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SFO Wake Turbulence Measurement System: Sensors and Data Descriptions

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13. ABSTRACT (Maximum 200 words)

This report addresses aspects of an extensive aircraft wake turbulence measurement program conducted at San Francisco International Airport (SFO) over a two-year period. Specifically, this report describes the sensors used for data collection and the resulting data sets that were used for analysis of the Simultaneous Offset Instrument Approach (SOIA) procedure proposed for use at SFO. Three anemometer Windlines were deployed perpendicular to and between Runways 28L and 28R to measure and record wake vortex motion between the runways near the threshold and touchdown regions. Because Runways 28L and 28R are used for 80% of SFO arrivals, the SFO wake turbulence Windline dataset, comprising approximately 250,000 arrivals, is the largest ever accumulated. Pulsed Lidar wake measurements were made for approximately one month at a location where aircraft were approximately 500 feet above San Francisco Bay (about 9,000 feet from the thresholds). The ambient wind at 20 feet above ground was monitored on either side of the two runways, and a wind Sodar was used to measure wind profiles up to a height of 656 feet. Automated Surface Observation System (ASOS) winds at 33 feet above ground were also obtained.

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PREFACE

Although the United States has one of the best air traffic systems in the world, continued growth in air travel is severely straining the system. The challenge to relieving congestion and increasing capacity is made more difficult by the fact that the traditional solution of building more runways can, in many instances, only be implemented over a long period of time due to environmental and other restrictions. Because of wake turbulence concerns, airports with closely-spaced parallel runways (CSPR) — defined as having centerline separations of less than 2,500 feet* — are required to limit arrival operations to a single traffic stream under reduced ceiling/visibility conditions. At San Francisco International Airport (SFO), this restriction effectively halves arrival capacity and produces extensive delays.

Current CSPR rules (embodied in Federal Aviation Administration [FAA] Order 7110.65) are designed to deal with all possible situations — e.g., combinations of aircraft size, wind speed/direction, and runway threshold stagger. As a result, the rules are overly conservative in some situations. The Simultaneous Offset Instrument Approach (SOIA) procedure was developed at San Francisco International Airport (SFO) to improve CSPR arrival capacity when the ceiling/visibility do not allow dual-stream visible approach operations. In response to SFO's SOIA plans, the Department of Transportation (DOT) Research and Innovative Technology Administration (RITA) Volpe National Transportation Systems Center (Volpe Center), in support of the FAA, conducted a wake turbulence measurement program at SFO to characterize the transport properties of wake vortices between the parallel runways 28L and 28R. This report describes the SFO Wake Turbulence Measurement System (WTMS) and documents the data collected by it.

The primary goal of this report is to guide users of the SFO WTMS datasets in selecting appropriate data for future analyses. Critical issues in this regard are data validation, aircraft-wake matching and processing algorithms. Data from this measurement program have been used to study the effects of crosswind on wake vortices, in order to (a) assess the longitudinal spacing requirements of SOIA, and (b) improve models for wake vortex transport in ground effect.

This project could not have been successfully completed without the cooperation and help of several individuals and groups working at SFO. Particular thanks go to Paul Candelaire, FAA Facilities Manager, and his technicians who helped us establish connectivity from our test site trailer to the Air Traffic Control Tower. Others who contributed to the project's success include: Trig McCoy, SFO Operations Manager; Dennis Reed, SFO Operations Coordinator for Airfield Construction; Jim Chui and Hugo Tupac, SFO Engineering; Scott Speers, FAA Assistant Tower Chief; David Ong, SFO Aircraft Noise Abatement Office; and Petullia Mandap, FAA Western Region District Office.

* CSPR is defined herein as parallel runways having centerline separation of less than 2,500 feet, because, in this regime, wake-based aircraft separation rules may (depending upon the operation and meteorological conditions) govern approaches and departures. In other contexts, CSPR is sometimes defined as parallel runways with centerlines separated by less than 4,300 feet, because, in this regime, conducting simultaneous ILS approaches during instrument meteorological conditions requires use of a precision aircraft monitoring (surveillance) system.

ABSTRACT

A program was conducted at San Francisco International Airport (SFO) to acquire landing aircraft wake vortex transport data between parallel Runways 28L and 28R. Three anemometer Windlines were deployed perpendicular to and between Runways 28L and 28R to measure and record wake vortex motion between the runways near the threshold and touchdown regions. The three closely-spaced measurement planes permitted wake vortices to be displayed, in real time for the first time, as continuous tubes, rather than as point locations in a single measurement plane. Real-time displays were placed at several airport locations and a near-real-time display was provided over the Internet. Data collection lasted for approximately two years.

Because Runways 28L and 28R are used for 80% of SFO arrivals, the SFO wake turbulence Windline dataset, comprising approximately 250,000 arrivals, is the largest ever accumulated. Pulsed Lidar wake measurements were made for approximately one month at a location where aircraft were approximately 500 feet above San Francisco Bay (about 9,000 feet from the thresholds). Concurrent Lidar and Windline data were collected for one day near the runway thresholds, for the purpose of sensor data comparison/validation. The ambient wind at 20 feet above ground was monitored on either side of the two runways, and a wind Sodar was used to measure wind profiles up to a height of 600 feet. Automated Surface Observation System (ASOS) winds at 33 feet above ground were also obtained.

This report describes the data collection and processing procedures for the Windlines, and documents the datasets available from the Windline and Lidar measurements. The report is intended to guide potential dataset users in selecting the most appropriate data for a particular analysis.

Key Words: IFR approaches, parallel runways, wake turbulence, wake vortices, Windline, Lidar, SOIA, SFO

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LIST OF ACRONYMS

ASOS	Automated Surface Observation System
ATC	Air Traffic Control
C/L	Centerline
CSPR	Closely-Spaced Parallel Runways
CTI	Coherent Technologies, Inc. (now part of Lockheed Martin Corp.)
CW	Continuous Wave
DEN	Denver Stapleton Airport
DFW	Dallas-Fort Worth Airport
DME	Distance Measuring Equipment
DOS	Disk Operating System
DOT	Department of Transportation
DSL	Digital Subscriber Line
FAA	Federal Aviation Administration
FMC	Final Monitor Controller
GPS	Global Positioning System
IFR	Instrument Flight Rules
IGE	In Ground Effect
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
JFK	New York Kennedy Airport
LAN	Local Area Network
LDA	Localizer-type Directional Aid
LHR	London Heathrow Airport
LIDAR	LIght Detection And Ranging
MAP	Missed Approach Point
MCGTOW	Maximum Certificated Gross TakeOff Weight
MEM	Memphis Airport
MVICW	Maximum Vortex-Induced CrossWind
NASA	National Aeronautics and Space Administration
OGE	Out of Ground Effect

LIST OF ACRONYMS (cont.)

ORD	Chicago O'Hare Airport
PPI	Plan Position Indicator
PRM	Precision Runway Monitor
RITA	Research and Innovative Technology Administration
RVR	Runway Visual Range
SFO	San Francisco International Airport
SODAR	SOund Detection And Ranging
SOIA	Simultaneous Offset Instrument Approach
SSD	Sum of Squared Differences
STL	Lambert – St. Louis International Airport
TAMIS	Total Airport Management Information System
UTC	Universal Coordinated Time
VAD	Variable Azimuth Display
VMC	Visual Meteorological Conditions
VAOs	Visual Approach Operations
WTMS	Wake Turbulence Measurement System
YYZ	Toronto Pearson Airport

SUMMARY

PURPOSE

This report documents the San Francisco International Airport (SFO) Wake Turbulence Measurement System (WTMS) and the datasets derived from that system during the collection campaign conducted from March 2000 to October 2002. While the impetus for the SFO WTMS data collection effort was to support development of the Simultaneous Offset Instrument Approach (SOIA) procedure, the extensive data obtained may be useful for other purposes.

SFO has crossed pairs of parallel runways, numbered 1-19 L/R and 10-28 L/R. Both pairs have centerline spacing of 750 feet. When visual approach operations (VAOs) are permitted, often simultaneous paired arrivals on Runways 28L and 28R are conducted, with simultaneous departures intermixed on Runways 1L and 1R. VAOs are generally authorized at SFO when the ceiling is above 3500 feet and the visibility is greater than 4 statute miles. Much of the data collected by the SFO WTMS are from paired arrivals to Runways 28L and 28R.

EQUIPMENT LAYOUT

Figure S-1 shows the on-airport WTMS installation, including three Windlines, two 20-foot poles for ambient wind measurements, a Sodar wind profiler, and an equipment trailer. Windline 1 was 1,275 feet long, was located 250 feet before the Runway 28L/R thresholds and covered the entire approach region under the arrivals including the runway aprons. Windlines 2 and 3 were each 500 feet long and covered only the region between Runways 28L and 28R. The Windlines were separated by 750 feet in the longitudinal (along-runway) direction.

Figure S-2 shows the two sites where the Pulsed Lidar was operated. At the First site, used most of the time, the Pulsed Lidar measured wakes generated by aircraft at an altitude of approximately 500 feet above San Francisco Bay, 1.4 nautical miles from the runway thresholds. For one day the Lidar was located at the Second site where it could scan above Windline 1.

CHRONOLOGY

Windlines

Installation of the Windline portion of the SFO WTMS started in late 1999 and was completed in March 2000. The first data collection period ended in May 2001 when construction started on a new apron for Runway 28L. Windline 1 was reinstalled on the new 28L apron. The second data collection period started in September 2001 and was completed in October 2002. The site was subsequently restored to its original condition.

Pulsed Lidar

The Coherent Technologies, Inc. (CTI) Pulsed Lidar was deployed at SFO for one month, starting in September 2001. Measurements over Windline 1 were conducted on September 25, 2001.

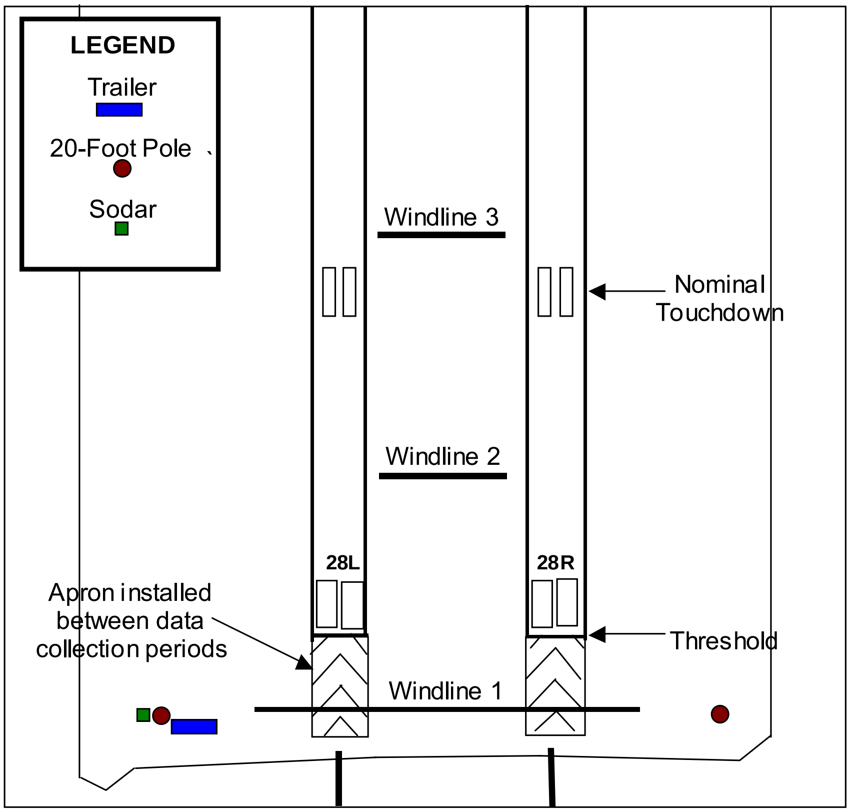

Figure S-1. On-Airport Installation of SFO WTMS

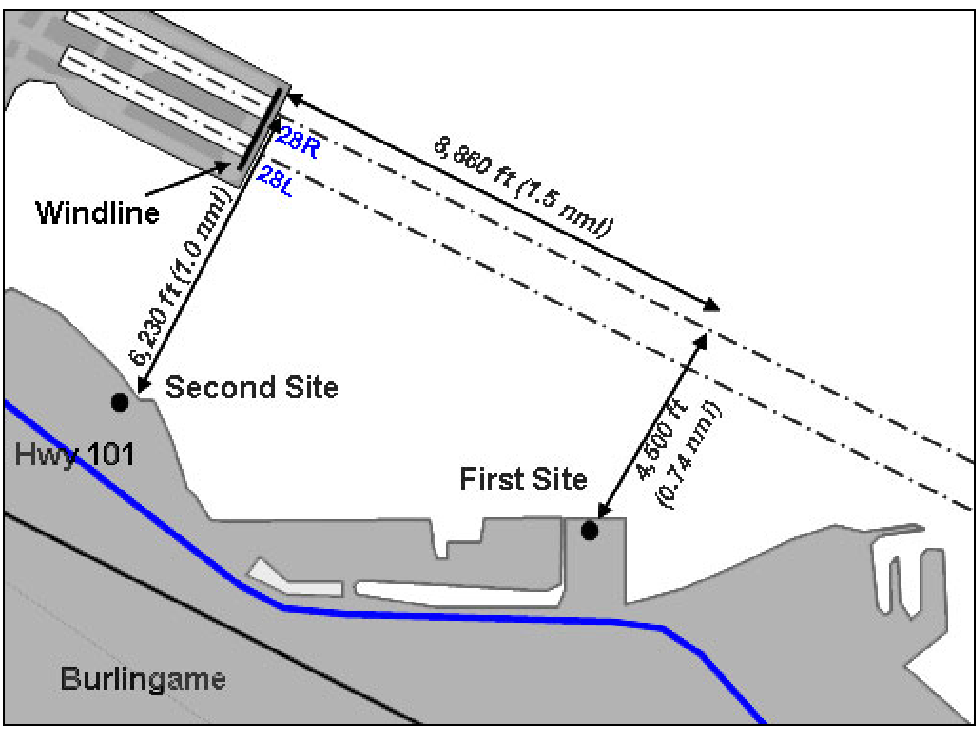

Figure S-2. Layout of SFO WTMS Showing Windline 1 and Two Lidar Sites

VALIDATION

The Windline data collection process involved validation at several levels:

- Data collection system operating correctly;
- Windline data recorded correctly;
- Enough Windline anemometers operating correctly to give valid wake detections; and
- Windline aircraft detections matched with valid arrivals.

Validation efforts were more thorough for the first data collection period. For the second period, the Windline anemometers were validated only for Windline 1, which had been determined to be the most useful for SOIA analysis.

DATA PROCESSING

Windlines

The SFO WTMS recorded Windline data in several different formats. The most useful for off-line processing was the "run" file, which contains data for one or two arrivals (one on each of Runways 28L and 28R), starting 10 seconds before the first arrival and having a maximum possible wake age (for the first arrival) of 180 seconds. If paired arrivals were separated by less than 50 seconds, then their wake data were saved in a single run file. However, if they were separated by 50 seconds or more, their wake data were stored in separate run files. For these situations, the Windline processing/ analysis program looks in both the run file containing the arrival and the following run file in order to analyze the behavior of the wakes.

Windline processing/analysis software development continued after completion of SFO data collection. The next set of Windlines installed by the Volpe Center, at Lambert – St. Louis International Airport (STL) beginning in 2003, re-enforced attention on Windlines like SFO Windlines 2 and 3 that measure only between two parallel runways. This additional attention resulted in processing improvements which have minor only impact for SFO Windline 1 but significant impact for SFO Windlines 2 and 3.

In analyzing Windline data, it should be borne in mind that Windline determinations of vortex lateral position are robust. However, as the Windline anemometers are far be below the vortex core, Windline estimates of vortex height and circulation are less reliable.

Pulsed Lidar

The CTI Pulsed Lidar was a developmental wake sensor at the time of SFO WTMS data collection. Four major versions of the wake vortex processing algorithms have been released since the WTMS Lidar data were processed, and have provided significant improvements. Generally, for the SFO Lidar data sets, vortex locations are well defined. However, the circulation values and vortex identification have uncertainties. Future analysis of SFO Lidar data must take account of these issues and should consider re-processing the recorded "raw" data using the most recent software release.

1. INTRODUCTION

This section explains the rationale for the San Francisco International Airport (SFO) Wake Turbulence Measurement System (WTMS) data collection effort and outlines the rest of the report.

1.1 APPROACHES TO CLOSELY-SPACED PARALLEL RUNWAYS

Separation standards for *instrument* approaches to a single runway prevent hazardous wake encounters by requiring increased longitudinal spacing (from those based on radar considerations) when an aircraft in a lighter wake class follows an aircraft in a heavier class (Table 1-1). The same longitudinal spacing rules are utilized for aircraft approaching Closely-Spaced Parallel Runways (CSPR, defined as having centerline spacing less than 2,500 feet) under instrument rules.* That is, CSPR are treated as a single runway (arrival traffic are regarded as a single stream) for wake separation purposes. This “2500-foot rule” greatly reduces the utility of CSPR.

Table 1-1. FAA Aircraft Wake Turbulence Classes

Class	MCGTOW* (W, k lb)
Heavy	255 < W
B-757	N/A
Large	41 ≤ W ≤ 255
Small	W < 41

* MCGTOW = Maximum Certificated Gross Takeoff Weight

SFO has crossed pairs of parallel runways (Figure 1-1), both pairs having centerline spacing of 750 feet. When visual approach operations (VAOs) are permitted, simultaneous paired arrivals on Runways 28L and 28R are often conducted, with simultaneous departures intermixed on Runways 1L and 1R. FAA Order 7110.65, *Air Traffic Control* (Ref. 1) defines a visual approach as “ATC [Air Traffic Control] authorization for an aircraft on an IFR [Instrument Flight Rules] flight plan to proceed visually to the airport of intended landing.” VAOs are generally authorized at SFO when the ceiling is above 3500 feet and the visibility is greater than 4 statute miles. Much of the data collected by the SFO WTMS are from paired arrivals to Runways 28L and 28R.

Wake turbulence safety for CSPR arrivals is actually enhanced when the longitudinal spacing for two aircraft is kept sufficiently small that the wake from the leading aircraft does not have time to transport to the runway of the following aircraft. This wake avoidance method is used for the paired *visual* approaches normally executed on Runways 28L and 28R at SFO. When ceiling or visibility conditions deteriorate to the point that VAOs are not permitted, then the CSPR *instrument* rule must be followed and the landing capacity of Runways 28L and 28R is reduced to approximately half the visual capacity.

1.2 SIMULTANEOUS OFFSET INSTRUMENT APPROACH (SOIA) PROCEDURE

The SOIA procedure (Ref. 2) was developed as a means to recover some of the capacity lost during cloud cover below 3500 feet. The SFO SOIA involves the following airport systems: (a) a Precision Runway Monitor (PRM) consisting of a high-accuracy/high-update-rate beacon radar, radar data processing and alerting algorithms, and a color display for a dedicated controller position; (b) an

* In other contexts, CSPR is sometimes defined as parallel runways with centerlines separated by less than 4,300 feet, because, in this regime, conducting simultaneous ILS approaches during instrument meteorological conditions requires use of a precision aircraft monitoring (surveillance) system.

