraft would not have sufficient time to drift laterally to the approach course of the trailing aircraft. Thus, knowledge of the lateral transport properties of wake turbulence is the determining factor. Of course, the longitudinal separation distance is still important between consecutive pairs of arrival aircraft.

The SOIA procedure was proposed as a means to recover some of the capacity lost during cloud cover and ceilings below 3500 feet. SOIA at SFO involves the installation of a Precision Runway Monitor coupled with a Localizer type Directional Aid (LDA) approach and a sidestep maneuver to Runway 28R under conditions of cloud cover below the practical visual approach ceiling of 3500 feet.

The SOIA paired-approach procedure is schematically depicted in Figure 2 and consists of the following steps:

1) The aircraft bound for Runway 28L makes a normal straight-in approach using glide slope and localizer guidance.
2) The aircraft bound for Runway 28R makes an LDA approach, also using glide slope and localizer guidance. The approach path is, however, angled out from the runway centerline by 2.5 degrees and reaches a distance of 3000 feet from the Runway 28L centerline at the Missed Approach Point (MAP) at 4.0 DME.
3) If the pilot approaching 28R can see the 28L bound aircraft and the ground before descending to the MAP, the pilot reports this and accepts a visual approach, performs an S-turn to align with Runway 28R after reaching the MAP, and proceeds for landing. Otherwise, the pilot must execute a missed approach.

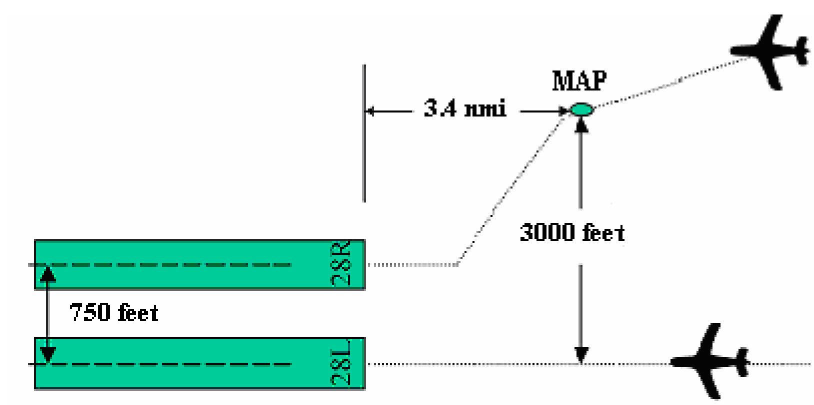


Figure 2. Schematic top view of the SOIA procedure at SFO.

Although the SOIA is similar to the standard visual paired approach, it differs significantly in the amount of time the Runway 28R pilot has to assure safe separation from the Runway 28L aircraft and its wake turbulence. The lateral spacing of the two aircraft flight paths are comparable to the runway spacing only for altitudes below 600 feet. Consequently, the region where wake turbulence is an issue is more limited than for the standard VFR paired approach, where both aircraft are aligned with the runways at altitudes much higher than 600 feet.

Wake Turbulence Transport

The horizontal transport of wake vortices is qualitatively illustrated in Figure 3. Measurements have shown that when vortices are out-of-ground effect (OGE), that is, at heights above the initial wake vortex spacing (approximately a wingspan), the horizontal transport speed is equal to the crosswind (CW) speed. The two wake vortices also induce each other to descend toward the ground. When the wake vortices are closer to the ground, or in-ground effect (IGE), the interaction with the ground causes the two vortices to separate. If the wake vortices are generated OGE, the two vortices typically level off above the ground at approximately half their initial spacing and separate at a speed approximately equal to their initial descent rate. When there is a crosswind (as in Figure 3), the downwind vortex travels faster than the crosswind and the upwind vortex travels slower than the crosswind. Therefore, IGE the downwind vortex can reach the other runway more quickly because it starts off closer to the other runway and because its ground-induced motion (typically, 2 to 4 knots) adds to the crosswind magnitude.

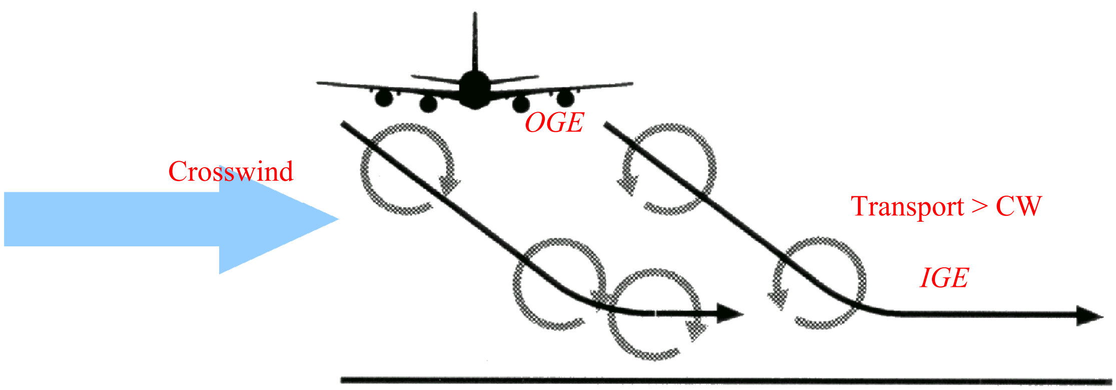


Figure 3. A heuristic description of the lateral transport of aircraft vortices.

For the SFO data collection, the glide slope height is approximately 65 feet, so the aircraft are essentially IGE as they pass over the wake vortex sensors. Typically, the two vortices will level off above the ground at less than half their initial spacing. The proximity to the ground affects the lateral transport of the IGE vortices as noted above.

Data Collection at SFO

The primary measurements at SFO were obtained using three lines of anemometers (termed windlines) installed near the thresholds of Runways 28L and 28R. The locations of these windlines (WL) are shown in Figure 4. The locations of the windlines were selected to monitor wake vortex behavior between the closely-spaced parallel runways. The aircraft altitude at windlines 2 and 3 was sufficiently low that the vortex wakes interacted with the ground and decayed quickly. Therefore, only data and analysis from windline 1, where aircraft were typically at an altitude of about 65 feet, are presented in this summary report.

Figure 4. Relevant dimensions between Runways 28L and 28R as well as positions of the three windlines relative to the runways.

Between March 2000 and October 2002, a total of 311,979 arrivals at SFO were documented by the windlines, under all wind and weather conditions. To determine if there were vortex data at windline 1, a vortex detection criterion was used: a vortex signature was required to be registered within the first 18 seconds after aircraft passage (sufficient time for a vortex to be detected by the windline) or else it was assumed that any detection was a wind gust and not a wake vortex. This criterion excluded mostly very Small aircraft. Of the 261,416 leadings with vortex data at windline 1, there were 244,691 with concurrent ASOS wind data (93.6%, due to down time of ASOS). Of these, 229,234 had a crosswind component within +10 and –10 knots. Figure 5 shows the 261,416 landings by month; Table 1 lists this windline data by year.

Note that Figure 5 shows data only when windline 1 was operational. Due to runway construction and equipment failure, there were times when windline 1 was not operational. Therefore, data in Figure 5 should be interpreted not as the total number of arrivals on 28L and 28R at SFO during each month, but only as those arrivals for which wake vortex data were obtained at windline 1.

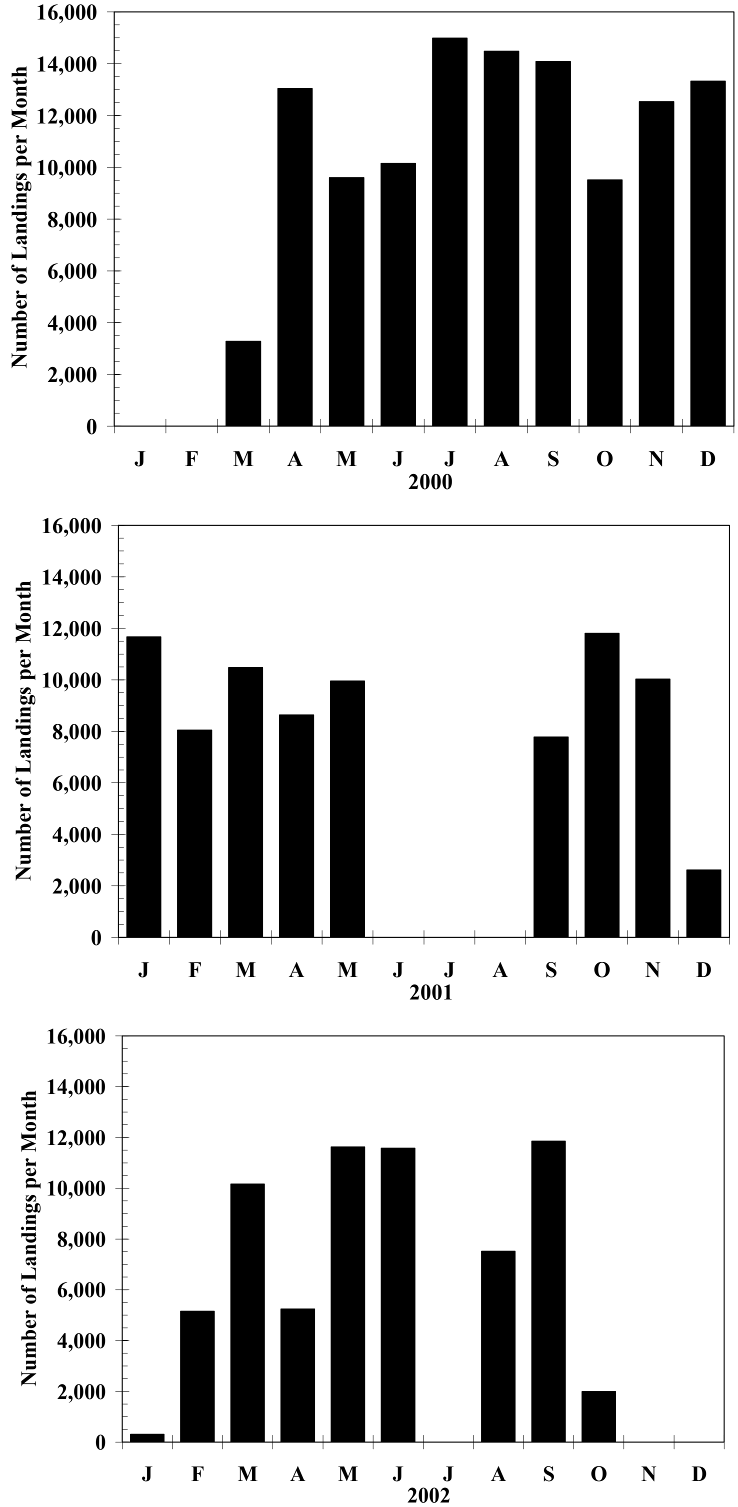


Figure 5. Number of landings per month at SFO for which wake vortex data were obtained at windline 1, under all wind conditions, for the year 2000 (top), 2001 (middle), and 2002 (bottom).

	Unknown Aircraft Landings	Small Aircraft Landings	Large Aircraft Landings	B-757 Aircraft Landings	Heavy Aircraft Landings	Total Aircraft Landings
2000	15,070	5,009	56,202	17,029	21,681	114,991
2001	18,923	3,451	34,436	10,366	13,824	81,000
2002	9,762	3,858	28,773	10,499	12,533	65,425
Total:	43,755	12,318	119,411	37,894	48,038	261,416

Table 1. Landing aircraft by year for which there were wake vortex windline 1 data at SFO.

Figure 6 shows the breakdown of the total landings given in Figure 5 and Table 1 by aircraft type within aircraft category. In this figure, the white bar indicates the landings by unknown aircraft, the black bars indicate landings by Small category aircraft, the diagonally striped bars indicate landings by Large category aircraft, the solid gray bar shows landings by B-757 aircraft, and the horizontally striped bars indicate landings by Heavy category aircraft. This figure shows that, during the data collection period, the most common landing aircraft were, in descending order, the B-737, B-757, A-319-321 series, B-767, B-747, MD-80 series, E-120, and B-777. Of the 261,416 landings for which wake vortex data were obtained at windline 1, 106,716 landings were on Runway 28L (40.8%) and 154,700 landings were on Runway 28R (59.2%).

