Determination of a Wake Protection Zone (WPZ) for SOIA Operations at San Francisco International Airport

Flight Systems Laboratory
DOT-FAA-AFS-450-27

June 2008

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Determination of a Wake Protection Zone (WPZ) for SOIA Operations at San Francisco International Airport

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June 2008

Technical Report
Three wake mitigation strategies for the San Francisco International Airport (SFO) Simultaneous Offset Instrument Approach (SOIA) operation have been identified in a previous study: 1) Ensure that the lead aircraft is not a Heavy, B757, or a Large followed by a Small 2) The lead aircraft approaches the downwind runway and 3) The trailing aircraft stays within an “operational window” behind the lead aircraft. Any one of the three strategies is sufficient for wake mitigation. The previous study defined the dimensions and location of the “operational window” with respect to the leading (wake generating) aircraft. The wake turbulence analysis used to determine the location of the far end of the original operational window was based solely on analytical assumptions and modeling.

This study presents a reevaluation, based on data taken at SFO, of the operational window dimensions described in the previous report. Since the initial report, wake vortex data have been collected at SFO from over 250,000 landings on Runways 28R and 28L. The results reported in this study, performed by the FAA’s Flight Systems Laboratory (AFS-450), update the size of the operational window based on the data collection results analysis. This study concludes that the far end location of the operational window can be increased to a range from .97 NM to 1.20 NM (depending upon ground speed) for aircraft trailing a Large aircraft and .87 NM to 1.07 NM (depending upon ground speed) for aircraft trailing a Heavy aircraft from the location of the leading aircraft.
Executive Summary

Three wake mitigation strategies for the San Francisco International Airport (SFO) Simultaneous Offset Instrument Approach (SOIA) operation have been identified in a previous study (Reference 1): 1) Ensure that the lead aircraft is not a Heavy, B757, or a Large followed by a Small 2) The lead aircraft approaches the downwind runway and 3) The trailing aircraft stays within an “operational window” behind the lead aircraft. Any one of the three strategies is sufficient for wake mitigation. The previous study defined the dimensions and location of the “operational window” in respect with the leading (wake generating) aircraft.

This study presents a reevaluation, based on additional data, of the operational window dimensions described in the previous report. The wake turbulence analysis used to determine the location of the far end location of the original operational window was solely based on analytical assumptions and modeling. However, since that time, actual wake vortex data have been collected at SFO from over 250,000 landings on Runways 28R and 28L. The results reported in this study, performed by the FAA’s Flight Systems Laboratory (AFS-450), update the size of the operational window based on the data collection results analysis. This study concludes that the far end location of the operational window can be increased to a range from .97 NM to 1.20 NM (depending upon ground speed) for aircraft trailing a Large aircraft and .87 NM to 1.07 NM (depending upon ground speed) for aircraft trailing a Heavy aircraft from the location of the leading aircraft.

A trailing aircraft that is outside the operational window will not necessarily encounter a wake vortex as the specified operational window boundaries are very conservative. However, the risk of encountering a wake vortex increases with distance outside the operational zone, particularly when trailing a Heavy aircraft. It may be difficult for trailing aircraft with an approach speed significantly less than that of the leading aircraft to remain within the operational window. For these slower and typically smaller trailing aircraft, one or more of the other wake mitigation strategies should be considered.
Table of Contents

1.0 Introduction
   1.1 Purpose and Structure of the Report 1
   1.2 Statement of the Area of Interest 1

2.0 Description of the Study
   2.1 San Francisco International Airport 3
   2.2 Wake Turbulence Aircraft Categories 4
   2.3 SFO Wake Turbulence Data Collection 5

3.0 Summary of Data Analysis & Operational Window Determination Methodology
   3.1 Extent of Operational Window Following a Large Aircraft 8
   3.2 Extent of Operational Window Following a Heavy Aircraft 10