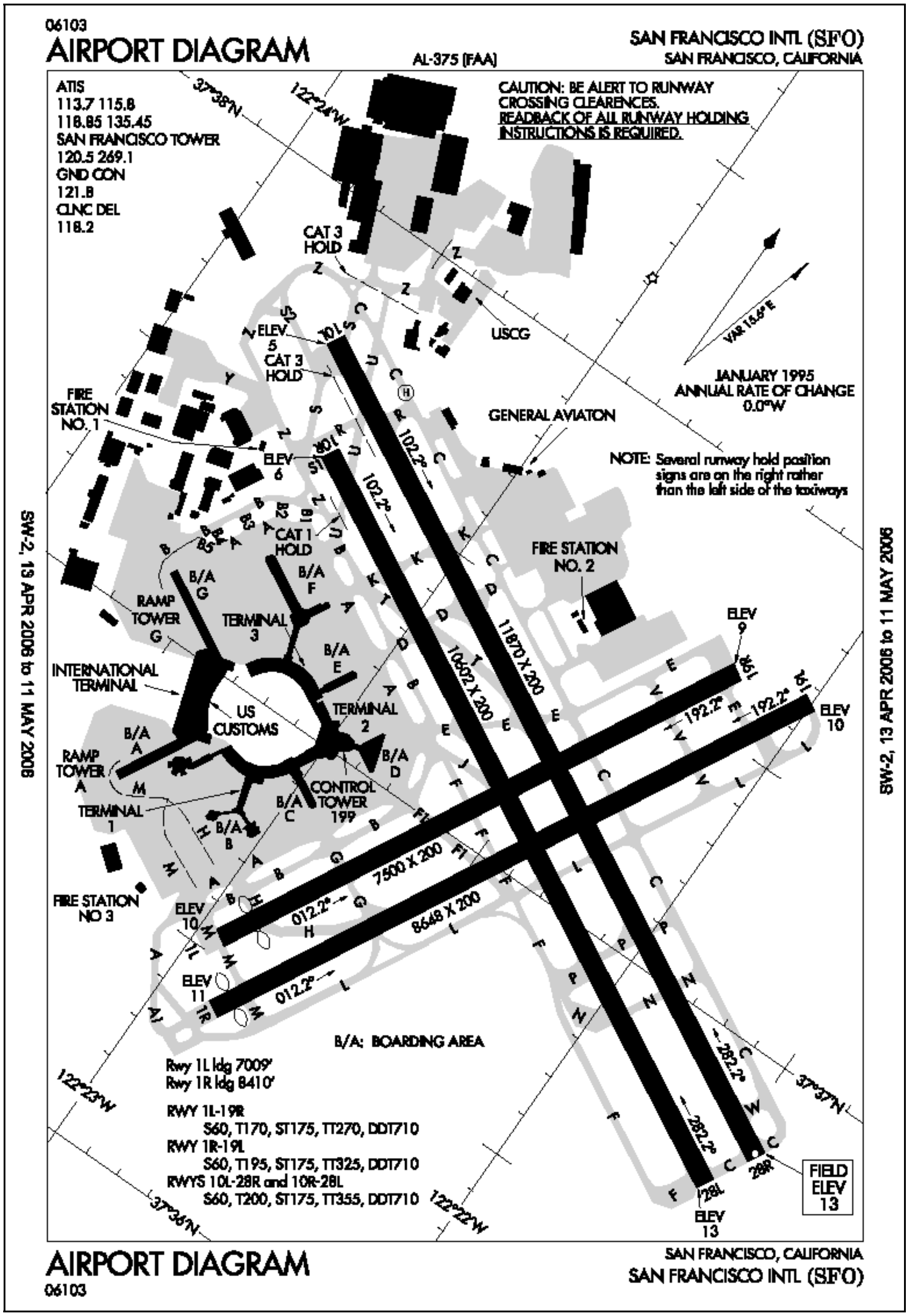

Figure 1-1. SFO Airport Diagram

Instrument Landing System (ILS) on Runway 28L; and (c) a Localizer-type Directional Aid (LDA) on Runway 28R.

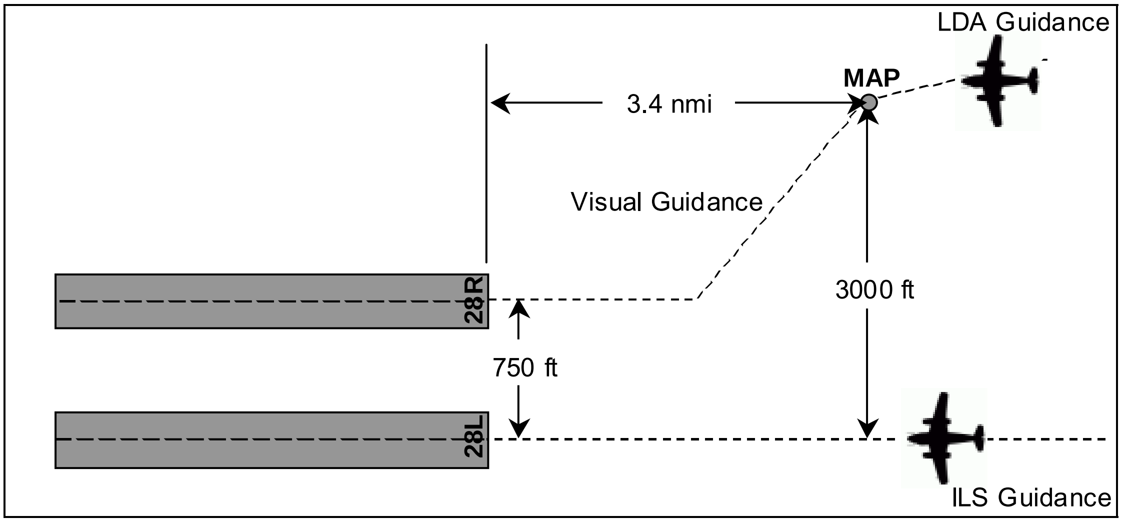

Figure 1-2 Plan View of the SFO SOIA Procedure

During operational use, the SOIA paired-approach procedure (schematically depicted in Figure 1-2) consists of the following steps:

1. The aircraft bound for Runway 28L makes a normal straight-in approach using Instrument Landing System (ILS) glide slope and localizer guidance.
2. The aircraft bound for Runway 28R makes an LDA approach, also using lateral and glide slope guidance. The LDA approach path is angled away from the runway centerline by 2.5 degrees and reaches a distance of 3,000 feet from the Runway 28L centerline at the Missed Approach Point (MAP), which is defined as 4.0 nautical miles in range from the airport Distance Measuring Equipment (DME) transponder.
3. If the pilot conducting an approach to 28R can see the 28L-bound aircraft and the ground before descending to the MAP, the pilot reports this and accepts a visual approach. If a "visual" is accepted, after reaching the MAP, the pilot performs an S-turn (or sidestep maneuver) to align the aircraft with Runway 28R and proceeds for landing. If a visual approach is not accepted, the pilot must execute a missed approach.
4. A Final Monitor Controller (FMC) is assigned to monitor the flight paths of the aircraft during the operation. The FMC utilizes surveillance data from the PRM radar, which is displayed on the PRM high resolution color display.

Relative to parallel straight-in approaches, the SOIA procedure greatly reduces the region where wake encounters might occur — namely only where the flight paths are finally lined up with the runway centerlines.

In response to the SFO SOIA plans, the Department of Transportation (DOT) Research and Innovative Technology Administration (RITA) Volpe National Transportation Systems Center (Volpe Center), in support of the FAA, conducted a wake turbulence measurement program at SFO to characterize the transport properties of wake vortices between the parallel runways 28L and 28R. This report describes the SFO Wake Turbulence Measurement System (WTMS) and documents the data collected by it.

SFO WTMS was designed to cover the region where wake encounters might occur for aircraft following the SOIA procedure (particularly the trailing aircraft approach Runway 28R):

- Windline measurements cover the region near the ground where the ground-induced motion can speed wake transport between the runways, and
- Pulsed Lidar measurements cover the region near 500-foot altitude where the crosswind might be stronger than near the ground.

Another report (Ref. 3) summarizes the SFO WTMS results pertinent to SOIA.

1.3 OTHER PURPOSES OF SFO WTMS

The geography of the Runway 28L-28R region dictated where sensors could be deployed. The location for Windline 1 was completely constrained. Windlines 2 and 3 were added to explore wake behavior in the vicinity of the nominal touchdown point. Observations of SFO traffic showed that many aircraft floated in ground effect far beyond the nominal touchdown point.

The installation of three adjacent Windlines had another advantage over earlier sensor installations. Vortex detections on the three Windlines could be connected to display the vortex location as a tube rather than simply as a point in a plane. The vortex display could be more like that obtained by flow visualization. Under most atmospheric conditions, wake vortices are invisible. As a result, their existence is known to pilots and controllers but their location and strength are unclear. To provide a better understanding of wakes, real-time displays were placed at several locations in the SFO tower building and a near-real-time display was available over the Internet.

1.4 REPORT OUTLINE

The primary intent of this report is to document the SFO WTMS sensors and the resulting datasets, so that the datasets can be used for future analyses with a full understanding of (a) strengths and weaknesses of the measurements, and (b) available processing options. Chapter 2 places the SFO WTMS in the context of wake sensor development and deployments, both prior to and after the SFO deployment. Chapter 3 outlines the SFO WTMS installation and describes the real-time and post-time processing features that were implemented. Chapter 4 provides detailed information about the datasets derived from the SFO WTMS measurements and provides guidance for selecting the correct dataset for analysis. Chapter 5 draws conclusions about the SFO dataset.

2. WAKE SENSOR DEVELOPMENT AND DEPLOYMENTS

Wake turbulence data collection by the Volpe Center at U.S. and foreign airports, under FAA and National Aeronautics and Space Administration (NASA) sponsorship, started in the early 1970s. The same sensor types have been used, in different forms, at many different airports. This chapter places the SFO datasets in the context of earlier and subsequent datasets by presenting a historical review of the wake sensors deployed at SFO — Windlines and Pulsed Lidar.* Fundamental differences in various datasets are explained.

2.1 WINDLINE

2.1.1 Concept

Windlines are based on the concept that, near the ground, every wake vortex pair generates opposite-sign crosswind peaks that are located under the vortex cores. The crosswind profile is measured by an array of single-axis anemometers installed on a baseline perpendicular to the aircraft's flight path (Figure 2-1).

Figure 2-1. B-777 Aircraft over SFO Windline 1

Windlines are not manufactured commercially. Instead they are designed and fabricated specifically for each project, based on the project technical/operational requirements and the space available near the airport's runway(s) of interest. The basic components of an airport installation are the anemometers, poles and fixtures for mounting the anemometers, dataloggers (which perform analog-to-digital conversion, real-time processing, and storage), and cabling/conduit inter-connecting the anemometers and dataloggers.

Post-test Windline data processing software has been developed to the point that algorithms can automatically estimate the lateral transport, circulation, and height of wakes from arrivals on a single runway or a CSPR pair, for an anemometer array of essentially arbitrary length, spacing and placement (i.e., in front of or beside the runway, on either or both sides). Real-time arrival wake data processing software has been developed for special situations such as SFO. Departure wakes have been measured less frequently, and their processing is less mature.

Figure 2-2 illustrates data collected by SFO Windline 1 and processed by the Windline software for a B-747-400 arrival on Runway 28R. Lateral position values are for the SFO WTMS coordinate

* Consistent with their scientific origins, the SFO WTMS instruments generally utilized the metric system for measurement and recording. However, to the maximum extent possible, the descriptions and sample results presented herein are in English units, as these are standard for aviation.

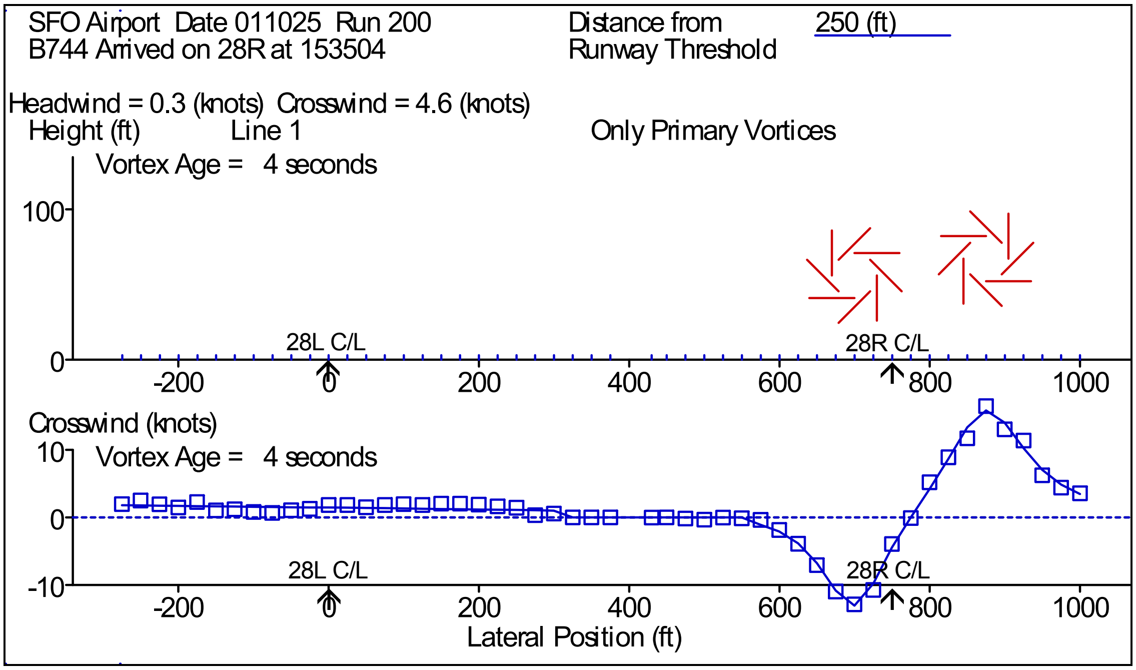

Figure 2-2. Sample SFO Windline 1 Measured and Processed Data

system: the origin is at Runway 28L centerline (C/L) and the positive direction is toward Runway 28R. The bottom plot is a snapshot of the crosswind 4 seconds after the aircraft passed Windline 1. The port vortex is sensed as a strong negative crosswind (from Runway 28R toward Runway 28L) centered at a lateral position of 700 feet. The starboard vortex is sensed as a strong positive crosswind (from Runway 28L toward Runway 28R) at a lateral position of 875 feet. Small squares depict the anemometer measurements and the solid line is a curve fitted to the measurements. The analytic form of the curve is based on a model for vortex behavior. The upper plot shows the calculated vortex locations in the plane above the Windline, based on the model (see Section 3.2.4).

2.1.2 Original Implementations

Windlines were first implemented (Ref. 4) in the 1970s, and have been used to measure landing wakes at New York's Kennedy Airport (JFK), Denver's Stapleton Airport (DEN), London's Heathrow Airport (LHR) and Chicago's O'Hare Airport (ORD). Windlines have also been used to measure departure wakes at Toronto's Pearson Airport (YYZ) and ORD. Characteristics of these Windlines are:

- Crosswind propeller anemometers were installed at a height of 10 feet and lateral spacing of 50 feet.
- Anemometer signals were sampled at 16 Hz and stored (originally on magnetic tape).
- An on-site operator identified the aircraft generating the measured wakes.
- Windline data were processed in 2-second blocks. Visual data analysis used printer plots showing: (a) the location of the anemometers having largest positive and negative crosswind values, and (b) the number of the 32 samples that indicated the peak crosswind. The track was terminated when the peak anemometer jumped discontinuously to a different location.

2.1.3 Recent Implementations

The current series of Volpe Center Windline installations started at JFK airport, on the approach to Runway 31R:

- Both vertical wind and crosswind anemometers were installed on 28-foot poles with 50-foot lateral spacing.
- Data were recorded as 2-second averages.
- Data collection and processing were both completely automated.
- An analytic model was fitted to the data and then used to estimate vortex circulation and height, in addition to lateral position. The height and circulation values are, however, less robust than the lateral position values.

Implementations similar to the JFK Windline were installed at other airports, with changes dictated by airport-specific considerations. For example, the SFO deployment addressed in this report had the following differences:

- Because of the Windlines proximity to the runways, 3-foot poles were used (see Figure 2-1). At that height the vertical wind component is effectively zero, so only the crosswind component was measured. However, the pole spacing was halved to 25 feet, to give the same spatial measurement rate for use in fitting the data to a model.
- Because anemometers could not be installed on the runways, the second and third SFO Windlines could not completely cover the region under the approach path. Consequently, vortex detection had to wait for wake lateral transport onto the Windline, not just vertical descent.
- The Windline processing algorithms/software had to be modified to permit simultaneous tracking of wakes generated by arrivals on both runways; as many as four vortices could be present at the same time.

Windlines have the following limitations:

- Vortex detection is effective for wakes generated near the ground or descending toward the ground. However, detection sensitivity for vortices rising from the ground can be much less than for vortices remaining close to the ground. Thus, the apparent lifetimes for rising vortices can be shorter than their actual lifetimes.
- When vortices are transported laterally by the ambient crosswind, the downwind vortex usually rises because of interaction with the ambient windshear at the ground. Thus, care must be taken in analyzing Windline transport distances from these vortices, which present the most significant safety risk for CSPR operations.

2.2 PULSED LIDAR

The Pulsed Lidar represents a major improvement in spatial coverage (up to several thousand yards) over the Continuous Wave (CW) Lidar that was developed in the 1970s. The CW Lidar obtained range resolution by beam focusing, and had a maximum effective range of approximately 250 yards.

2.2.1 Concept

Pulsed Doppler Lidars function by transmitting pulses of light into the atmosphere and detecting frequency shifts that are induced by motion of natural particulates or aerosols suspended in the atmosphere. The motion of the scatterers, arising due to the wind and/or vortex, alters the frequency of the scattered light via the Doppler effect. The return signal is detected by a photodetector, and the resulting electrical signal is then amplified, digitized and analyzed via various spectral techniques. The processed return signals for multiple pulses are averaged together as the system's scanner is swept through the region of interest. Time gating, coupled with the pulsed transmission, enables resolution of features in range. The Doppler Lidar can only sense the component of the local velocity vector that is along the beam look direction (i.e., line-of-sight velocity).

The Doppler lidar pulses travel through the atmosphere at the speed of light and operate at an infrared wavelength of around 2 microns (0.000,006,6 feet). This short wavelength helps counteract the fact that any pulsed remote sensor has a tradeoff between range and velocity resolution that depends upon the speed of propagation and the wavelength of illumination. At the 2 micron wavelength, the laser light is invisible to the naked eye and is eyesafe at power levels that give good backscatter signals from natural aerosols in the atmosphere.

2.2.2 Recent Implementations

In the early 1990s the Air Force and NASA funded the initial Pulsed Lidar development for wake measurements. The NASA Pulsed Lidar used a Coherent Technologies, Inc. (CTI) transceiver and was deployed at JFK airport from 1996 through 1998 and at Dallas-Fort Worth (DFW) airport in 2000. NASA developed its own processing algorithm for these tests. CTI developed an alternative algorithm using Air Force and NASA data. The first wake measurements with the current CTI Pulsed Lidar system were conducted at DFW in 2000. The SFO WTMS was the first major deployment of the current CTI Pulsed Lidar for wake measurements (Figure 2-3).

Figure 2-3. CTI Pulsed Lidar at SFO

The CTI Pulsed Lidar operates with a range resolution of 200 feet and a velocity resolution of less (better) than 6 feet/second. Pulses are transmitted at 500 Hz. Spectra are generated in real time for overlapping range gates with spacing less than 200 feet. Spectra are averaged over 25 pulses to reduce fluctuations, resulting in an update rate of 20 Hz.

The Lidar beam is expanded to an aperture of approximately 4 inches before it enters the scanner. The Lidar scanner can point the beam in azimuth and elevation. The most useful wake scan mode uses a fixed azimuth angle perpendicular to the flight path and scans through the wake in elevation.

Elevation angle resolution depends upon the scan rate and the update rate and is adequate to give vertical wake locations to better than 10 feet. The wake processing looks for the peak response from the high velocity Doppler components near the vortex core, and can achieve a range accuracy much better than the 200-foot pulse resolution.

2.3 AIRCRAFT DETECTION AND IDENTIFICATION

For each aircraft for which wake data are collected (by Windlines, Lidar or other sensor), one or more means must be in place for (a) determining the time that aircraft passes the wake sensor, and (b) identifying the aircraft type — preferably, the make, model and series. In the original Windline implementations — e.g., at JFK, DEN and ORD — an operator was stationed near the windline and observed/recorded the aircraft passage time and its type. At SFO both of these functions were automated. Acoustic noise and camera images were used for aircraft detection (see Section 3.3); a Mode S radar receiver and the Total Airport Management Information System (TAMIS) were used for aircraft identification (see Section 3.4).

3. SFO WTMS INSTALLATION

3.1 DATA COLLECTION ARCHITECTURE

3.1.1 Requirements

The SFO WTMS wake sensors were sited to support evaluation of the proposed SOIA operational procedure (Section 1.2). In contrast, the data collection system fed by the wake and supporting sensors was designed to meet two engineering/data management requirements:

1. Data could be processed in both real time and post time.
2. Data collection system could be accessed remotely for real-time processing, trouble-shooting and data transfer.