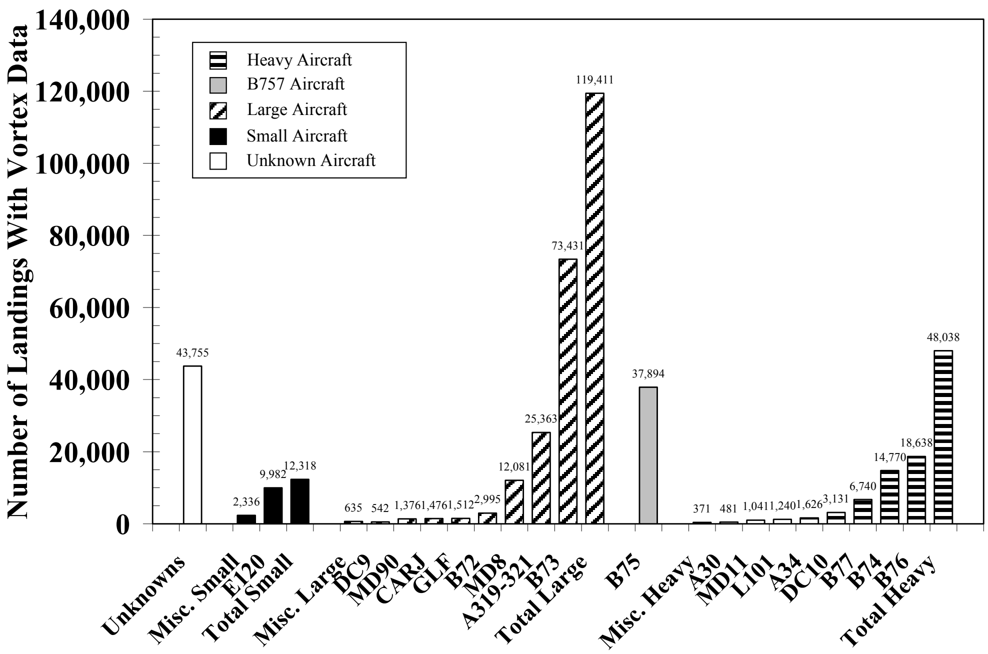


Figure 6. SFO landings by aircraft type for which there is wake vortex data at windline 1.

Sensors Used at SFO

Windlines

Each windline in Figure 4 contains a row of 3-foot high poles spaced 25 feet apart in a line perpendicular to the runways. On the top of each pole is a propeller anemometer to measure the crosswind of both the background atmosphere and of the vortex-driven flow (Figure 7). Since the anemometer poles are located in a critical region of the airport, the 3-foot poles must be frangible and not protrude into TERPS surfaces. An earlier study[3] showed that the boundary layer under a wake vortex is very thin, and vortex-induced crosswinds measured at 3 feet are sufficient to allow wake vortex tracking (and were as effective as anemometers 28 feet above the ground).

Figure 7. (Left) Close-up view of windline 1 showing the 3-foot high poles and the propeller anemometer on top of each pole. (Right) B-777 aircraft landing over windline 1.

The windline anemometers located on top of each 3-foot pole measured the cross-runway wind component at 10 Hz. When no vortices are present, the cross-runway wind component is due only to the ambient wind; when a vortex is present, the vortex alters the cross-runway wind component. These data were stored as 2-second averages. These 2-second data were processed using a windline vortex algorithm to estimate the position of each vortex every 2 seconds and thus the lateral transport distance of each vortex with time, that is, the travel of each wake vortex from one runway toward the adjacent runway. These lateral transport distances are the primary measurements analyzed in this report.

It is important to note the limitations of the windline system and algorithm. Like all measurement systems, the accuracies of the wake vortex measurements and algorithm estimates increase with signal strength. That is, strong vortices close to the ground are more easily and more accurately detected than weaker vortices farther from the ground. In the case of the windline algorithm, a weak, nearly decayed vortex close to the ground may look similar to a stronger vortex farther from the ground. Thus, a vortex that rises above the ground may be difficult to detect.

Pulsed Lidar

In September 2001, an optical pulsed lidar measured wake vortices from landing aircraft (Figure 8). The primary reason for the lidar was to make measurements further up the glide slope, where the windlines could not be used. The wakes from 2274 aircraft (710 B-737, 480 B-757, 304 A-319/A-320, 226 B-707, 197 B-747, 100 B-777, 93 MD-80/DC-9, etc.) were measured over the bay, where approaching aircraft were approximately 530 feet above the water.

Figure 8. B-747 aircraft above the optical pulsed lidar. The WindTracer® Lidar is manufactured by CLR Photonics.

The use of pulsed lidars in wake vortex measurements is a relatively recent development, and the technology can be thought of as a radar operating in optical frequencies with high energy, but eye-safe, pulses. As is also the case with radars, pulsed lidars utilize time-gating techniques to make measurements at various distances from the lidar. Natural air-borne aerosols and engine produced particulates and vapor droplets provide the source of seed particles to scatter laser energy back to the lidar. At each measurement location, the system converts the Doppler shift frequency detected in the returned signal into a line-of-sight velocity along the direction of transmitting pulses. Wake vortex location updates are provided nominally at five-second intervals, which is the nominal time necessary to complete an arc-sweeping scan across the vortex and process the data from the scan.

Surface Winds

The surface winds at SFO were characterized using ASOS (Automated Surface Observing System) archived data. The ASOS uses a Handar sonic anemometer for the wind measurements. The unit is located to the right of 28R approximately 3000 feet from the threshold. ASOS wind speeds and directions were measured at a height of 33 feet. The ASOS wind direction has a resolution of 1 degree and the wind speed has a resolution of 1 knot. The wind data are averaged for 2 minutes and updated every minute.

Aircraft Detectors

An aircraft noise detector was deployed at the end of each runway near windline 1 to detect the arrival of aircraft. Data from these acoustic noise measurements were combined with aircraft arrival information from the Total Airport Management Information System (TAMIS) to generate a database of aircraft arrivals.

The aircraft noise data were used to classify the type of landing approach as either single or paired. Two landings are considered to be in a paired approach when the noise peaks from two arrivals on separate runways are within 50 seconds of each other. Although 50 seconds is somewhat arbitrary, larger time separations may not be paired approaches because a departure may be fit between the arrivals.

Primary Results

Aircraft wake lateral transport data from windline 1 were analyzed for periods of time when the ASOS-measured cross-runway component of the wind (crosswind) was between -10 kt and 10 kt, a limit imposed by the SOIA procedure. A specific objective was to determine the maximum longitudinal spacing, or stagger, of aircraft on adjacent runways for which the measurements indicate a wake vortex encounter would not have occurred. Since the wake turbulence data were time based, a maximum longitudinal time spacing was determined which was converted to distance using typical aircraft approach speeds. For Large category leading aircraft, a distance spacing of approximately 1 nautical mile corresponds to a time spacing of 28 seconds for a following aircraft at a speed of 130 knots. (Note that a shorter time at the higher approach speed typical of many Heavy aircraft can still be close to 1 nm.) This time (or distance) is indicated in the schematic arrival diagram in Figure 9.

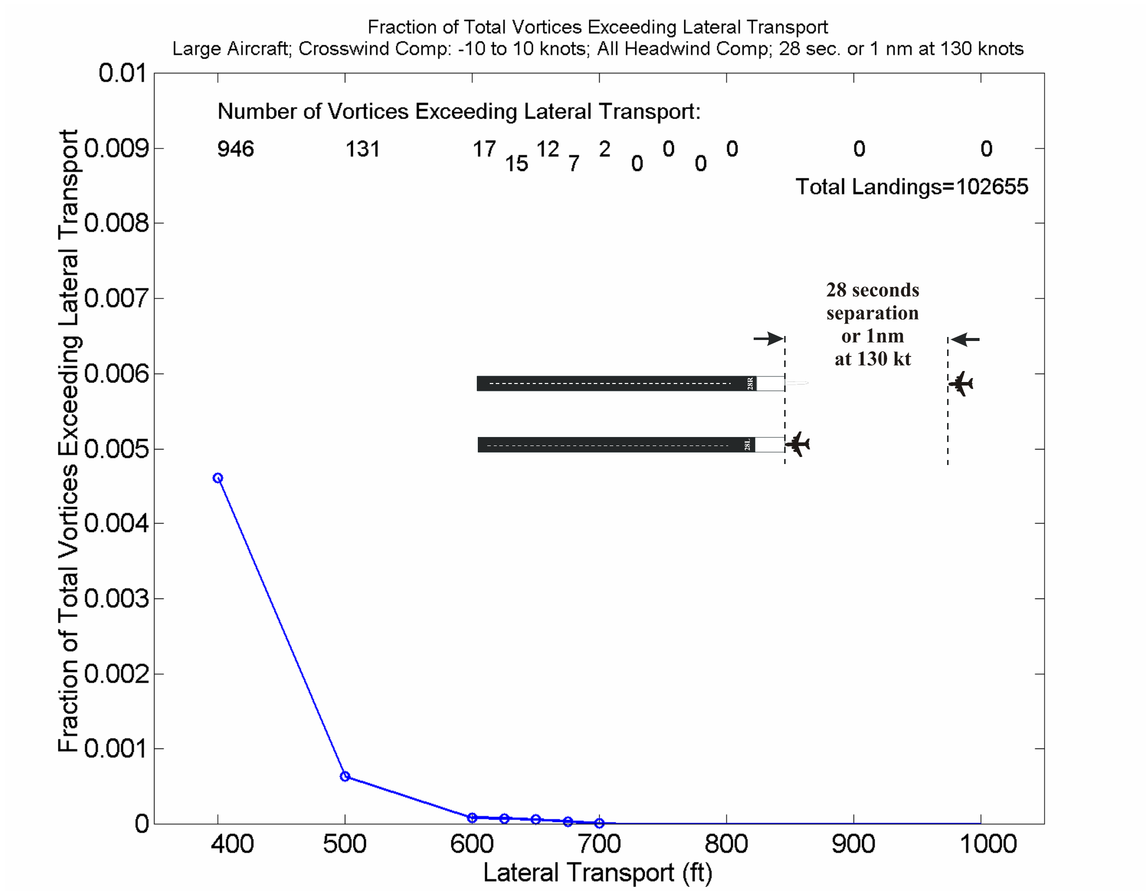


Figure 9. Measurements of the maximum lateral travel distance of vortex wakes at SFO from 102,655 landing Large aircraft with crosswinds from -10 to 10 kt and all headwinds. The plots show the fraction of vortices exceeding a given lateral travel within 28 seconds after passage of the aircraft over windline 1.

Figure 9 shows the results for 102,655 landings of Large category aircraft. In this figure, the solid curve shows the fraction of the total number of vortices exceeding a given lateral travel distance vs. the maximum lateral travel distance of a wake vortex from a Large aircraft towards the adjacent runway in 28 seconds. For example, the fraction of vortices exceeding a lateral travel of 400 feet in 28 seconds is less than 0.005 or 5 out of a 1000 vortices of Large category aircraft. (Note that 1000 vortices are generated in 500 landings, so a value of 0.005 in Figure 9 corresponds to 5 out of 500 landings.) For larger distances, the fraction is much smaller, and only two vortices reached a lateral travel distance of 700 feet in 28 seconds, and no vortices were measured at a distance of 725 feet or greater in 28 seconds. For times (distances) somewhat greater than 28 seconds (or 1 nm at 130 kts), the fraction remains low, though not zero, as relatively few wakes ever reach 750 feet (see Figure 12). However, the key point is that no Large wakes were detected beyond 700 ft in 28 seconds.

Figure 10 is similar to Figure 9 except for 33,586 landings of B-757 aircraft. Here, one wake from a B-757 aircraft reached a lateral travel distance of 750 feet in 28 seconds; it did so during a time when visual approaches were being conducted, i.e., during non-SOIA conditions, with ceilings above 4000 ft.