4.0 Results and Conclusions 11

References 12
LIST OF ILLUSTRATIONS

Tables

Table 3.1.1 Large Aircraft Operational Window Length versus Trailing Aircraft Ground Speed

Table 3.2.1 Heavy Aircraft Operational Window Length versus Trailing Aircraft Ground Speed

Figures

Figure 1.2.1 Operational Window Concept

Figure 2.1.1 Aerial View of SFO

Figure 2.3.1 SFO Wake Vortex Landings by Aircraft Type

Figure 3.0.1 Percentage of Vortices that Reached a lateral distance of 750 Feet or More from Runway 28L centerline versus Aircraft Class

Figure 3.0.2 Geometry Used for Analysis
Determination of a Wake Protection Zone (WPZ) for SOIA Operations at San Francisco International Airport

1.0 Introduction.

This section of the report describes the purpose and structure of this document, and provides a description of the area of interest.

1.1 Purpose and Structure of the Report.

The purpose of this report is to document the reevaluation of the operational window outlined in the prior study “San Francisco International Airport Simultaneous Offset Instrument Approach Procedures (SOIA), Volume I,” and dated April 2000 [1]. The original wake turbulence analysis was based solely on analytical assumptions and modeling. Since the publication of the prior report [1], actual wake vortex data has been collected at San Francisco International Airport (SFO) “Summary Results from Long-Term Wake Turbulence Measurements at San Francisco International Airport,” July 2004 [2]. This study uses the data collected from over 250,000 landings at SFO included in [2], to update the dimension of the operational window defined in the prior report [1]. In addition, this report presents new guidelines for the implementation of the operational window at SFO.

1.2 Statement of the Area of Interest.

In order to increase capacity at SFO during periods of inclement weather, the FAA has implemented a Simultaneous Offset Instrument Approach (SOIA) operation. The SOIA operation consists of a straight-in Instrument Landing System (ILS) approach to Runway 28L and a Localizer Type Directional Aid (LDA) with a glide slope approach to Runway 28R. The LDA final approach course to Runway 28R is offset approximately 2.5° from the extended centerline of Runway 28R. After passing the LDA 28R Missed Approach Point (MAP), the aircraft must perform a lateral course change maneuver to align the aircraft for landing. Planning and support efforts for the SOIA operation involved not only the FAA but also industry partners and pilot organizations.

The safety aspects of these efforts were extensively studied by the FAA’s Flight Procedures Standards Branch (AFS-420), and published [1].

Since Runway 28L and Runway 28R centerlines are separated by only 750 ft, one of the primary safety concerns, indicated in the report [1], was that of wake turbulence. By design, the SOIA operation mitigates wake turbulence encounters prior to the Runway 28R MAP by laterally separating the aircraft by at least 3,000 feet. However, after the LDA MAP, during the visual segment of the approach, the aircraft get closer to one another as they align to land on the closely spaced parallel runways. As the aircraft
approach runway thresholds, wakes can no longer descend and the potential for wake turbulence encounters must be addressed.

The prior report [1] identified three wake mitigation strategies:

1) Ensure that the lead aircraft is not a Heavy, B757, or a Large followed by a Small.
2) The lead aircraft approaches the downwind runway.
3) The trailing aircraft stays within an “operational window” behind the lead aircraft. The length of the operational window as recommended in the prior report [1] was 0.6 NM for a Heavy/B757 following a Heavy/B757.

It was reported that any one of the three strategies is sufficient for wake mitigation.

To provide sufficient time for the pilot to execute a mitigation strategy, since wake turbulence mitigation was the responsibility of the pilot, the SOIA ceiling minimum was set at 2100 ft, instead of the 1600 ft approved in the report. To achieve the 1600 ft ceiling minimum, the FAA conducted data collection and analysis to reevaluate the length of the operational window. The other two wake mitigation strategies remain applicable.