3.1.2 Implementation

As shown in Figure 3-1, the SFO WTMS was (except for the Pulsed Lidar) implemented using an array of sensors on the airport surface and an Ethernet local area network (LAN) with components at two sites — the Shadow Cab located near the ATC Tower, and the Data Collection Trailer located adjacent to the Runway 28L threshold. The two network sites were connected by a fiberoptic link. The data collection computers in the trailer used the personal computer Microsoft Disk Operating System (DOS), which is efficient for handling real-time processing. Measurements from the data collection computers were synchronized by reading time from the fileserver, which in turn was synchronized to a Global Positioning System (GPS) receiver. All data files were stored on the fileserver, where they could be accessed by other computers. Real-time data processing was implemented using personal computers running Microsoft Windows.

3.1.2.1 Data Recording Files

The main data collection computer had multiple serial ports to ingest data from the Windline dataloggers and other sensors. Data were written to a number of different files:

- The file *current.dat* contained all the measurements for the past minute, i.e., one-minute data blocks.
- The file *WMMmmDdd.Yyy* (mm=month, dd=day, yy=year) recorded all the one-minute data blocks for a day.
- The file *local.dat* contained the last 2-second block of Windline data.
- Run files (*RMyymmdd.nnn*, where nnn is the run number for the day) contained 2-second windline data blocks data from 10 seconds before the first arrival of a pair until 180 seconds after the first arrival of a pair or until the next arrival 50 seconds or more after the first arrival.
- The file *currrun.dat* contained 2-second windline blocks up to the present for the current run.

3.1.2.2 Real-Time Processing

Real-time processing involved two programs:

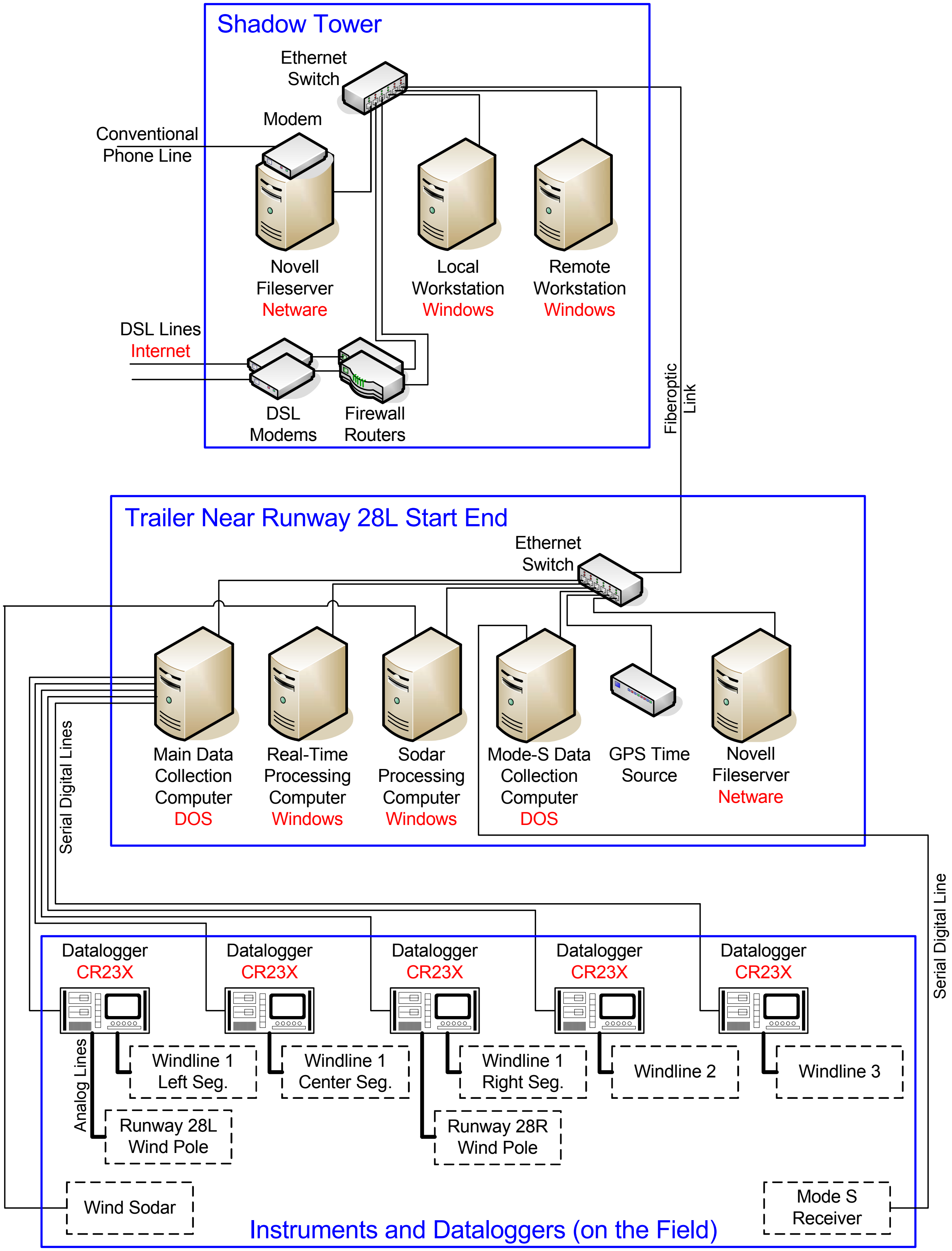

Figure 3-1. SFO WTMS Network Architecture (Except Pulsed Lidar and Cameras)

- The first program (a) read the *current.dat* file, (b) calculated means and standard deviations for the minute for each windline measurement and recorded them in the file *DMMmmDdd.Yyy*, and (c) calculated the crosswind turbulence and stored 5-, 10-, 15- and 20-minute averages in the file *currturb.dat*. To avoid wake contamination, the crosswind turbulence for each minute was taken as the smaller of the crosswind standard deviations for the two 20-foot poles on opposite sides of Runways 28L and 28R (see Figure 3-2).
- The second real-time program processed the windline data for wake vortices using (a) *local.dat*, (b) *currrun.dat* or (c) the last run file as the data source.

3.2 WINDLINES

3.2.1 Airport Installation

Figure 3-2 depicts the locations of the three Windlines. As discussed in Section 2.1.3, the SFO WTMS was the fourth Volpe Center Windline installation employing automatic/unstaffed data collection (after JFK in 1994, Memphis Airport (MEM) in 1996, and DFW in 1997). Real-time data processing started with the DFW installation and continued at SFO. The SFO installation involved several significant changes from earlier sites, which monitored arrival wakes on a single runway with a single Windline:

1. Data collection logic accommodated paired arrivals, which are frequent at SFO. Two aircraft noise detectors were used, one for each runway.

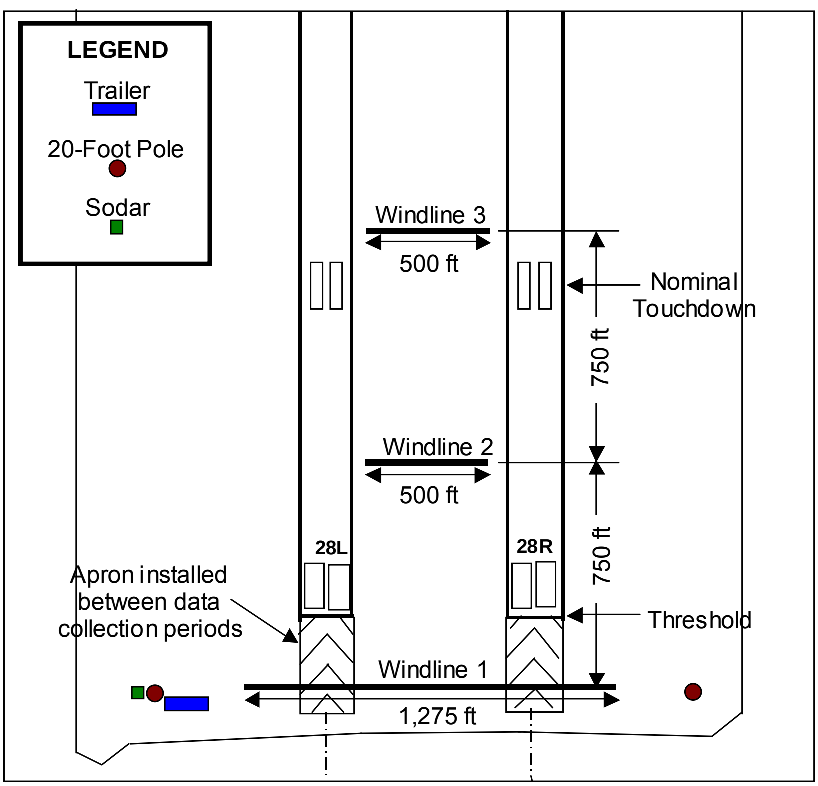

Figure 3-2. SFO WTMS Equipment Locations

2. Pole height was reduced from 28 feet to 3 feet because of proximity to the runways. At this low height the vertical wind component of the vortex is insignificant and was not measured.
3. Three Windlines were installed at different positions along the CSPR. Because two of the Windlines did not cover the approach path, vortex detection had to wait until vortices drifted onto the Windline.

WL1 was located 250 feet before the runway thresholds and completely covered the region between and adjacent to the runways. WL1 had crosswind anemometers located at lateral positions -275 feet to +1,000 feet[*], spaced by 25 feet for a total of 51[†]. This coverage enabled wake vortices to be detected as soon as they reached ground effect. Windlines that extend well past both sides of a runway (or its longitudinal extension) are termed "normal" and were also deployed for the three earlier airport tests.

Windlines WL2 and WL3 were located 500 feet and 1,250 feet past the runway thresholds, respectively, but covered only the region between the runways. WL2 and WL3 each had 21 crosswind anemometers, located at lateral position between 125 feet to 625 feet and spaced by 25 feet. Such Windlines are termed "abnormal," and their use at SFO required development of new processing algorithms. WL2 and WL3 could detect wake vortices only after they had transported laterally onto the Windline. Wakes sensed by WL2 and WL3 were generated in ground effect.

3.2.2 Sample Wake Behavior

Figure 3-3 shows the Windlines in one of the display formats developed during the project. It shows a plan view of the SFO Windlines with overlays of the ambient wind vector and wake locations. The wakes are for a paired arrival with a B-747-400 (abbreviated B744) landing first on Runway 28R and a B-737-300 (abbreviated B733) arriving 22 seconds later on Runway 28L. The wind vector is shown at the left between the runways; a 5-knot crosswind from 28R toward 28L is depicted. The vortices are plotted as black lines with colored symbols at the Windlines where the vortices were detected. The display shows the two wake vortices from the B744 30 seconds after its arrival (at WL1, where the aircraft noise detectors were located). The port vortex from the B744 (green X) is detected on all three Windlines and (consistent with the wind direction) has transported part way toward Runway 28L; however, it did not pose a threat to the B733 aircraft. The starboard vortex (orange □) from the B744 aircraft remains near the centerline of Runway 28R and hence is detected only by WL1. The B733 can be seen on Runway 28L, 8 seconds after it passed the aircraft detector on Windline 1 (WL1). The two wake vortices from the B733 are detected at WL1 (red ◇ and red +).

3.2.3 Windline Hardware

As shown in Figure 3-4, the SFO Windlines were arrays of single-axis propeller anemometers (manufactured by the R.M. Young Company, model number 27106), oriented to measure the crosswind, mounted on 3-foot poles. All poles had crosswind anemometers, and some (e.g., the end pole in Figure 3-4(b)) also had headwind anemometers.

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[*] Lateral positions are measured relative to the Runway 28L centerline, with the positive direction toward Runway 12R.

[†] For Windline 1, a pole was not installed at lateral position +400 feet, to avoid a road.

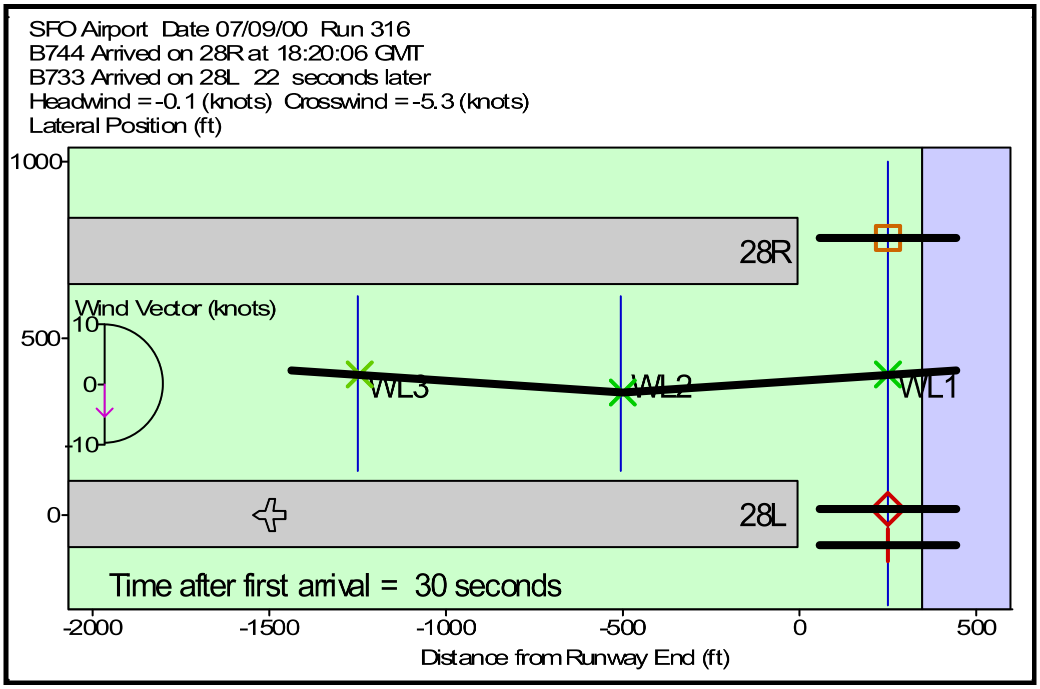

Figure 3-3. SFO Windline Display

The selection of short poles for the Windline was based on two considerations:

1. Earlier studies (Ref. 5) showed that the boundary layer under a wake vortex is very thin; thus crosswind measurements at 3 feet are not greatly reduced from those at greater heights.
2. The anemometers are located in a critical region of the airport; the 3-foot poles are reasonably frangible (several were broken by surface traffic) and do not intrude into protected airspace.

(a) Near Runway 28L Prior to Apron Construction (b) Near Runway 28R on the Apron

Figure 3-4. SFO Windline 1

The approach apron to Runway 28R posed a particular installation challenge for WL1 because it was covered with asphalt, eliminating the possibility of trenching. Figure 3-4(b) shows how WL1 was installed there. A steel pipe was nailed to the surface to support the anemometer poles and carry the cabling. Every other pole on the 28R apron measured the headwind, to give a profile of the jet blast from aircraft departing Runway 28R. Figure 3-5 shows the similar installation used during the second data collection period for the newly constructed apron of Runway 28L. A headwind anemometer was also added on the runway centerline to detect Runway 28L departures.

Figure 3-5. WL1 at Threshold of Runway 28L after Apron Construction

The Windline anemometers and aircraft detectors (see Section 3.3) were connected to five Campbell Scientific Dataloggers (model number CR23X) that can accept 24 analog inputs each. Three were used for Windline 1, and one each was used for Windlines 2 and 3. The analog signals were digitized at a 10 Hz rate and converted to 2-second averages that were sent as serial messages to the main data collection computer. Both the real-time and post-test processing used the 2-second-average data.

3.2.4 Post-Time Windline Processing

This description pertains to post-time processing, when all the wake measurements are available at the start of processing (see Section 3.1). Run files were created in real time based on outputs of the aircraft noise detectors (Section 3.3). An aircraft detection was declared when a noise peak exceeded a specified noise threshold. If paired arrivals were separated by less than 50 seconds, then their wake data were saved in a single run file. Otherwise, their wake data were stored in separate run files.

Each run file started with a header containing logistical information about the run, including the first arrival time, second arrival time (if appropriate), aircraft type(s) (see Section 3.4) and ambient wind turbulence levels (see Section 3.1). Each run file contained the data from 10 seconds before the first arrival to the lesser of (a) 180 seconds after the first arrival or (b) the time of the next arrival at

50 seconds or more after the first arrival. When the processing program encounters a run file shorter than 180 seconds, it retrieves the rest of the data from the next run file.

The automatic processing is most easily understood for a single aircraft arrival, where only two wake vortices are present: the starboard vortex induces a positive crosswind peak and the port vortex induces a negative crosswind trough. The processing incorporates two basic concepts:

- For each 2-second snapshot of Windline measurements, the characteristic signature of a wake (Figure 2-2) is detected by comparing the negative and positive crosswind extrema to the median crosswind. The differences between the extrema and the median crosswind (both positive numbers), called the Maximum Vortex-Induced CrossWind (MVICW), must both exceed a tracking threshold to declare a vortex present. Before a vortex is first detected, the MVICW are compared to the start-track threshold. After a vortex detection is declared, the MVICW are compared to the stop-track threshold.
- The snapshot-detected vortices are then validated by looking for consistency at different wake ages. The validation process starts at the wake age when the largest vortex induced crosswind is detected, and then proceeds both backward and forward in time. During validation the stop-track threshold is used at both the beginning and end of the track.

Figure 3-6 summarizes the SFO Windline data post-test processing. Additional details are provided in the following list, numbered according to Figure 3-6:

1. (a) Run files are opened sequentially. When the file being processed does not contain the full 180 seconds of data, then the next run file of the day is opened to provide the rest of the data. This method fails only for the last run of the day. (b) Measurements are invalidated for anemometers listed in a failed anemometer file or if the magnitude is greater than 50 knots. Some types of measurement errors are corrected for specific anemometers. (c) To avoid tracking wind gusts under turbulent conditions, the start-/stop-tracking thresholds are each assigned to the larger of two quantities:
    - Analyst-specified minimum start/stop tracking thresholds
    - The 10-minute crosswind turbulence level (determined by the real-time processing) multiplied by analyst-specified start/stop factors.
2. The median crosswind for each snapshot of anemometer measurements is taken between the two runways for Windline 1 to optimize Windline performance between the runways.
3. (a) The vortex pair is assumed to be centered on the arrival runway and separated by a nominal spacing. (b) The Windline median crosswind is scaled up from its 3-foot height to estimate the vortex lateral transport speed; the two vortices are assumed to separate in ground effect by a nominal induced transport speed. (c) The search window is set at a generous width to assure that vortices are not missed; vortices are usually found near the middle of the window. The search window is expanded with wake age to account for uncertainties in wake transport.

1. Collect Complete Set of Wake Measurements

1) Read Run Files(s), Validate and Correct 2-second Wind Measurements, and Store in Wind Component Arrays for Each Windline. Complete Dataset Includes Wake Ages from -10 to +180 seconds Relative to First Arrival.
2) Calculate Start- and Stop-Track Thresholds from 10-minute Crosswind Turbulence

2. Calculate Crosswind Parameters Used in Vortex Detection

Calculate Maximum, Minimum and Median Crosswind for each 2-second Crosswind Array for Each Windline

3. Determine Where to Look for Wake Vortices

1) Calculate Predicted Lateral Positions of All Vortices at All Windlines for All Wake Ages Assuming Ambient Crosswind = Scaled Median Windline Crosswind
2) Calculate Vortex Search Window Relative to Predicted Locations

4. Detect Wake Vortices — Must Be Located within Search Window

Start when Wake Age > Zero

1) Before First Detection: Compare MVICW to Start-Track Threshold
2) After First Detection: Compare MVICW to Stop-Track Threshold
3) MVICW is taken as difference between Max/Min and Median Crosswind

If No Detections, Stop when Wake Age > Maximum Detection Age

Assign Wake Vortices — If MVICW > Tracking Threshold:

1) First assign Maximum and Minimum Crosswind
    If Min/Max inside Search Window for Two Vortices, Assign One with Closest Prediction
2) Place Exclusion Zone around Detection—Assign Each Max/Min Only Once
3) Look for Each Unassigned Vortex inside Its Search Window but Outside Exclusion Zone

5. Validate Vortex Trajectories

1) Start at Age with Highest MVICW (Best Windline Measurement)
2) Track Backwards to Earlier Ages
3) Track Forward to Later Ages
4) Stop Track If
    Location of MVICW Jumps by Too Many Poles
    Track Goes off End of Windline
    MVICW is below stop-track threshold for longer than 6 seconds

6. Fit Crosswind Measurements at Each Wake Age to Wake and Ambient Crosswind Parameters

1) Derive Initial Parameter Estimates from Windline Data
2) Assign Initial Parameter Change Increments
3) Systematically Change Parameters Up and Down by One Increment to Reduce Sum of Squared Differences (SSD) between Calculated and Measured Crosswinds
4) Exit If Process Does Not Converge (Too Many Changes)
5) When No Possible Changes Will Reduce SSD, Divide Increments by Two and Repeat
6) Stop after Third Division by Two

7. Output Measurement Results—Most Important Are

1) Windline Status File—Maximum Age in Data; Detection Count, First & Last Age for Each Vortex
2) Vortex Measurement File—Tracks and Fitted Parameters
3) Meteorological File—Average and Standard Deviation over Age 0-60 seconds for: Windline Median Crosswind, Three Wind Components from 20-foot Poles)

Figure 3-6. Summary of SFO Windline Processing

4. The initial vortex detection process looks independently at the data for each snapshot. (a) For Windline 1 the maximum vortex detection age was set at 18 seconds; this low value results in missing (failing to detect) a small percentage of vortices from Large aircraft (e.g., B-737) but prevents the detection of wind gusts near the opposite runway that would interfere with the primary purpose of the SFO data collection. For Windlines 2 and 3 the maximum detection age was set at 60 seconds to give vortices sufficient time to drift onto the Windlines.
(b) Vortex detection requires that the MVICW found by the Windline be greater than the tracking threshold (the MVICW is always positive). (c) When wakes from two arrivals are present, each identified peak or trough in the crosswind must be matched with the arrival that generated it.
5. The validation process looks for consistency in all the detections for each vortex. Validation starts at the age with the strongest Windline signal and tracks backwards and forward in time.
6. The fitting process uses the image model to calculate the vortex flow field. The vortex parameters are lateral position (initial value equal to the MVICW anemometer location), circulation/height ratio* and height (nominal initial value). A fixed ambient crosswind is added to the vortex flow field (initial value equal to the median crosswind). For long Windlines (such as Windline 1) a gradient is also added (zero initial value).
7. A number of other output files are generated. For configuration control, each line in the output files contains (a) the software version, (b) the Windline configuration and (c) the processing parameter set.