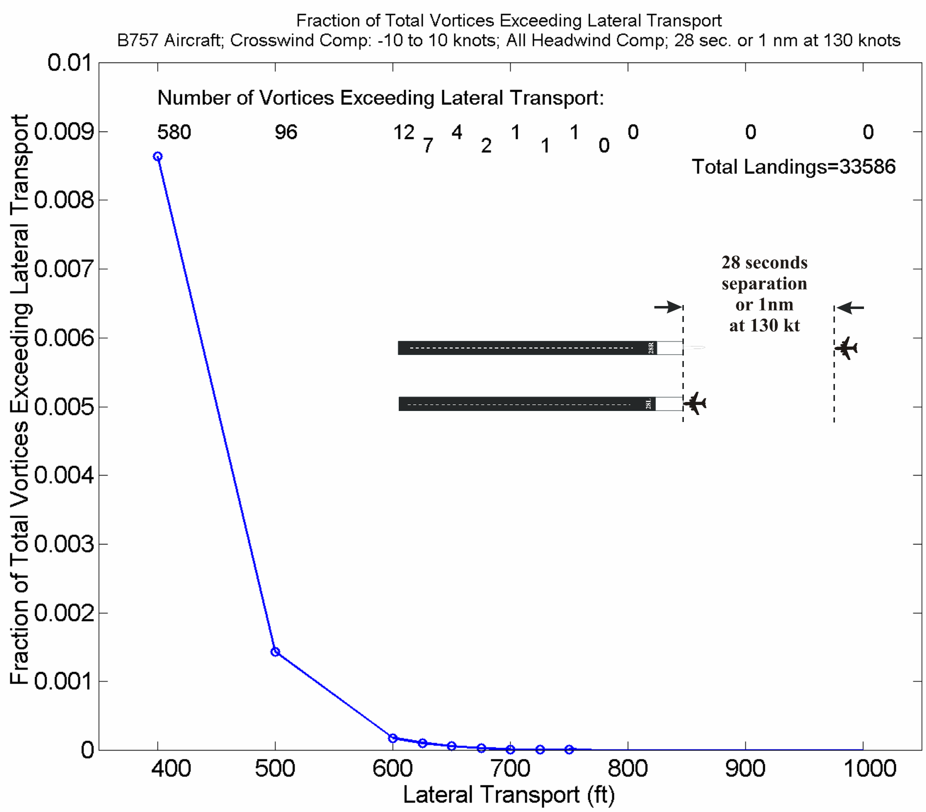


Figure 10. Measurements of the maximum lateral travel distance of vortex wakes at SFO from 33,586 landing B-757 aircraft with crosswinds from -10 to 10 kt and all headwinds. The plots show the fraction of vortices exceeding a given lateral travel within 28 seconds after passage of the aircraft over windline 1.

Figure 11 shows data similar to Figures 9 and 10 for 42,223 landings of Heavy category aircraft. In this figure, more vortices travel farther in 28 seconds than seen in Figures 9 or 10, as expected, since the Heavy aircraft generate stronger vortices. However, only 4 vortices exceed a lateral travel distance of 750 feet in 28 seconds and, again, all the vortices exceeding 750 feet did so during times when visual approaches were being conducted, i.e., during non-SOIA conditions, with ceilings above 4000 ft.

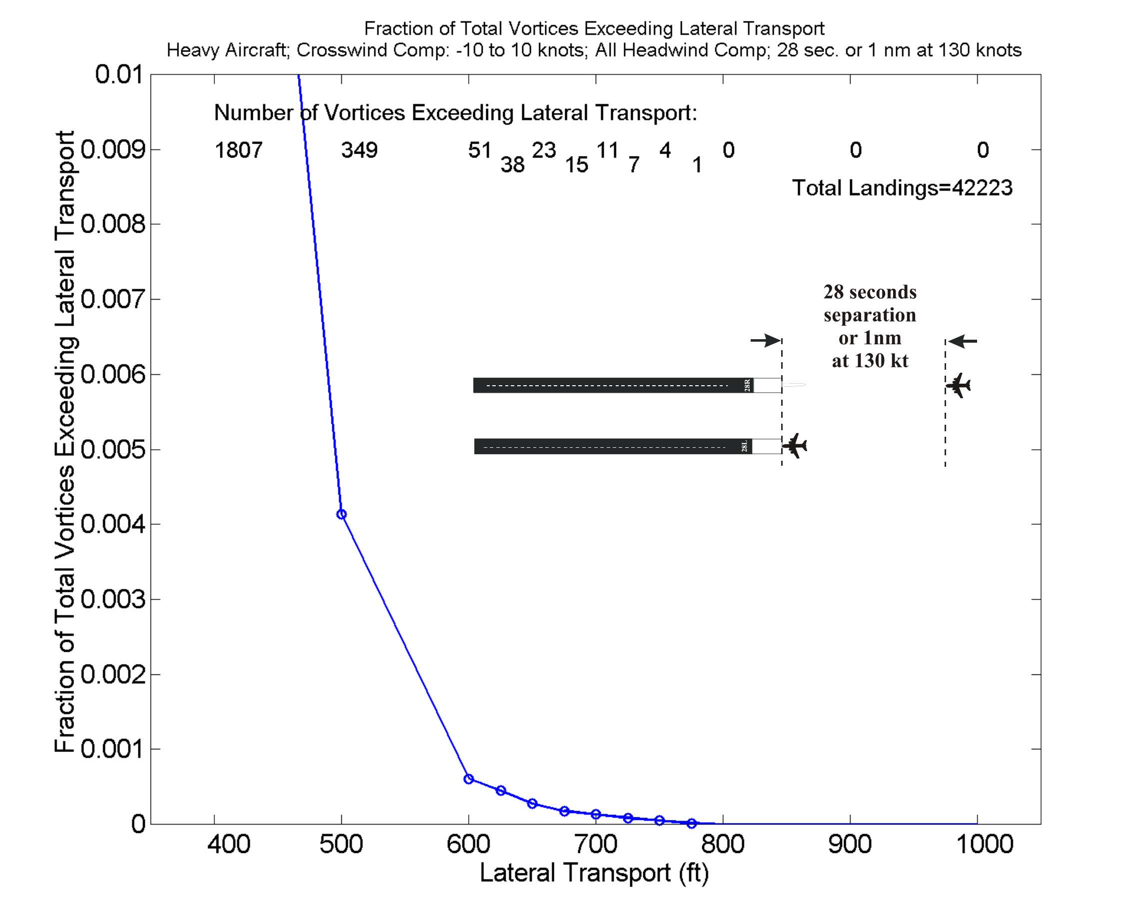


Figure 11. Measurements of the maximum lateral travel distance of vortex wakes at SFO from 42,223 landing Heavy aircraft with crosswinds from -10 to 10 kt and all headwinds. The plots show the fraction of vortices exceeding a given lateral travel distance within 28 seconds after passage of the aircraft over windline 1.

Figure 12 shows the percent of landings with a vortex exceeding 750 feet lateral transport distance vs. the time after passage over the wind line. Only data for crosswinds of 10 kt or less are shown. The dotted line shows data for Large category aircraft (102,655 landings), the dashed line for B-757 aircraft (33,586 landings), and the solid line for Heavy category aircraft (42,223 landings). The percent of landings at a given time after landing increases from Large category to B-757 to Heavy category aircraft, as expected, since larger aircraft generate stronger and more persistent wakes. Only 0.07% of landings (7 in 10,000 landings) from Large category aircraft generate a vortex which exceeds 750 feet lateral transport distance in 60 seconds. Thus, Figure 9 shows that the probability of a wake from a Large aircraft transporting 750 feet in 28 seconds is zero at this windline location, and Figure 12 shows that this risk remains small for at least 60 seconds.

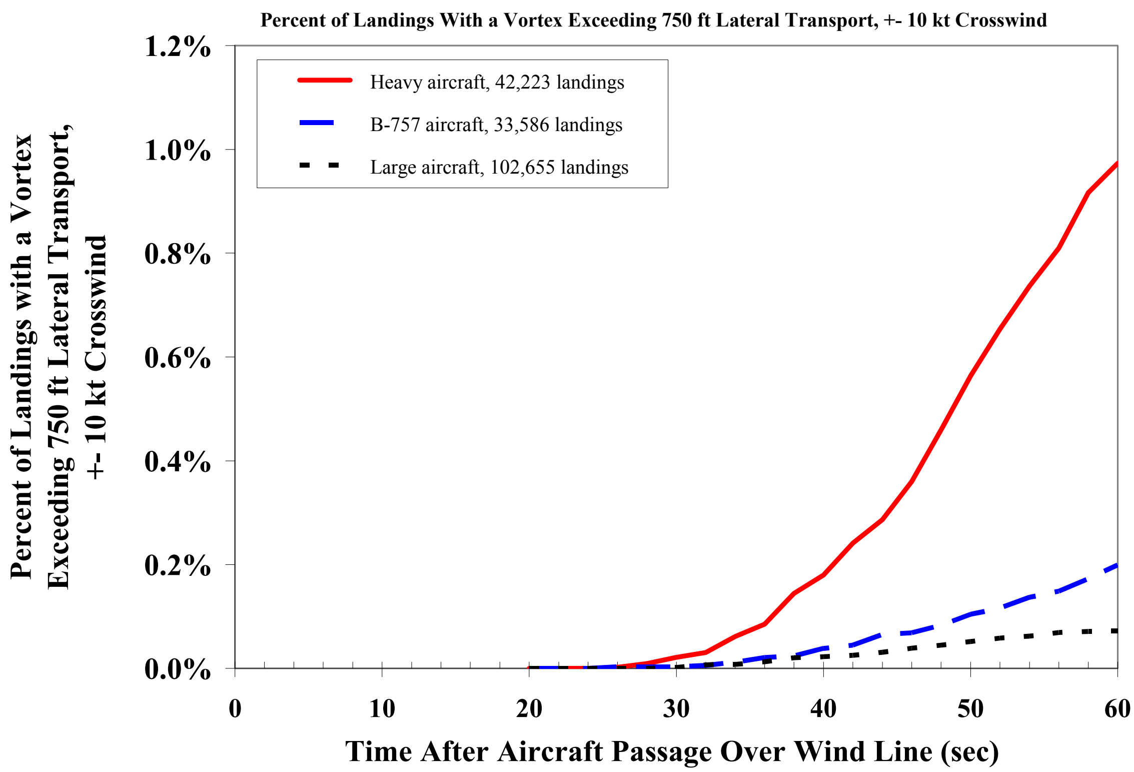


Figure 12. Percent of landings with a vortex exceeding 750 feet lateral transport distance vs. the time after landing for Large category aircraft (dotted line), B-757 aircraft (dashed line), and Heavy category aircraft (solid line).

During the entire measurement period, only 4 vortex wakes out of 12,318 landings of Small category aircraft were found to reach the centerline of the adjacent runway (750 feet). The minimum time to travel 750 feet was 58 seconds, which indicates that this occurred only during times of relatively low crosswind. Apparently, higher crosswinds along with the interaction with the ground were sufficient to cause the vortex wakes to decay prior to reaching the adjacent runway. This time of 58 seconds corresponds to a longitudinal separation of over 2 nautical miles at 130 knots.

Taken together, these results for all aircraft categories indicate that the occurrence of a vortex wake having moved to the adjacent runway at SFO in an operationally significant time is an infrequent event for any type of aircraft.

Of the few vortex wakes that travel 750 feet or more, most are from Heavy category aircraft. Figure 13 shows the fraction of landings with a vortex that transports more than 750 feet laterally in any amount of time in crosswinds of 10 kt or less. Most of these wakes are from Heavy category aircraft, the largest fraction belonging to B-747 aircraft, the heaviest aircraft. Of potential interest are the vortex wakes from the A-321 aircraft, whose fraction is comparable to several Heavy category aircraft, and is larger than the fraction for the B-757 aircraft. Although these statistics are based on a relatively small number of limiting values, it may be of interest to watch emerging trends as the technology of newer aircraft improves.

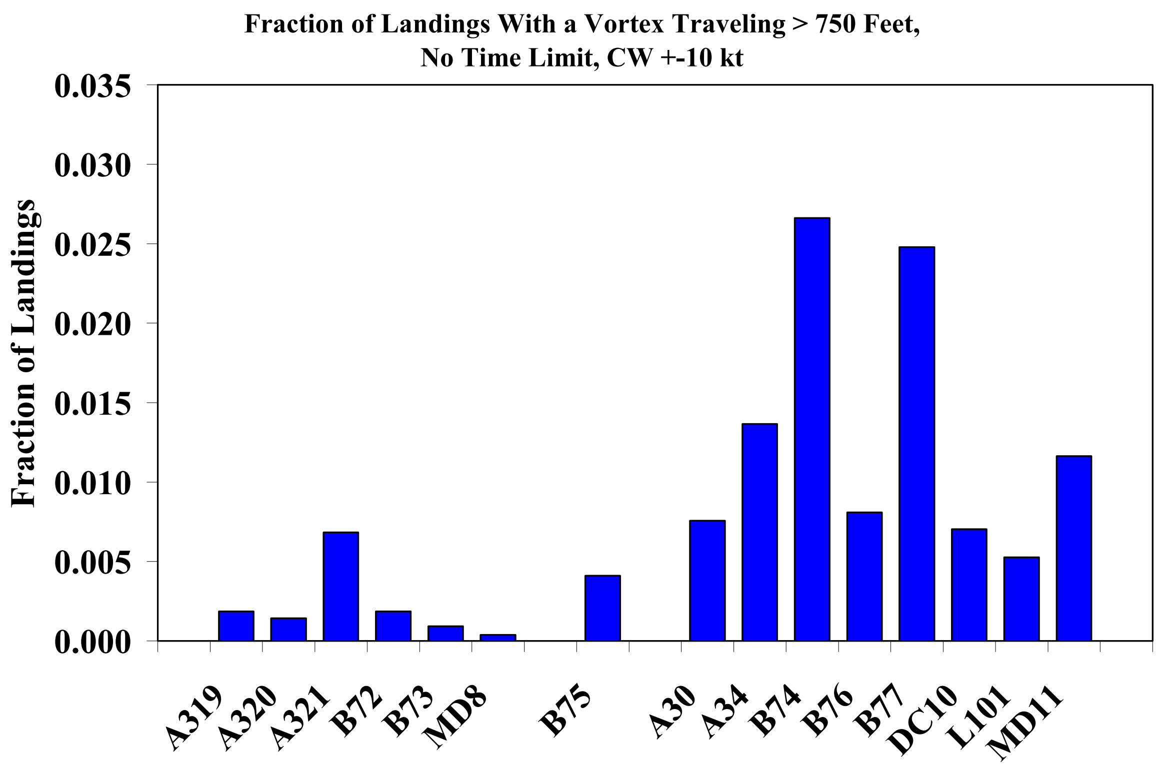


Figure 13. Fraction of landings with a vortex that transports more than 750 feet laterally in any amount of time in crosswinds of 10 kt or less.