Under the wake protection window concept at SFO, the aircraft landing on Runway 28L is in the lead and the aircraft landing Runway 28R is in-trail. To mitigate the risk of a potential wake vortex encounter, the aircraft approaching Runway 28R must not exit the far end of the operational window that was numerically determined [1]. This report addresses the re-definition of the rear window boundary, based upon the data described in [2]

Figure 1.2.1 shows the far end of the operational window. The lower aircraft in Figure 1.2.1 is leading and landing on Runway 28L and the upper aircraft is trailing and landing on Runway 28R. For wake mitigation, the Runway 28R aircraft must not fall behind the far boundary of the operational window, as shown.
The original wake turbulence analysis was based solely on analytical assumptions and modeling. Since the publication of the prior report [1], actual wake vortex data has been collected at San Francisco International Airport (SFO) “Summary Results from Long-Term Wake Turbulence Measurements at San Francisco International Airport,” July 2004 [2]. This study uses the data collected from over 250,000 landings at SFO included in [2], to update the dimension of the operational window defined in the prior report [1]. In addition, this report presents new guidelines for the implementation of the operational window at SFO.

2.0 Description of the Study

This section of the report provides a description of the configuration of SFO, wake turbulence classes for aircraft, and summarizes the data collected at SFO and included in “Summary Results from Long-Term Wake Turbulence Measurements at San Francisco International Airport,” [2].

2.1 San Francisco International Airport

Figure 2.1.1 depicts an aerial view of SFO and shows some of the parameters of interest such as the geometry of the runways, the leading (Runway 28L) and trailing (Runway 28R) aircraft approach paths and the direction of the critical crosswind component. Since the trailing aircraft is on the right side of the leading aircraft, this analysis focuses only on crosswinds that transport the wake vortices of the leading aircraft towards the direction of the trailing aircraft, namely a left crosswind component as shown in Figure 2.1.1. One of the constraints placed on the SFO SOIA operation is a maximum crosswind component of 10 knots. Runways 28L and 28R are both 200 ft wide.
2.2 Wake Turbulence Aircraft Categories

Wake turbulence separation minima for Air Traffic Control (ATC) purposes are provided in FAA Order 7110.65, Air Traffic Control [3]. For wake turbulence purposes, FAA Order 7110.65, Air Traffic Control [3] classifies aircraft as Heavy, Large, and Small as follows:

- **Heavy** - Aircraft capable of takeoff weights of more than 255,000 pounds whether or not they are operating at this weight during a particular phase of flight
- **Large** - Aircraft of more than 41,000 pounds, maximum certificated takeoff weight, up to 255,000 pounds (The B757 is a special case aircraft with models both below and above the 255,000 pound limit. However, for all practical purposes, the B757 is treated as a Heavy aircraft for wake turbulence separation minima.)
- **Small** - Aircraft of 41,000 pounds or less maximum certificated takeoff weight
2.3 SFO Wake Turbulence Data Collection

The primary wake turbulence measurements at SFO were obtained using three lines of anemometers (called wind lines) installed between and perpendicular to Runways 28L and 28R. Wind Line 1 was placed very near the runway thresholds where aircraft were typically at an altitude (glide slope height) of about 65 feet AGL. The other two wind lines were placed farther down the runways where the aircraft altitude was low enough that the wake vortices strong interaction with the ground (also known as “Ground Effect”) caused rapid decay. Therefore, only data from Wind Line 1 were considered meaningful in the context of this study. In addition, in keeping with the SOIA-imposed crosswind constraint of 10 knots, only landings when the crosswind component, as measured by the airport Automated Surface Observing System (ASOS), was 10 knots or less were considered relevant to this study. It should be noted that the winds at the runway end may be different from those at the ASOS measurement site. Thus data analyzed with a 10 knot crosswind limit as measured by ASOS includes those cases when the winds at the runway end were higher than measured by ASOS. For a more complete description of the SFO data collection program, please refer to reference 2.

Between April 2000 and October 2002, a total of 261,416 landings with vortex data at Wind Line 1 were documented. Figure 2.3.1 shows the 261,416 landings at SFO by aircraft type and wake turbulence class¹.