The many Windline processing parameters were selected to produce reliable vortex tracks.

- The vortex search windows were made large enough to be sure that no vortices were overlooked.
- The start- and stop-track turbulence factors were set to eliminate wind gust detections for a set of runs with high turbulence levels.
- The minimum start- and stop-track thresholds are less easily defined. A stop-track threshold of 1.0 meters/second (approximately 2 knots) generally produces realistic tracks; the wake durations are, however, significantly longer than current separation standards (see Section 4.2.6). A stop-track threshold of 2.0 meters/second (approximately 4 knots) gives a better match between wake duration and current separations standards and was selected for early processing of SFO Windline data.

Other choices for tracking parameters are discussed in Section 4.2.1.

3.3 AIRCRAFT DETECTORS

3.3.1 Noise

Figure 3-7 shows the two aircraft noise detectors for the second data collection period. Each runway had a noise detector located at WL1, next to an electronic interface box on the side of the runway

* Circulation/height is proportional to MVICW, which is well determined by a Windline and is used as the initial parameter estimate. The fitting process may not converge if circulation and height are used as independent parameters.

closer to the other runway. The detection logic disabled a detector for 25 seconds after an arrival detection (to prevent multiple triggers from the same arrival) and treated arrivals within 48 seconds of an arrival detection on the other runway as the second arrival of a pair.

Figure 3-7. Aircraft Detector Locations for Both Runways after 28L Apron Construction

Each aircraft detector used a horn loudspeaker as a microphone, obtaining its basic directionality from the horn, which was pointed up toward the arriving aircraft. Figure 3-8 shows close-ups of the aircraft detectors in Figure 3-7. Plywood shielding reduced the detector response to arrivals on the opposite runway and to departures.

For the first data collection period the 28L aircraft detector was mounted on the runway centerline rather than on the side. This difference in location did not produce a significant bias in the aircraft arrival times.

Figure 3-8. Aircraft Detectors: Runway 28L (left), Runway 28R (right)

3.3.2 Video

Video cameras were installed in the trailer to view arriving aircraft. Two were connected to a device that could be accessed remotely via telephone line. A third was connected via Ethernet to the LAN, where it could be accessed from any networked computer. Thus, a computer showing the real-time wake display in one window could show video of the arriving aircraft in another window.

3.4 AIRCRAFT IDENTIFICATION

A major challenge for automatic/unstaffed data collection is identification of the arriving aircraft. The Windline aircraft noise detections on the two runways must be matched with identification data from another source.

3.4.1 Mode S Receiver

Aircraft equipped with a Mode S radar transponder (which includes all Part 121 aircraft having 30 or more passenger seats) broadcast, once per second, a unique 24-bit code that identifies the tail number. A Mode S receiver was deployed at SFO during the second data collection period. It could identify aircraft in the vicinity, but could not readily determine the landing runway (this is not one of its intended functions). An algorithm was developed to (a) estimate the landing runway from Mode S data in real time, and (b) incorporate aircraft types into the run file header. This algorithm was used for the displays described in Section 3.6.

3.4.2 TAMIS

The SFO Noise Office provided aircraft arrival data for the entire test period from the airport TAMIS. TAMIS arrival times and runway determinations are derived from surveillance radar data, and have greater time variability and poorer runway accuracy than the Windline noise detectors. (Part of this lack of accuracy may be due to the fact that SFO does not have a surveillance radar on the airport; instead, surveillance service is provided by the Oakland airport radar.) Matching noise and TAMIS arrival times gave a typical spread (full width at half maximum) of 7 seconds with broad tails. The matching process accepted arrival-time matches within ±15 seconds. The highest quality matches (approximately 80%) had unique TAMIS and Windline arrivals within the arrival time tolerance. Other, less precise methods were used to match the rest of the arrivals, which were included in two or more TAMIS-Windline matches.

Figure 3-9. Sodar and 20-ft Anemometer Pole (beyond Runway 28L end of WL1)

3.5 METEOROLOGICAL SENSORS

Because wake behavior is known to depend strongly on meteorological (especially wind) conditions, a number of sensors were deployed (see Figure 3-2 for their locations) and/or used to determine the meteorological conditions:

1. Three-axis anemometer configurations* were installed on 20-foot poles on both ends of WL1. One pole was located 500 feet to the right (as seen from an approaching aircraft) of the extended Runway 28R

* The same single-axis anemometer model was used for the Windlines.

centerline. The other (Figure 3-9) was located 686 feet to the left of the extended Runway 28L centerline.

2. A Sodar (originally Aerovironment Model 3000, later Model 4000) was installed near the left 20-foot pole (see Figure 3-2 and Figure 3-9). The Model 3000 can measure the vertical profile of the three wind components up to a maximum height of 1,000 feet. The Model 4000 operates at a higher frequency and measures to a maximum of 656 feet. The maximum height actually achieved depends upon atmospheric conditions and is often much less than the manufacturer's stated value. The Sodar generated 2- or 5-minute averages (selectable) of the ambient wind.
3. A Vaisala Lidar ceilometer was installed near the trailer to measure the cloud ceiling, which is the major limitation on visual approaches to SFO Runways 28L and 28R. The ceilometer measured possible cloud hits twice a minute.
4. The SFO Automated Surface Observation System (ASOS) — provided and maintained by the FAA — is located in the vicinity of the crossing point of the four SFO runways (see Figure 1-1). ASOS archives wind measurements every minute (2-minute averages from a 33-foot pole) and ceiling/visibility measurements every 5 minutes.

3.6 PULSED LIDAR

A Pulsed Lidar was leased from and operated by Coherent Technologies, Inc. (CTI) for one month at the beginning of the second data collection period (Ref. 6). The Lidar was installed at two sites (Figure 3-10). At the First site (the one used most), it was installed in a parking lot next to San Francisco Bay, where it had a clear view of aircraft approaching Runways 28L and 28R at approxi-

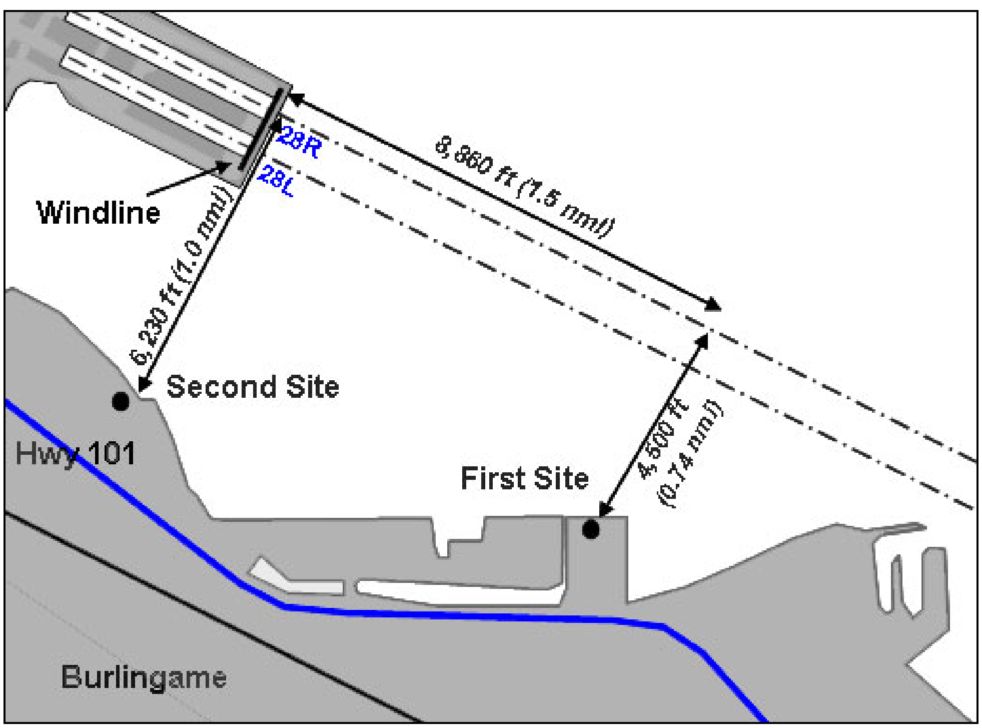

Figure 3-10. Two Lidar Sites Near SFO Airport

mately 500 feet above ground level (Figure 2-3 and Figure 3-11). This is roughly the height at which an aircraft intending to land on Runway 28R using the SOIA procedure will first be aligned with the runway's extended centerline (Figure 1-2). The Lidar was at the Second site for one day (September 25, 2001), to collect data for comparison with Windline data.

Figure 3-11. B-747 Viewed above Pulsed Lidar Housing

3.6.1 Capabilities

The CTI Lidar has the following capabilities:

1. Transmits 500 pulses/second.
2. Measurement starts at a minimum range of 1000 to 1300 feet.
3. Real-time processing generates spectra from each received backscattered pulse for up to 80 range gates, whose spacing is generally less (better) than the nominal range resolution based on the pulse width.
4. Before being recorded, 25 spectra are averaged to give stable information for each range gate. The resulting spectrum recording rate is 20 per second for each range gate.
5. The Lidar scanner can aim the beam in any direction by scanning in azimuth and elevation. Figure 3-12 shows the two scanner windows. The larger window is for the laser beam and the smaller window is for a video camera that is bore sited with the laser beam and can be used to determine the pointing direction of the beam. The video display includes the current time, and hence can be used to visually determine the arrival time of an aircraft in the beam.

(a) Front View (b) End View

Figure 3-12. Pulsed Lidar Scanner

6. In single-plane wake-vortex mode, the Lidar scans a specified elevation angle range at a fixed azimuth angle; scan time is typically 3.5 seconds (providing averaged spectra for 70 different elevation angles at each range gate), with a 1.5-second return to the initial elevation angle while the data from the scan are processed. Thus, the update rate is one wake measurement every 5 seconds.
7. In dual-plane wake-vortex mode, the Lidar executes the elevation angle scan alternately at two different azimuth angles; the azimuth angle is changed during the 1.5-second return time of the elevation scan. The update rate in each plane then becomes every 10 seconds.
8. The Lidar can measure the line-of-sight ambient wind and turbulence levels simultaneously with the wake turbulence scan. It can also make complete wind profile measurements using a Velocity Azimuth Display (VAD) scan mode.
9. The Lidar can be scheduled to operate in its various modes automatically. For example, a VAD scan can be conducted every 15 or 30 minutes while the Lidar is otherwise in the wake vortex mode.
10. Real-time wake-vortex analysis examines a window defined by the operator. Aircraft passages through the analysis plane are detected via their wakes. The first detection is typically used as the arrival time, but corrections are possible. Current software can handle the wakes from two aircraft simultaneously.
11. The vortex detection algorithm uses a matched filter method to identify vortex location and circulation. The two vortices have opposite circulation values and are designated "positive" (the nearer) and "negative" (the farther) vortices.
12. Recorded data files can be processed in post-time by the same software used for real-time processing. The processing parameters can be optimized for off-line processing.
13. Off-line processing consists of two steps. The first step produces track files of vortex-like structures found in the atmosphere; some are wind eddies, not wake vortices. The second matches the detected vortices with aircraft arrivals and validates the track files.

3.6.2 Operational Modes

At SFO the Lidar operated in three modes:

1. Wake Mode – Elevation angle is varied (scanned) up and down at a fixed azimuth angle. This mode permits simultaneous tracking of wake vortices and measuring the vertical profile of the line-of-sight wind component. The azimuth angle was selected to scan in a plane perpendicular to the extended runway centerline, and low elevation angles were used. Thus, line-of-sight wind is approximately the crosswind component.
2. Plan Position Indicator (PPI) Mode – Scan angle is varied continuously in azimuth with a fixed elevation angle, typically less than 3 degrees. The resulting line-of-sight velocity field shows the irregularities in the atmospheric flow field.
3. Velocity Azimuth Display (VAD) Mode – Measurements are made at eight discrete azimuth angles with 10-degree elevation angle. Measurements at each range are fitted to best estimate of wind speed and direction. Measurements give the wind profile above the Lidar. The low

elevation angle was selected to give a minimum measurement height of 230 feet, considering the minimum range limits of the Lidar. However, the low elevation angle means that the measurements represent an average over a large horizontal region.

The Lidar can be programmed to invoke the three modes according to a schedule. The usual SFO schedule involved operation in Wake Mode most of the time, with PPI and VAD scans performed every 30 minutes. Each time period and mode in a schedule generates its own (a) spectra files and (b) product files from real-time processing. The Wake-Mode product files contain vortex tracks. The VAD product files contain wind profiles.

3.6.3 Real-Time Display

Lidar operation can be monitored by a real-time display of processed data.

3.6.3.1 Elevation-Angle Scan Mode

Figure 3-13 shows the display of the normal windows for the elevation-angle scan mode; the first five windows are related to the vortex detection algorithm:

Figure 3-13. Real-Time Screen for Lidar Elevation-Angle Scan Mode

1. Top-Left — Vortex lateral position for many scans. The first three windows are updated after every elevation-angle scan and show the data from three aircraft arrivals, two on Runway 28R and one on Runway 28L.
2. Middle-Left — Vortex height for many scans.
3. Bottom-Left — Circulation for many scans.
4. Top-Right/Center — Last-scan location likelihood in the range-height plane: positive vortex. The tracking algorithm uses a matched filter to find the maximum likelihood for the vortex location and circulation. The two vortices are designated positive and negative according to the sign of the circulation.
5. Middle-Right/Center — Last-scan location likelihood in the range-height plane: negative vortex.
6. Bottom-Right/Center — In-plane velocity (i.e., crosswind) versus height.
7. Top-Right — Raw spectra versus range for last pulse.
8. Middle-Right — Vortex velocity color plot in the range-height plane.
9. Bottom-Right — Shape of transmitted pulse shape.

The pictures shown here were taken near the end of the day (UTC) on September 15, 2001.

3.6.3.2 Variable Azimuth Display (VAD) Scan Mode

Figure 3-14 shows the real-time VAD wind profiles: wind direction and speed. The measurement range reaches to almost 700 meters (equivalent to approximately 2,300 feet) in altitude.

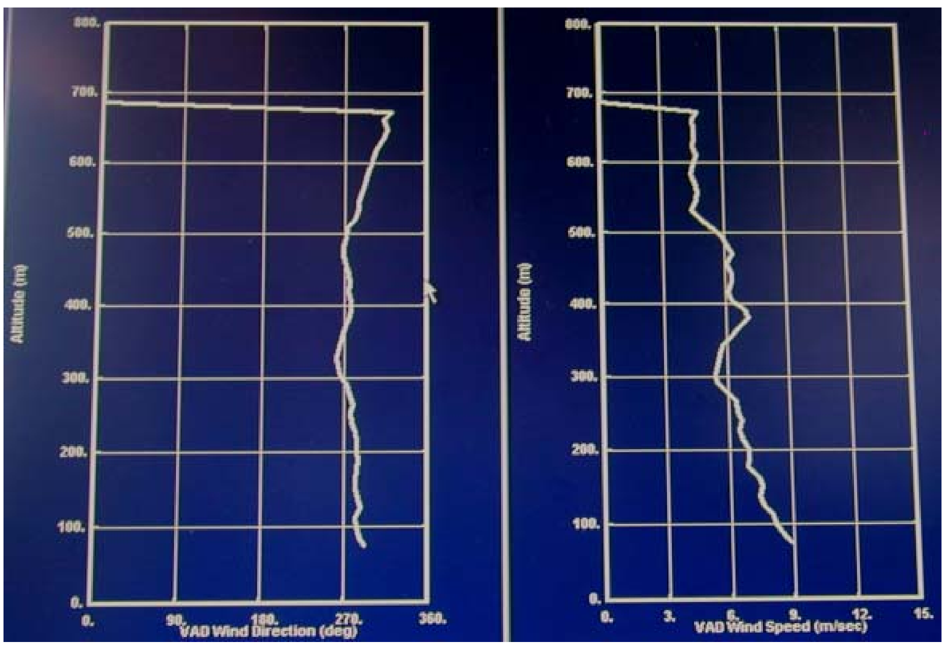

Figure 3-14. Real-Time VAD Wind Profile

3.6.3.3 Plan Position Indicator (PPI) Scan Mode

Figure 3-15 shows the real-time PPI radial wind plot; the line-of-sight wind component is color coded. The maximum range at which valid data is collected varies with azimuth angle, from approximately 3 to 6 kilometers (9,900 to 19,800 feet, or 1.6 to 3.2 nautical miles).

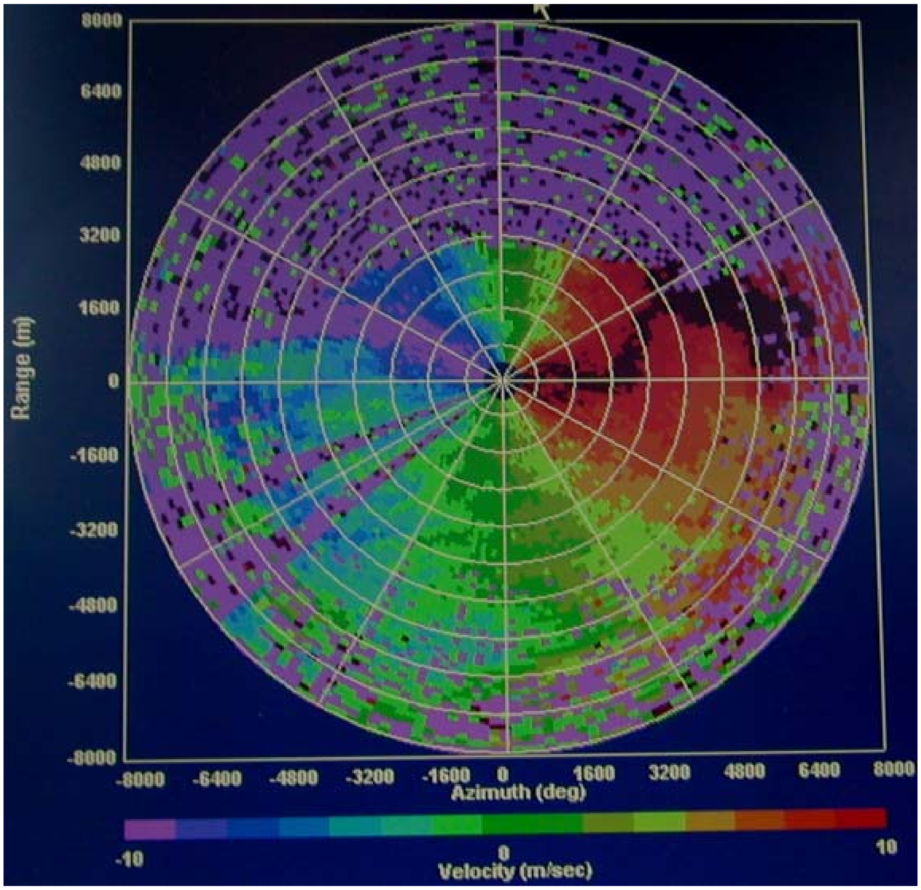

Figure 3-15. Real-Time PPI View of Radial Wind Component

3.7 REAL-TIME WINDLINE DISPLAYS

Real-time Windline displays were designed to familiarize operations personnel (e.g., controllers and pilots) with the behavior of wake vortices, which are normally invisible and hence difficult to visualize. Feedback from operations personnel led to some improvements in the original display.