Secondary Results

Unknown Aircraft

Table 1 showed that 43,755 of 261,416 landings were from Unknown aircraft, that is, aircraft for which the database has no FAA type designator for aircraft type. The large number of Unknowns in the SFO windline database is primarily due to difficulties in matching the aircraft from the TAMIS database to the windline data, due to time differences in each database and operational difficulties in matching aircraft with runway arrivals. Because of the large number of these landings, they were examined to confirm that no important information was being overlooked.

The analysis found that 6 wakes from the 43,755 landings of Unknown aircraft exceeded a lateral transport distance of 675 feet (from the wake centerline of one runway to the near edge of the adjacent runway, see Figure 4) in 28 seconds and that 3 of these wakes exceeded a lateral transport distance of 750 feet (from one runway centerline to the other centerline) in 28 seconds. [Note that a lateral transport distance of 675 feet (see Figure 4) is now used as often no wake vortices were observed to travel the 750 feet to the centerline of the adjacent runway.] Of the 6 wakes from Unknown aircraft that traveled 675 feet in 28 seconds, 3 occurred during the first week of windline operations, when aircraft type was not included in the dataset, and the remaining 3 occurred in the early morning hours during light traffic. It is likely that these 6 Unknown aircraft were Heavy aircraft. However, all 6 wakes occurred during times when visual approaches were being conducted, i.e., during non-SOIA conditions.

Potential Patterns in the Data

The dataset was also analyzed to determine if there was an identifiable pattern in the data that might be used to identify other operational procedures which might minimize the risk of wake encounters. Note that all of the results presented in this section are for the SOIA-procedure-imposed 10 knots or less operational limit on the cross-runway component of the wind. Figure 14 shows the distribution by month when a wake from any category aircraft exceeded a lateral transport distance of 675 feet in 28 sec. Although there were differences by month, there was not a concentration in a specific time of year which could be easily used to develop an operational solution for avoiding vortex wakes.

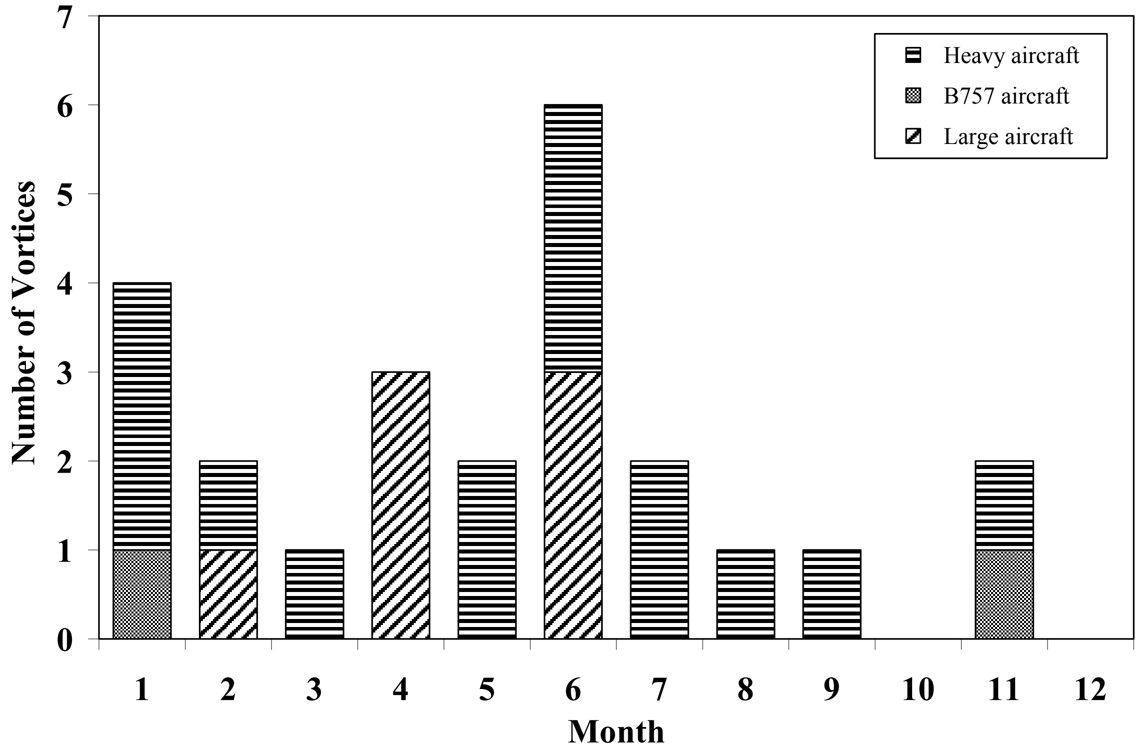


Figure 14. Time of year (month number) for all vortex wakes exceeding a lateral transport distance of 675 feet in 28 sec (1 nm at 130 kt).

The data were also analyzed to determine if there were times during the day when vortex wakes were more likely to reach an adjacent runway. Figure 15 shows the time of day distribution for vortex wakes traveling more than 675 feet in 28 seconds (1 nm at 130 kt). Again, although there is some clustering in the afternoon, when winds are typically stronger, the distribution is sufficiently broad to preclude easy use operationally.

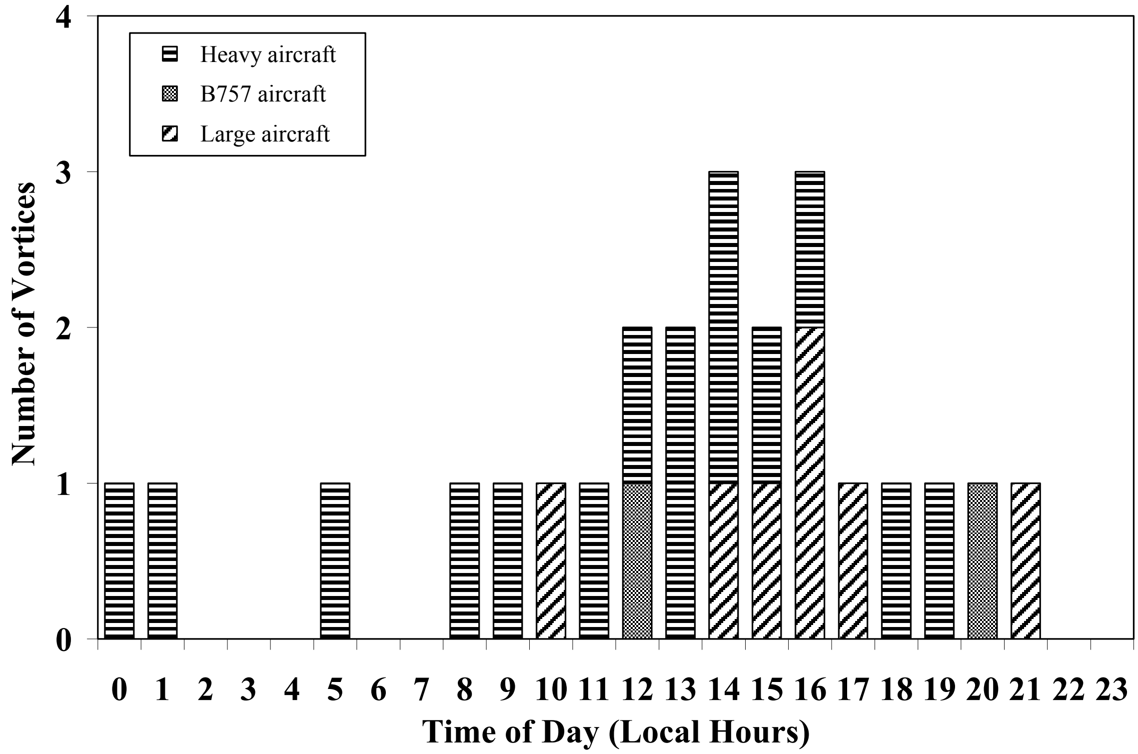


Figure 15. Time of day distribution (by hour after midnight) for vortex wakes traveling more than 675 feet in 28 sec (1 nm at 130 kt).

Figures 16-19 show distributions of various characteristics of the wind for vortex wakes traveling 675 feet in 28 seconds or less: wind speed, wind direction, cross runway component of the wind (crosswind), and the along runway component of the wind (headwind / tailwind). These distributions were analyzed to determine if there were patterns which could be of use operationally. Of these wind characteristics, only the cross-runway component of the wind (crosswind) shown in Figure 18 appears to have any potential operational application. Lateral wake transport distance depends strongly on the crosswind.

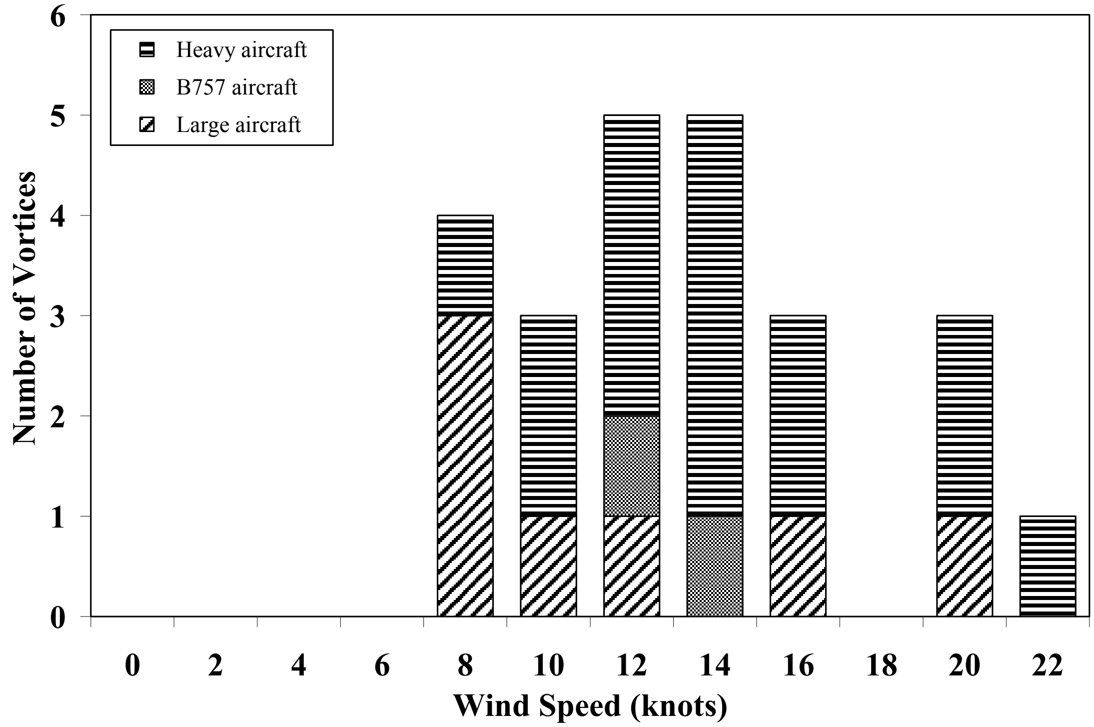


Figure 16. Wind speed distribution for vortex wakes traveling 675 feet in 28 seconds.