3.7.1 Local Display

Initially, the real-time display required access to the WTMS LAN. Workstations were located in the Volpe Center trailer and in several locations near the control tower. The LAN could also be accessed from anywhere via telephone dial-up. The wake processing for such displays takes only a few seconds; consequently, the display on a local workstation can be readily compared with actual operations on the airfield.

3.7.2 Display Options

Figures Figure 3-16 through Figure 3-18 show the three display* options developed for real-time. The paired arrivals are the same as in Figure 3-3; several different wake ages are shown:

- Figure 3-16 shows the runways from the approach end (pilot's view).
- Figure 3-17 shows the runways from the middle of the airport (controller's view). For both of these displays the distance along the runway is greatly compressed compared to the distance between the runways.
- Figure 3-18 views the runways from above with equal scales for both axes. This view seems easiest to understand and was adopted as the usual real-time display.

On a computer monitor, the displays used to derive Figure 3-16 through Figure 3-18 fill only half a screen having 1024 x 768 pixel resolution. The actual real-time display fills an entire screen, as shown in Figure 3-19 (for an earlier wake age, to show the B744 aircraft). A number of features can be noted in Figure 3-19:

1. The aircraft icon size is scaled to the actual wingspan when the aircraft type is known.
2. The wind vector derived from the 20-foot anemometer poles is shown so that the wake motion can be understood.
3. The wake vortices are drawn as heavy lines extending beyond their detection locations.

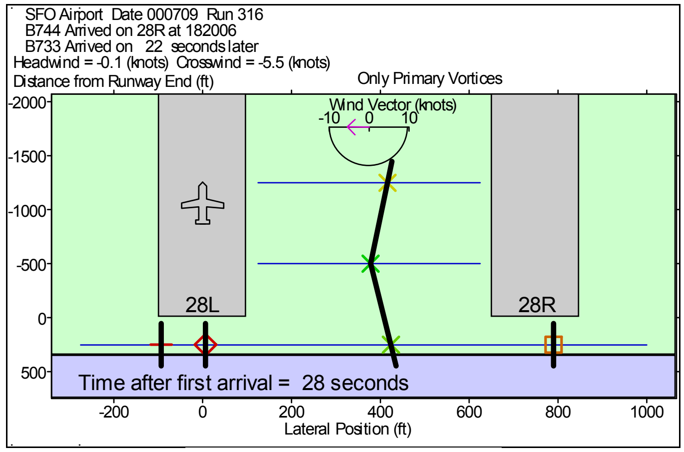

Figure 3-16. Pilot's View

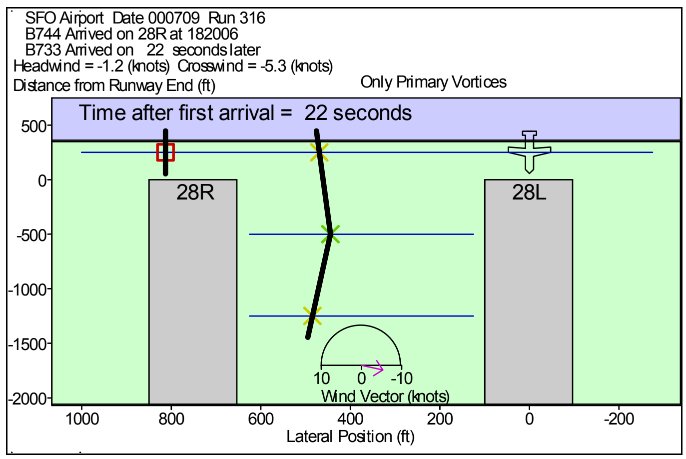

Figure 3-17. Controller's View

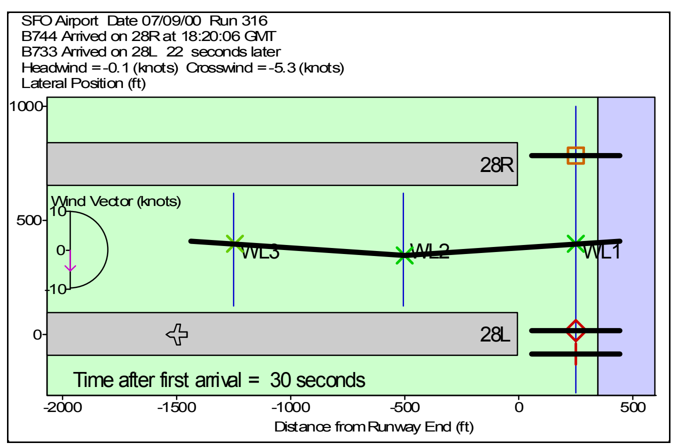

Figure 3-18. Equal-Axis Plan View

* These figures are not screen captures. Instead they are derived from Windows enhanced metafiles, which have smaller character spacing than observed on a computer screen.

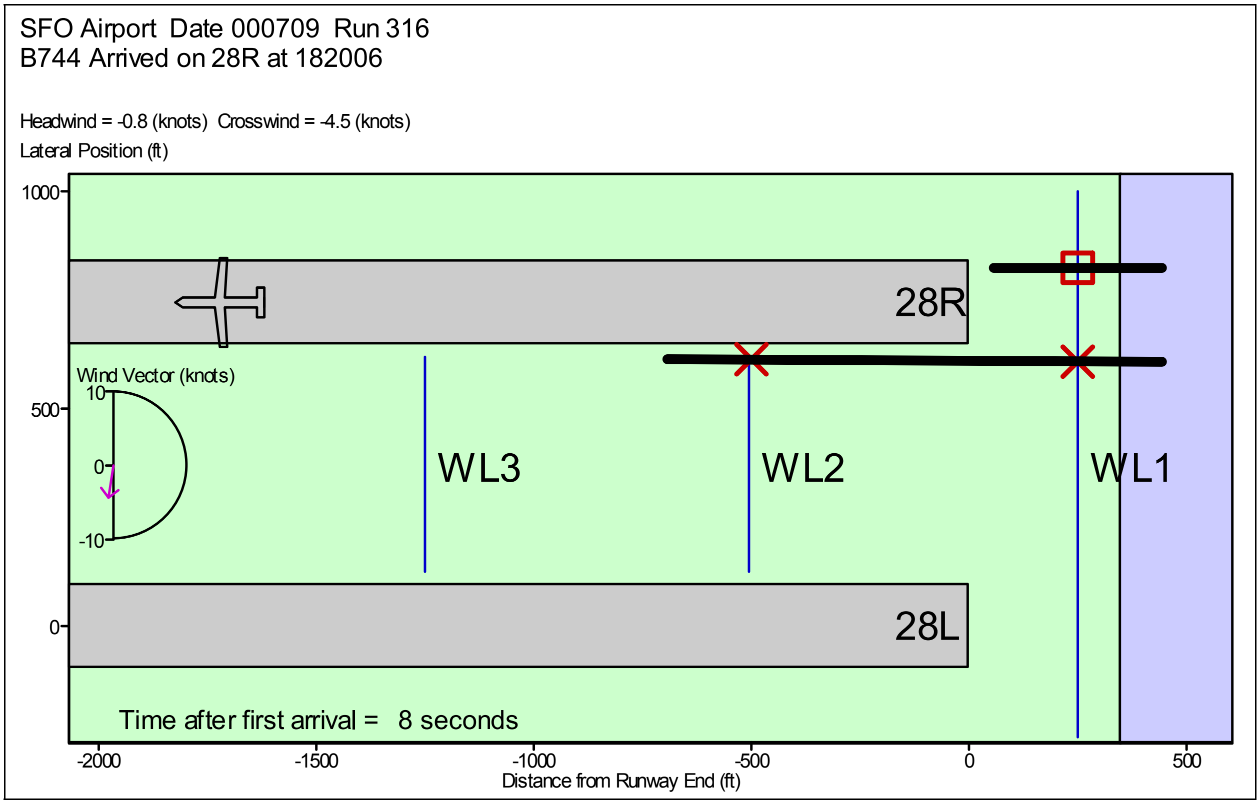

Figure 3-19. Full-Screen Equal-Axis Plan View

4. On a color display, the runways are light gray, the land beside the runways is light green, and the water off the end of the runway is light blue.
5. The color of a vortex symbol indicates the magnitude of the Windline vortex signal. The color varies from red for a fresh wake to green for a vortex detected just above the tracking threshold.

3.7.3 Web Display

In early 2002 a near-real-time display was provided on the Internet at a web site hosted at the Volpe Center. The associated processing steps delayed the display for approximately 7 minutes after an arrival. This delay would be significant only to viewers with direct, real-time access to SFO flight operations. The delay also served as a security measure to eliminate possible use of the web site for obtaining real-time information about SFO operations. The web display is based on Figure 3-18, which is 512 pixels across and is therefore an appropriate size for display in a web browser.

3.8 USER EXPERIENCE WITH REAL-TIME DISPLAYS

3.8.1 Local

Following the second year of data collection at SFO, the Tower air traffic controllers and facility technicians were given a presentation on the WTMS. The audience was very interested in how the characterization of wake transport properties could be used to help solve the capacity issues being experienced at SFO. At the conclusion of the presentation a demonstration of wake detection and transport was given in the SFO Shadow Cab (see Figure 3-20). Controllers and technicians attended in small groups. The demonstration consisted of the following steps:

1. An arriving aircraft and its intended landing runway were identified by looking out the Shadow Cab windows.
2. The same aircraft was then identified on the WTMS display.
3. The detected wakes and their motion were then viewed on the display.
4. The display was cycled through the pilot, controller, and scientific screens (see Section 3.6.2)

Figure 3-20. Shadow Cab Overlooking SFO Airport

FAA Technicians were very impressed with the display. Controller feedback was indifferent. However, the Tower Chief and Deputy Tower Chief thought it had the potential to be a useful tool in the cab. With that endorsement, a display was set up in the Control Tower.

After surveying the Tower Cab and selecting a location, a plasma flat screen display was set up in the northeast corner (Figure 3-21). The display did not hinder or obscure the view of aircraft or the field, and it was segregated from displays used for operations.

The full-screen display of Figure 3-19 was used in the Tower Cab. During the first two weeks of

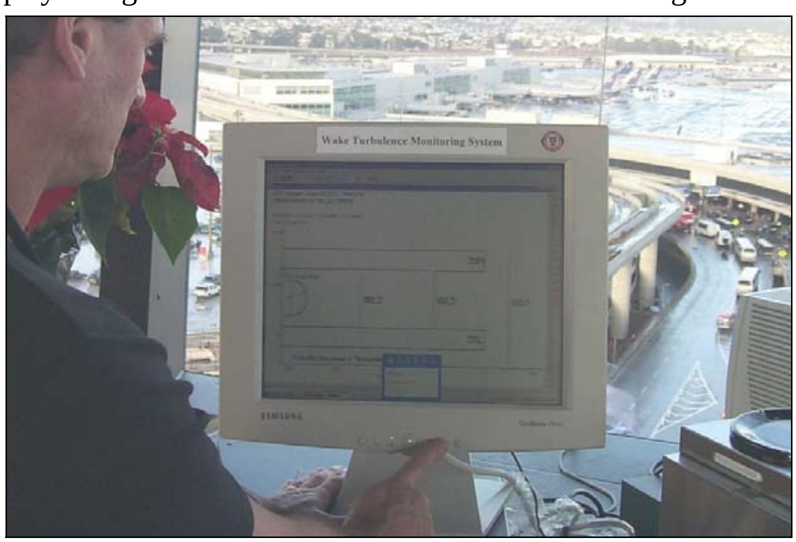

Figure 3-21. WTMS Display in Tower Cab

operation Volpe Center personnel received several calls from controllers with various questions concerning vortex behavior and the display symbology. However, after several weeks (as with the Shadow Cab display) the controllers failed to see any benefit of viewing vortex transport. They thought the display might be more useful in an aircraft cockpit. After six months the display was removed from the Tower Cab.

3.8.2 World Wide Web

During the third year of data collection a website with a near real-time WTMS display was created (Section 0). The site was opened to specified FAA personnel, Volpe Center personnel and airport officials at SFO and DFW. Most of the feedback on the website was positive.

4. DATASETS

4.1 COORDINATE SYSTEM

Before considering the datasets, it is helpful to define the coordinate system and wind direction conventions used for the SFO data. There were selected to facilitate analyses of aircraft approaching Runways 28L/28R.

4.1.1 Origin and Axes

The coordinate system origin is the intersection of three lines/planes associated with Runway 28L (Figure 4-1): (a) the centerline, (b) the threshold, and (c) the surface.

- *x* is the along-runway coordinate. Positive *x* follows the extended Runway 28L centerline away from the threshold out over the bay. Windlines 2 and 3 have negative *x* locations.
- *y* is the cross-runway coordinate. Positive *y* extends to the pilot's right. The *y* coordinate of the Runway 28R centerline is +750 feet.
- *z* is the vertical coordinate. Positive *z* extends upward from the runway surface. Aircraft always have positive *z* coordinates.

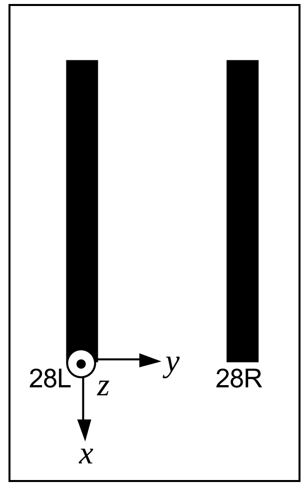

Figure 4-1. SFO Coordinate System

4.1.2 Wind Components

The three wind components are similarly defined:

- Positive headwind is toward an aircraft approaching Runway 28L/R.
- Positive crosswind is from Runway 28L to 28R.
- Positive vertical wind is upward.

4.2 WINDLINE

4.2.1 Processing Parameters

As discussed in Section 3.2.4, the Windline processing program has a large number of parameters, most of which have been fixed for many years. The four parameters used by the program to set the tracking thresholds, however, have been changed for various reasons. Table 4-1 lists the five sets that

Table 4-1. Variable Windline Processing Parameter Sets

Processing Parameter \ Parameter Set #	002	019	020	021	022
Minimum Start-Track Threshold (m/sec)*	2.5	2.5	2.0	1.5	1.0
Minimum Stop-Track Threshold (m/sec)*	2.0	2.5	2.0	1.5	1.0
Start-Track Turbulence Factor	6.5	0.0	0.0	0.0	0.0
Stop-Track Turbulence Factor	4.5	0.0	0.0	0.0	0.0

* 1 m/sec = 1.94 kt ≈ 2 kt

have been used for SFO data analysis.

The start/stop tracking thresholds used internally by the Windline program are each set by the program as the maximum of two choices:

- The Minimum Start-/Stop-Track Threshold (analyst-selected)
- The product of the 10-minute turbulence level (Section 3.1.2.2) times the Start-/Stop-Track Turbulence Factor (analyst-selected). This capability enables the analyst to increase the tracking threshold above the minimum value under turbulent conditions.

For a vortex to be first declared, the vortex-induced crosswind peaks relative to the median crosswind must exceed the start-track threshold. After initial detection, the vortex induced crosswind relative to the median crosswind is compared to the stop-track threshold. The track is terminated when the vortex-induced crosswind is below the stop-track threshold for longer than six seconds.

4.2.1.1 Initial SFO Parameter Set

Parameter Set 002 was used for the analysis presented in the SFO summary report (Ref. 3). This parameter set has several characteristics/advantages:

- The turbulence factors were selected to reduce the probability of gusts being detected as vortices under turbulent conditions;
- The tracking thresholds were designed to result in computed wake lifetimes that match current single-runway separations standards, when converted to time, for a Small class following aircraft. That is, (a) only a very small fraction of vortices last longer than the separation standards, and (b) the fraction is similar for Heavy, B-757 and Large leading aircraft.
- The start-track threshold is higher than the stop-track threshold, which reduces the likelihood of detecting atmospheric eddies but allows aircraft wakes to be tracked longer.

In addition to the positive aspects of Parameter Set 002 cited above, there are some ambiguous aspects:

- Raising the start track threshold under turbulent conditions does not eliminate all gust detections (see Section 4.2.7). In the analysis associated with Ref. 2, some gusts detections affecting the results for SOIA had to be removed manually. Having a variable threshold that depends upon turbulence conditions also means that Windline data cannot be used to assess the impact of turbulence on wake lifetime. [Further processing development during the STL program led to a different method of removing wind gusts (see Section 4.2.7) while keeping a fixed tracking threshold. This method automatically removes the cases previously removed manually.]
- The rationale for matching the stop-track threshold to current separation standards is open to alternative interpretations (Section 4.2.6 shows how the wake duration depends upon the selected tracking threshold). The selection was based on the longest lasting vortices that are normally the upwind vortices when there is a crosswind. The downwind vortex typically rises from the ground more quickly than the upwind vortex because of its interaction with the windshear gradient at the ground. It might be useful to use a lower stop-track threshold for

downwind vortices so that they could be tracked to the same circulation limit as upwind vortices.

- Having the start-track threshold larger than the stop-track threshold is not required for tracking stability, because tracks are enabled after an aircraft arrival and are not allowed to be restarted after they are terminated. [A more specific need for equal start- and stop-track thresholds arose at STL, where wakes might be tracked from the end of one Windline to the beginning of another; the track initiation on the second Windline should have the same starting threshold as the stop-track threshold on the first.]

4.2.1.2 Alternative Parameter Sets

For these reasons, the SFO Windline dataset was also processed with the other parameter sets listed in Table 4-1. Parameter Sets 019 through 022 use the STL processing philosophy of zero turbulence factors and equal start- and stop-track thresholds. The four different tracking thresholds can be used to assess the influence of tracking threshold on the results. Tracking parameters are expected to have little impact on SOIA results, which concentrated on wake behavior during the initial 30 seconds.

4.2.2 FAA Aircraft Wake Classes

FAA wake turbulence separation rules are based on the aircraft classes listed in Table 4-2. The Heavy, Large and Small classes are based on Maximum Certificated Gross TakeOff Weight (MCGTOW). The B-757 has its own separation rules and hence acts much like a fourth class. Because the ranges of aircraft sizes in the Large and Heavy classes are great enough to have significantly different wake properties, the analysis of SFO data generally splits each of them into two subclasses — designated L+ and L- and H+ and H-, respectively — which are described below. (The FAA has already split the Small class into subclasses S and S+.) Separation rules are determined by the effect of wakes generated by the largest aircraft in each class — namely the H+, B5 (abbreviation for B-757), and L+ subclasses — on the smallest aircraft in each class.

Table 4-2. FAA Aircraft Wake Turbulence Classes

Class	MCGTOW (W, k lb)	Code
Heavy	255 < W	H
B-757	N/A	B5
Large	41 ≤ W ≤ 255	L
Small	W < 41	S

4.2.3 SFO Traffic

The SFO dataset is large enough that stringent controls on data quality are possible without reducing the number of cases to an unusable level. The traffic information in this section requires:

- Unique aircraft arrival time matches.
- Raw Windline data lasting more than 170 seconds (maximum wake age from Windline status file). This requirement assures that wake track duration will not be significantly limited by data truncation. It also eliminates most of the second arrivals in a run file.

Table 4-3 presents the traffic counts by runway and data collection period for the H+, H- and B5 classes. Table 4-4 presents the same data for the L+ class. The total count for two tables is 143,446 approaches by the four heaviest aircraft subclasses.