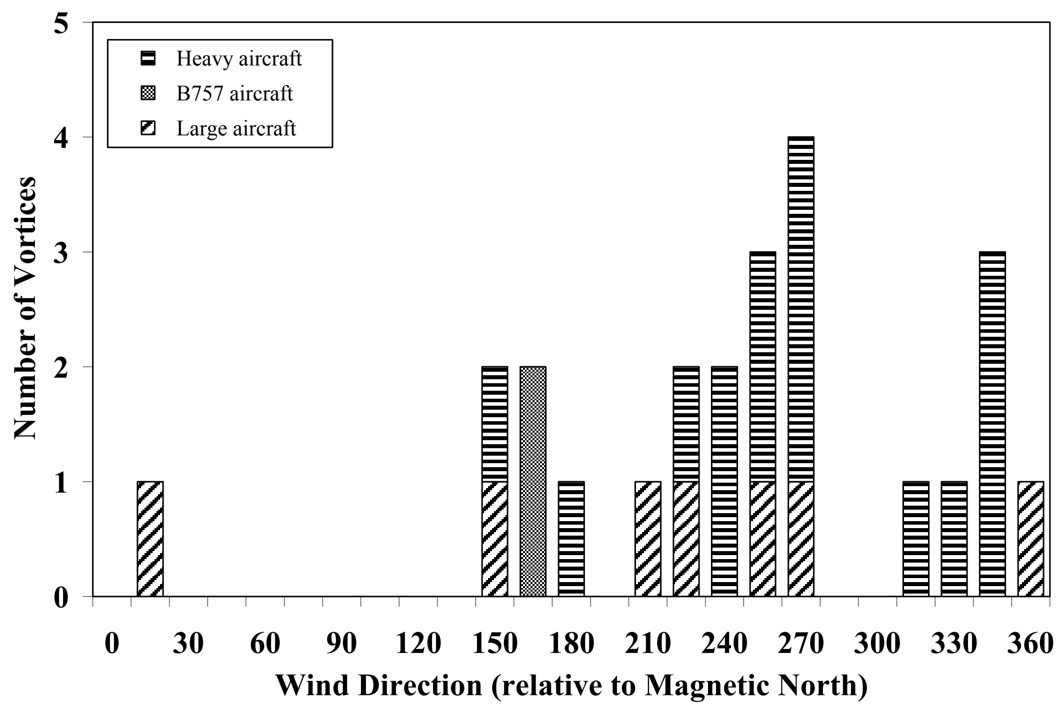


Figure 17. Wind direction (magnetic) distribution for vortex wakes traveling 675 feet in 28 sec.

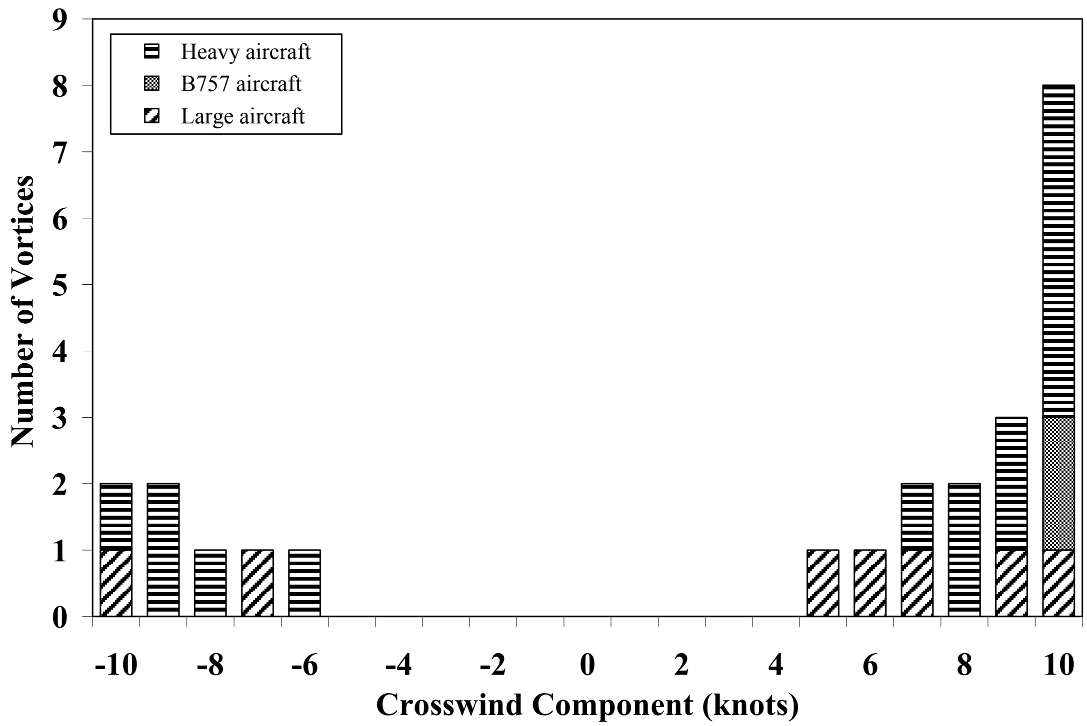


Figure 18. Cross-runway wind component (crosswind) distribution for vortex wakes traveling 675 feet in 28 seconds.

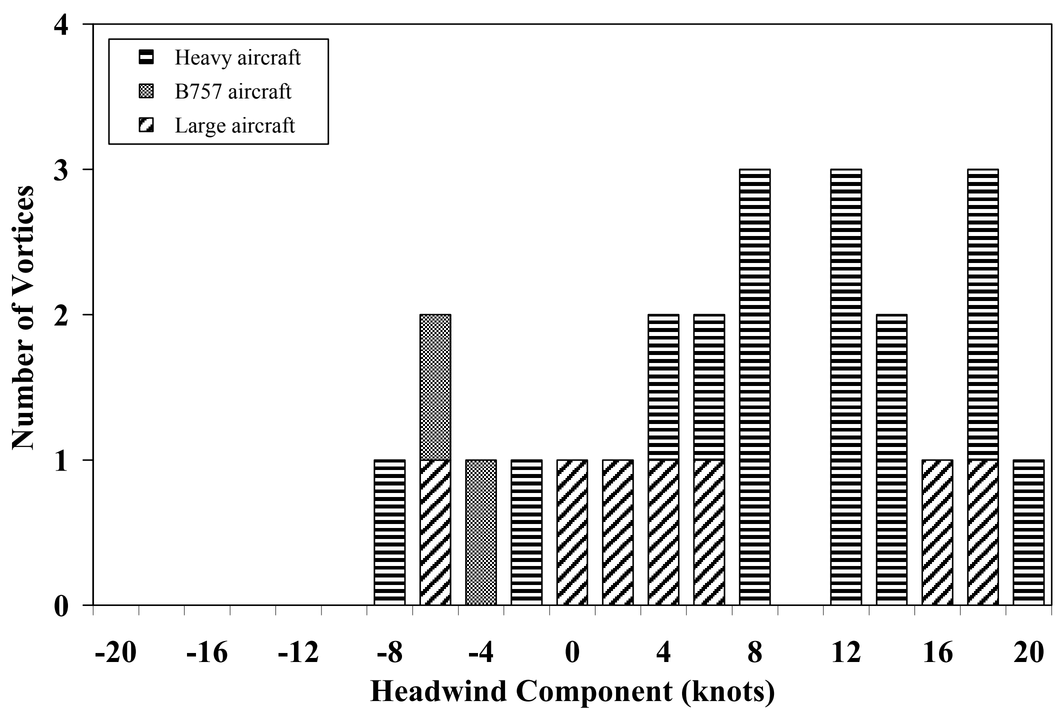


Figure 19. Headwind distribution for vortex wakes traveling 675 feet in 28 seconds or less.

Lidar Measurements at 530 Feet AGL

Most of the vortex wake measurements in this study were made near the runway thresholds where the aircraft are close to the ground and wake behavior is most complex. In addition to these near-ground vortex wake measurements, a limited set of measurements (2274 aircraft) using a pulsed lidar was made further up the glide slope to confirm widely accepted models of less-complex vortex wake behavior at altitude. Most of the pulsed lidar measurements of aircraft wakes were made for aircraft which were at an altitude of approximately 530 feet. This altitude is well above the height for which the ground should have an effect on the vortex wakes.

There were two principal aspects of vortex wake behavior which were of interest in this limited study. The first objective was to confirm the widely accepted belief that vortex wakes are transported laterally by the wind at the speed of the crosswind component of the wind. The second objective was to demonstrate that vortex wakes either decayed rapidly enough to not pose a hazard to an aircraft approaching the adjacent runway or descended well below the glide slope of the adjacent runway if they were transported toward the adjacent runway by the wind.

Figure 20 shows the crosswind component of the wind measured by the lidar at the wake altitude (horizontal axis) vs. the lateral transport velocity of the vortex wakes measured by the lidar (vertical axis). Although there is scatter in the data, the straight line trend confirms the first objective and earlier results showing that, out of ground effect, vortex wakes are transported by the crosswind component of the ambient wind.

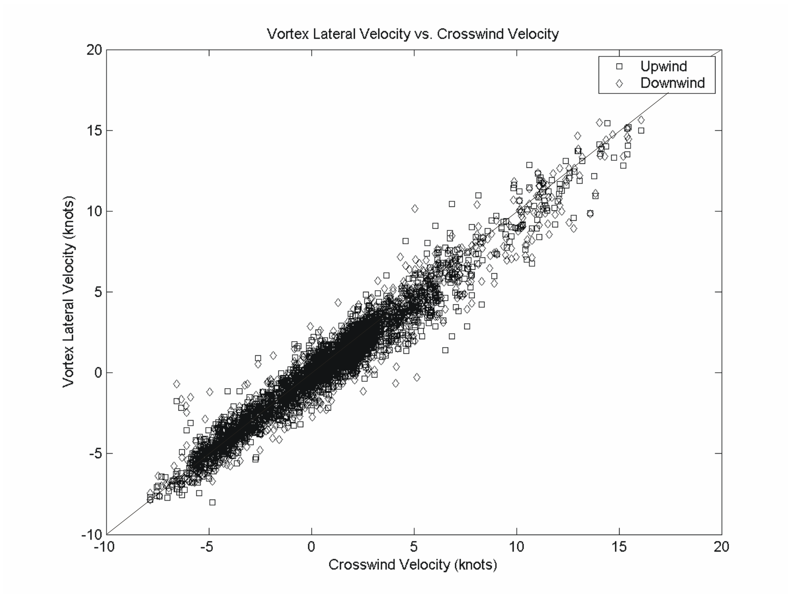


Figure 20. Measurements of the crosswind component of the wind measured by the pulsed lidar (horizontal axis) vs. the lateral transport velocity of the vortex wakes measured by the lidar (vertical axis).

Figure 21 shows the location of wake vortices from the lidar data for Large aircraft landing on 28R. The small box above the wake vortex data (at zero lateral position and zero feet below the glide slope) represents the initial range of locations of the vortex-generating aircraft; the small aircraft indicates the nominal location of an aircraft following on the parallel runway. Because the lidar wake vortex locations are only updated nominally every 5 seconds, Figure 21 (and, subsequently, Figure 22) only shows vortices where the initial vortex locations were measured within the first lidar scan. Thus, the lidar data shown have wake ages from 28 to 33 seconds. [Since the wake vortex locations are updated every 5 seconds, a wake vortex that is first observed 5 seconds after generation would have a wake age of 33 seconds at the time a measurement is made 28 seconds after the first observation.]

Figure 22 shows the location of wake vortices from the lidar data for Large aircraft landing on 28L. Again, the vortex wake ages shown are from 28 to 33 seconds. The 8 data points to the right in Figure 22 are the port and starboard vortices for 4 landings. The crosswind components varied from 11.2 to 16.1 knots for these cases, thus transporting the vortices to the region of the extended centerline of Runway 28R but well below the glide slope altitude.

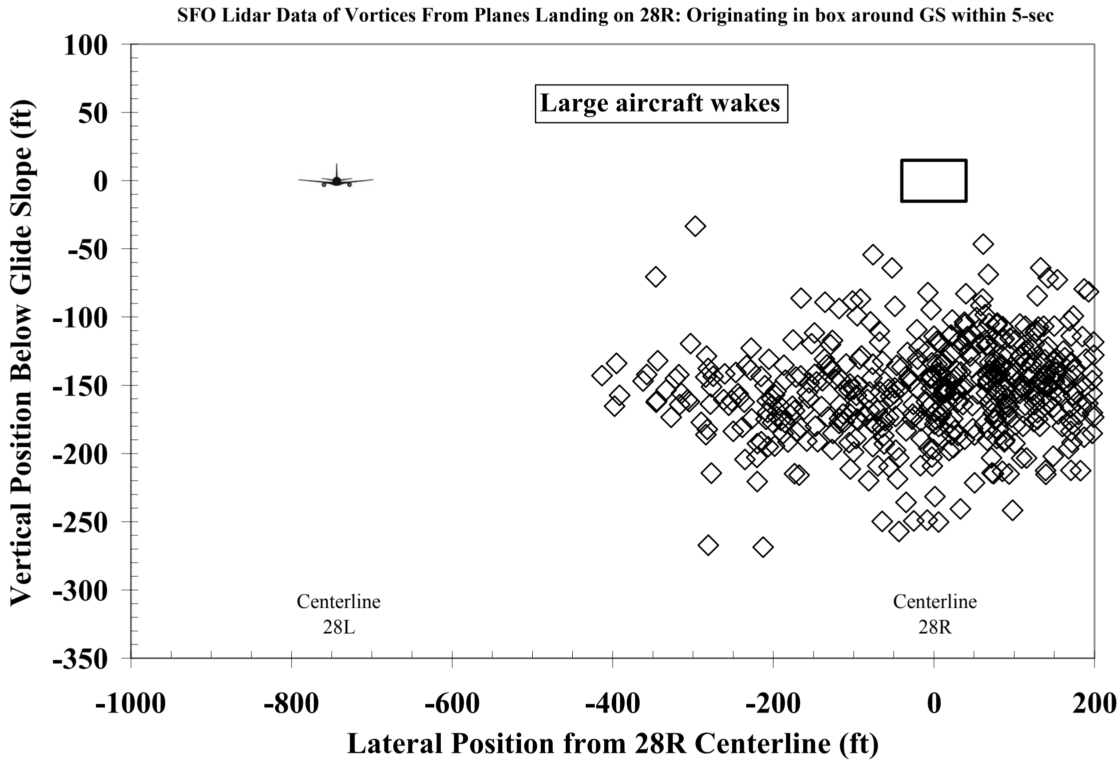


Figure 21. Lidar data showing the location of wake vortices 28 seconds after initial detection from Large aircraft landing on Runway 28R. The centerline of Runway 28L is located at -750 feet.

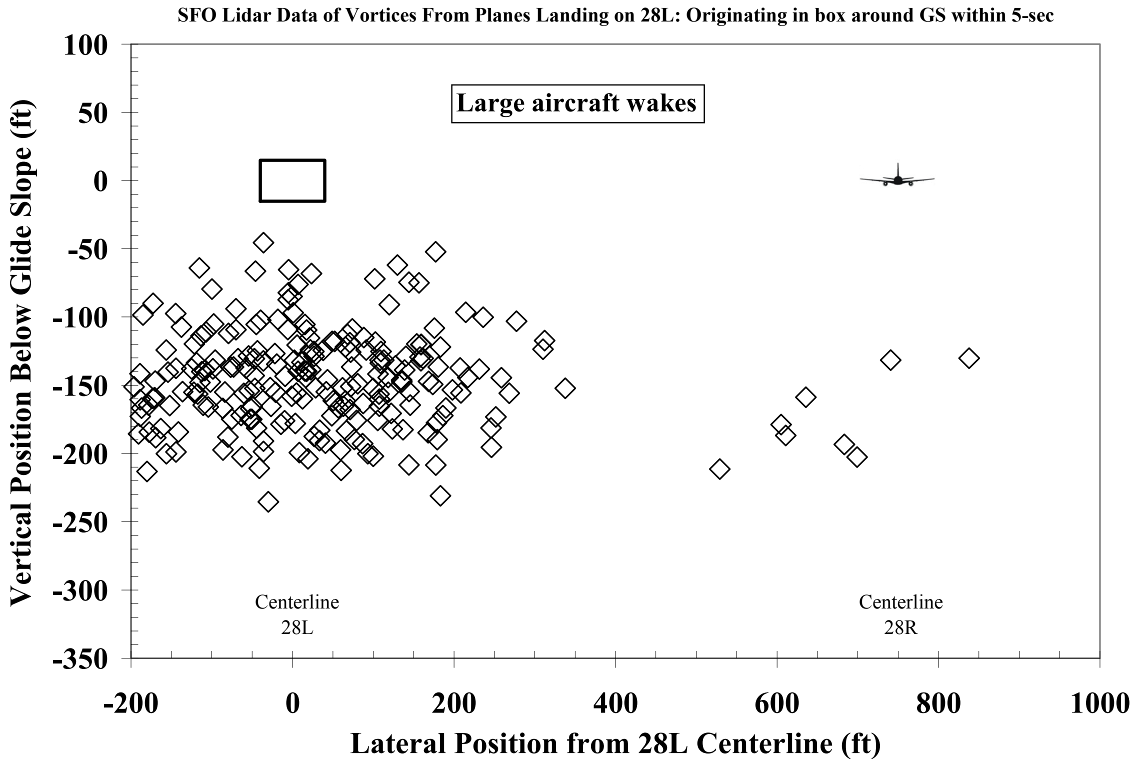


Figure 22. Lidar data showing the location of wake vortices 28 seconds after initial detection from Large aircraft landing on Runway 28L. The centerline of Runway 28R is located at 750 feet.

Conclusions

The long-term wake turbulence measurements at SFO examined the transport of wake vortices near the ground. Over 0.26 million landing aircraft were monitored near the thresholds of Runways 28L and 28R where the aircraft were typically at an altitude of 65 feet. Limited measurements were also made at a glide slope altitude of about 530 feet. The primary purpose of the measurements was to provide data to support the safety assessment of the SOIA procedure being designed for SFO; the procedure would permit continued use of the CSPR in deteriorating weather.

As currently designed, the SOIA procedure at SFO will be used when the cross-runway component of the total wind (the crosswind) is 10 knots or less. The vortex wake transport data support the conclusion that, for Large category aircraft, when the stagger distance/time between aircraft on the adjacent approach course is approximately 1 nm/28 seconds or less, a vortex wake from one runway cannot move into the path of another aircraft following on the adjacent runway.

In addition, the data support the following general conclusions:

- Only a small fraction of wakes generated near the ground ever reach the adjacent runway under any conditions.

- Wake transport times are determined largely by the cross-runway component of the total wind, i.e., wakes consistently required longer to reach the adjacent runway during low cross-runway-component wind conditions.

- Wakes from Heavy category aircraft are more likely to reach the adjacent runway than wakes from smaller aircraft.

- Although the wake data for this report were collected exclusively at SFO, they have potentially broader applicability to other CSPR airports as well.

Appendix A – Analysis of Windline Data Outliers

For each wake vortex for each landing, the maximum lateral travel distance from the runway centerline within a given wake age (e.g., 28 seconds) was computed. This database was searched to find the number of vortices with a maximum lateral travel distance exceeding a given lateral distance (e.g., 675 or 750 ft). The number of vortices exceeding this distance in a specified time divided by the total number of vortices observed is the probability of finding wake vortices exceeding this given lateral distance. In addition, using the FAA-designated aircraft type associated with each wake vortex, the vortices (and therefore their probabilities) were grouped into aircraft categories (Small, Large, B-757, Heavy, and Unknown). The results are shown in Figures 9 to 19.

Data that fall outside the normal range of values are termed "outliers." In this summary report, the focus is on the lateral transport of vortices from one runway to the adjacent runway. The vortices exceeding a specified lateral travel distance in a certain time were called "outliers," and were subjected to additional analyses.

In spite of potential difficulties with data and possible erroneous detection, all of the data obtained were used in the analysis unless there was a compelling reason not to do so. A discussion of what data were included and excluded is given below. In practice, the only cases that were deleted from the database were cases when vortices were attributed to a landing aircraft but were due to jet blast from an aircraft waiting between the two runways to take off from Runway 28R.

Outliers were given special consideration in the data analysis. First, plots of the windline vortex algorithm were made to determine if the data were "reasonable." An example of reasonable data for a single approach is shown in Figure A-1. This figure shows the output of the windline vortex algorithm for the landing of a B-737-700 at 2:50:48 on April 13, 2001. The aircraft landed on Runway 28L (zero lateral location on the y-axis) in a 17 kt headwind with a 12 kt crosswind component. The location of the port vortex from the aircraft with time is shown as the "x" symbols, and the location of the starboard vortex with time is shown as the "+" symbols. Because both vortices appear to originate near the location of the generating aircraft, the data are considered reasonable.

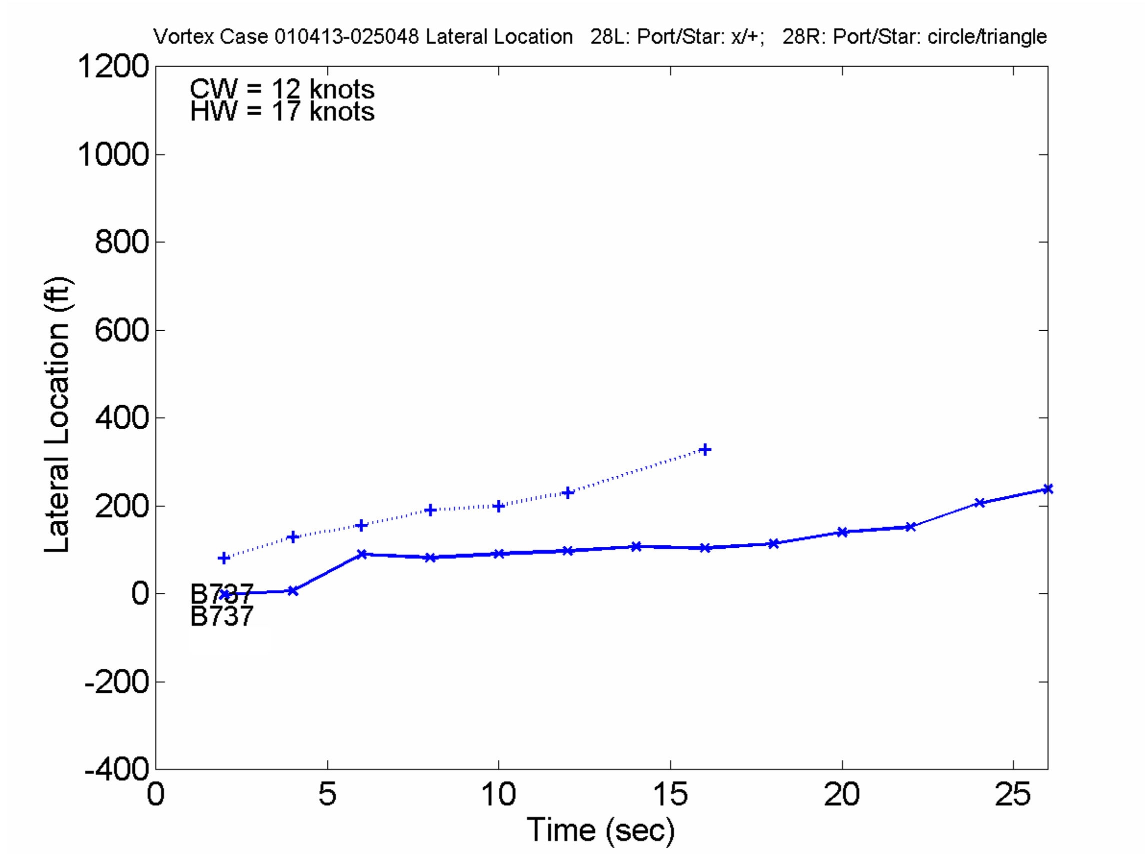


Figure A-1. Output from the windline vortex algorithm for the landing of a single B-737-700 at 2:50:48 on April 13, 2001. Because both vortices appear to originate from the generating aircraft, landing on Runway 28L, the data are considered to be reasonable.

Figure A-2 shows an example of reasonable data from a paired approach. This figure shows the output of the windline vortex algorithm for the landing of a B-757-200 at 3:42:09 on the same day (April 13, 2001) on Runway 28L (centerline at 0 feet on the y-axis), shown with the "x" and "+" symbols, and the landing of a B-767-200 on Runway 28R (centerline at 750 feet on the y-axis), shown with the circles and triangles. The data have been time shifted so that the landings appear to originate at the same time, but there was, in reality, a time shift of 40 seconds (the B-767 behind the B-757) between the two landings. Because both vortices from both aircraft appear to originate near the location of the generating aircraft, the data are considered reasonable.