Table 4-3. Arrival Counts with Valid Windline Data for H+, H- and B5 Classes

Wake Class	FAA Code	Data Collection Period 1			Data Collection Period 2			Total Both Rwys & Periods
		Runway			Runway			
		28L	28R	Total	28L	28R	Total	
H+	A340	88	135	223			0	223
	A343	142	173	315	206	273	479	794
	B741	9	50	59	1	2	3	62
	B742	448	1,304	1,752	225	326	551	2,303
	B743	28	69	97	21	21	42	139
	B744	1,424	3,035	4,459	1,271	1,689	2,960	7,419
	B747	9	23	32	4	2	6	38
	B74A	1	3	4		2	2	6
	B74B	3	1	4			0	4
	B74R	5	8	13	1		1	14
	B772	690	1,462	2,152	937	1,429	2,366	4,518
	B773	1	2	3	1	1	2	5
	B777	2	6	8			0	8
	DC10	582	1,217	1,799	159	151	310	2,109
	L101	235	513	748	60	24	84	832
	MD11	105	333	438	139	186	325	763
	H+ Total	3,772	8,334	12,106	3,025	4,106	7,131	19,237
H-	A300		2	2		1	1	3
	A306	23	101	124			0	124
	A30B	23	98	121	34	61	95	216
	A310	1	1	2			0	2
	B762	778	2,892	3,670	535	1578	2,113	5,783
	B763	848	2,839	3,687	937	1949	2,886	6,573
	B764	36	137	173	156	195	351	524
	B767	7	17	24	3	5	8	32
	DC87		1		22	24	46	46
	DC8Q	38	156	194	63	26	89	283
	H- Total	1,754	6,244	7,997	1,750	3,839	5,589	13,586
B5	B752	3,853	13,083	16,936	3,467	6,940	10,407	27,343
	B753		1	1	113	71	184	185
	B757	52	68	120	8	13	21	141
	B5 Total	3,905	13,152	17,057	3,588	7,024	10,612	27,669

4.2.4 Crosswind Distribution

Analysis of various crosswind measurements, including those from the 20-foot WTMS poles and ASOS, found that the best predictor of lateral wake transport is obtained from the Windline measurements. The median crosswind from Windline 1 (WL1) is used herein to assess the crosswind conditions for the SFO datasets. It is scaled by a factor of 1.5 from the 3-foot Windline height to approximate the 33-foot height of ASOS wind measurements.

Table 4-4. Arrival Counts with Valid Windline Data for L+ Classes

Wake Class	FAA Code	Data Collection Period 1			Data Collection Period 2			Total Both Rwys & Periods
		Runway			Runway			
		28L	28R	Total	28L	28R	Total	
L+	A319	647	1,979	2,626	1,198	1,489	2,687	5,313
	A320	2,214	5,374	7,588	2,170	2,688	4,858	12,446
	A321	3	58	61	161	587	748	809
	B721	2	10	12	1	7	8	20
	B722	33	31	64	1	5	6	70
	B727	30	37	67	1	1	2	69
	B72Q	449	1,389	1,838	19	39	58	1,896
	B732	430	482	912	137	157	294	1,206
	B733	8,515	8,682	17,197	3,245	2,873	6,118	23,315
	B734	1,029	1,308	2,337	1,161	1,022	2,183	4,520
	B735	5,055	4,661	9,716	2,655	1,731	4,386	14,102
	B737	731	782	1,513	344	568	912	2,425
	B738	715	1,819	2,534	1,130	1,628	2,758	5,292
	B73F		3	3				3
	B73Q	290	559	849	90	110	200	1,049
	B73S	1	3	4		4	4	8
	DC9	2	5	7	121	101	222	229
	DC9Q	68	233	301			0	301
	MD80	2,311	3,642	5,953	1,312	1,204	1,365	7,318
	MD82	32	48	80	5	64	76	156
	MD81				86	1	6	6
	MD83	44	99	143	11	30	31	174
	MD88	1		1	25	49	50	51
	MD90	621	247	868	9	40	41	909
	L+ Total	23,223	31,451	54,674	13,882	14,398	28,280	82,954

Figure 4-2 shows the crosswind distribution separately for arrivals on the two runways with separate plots for the four heaviest subclasses. The crosswind resolution is 1 knot. Figure 4-3 provides logarithmic scales so that the small number of cases with strong crosswinds can be assessed more accurately. The spike at zero crosswind is caused by stalling of the Windline propeller anemometers in low winds.

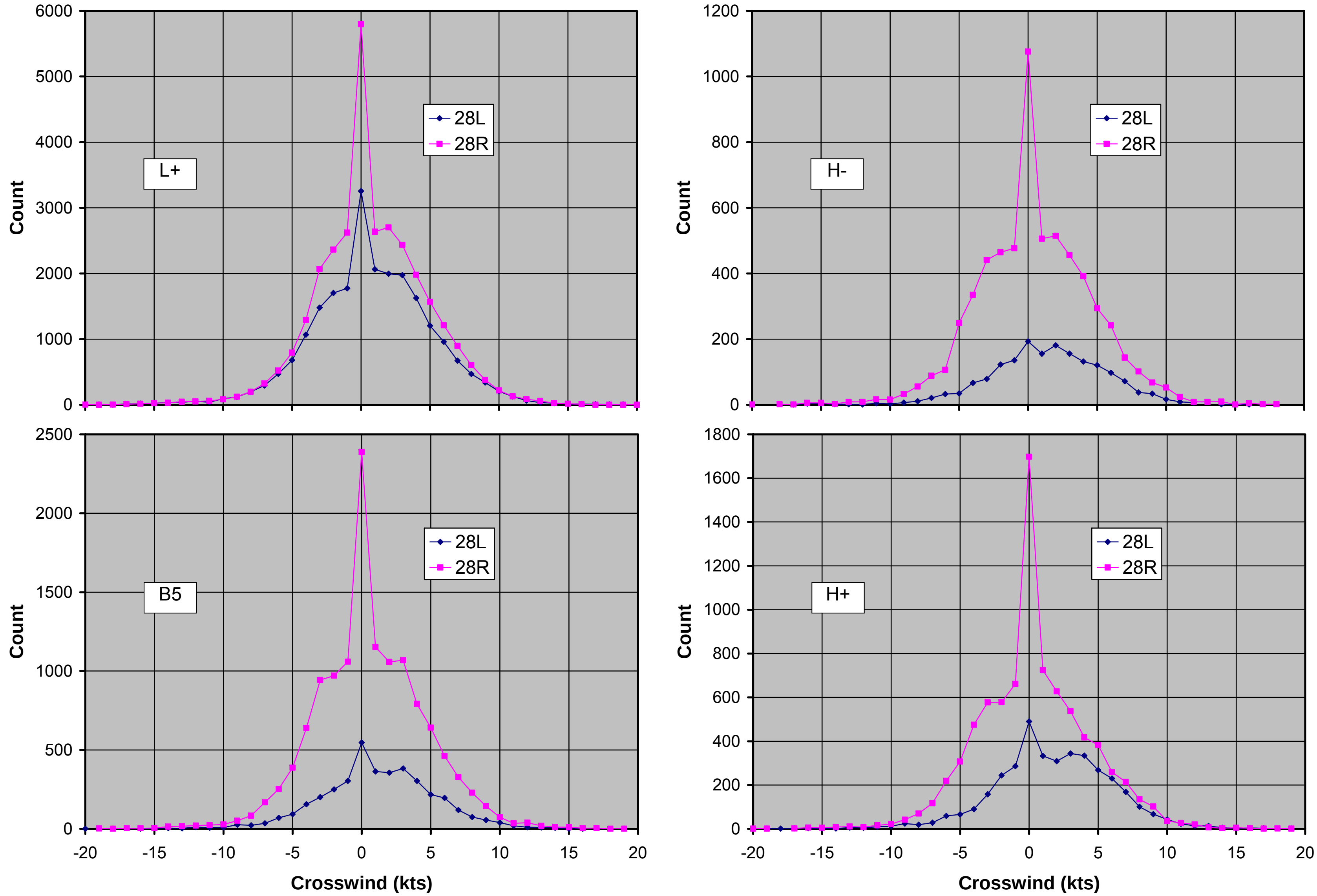

Figure 4-2. Crosswind Distribution for Arrivals by Aircraft Weight Sublass (linear scale)

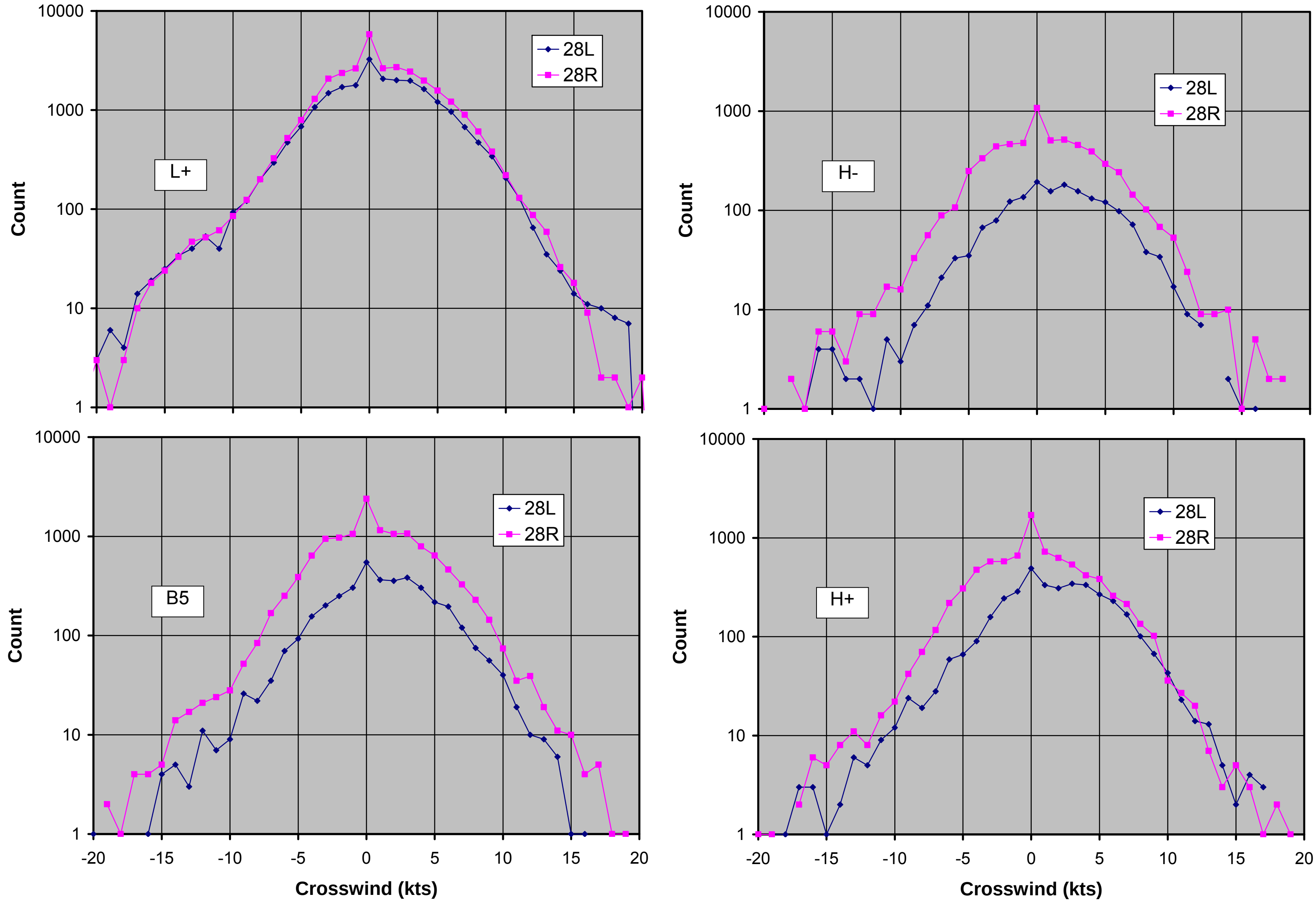

Figure 4-3. Crosswind Distribution for Arrivals by Aircraft Weight Subclass (logarithmic scale)

4.2.5 Windline Detection Probability

The usefulness of Windlines depends upon their having a high probability of wake vortex detection. For SFO WL2 and WL3 that cover only the region between the two runways, the detection probabilities depend upon the crosswind and will be different for port (denoted vx0) and starboard (denoted vx1) vortices. Ideally, WL1 would detect all wake vortices; however, wakes from smaller aircraft can blow off the end of the Windline or not descend close enough to the ground within the 18-second detection limit used in processing.

Table 4-5 presents the information needed to interpret the influence of the crosswind on the detection probabilities. For example, positive crosswinds tend to blow the wakes from 28R arrivals off the end of the Windlines.

Table 4-5. Interpretation of Crosswind Sign

Crosswind Direction	Downwind Vortex	Upwind Vortex	Runway 28L Arrival	Runway 28R Arrival
Positive: 28L to 28R	Starboard = vx1	Port = vx0	Toward other runway	Away from other runway
Negative: 28R to 28L	Port = vx0	Starboard = vx1	Away from other runway	Toward other runway

Figure 4-4 and Figure 4-5 present the detection probability for four aircraft subclasses as a function of crosswind for Runways 28L and 28R, respectively. (Data from Period 1, when all three Windlines were validated, were selected, and were processed using Parameter set 020.) The crosswind limits in the plots are ±10 knots. The number of cases is almost always greater than 10 (see Figure 4-3) so that the probabilities are statistically significant. In any case, the trends in the data are well defined before the crosswind reaches the ±10-knot edge of the plots.

As would be expected, the detection probabilities are quite different for WL1, which covers under the approach path, than for WL2 and WL3, which cover only the region between the runways:

- The detection probability is always high (95 % or greater) for WL1. Detection is virtually certain for H+ arrivals. The probability drops slightly as the aircraft size decreases, especially for crosswinds blowing the wakes off the end of the Windline.
- For WL2 and WL3 the detection probability is high for the downwind vortex for crosswinds blowing toward the other runway. For WL2 the L+ probability reaches 100 % for 3- or 4-kt crosswind toward the other runway. For WL3 the probabilities are somewhat smaller, as might be expected since some aircraft touch down before WL3.
- For WL2 and WL3 the detection probability can be high for the upwind vortex for strong crosswinds blowing toward the other runway. The probabilities are lower for WL3 than for WL2 and are lower for 28R arrivals than for 28L arrivals. The latter effect is related to the well-established faster wake decay for crosswinds from the land (positive here) than for crosswinds from the bay (negative here).

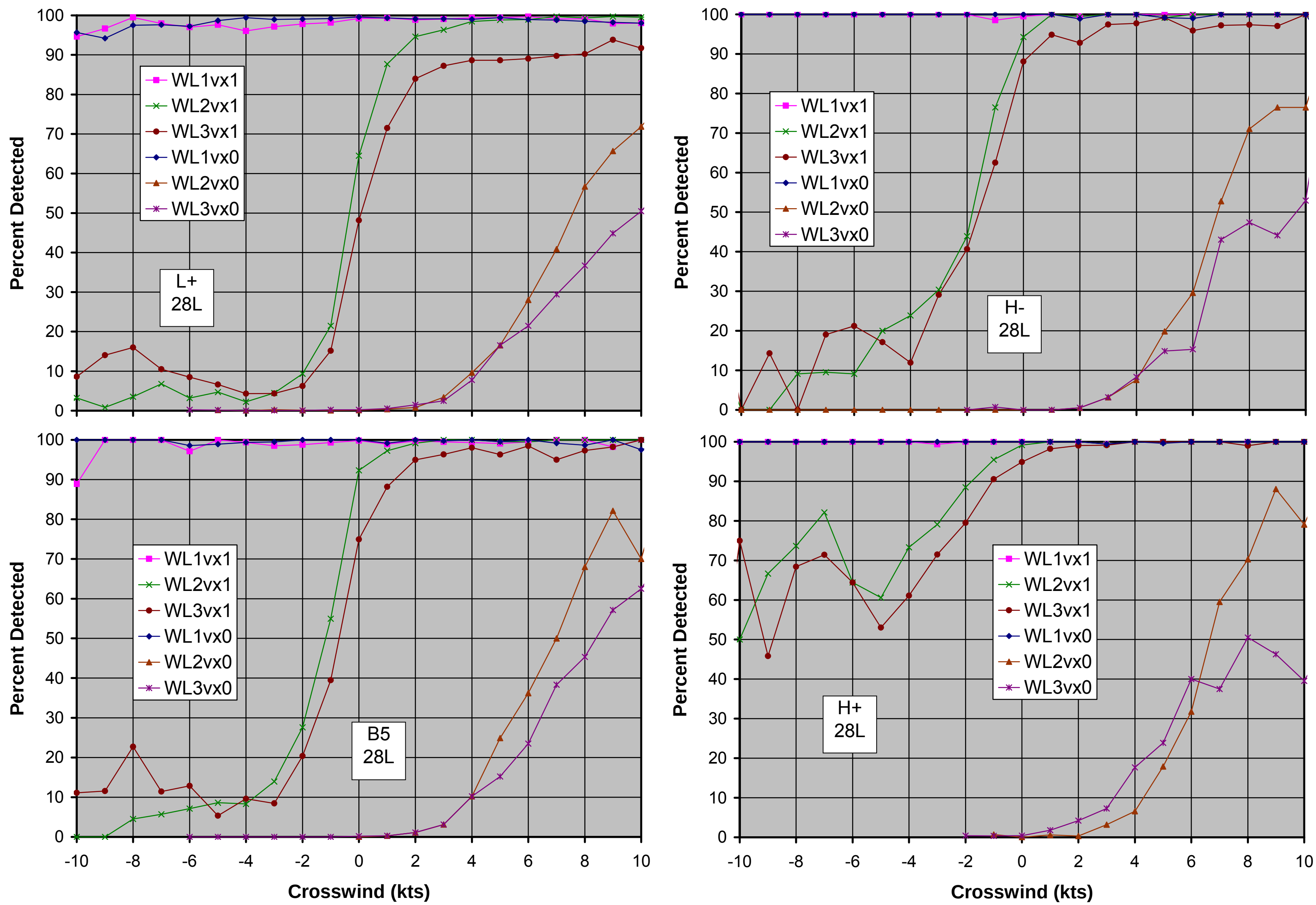

Figure 4-4. Vortex Detection Probability vs. Crosswind for RWY 28L and Four Aircraft Wake Subclasses

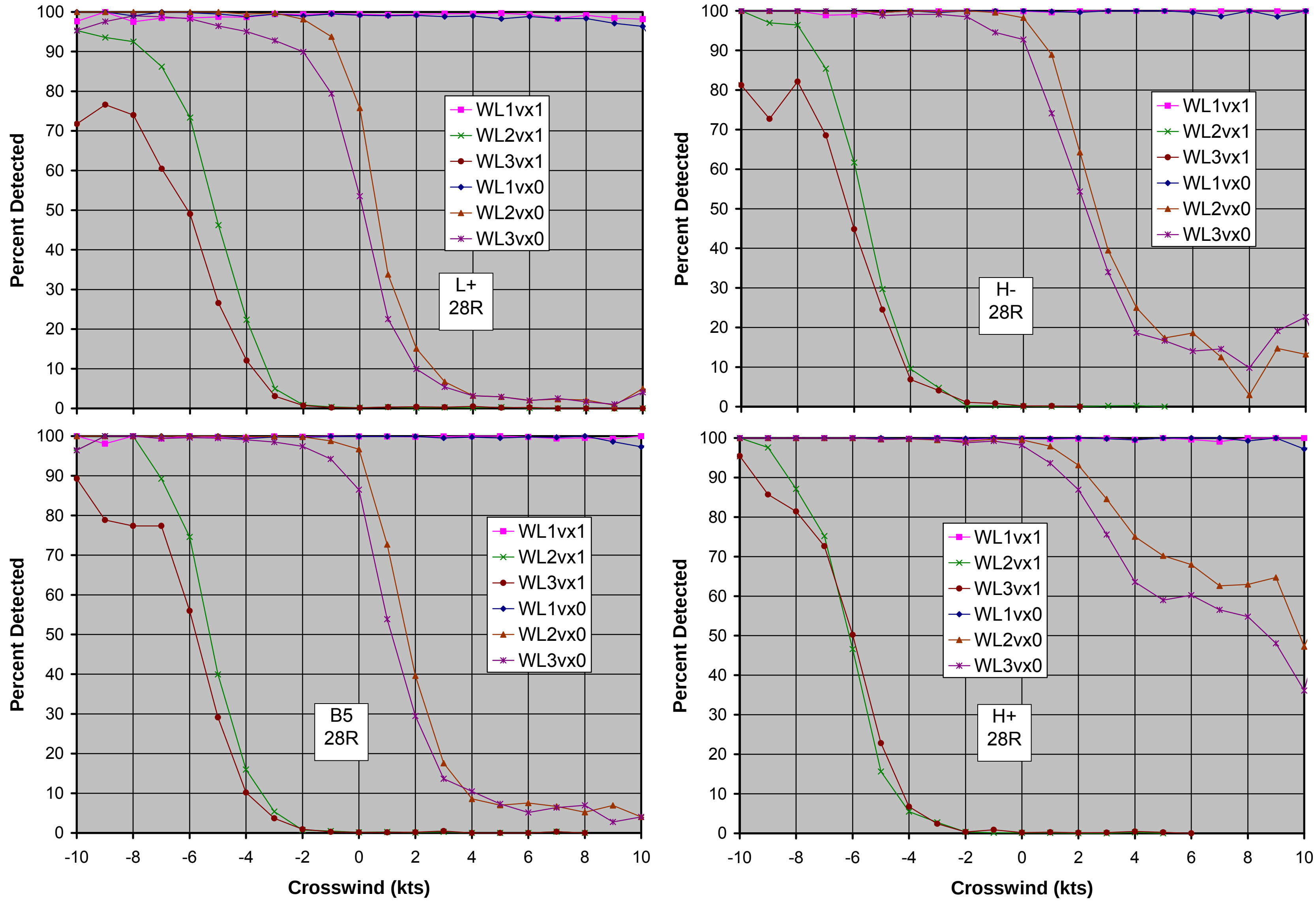

Figure 4-5. Vortex Detection Probability vs. Crosswind for RWY 28R and Four Aircraft Wake Subclasses

- For WL2 and WL3 the detection probability can be significant for the upwind vortex for strong crosswinds blowing from the other runway. For low-altitude aircraft, the wake can move onto the Windline against a strong adverse crosswind. The effect is small for L+ aircraft but is greater than 50% for H+ aircraft. This observation is a confirmation of the strong wake outflows generated when aircraft are below the normal ground-effect height. Whether or not this outflow rolls up into a persistent wake vortex is not clear; a focused study could provide an indication. In any case, the outflow from an H+ aircraft is strong enough to usually overcome, to some extent, a 10-knot adverse ambient crosswind. Note also that the wingtip of an H+ aircraft is at the edge of the runway and close to the first Windline anemometer.