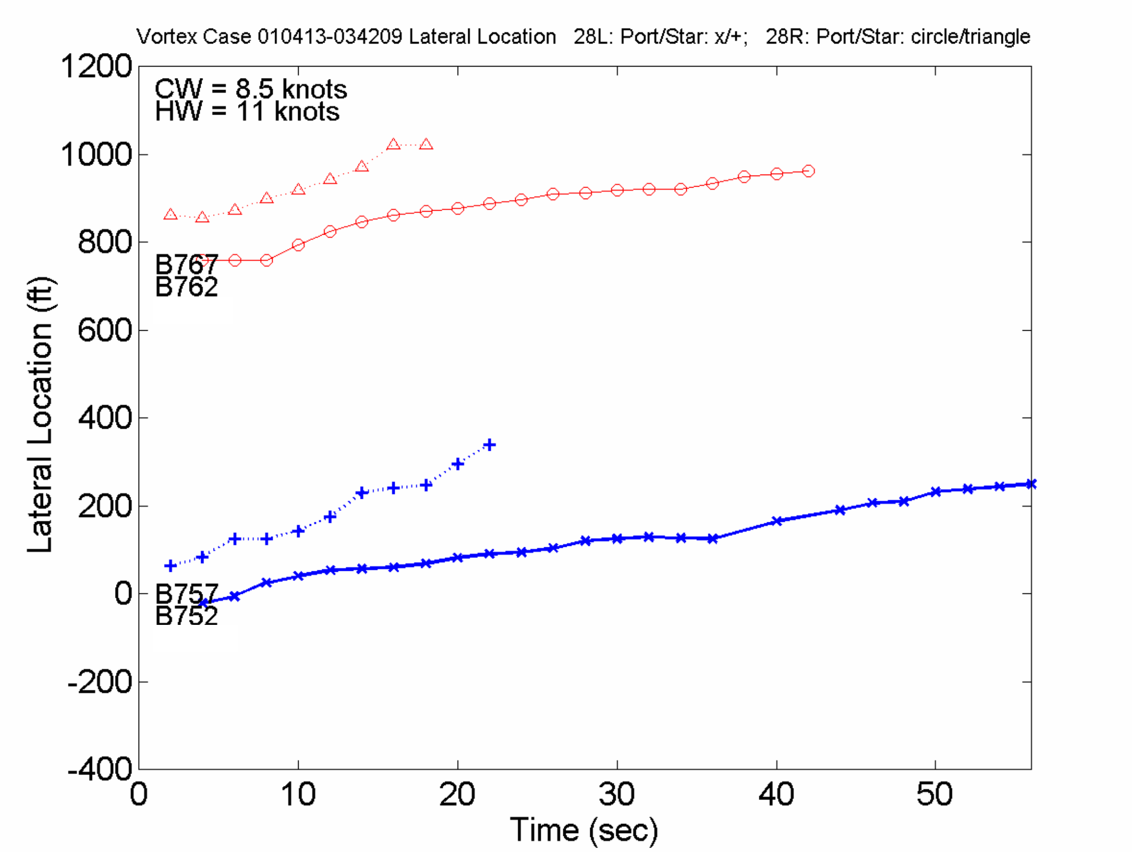


Figure A-2. Output from the windline vortex algorithm for a paired approach at 3:42:09 on April 13, 2001. Here, a B-757-200 is landing on Runway 28L ("x" and "+" symbols), and a B-767-200 is landing on Runway 28R (circles and triangles). Because both vortices from both aircraft appear to originate from the generating aircraft, the data are considered to be reasonable.

Figure A-3 shows an example of "unreasonable" or "bad" data. This example shows the output of the windline vortex algorithm for an A-320 landing on Runway 28R at 23:26:47 on August 5, 2000. The centerline of Runway 28R is at 750 feet on the y-axis. In this example, the measured ASOS headwind was 18 kt, and the crosswind component of the wind was 0.4 kt. In this example, although the locations of the starboard vortex (triangles) appear to be reasonable, the locations of the port vortex (circles) do not appear reasonable since they do not extrapolate back to the location of the generating aircraft (i.e., the extrapolation of the circles to zero time does not go back to near 750 feet). Thus, these data were deemed to be "bad" data, and they were excluded from the database. Had these data not been excluded from the database, then the port vortex (the circles in Figure A-3) would have traveled 650 feet (from the centerline of Runway 28R to a lateral location of 100 feet) in 16 seconds, which is clearly incorrect from Figure A-3. (The results in Figure A-3, and others like it, are due to jet blast from an aircraft waiting between the two runways to take off from Runway 28R.)

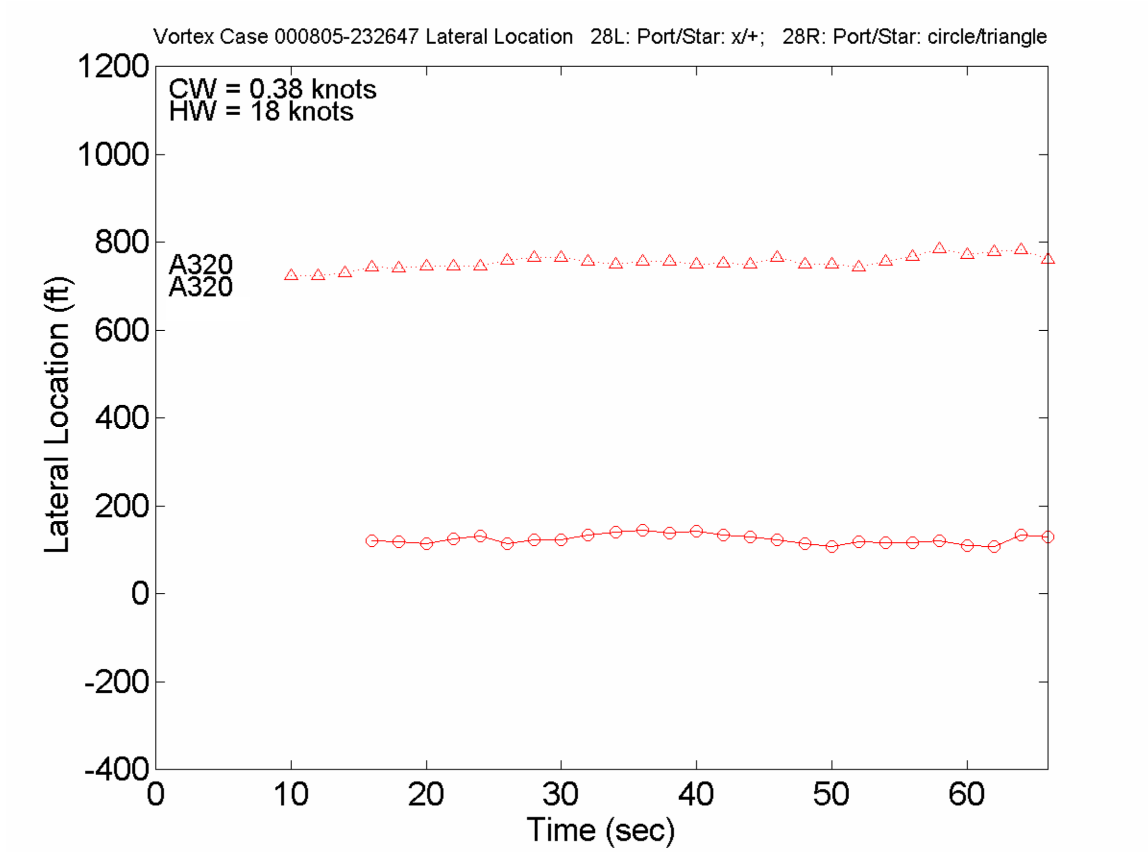


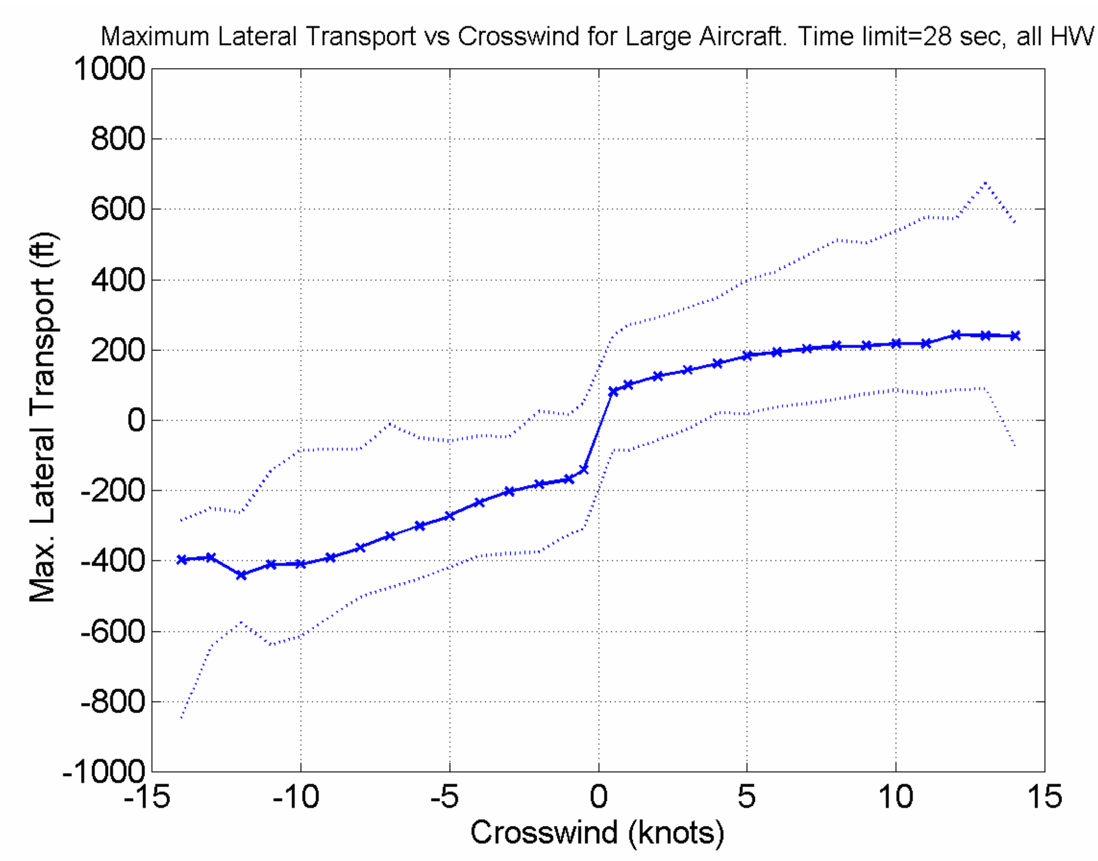
Figure A-3. Output from the windline vortex algorithm for the landing of a single A-320 at 23:26:47 on August 5, 2000. Because both vortices do not appear to originate from the generating aircraft, landing on Runway 28R (at 750 feet on the y-axis), the data are considered to be "bad."

In practice, the above plots proved to be of primary importance in determining whether the data from outliers were reasonable or unreasonable. Additionally, plots of the 2-second windline data were made to determine if anything unusual occurred during the landing in question. Finally, time series plots of maximum windline crosswind, estimated vortex altitude, and estimated vortex strength were make to ensure reasonable data.

Only clearly incorrect data, such as that shown in Figure A-3, were excluded from the database. If there were any doubt on the reasonableness of the data from any one landing, the data from that landing were retained in the database.

<u>Lateral Transport vs. Crosswind</u>

Figure A-4 shows the median lateral transport distance (solid line) in 28 seconds for Large category aircraft vs. crosswind, as well as the 1st-percentile and 99th-percentile (dotted lines) lateral transport distance. This figure shows that 99 percent of all vortices travel 600 feet or less in 28 seconds for all crosswinds of 10 kt or less. The median lateral transport distance also shows a difference between the lateral transport for positive winds (from the land) and negative crosswinds (from the Bay). This difference is less for the 99th-percentile lateral transports.



This is still Figure A-4, with the original caption:

Figure A-4. Median lateral transport (solid line) and 1st-percentile and 99th-percentile (dotted lines) for Large category aircraft vs. crosswind for all headwinds at a time of 28 seconds after the passage of the aircraft over windline 1.

Figure A-5 shows results similar to Figure A-4 only for B-757 aircraft. This figure shows that, in 28 seconds, 99 percent of all vortices from B-757 aircraft travel 650 feet or less for all crosswinds of 10 kt or less. There is, again, a difference in lateral transport between a positive and negative crosswind for the median but not for the 99th-percentile.

Figure A-6 shows data similar to Figures A-4 and A-5 but for Heavy category aircraft. Here, 99 percent of all vortices from Heavy aircraft travel 700 feet or less for all crosswinds of 10 kt or less. Here, too, there is a difference in lateral transport between a positive and negative crosswind for the median but not for the 99th-percentile.

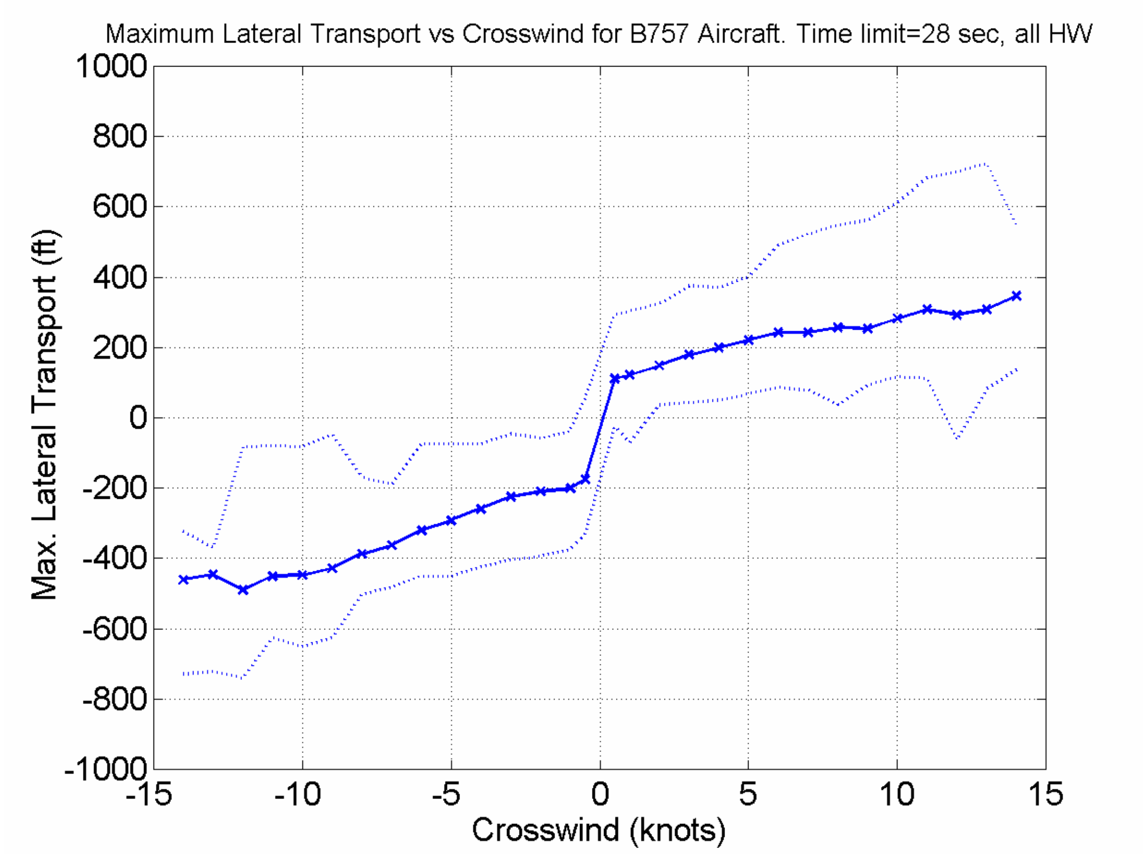


Figure A-5. Median lateral transport (solid line) and 1st-percentile and 99th-percentile (dotted lines) for B-757 aircraft vs. crosswind for all headwinds at a time of 28 seconds after the passage of the aircraft over windline 1.

Taken together, Figures A-4, A-5, and A-6 indicate that few wakes generated by an aircraft at the glide slope altitude of around 65 feet transport 750 feet in 28 seconds .

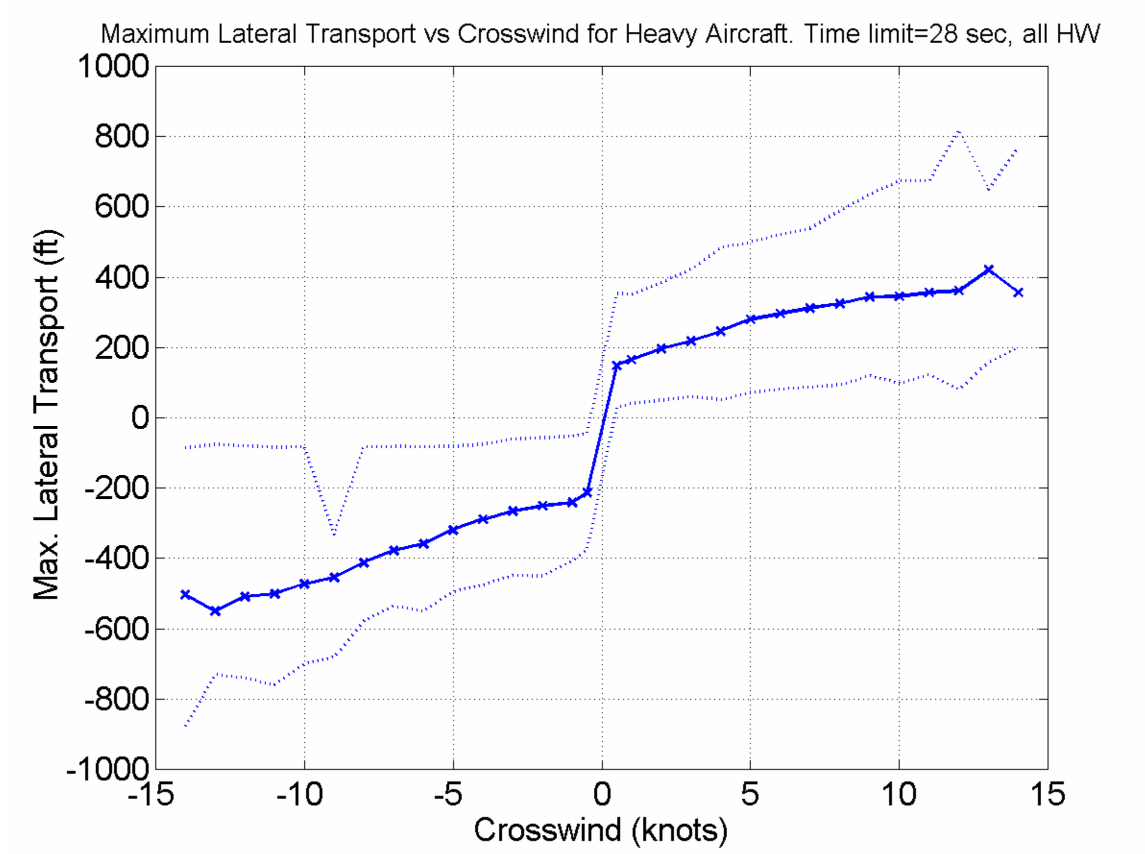


Figure A-6. Median lateral transport (solid line) and 1st-percentile and 99th-percentile (dotted lines) for Heavy category aircraft vs. crosswind for all headwinds at a time of 28 seconds after the passage of the aircraft over windline 1.

Figure A-7 shows the lateral transport for Large category aircraft for 28 seconds after the passage of the aircraft over windline 1 (the same data as in Figure A-4) and for no time limit after the passage of the aircraft. For positive crosswinds, there is little transport of Large category wakes after 28 seconds. This result is not true for negative crosswinds, where there is up to ~ 200 feet additional transport after 28 seconds. Even with this additional transport, Figure A-7 shows that most of the lateral transport for Large category aircraft takes place within the first 28 seconds.

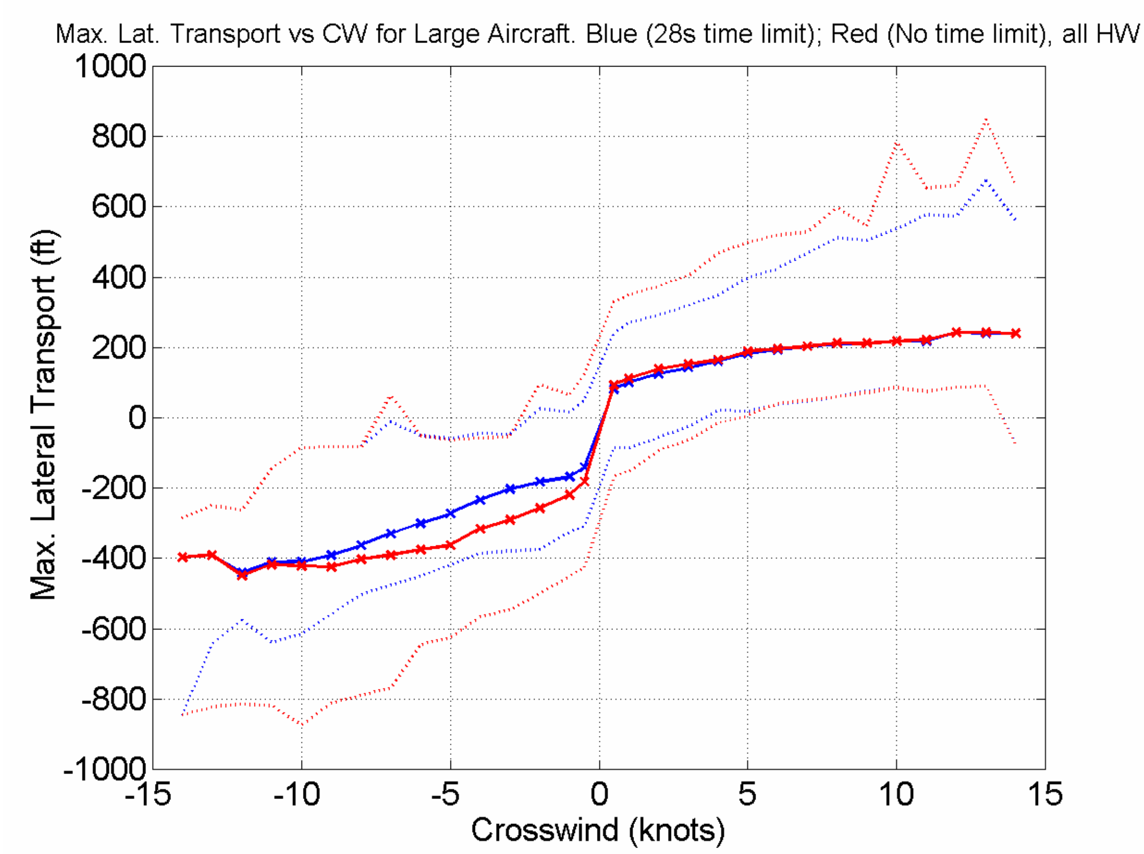


Figure A-7. Median lateral transport (solid line) and 1st-percentile and 99th-percentile (dotted lines) for Large category aircraft vs. crosswind for all headwinds at a time of 28 seconds after the passage of the aircraft over windline 1 (blue) and with no time limit after the passage of the aircraft over windline 1 (red).

Appendix B – Determination of Visual or Instrument Approach Conditions for Individual Landings

There were no direct indications in the database of whether, at any given time, SFO was landing aircraft under a visual approach or an instrument approach procedure. To determine if a given landing was under visual or instrument approach conditions, a number of steps were taken:

- First, all the adjacent landings for 30 minutes on each side of the landing in question were examined. That is, a total of one hour of landings centered on the time of the landing in question was examined.
- Second, the visibility and ceiling data included in the SFO and San Mateo Bridge ASOS data were examined.

If the landings near in time to the landing in question were labeled as paired approaches, indicating that the landings were within 50 seconds of each other, the airport was assumed to be operating under visual approach conditions.

If the landings near in time to the landing in question did not conclusively show paired approaches, the visibility and ceiling data in the SFO and San Mateo Bridge ASOS data were examined. If those sensors were working (e.g., showed low ceilings during a part of the day in question), but did not show low ceilings during the time in question, the airport was assumed to be operating under visual approach conditions.

If the above two steps did not indicate visual approach conditions, or if the ceiling was below 2000 feet, the airport was assumed to be operating under instrument approach conditions.

This procedure usually gave clear indications of visual or instrument approach conditions. Several times, the ceilings were just above 2000 feet, but paired approaches were being conducted. It was assumed these were times of visual approach conditions.

References

[1]Burnham, D. C., Hallock, J. N. and Greene, G. C., "Wake Turbulence Limits on Paired Approaches to Parallel Runways," Journal of Aircraft, Vol. 39, No. 4, July - August 2002, pp. 630 - 637.

[2]Lankford, D. N., McCartor, G., Hasman, F., Greene, G. C., Yates, J., Ladecky, S. and Templeton, D., "San Francisco International Airport Simultaneous Offset Instrument Approach Procedures (SOIA), Volume I," DOT-FAA-AFS-420-84, March 2000.

[3]Burnham, D. C. and Hallock, J. N., "Measurement of Wake Vortices Interacting with the Ground," AIAA Paper 1998-0593, Reno, NV, January 1998.