4.2.6 Wake Duration

This section presents an analysis of the sensitivity of duration to the tracking threshold (Table 4-1) for different aircraft subclasses. While this report is intended to present data collection and processing rather than analysis, this particular analysis is needed to support the decision to set the standard SFO tracking threshold to 2.0 meters/second (approximately 4 knots).

The maximum vortex age for detection by a Windline depends upon (a) the stop-track threshold used in processing and (b) the aircraft class. Figure 4-6 shows the variation by aircraft subclass of the detection probability versus vortex age — one plot each for processing parameter sets 019-022 having tracking thresholds from 1.0 to 2.5 meters/second (approximately 2 to 5 knots). Note that different vertical scales are used. Vortex duration is of course longer for the larger aircraft subclasses. The subclass variation becomes smaller for the lowest tracking thresholds of 1.0 and 1.5 meters/second (approximately 2 to 3 knots).

Figure 4-7 shows, for the five parameter sets, the variation of detection probability versus vortex age (one plot per aircraft subclass). As expected, vortex duration increases as the tracking threshold is lowered. Note that the curves for Parameter Sets 002 and 020, which have the same minimum stop-track threshold of 2.0 meters/second (approximately 4 knots), lie on top of each other. Parameter Set 002 has increased tracking thresholds under high turbulence conditions and a higher minimum start-track threshold of 2.5 meters/second (approximately 5 knots). These differences lead to a marginally lower detection probability that is most evident at early vortex ages. The implication is that long lasting vortices likely occur under low turbulence conditions.

Early SFO Windline analyses used Parameter Set 002. Future SFO Windline analyses might beneficially use Parameter Set 020 which has the same detection threshold under all conditions and could, for example, assess the wake duration as a function of turbulence level (not possible for Parameter Set 002 that explicitly varies the tracking threshold with turbulence level).

Any interpretation of Figure 4-4 and Figure 4-5 should consider the following technical details:

1. Both vortices are included.
2. Only vortices detected at more than a single age are included. Single-age detections seem more likely to be gusts and have little impact on final test results.
3. Only Windline 1 data were used. Thus, the initial vortex detection probabilities are large.

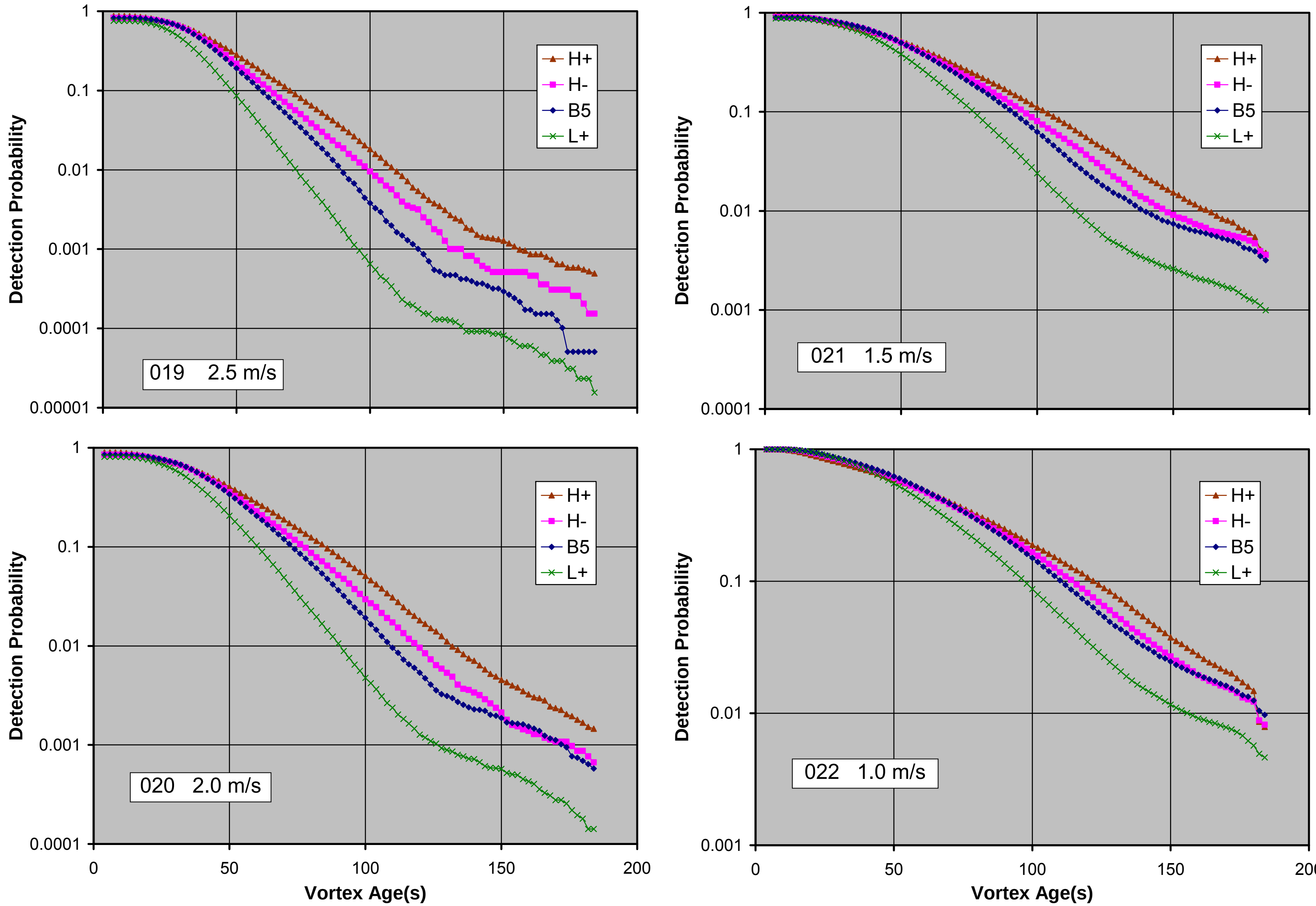

Figure 4-6. WL1 Vortex Detection Probability vs. Age for Four Aircraft Weight Subclasses and Four Parameter Sets

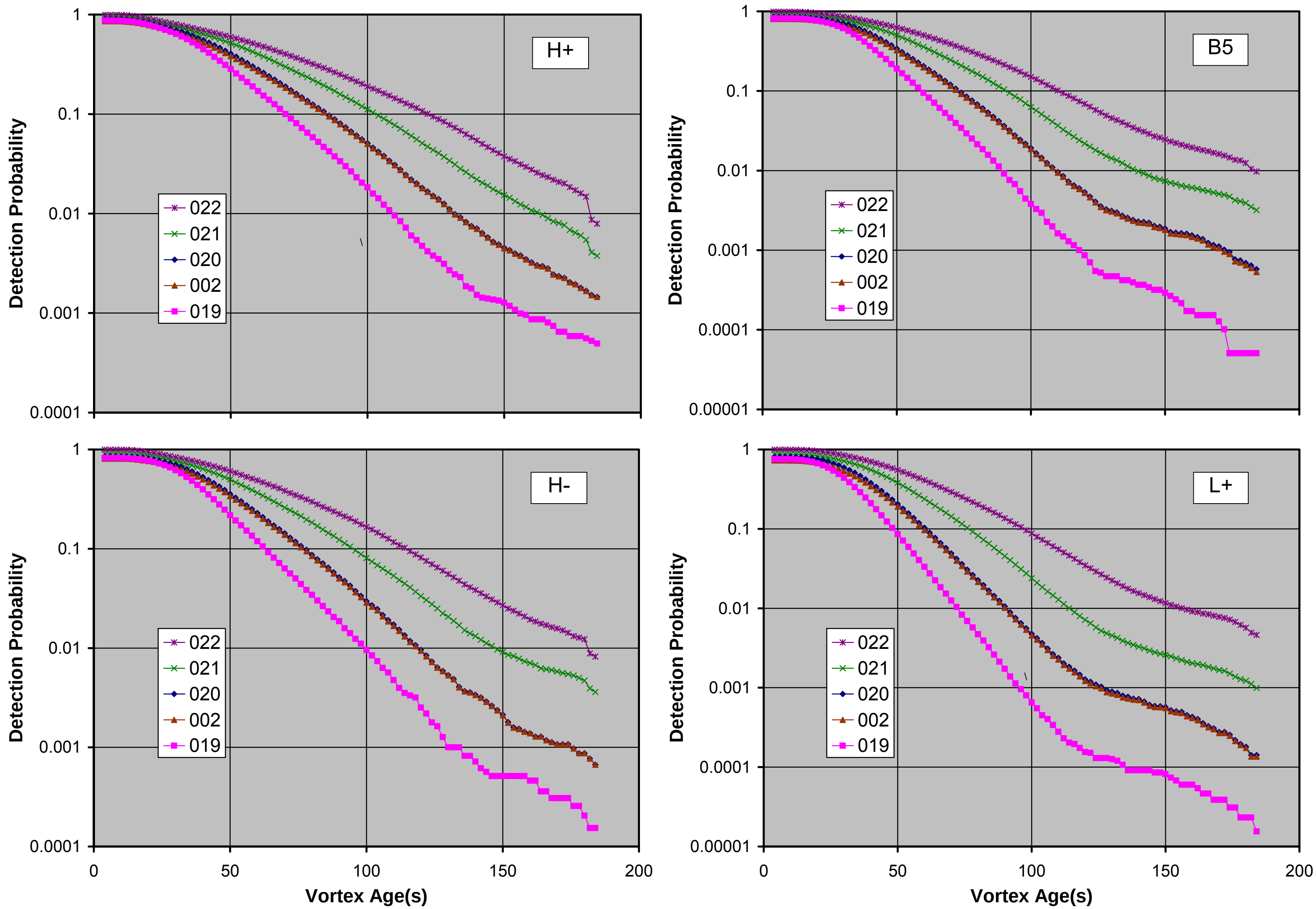

Figure 4-7. WL1 Vortex Detection Probability vs. Age for Five Parameters Sets for Four Aircraft Weight Subclasses

4. The detection probabilities for all Parameter Sets are normalized to the number of vortices detected by Parameter Set 022 that has the highest detection probability. This is a different normalization than the aircraft number of arrivals which is used in Figure 4-4 and Figure 4-5.
5. Detections are lost by vortices traveling off the end of the Windline as well as by decaying below the detection threshold while over the Windline.

As Item 5 indicates, this analysis is restricted by the physical length of WL1. It is thus not a definitive determination of wake duration, even as detected by an anemometer Windline, because it does not account for vortices lost off the ends of WL1 (i.e., wake duration probabilities are understated).

4.2.7 First Wake Detection

The location of the first vortex detection can be used to distinguish real vortex detections from wind gust detections. This method of gust rejection can be used as a substitute for increasing the tracking thresholds under high turbulence conditions. This section compares the first detection results for:

- Parameter Set 002, which used: (a) higher detection thresholds under turbulent conditions (note the nonzero turbulence factors in Table 4-1), and (b) a higher start-track threshold, 2.5 meters/second (approximately 5 knots), than stop-track threshold, 2.0 meters/ second (approximately 4 knots); and
- Parameter Set 020, which used fixed minimal tracking thresholds of 2.0 meters/second (approximately 4 knots).

First detection locations results are shown in Figure 4-8 through Figure 4-10 for Windline 1 through Windline 3, respectively. The results are generally as expected; Parameter Set 002 has significantly fewer (but not zero) apparent wind gust detections than Parameter Set 020. The Parameter-Set-002 vortex results can be used directly with only minor wind-gust contamination. The Parameter-Set-020 vortex results must have the wind gusts removed explicitly based on the observed locations of real vortices. A wind gust removal algorithm was developed and implemented on the location of the first vortex detection. It also automatically removes gusts caused by jet blast from aircraft waiting to depart on Runway 28R.

The first detection figures are designed to show single gust detections while simultaneously showing the much greater number of valid vortex detections. Each square or rectangle on the plot is color coded to show the number of cases for the specified aircraft classes where a wake vortex was first detected at a particular Windline pole (y-axis) with a particular integer scaled WL1 median crosswind (x-axis). The color scale is based on the natural log of the count; thus, each integer change in the color scale represents a factor of about 2.7. The value for zero count is set at -2 to give a clear difference between 0 (dark blue) and 1 (medium blue) count.

Other features of the plots are:

1. Each box contains two plots: the top for Starboard Vortices from 28L arrivals and the bottom for Port Vortices from 28R arrivals. These are the vortices generated closest to the other runway. These vortices travel fastest and with higher probability toward the other runway. The interesting crosswinds in the figures are those that promote travel toward the other runway, i.e. positive crosswinds for 28L arrivals and negative crosswinds for 28R arrivals.

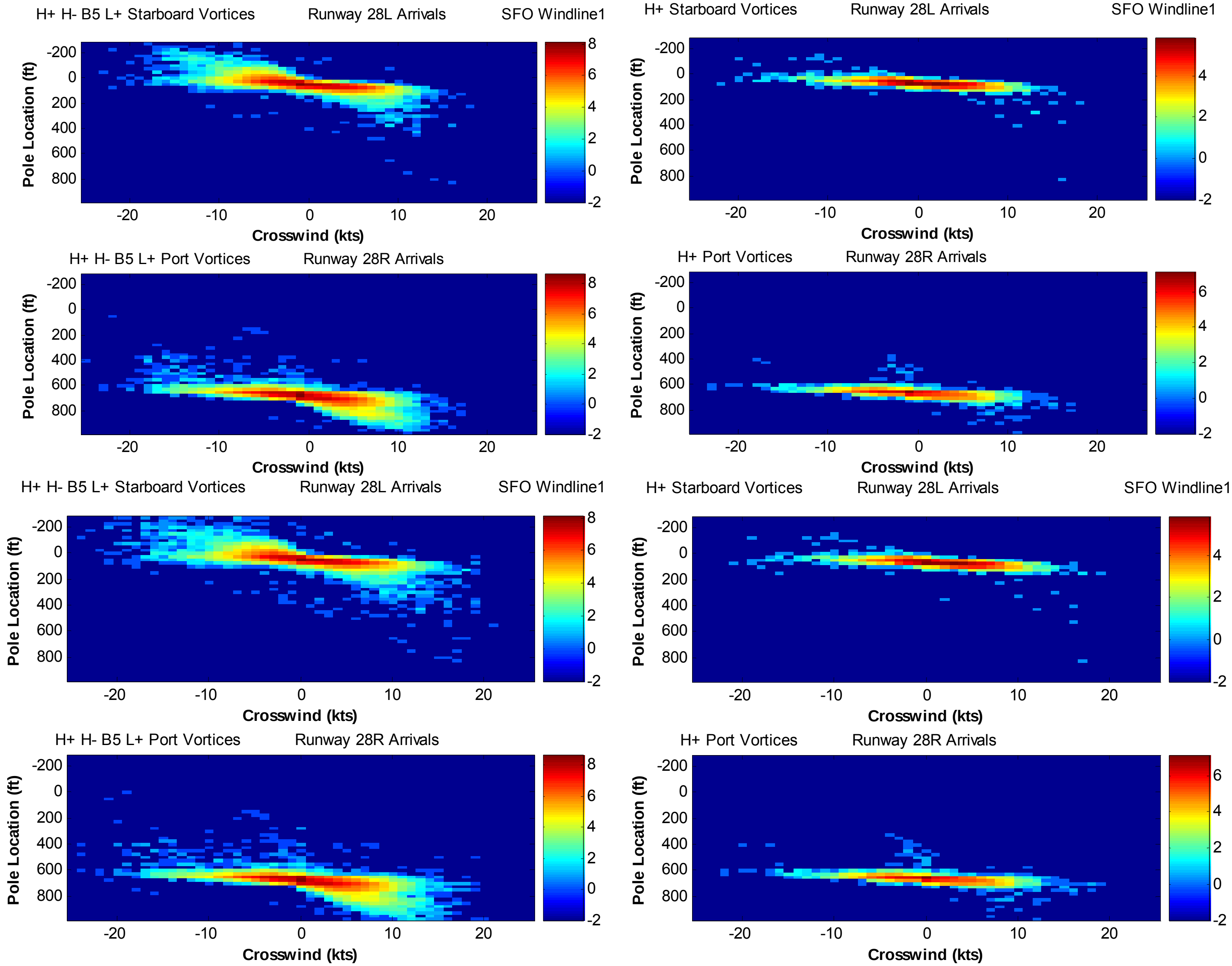

Figure 4-8. Locations and Crosswinds for First WL1 Vortex Detection: Parameter Sets: 002 (top) and 020 (bottom): Subclasses: L+ through H+ (left), H+ (right); In Each Box: 28L Arrivals & Starboard Vortices (top) and 28R Arrivals & Port Vortices (bottom).

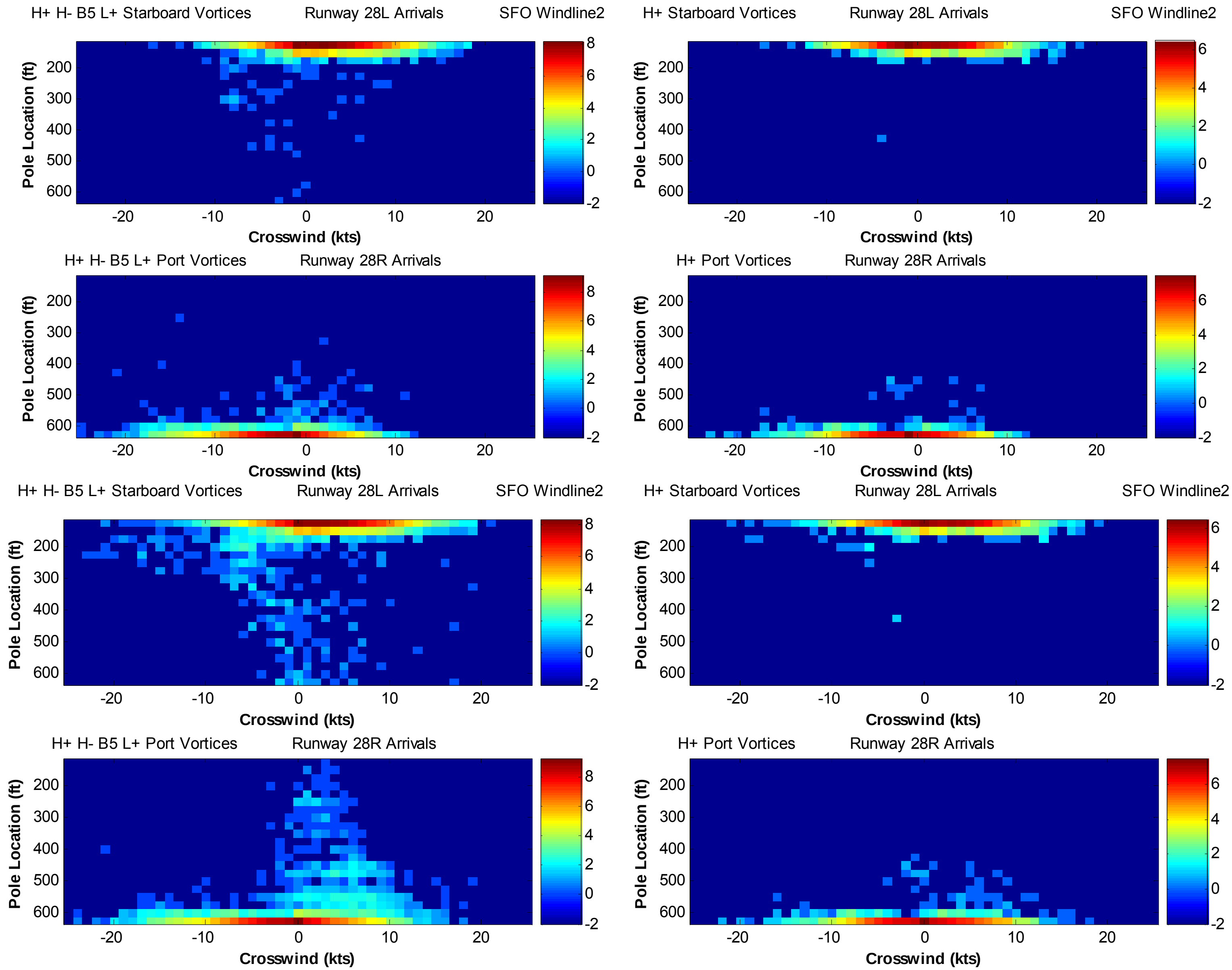

Figure 4-9. Locations and Crosswinds for First WL2 Vortex Detection: Parameter Sets: 002 (top) and 020 (bottom): Subclasses: L+ through H+ (left), H+ (right); In Each Box: 28L Arrivals & Starboard Vortices (top) and 28R Arrivals & Port Vortices (bottom)

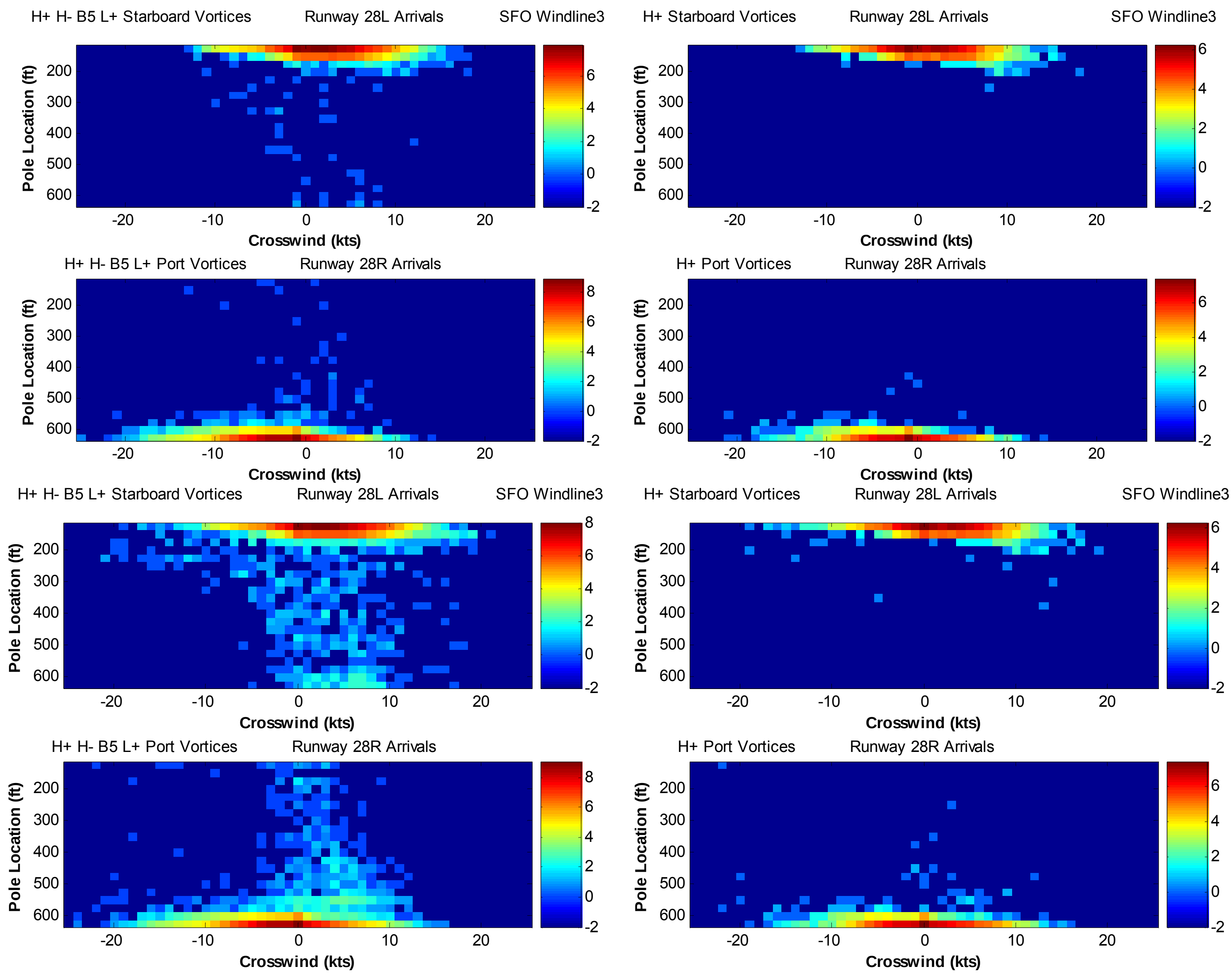

Figure 4-10. Locations and Crosswinds for First WL3 Vortex Detection: Parameter Sets: 002 (top) and 020 (bottom): Subclasses: L+ through H+ (left), H+ (right); In Each Box: 28L Arrivals & Starboard Vortices (top) and 28R Arrivals & Port Vortices (bottom)

2. The plots on the left show the data for four subclasses: L+, B5, H-, and H+. These plots are dominated by the L+ arrivals, which were the most numerous (see Table 4-4).
3. The plots on the right are for the H+ class alone. Because of the high detection probability for H+ vortices, the influence of wind gust detection is minimal for these cases. Consequently, their first detection locations are mostly valid.
4. The top plots are for Parameter Set 002 that features (a) a higher vortex-induced crosswind threshold for starting a track (2.5 meters/second, approximately 5 knots) than for terminating it (2.0 meters/second, approximately 4 knots) and (b) turbulence factors that increase the tracking thresholds under turbulent conditions.
5. In Figure 4-8 for WL1 the locations of the arrival runway are covered by the Windline. The vertical scale is compressed because there are 51 poles in the Windline.
6. In Figure 4-9 and Figure 4-10 for WL2 and WL3, respectively, the arrival runways are off the edges of the Windline. The vertical scale is expanded because there are only 21 poles in the Windline.
7. The bottom plots are for Parameter Set 020 that features: (a) equal vortex-induced crosswind threshold for starting a track and for terminating it (2.0 meters/second, approximately 4 knots), and (b) no turbulence factors to increase the tracking thresholds under turbulent conditions. It is not surprising that Parameter Set 020 leads to more gust detections. The difference is most notable for the four subclasses (left boxes) in Figure 4-9 (WL2) and Figure 4-10 (WL3). For these cases, Parameter Set 020 (bottom, left box) leads to vortices being detected at every anemometer in the Windline.

Interpretation of Figure 4-8 through Figure 4-10 provides a variety of information:

1. The aircraft height at WL1 (Figure 4-8) is approximately 60 feet. Most H+ aircraft have wingspans more than three times the aircraft height; their wakes are generated below the normal equilibrium ground effect height (approximately 3/8 span) and the wake vortices are normally detected very soon after aircraft passage. The plots on the right side of Figure 4-8 are very narrow and show only a slight variation in the first detection with crosswind. On the other hand, L+ aircraft have wingspans of approximately 100 feet (approximately 40 foot equilibrium ground effect height) and must descend for a short time before being detected by the Windline. Consequently, their first detection location drifts some with the crosswind, normally producing a wedge-shaped plot that extends with increasing crosswind magnitude. The wedges are similar for 28L arrivals with both crosswind signs and for 28R arrivals with positive crosswinds. Much less wedge is noted for 28R arrivals with negative crosswind.
2. The aircraft height at WL2 (Figure 4-9) is approximately 30 feet; all aircraft are in ground effect. WL3 (Figure 4-10) is located past the nominal touchdown point; aircraft already touched down should generate weakened wakes and those landing long are certainly in ground effect. Consequently, only a minimal crosswind drift is noted for these plots. Almost all the valid vortex detections are located at the first three poles of the Windline.

The characteristics of wind gust detections can now be summarized:

- Parameter Set 020 gives many more wind gust detections than Parameter Set 002. Nevertheless, some gust detections are detected for Parameter Set 002.
- The best way to avoid wind gust detections is to detect the real vortex. The H+ cases show fewer gust detections because the real vortices are more likely to be detected than for smaller aircraft. The number of wind gust detections increases progressively from WL1 to WL3, as the detection probability decreases.
- Wind gust detections are more frequent for positive than for negative crosswinds. This result is consistent with the higher turbulence levels expected from winds blowing from the land compared to winds blowing from the bay.

4.3 PULSED LIDAR

When configured for detecting wakes, the Pulsed Lidar was operated in two elevation-scan modes:

1. Single-azimuth angle (not necessarily perpendicular to the flight path) and
2. Dual-azimuth mode (alternate elevation-scans at different azimuth angles).

The statistics in the following subsections are based on the vortex track files generated during post-test data processing (documented in a CTI report, Ref. 6). The Lidar processing detects vortices and generates track files independent of external information about aircraft arrivals. Data from vortices detected at two-azimuth scans are saved in the same track file. Each track file can contain data from a single vortex or from a vortex pair. Track files are matched with aircraft based on Mode S data**.**

The 2002 vortex track file database, defined by site and location, contains 2,406 track files (see Figure 3-10 for Lidar site locations):

1. Site 1: 1,981 files generated during single vertical plane scanning and 278 files generated during dual vertical plane scanning.
2. Site 2: 73 files for transverse viewing of landing aircraft near the runway threshold and 74 files for viewing angles either 15 degrees or 30 degrees in azimuth up the glide slope.

4.3.1 Out of Ground Effect (OGE)

Table 4-6 summarizes the OGE single-azimuth Lidar data. Most of the track files contained vortex pairs and most were matched with arrivals detected by the Mode S receiver. Table 4-7 summarizes the OGE dual-azimuth data. The two azimuth angles were generally quite different (roughly 30 degrees) and always included a perpendicular scan (azimuth 28 degrees). A few dual-azimuth cases had angle differences of only 8-10 degrees.

4.3.2 In Ground Effect (IGE)

Table 4-8 summarizes the IGE measurements. All were single-azimuth scans. The Azimuth-30 data were collected over Windline 1.

Table 4-6. Summary of Lidar Single-Azimuth Track Files at Site 1

Date	Number of Files	Single Vortex Files	Vortex Pair Files	No Arrival Match
09/09	35	3	32	0
09/10	191	25	166	5
09/11	18	15	3	1
09/12	1	0	1	0
09/13	3	0	3	0
09/14	41	15	26	5
09/15	66	16	50	4
09/16	135	23	112	5
09/17	204	46	158	8
09/18	262	50	212	14
09/19	199	33	166	3
09/20	247	48	199	15
09/21	245	27	218	10
09/22	115	20	95	8
09/23	135	24	111	1
09/24	76	12	64	3
09/25	8	3	5	3
Total	**1,981**	**360**	**1621**	**85**

Table 4-7. Summary of Lidar Dual-Azimuth Track Files at Site 1

Date	Number of Files	Tracks at 28° Az	Tracks at 0° Az	Tracks at 60° Az	Tracks at 18/20° Az	Paired 2 Plane Files	No Arrival Match
09/21	10	5	0	0	5	5	0
09/22	107	55	26	26	0	40	13
09/23	95	48	11	25	11	41	4
09/24	66	32	10	0	24	26	7
Total	**278**	**140**	**47**	**51**	**40**	**112**	**24**

Table 4-8. Summary of Single-Azimuth Track Files at Site 2

Date	Number of Files	Tracks at 30° Az	Tracks at 45° Az	Tracks at 60° Az	No Arrival Match
09/25	137	71	40	24	23
09/26	12	2	0	10	12
Total	**147**	**73**	**40**	**34**	**35**

4.4 METEOROLOGICAL DATA

Ambient wind is the most important meteorological parameter predicting wake transport. Other parameters such as stratification and turbulence level can help predict wake lifetime.

Airport operations, e.g., runway selection, are also affected by the ambient wind. Additionally, operations are strongly affected by visibility and ceiling*, which define Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC). Archived ASOS data provide ceiling and visibility information. Tower logs are required to determine accurately how the airport was operated at any given time. However, the airport operating mode can be surmised by examining ASOS and arrival data.

4.4.1 ASOS

Archived 1-minute ASOS data include ambient wind (2-minute average updated every minute and 5-second gust) parameters, raw visibility sensor readings, and Runway Visual Range (RVR) data. Archived 5-minute ASOS data provide temperature, dew point, visibility, and cloud cover information. ASOS is not a totally reliable data source, as: (a) sometimes a measurement is marked missing, and (b) archived data are completely missing for some days.

4.4.2 Windline

The Windline recording system saved 2-second averages of all propeller anemometers, including the three-axis units installed on the two 20-foot poles (see Figure 3-2). These measurements were processed in real-time to generate files containing 1-minute mean and standard deviation values of all wind components.

The program that processed Windline data for wake vortices also calculates mean and standard deviation values for the first minute of each run for the following parameters:

1. The median crosswind across the Windline. For Windline 1 the median was taken only for anemometers between the runway centerlines to give a better estimate of wake transport between the two runways.
2. The three wind components from the two 20-foot meteorological poles.

4.4.3 Sodar

Useful Sodar data were recorded only during the second data collection period (September 2001 through October 2002). Table 4-9 summarizes the Sodar data, which was not very consistent. 2-minute averages were used for the first 17 days, and 5-minute averages were used for the rest of the data collection period. Sodar data were recorded for only a small fraction of the Windline dataset but for the complete Pulsed Lidar dataset. The Sodar calculates wind components for range gates from 5- to 200-meters (16 to 656 feet) heights at 5-meter (16 foot) steps. However, the range gates below 25 meters (82 feet) were not reliably valid because of interference from the transmitted pulse and side-lobe echoes.

Table 4-9. Sodar Data Summary

Year	Month	Averaging Time (min)	Full Days
2001	9	2	17
2001	9	5	4
2001	10	5	26
2002	2	5	17
2002	3	5	28
2002	6	5	2
2002	8	5	1

* Although a ceilometer was deployed as part of the SFO WTMS, its data were never processed because the ASOS ceiling data are more convenient.

The Sodar manufacturer's processing software is designed to reject data contaminated by noise. However, because this noise rejection algorithm is not totally effective, it is useful to reject measurement outliers by calculating the median wind component every half hour from the nominally valid measurements for that half hour. Because the Sodar update interval is 4 seconds, the maximum number of valid measurements is 30 and 75 for averaging times of 2 and 5 minutes, respectively. A median value is calculated only if at least 3 valid measurements are available out of the 15 2-minute measurements in a half hour.

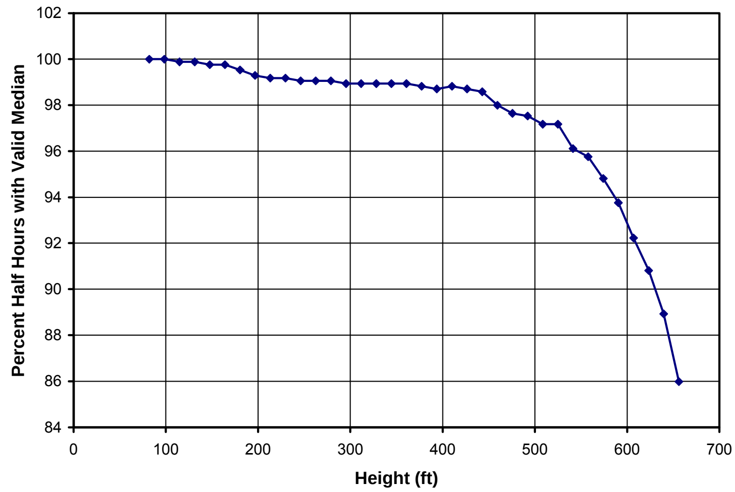

Figure 4-11. Sodar Measurement Validity vs. Height

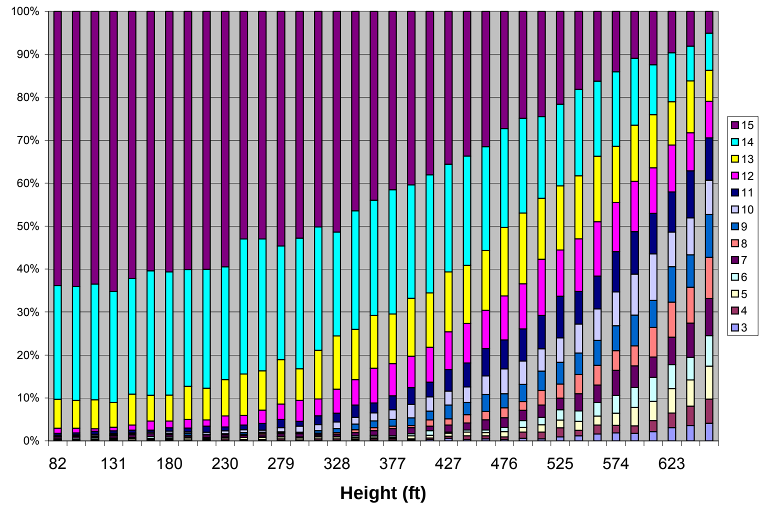

Figure 4-12. Sodar Valid Measurements vs. Height

Figure 4-11 and Figure 4-12 show the characteristics of the Sodar measurements for the 17 days with 2-minute averages. Figure 4-11 shows the percentage of half hours with valid median values as a function of measurement height. The percentage starts to fall off above 500 feet. Note that the range of valid measurement depends upon atmospheric conditions and the ambient noise level. Figure 4-12 shows the distribution of validation measurements versus height for cases with calculated median values. At 492 feet the number of cases with less than half valid measurements rises to 6 percent.

4.4.4 Lidar

The Lidar data collection schedule included a variable azimuth display (VAD) scan approximately every half hour. A VAD scan gives a vertical profile of the three wind components from approximately 70 to 700 meters (230 to 2300 feet). Low visibility or low ceiling can reduce the maximum altitude.

5. CONCLUSIONS

The SFO Windlines collected the largest wake vortex dataset ever recorded (approximately 246,000 arrivals with matched aircraft types of high reliability). Data collection efficiency at this busy airport was high because most arrivals (approximately 80%) used the two runways instrumented for wake measurements. The SFO traffic mix included all aircraft sizes, especially the largest (e.g., B-747-400) that define the operational limits for many wake turbulence procedures. This report is designed to guide users of this dataset.

The relatively short deployment of the CTI Pulsed Lidar also produced a unique dataset of wakes generated out of ground effect that is applicable to arrivals to closely-spaced parallel runways. Prior deployments of Lidars for wake measurement purposes were for much shorter durations and usually involved CW Lidars that could not provide the lateral coverage needed to assess the wake turbulence impact on CSPR operations.

The single day of concurrent Lidar and Windline measurements provided a new dataset that has been profitably used to:

1. Improve the Pulsed Lidar processing algorithms for vortices in ground effect, and
2. Better understand the height limitation of Windline measurements.

Windlines and Pulsed Lidars have complementary strengths. The Windline has better horizontal resolution and vortex identification capability, while the Lidar has better vertical resolution and away-from-the-ground sensitivity.

The demonstration of real-time wake displays was found to be instructive but not particularly useful for operational purposes.

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