¹ Figure 2.3.1 is reprinted from [2] where it appears as Figure 6.
Determination of a Wake Protection Zone (WPZ) for SOIA Operations at San Francisco International Airport

DOT-FAA-AFS-450-27

June 2008

Figure 2.3.1: SFO Wake Vortex Landings by Aircraft Type

![SFO Windline Vortex Data Set, 3/2000 to 10/2002](image)

- Heavy Aircraft: 119,411
- 757 Aircraft: 73,433
- Large Aircraft: 37,894
- Small Aircraft: 12,082
- Unknown Aircraft: 12,318
- Total: 261,416

Of the 261,416 landings with Wind Line 1 vortex data, 229,234 had a crosswind component of 10 knots or less. Crosswind information was obtained from time matched ASOS data. A total of 106,716 landings were on Runway 28L (40.8%) and 154,700 landings were on Runway 28R (59.2%).

3.0 Summary of Data Analysis & Operational Window Determination Methodology

Figure 3.0.1² shows the percent of landings with a vortex exceeding 750 feet lateral transport distance versus the time after passage over the wind line. As mentioned before, the analysis in reference 2, where Figure 3.0.1 was taken from, considered only landings with ASOS crosswinds of 10 knots or less. As Figure 3.0.1 shows, a total of 178,464 landings (42,223 Heavy, 33,586 B757, and 102,655 Large) were analyzed. Small aircraft were not included because in the entire measurement period only 4 wakes out of 12,318 landings traveled 750 feet or more with the minimum travel time of 58 seconds. In the SOIA plan, 58 seconds is too large a time span to be considered operationally feasible between leading and trailing aircraft. Also, considering the aircraft fleet mix at SFO, wakes from small aircraft are not strong enough to be of significant consequence during SOIA operations.

² Figure 3.0.1 is reprinted from [2] where it appears as Figure 12.
Figure 3.0.1: Percentage of Vortices that Reached a lateral distance of 750 Feet or More from Runway 28L centerline versus Aircraft Class

The location of the far end of the operational window in respect to the leading (wake generating) aircraft will be determined using the following steps (refer to Figure 3.0.2):

1. Definition of the “minimum acceptable vortex lateral distance” between a vortex and the centerline of runway 28R (where the trailing aircraft lands).
2. Definition of the “maximum acceptable vortex lateral position” in respect with runway 28L (where the vortex generator lands). This can be calculated using “1” above and runways 28L and 28R spacing.
3. Determination of the “initial vortex position”, the location where the vortex is generated based upon generating aircraft wing span.
4. Determination of the “original vortex travel distance” using data from Figures 9 and 11 from Reference 2 and average generator wing span.
5. Determination of the “maximum acceptable vortex travel distance” using data from “1”, “2” and “3” above.
6. Calculation of the average lateral transport speed of vortices for various aircraft types, using the “original vortex travel distance” from “4” and the 28 second reference time used in Reference 2 (1 nm @ 130 kts.)
7. Calculation of the times it will take vortices generated by various wake categories to be transported to the “maximum acceptable vortex lateral position” defined in “2”, using the “maximum acceptable vortex travel distance” calculated in “5” and the average lateral transport speeds calculated in “6”.

8. Determination of the operational window based upon a range of speeds for various aircraft types and the times calculated in “7”.

This methodology will be applied twice; once to determine the location of the far end of the operational window for a case where a Large wake category aircraft is in the lead and once for the case where a Heavy wake category aircraft is in the lead.

Figure 3.0.2: Geometry Used for Analysis

3.1 Extent of Operational Window Following a Large Aircraft

In order to determine the far end of the operational window the methodology described in the previous section will be applied.
NOTE: The numbers shown in the following section have been rounded to one decimal point. However, the calculations have been done using entire floating numbers.

3.1.1 **Minimum acceptable vortex lateral distance**: This value has been chosen to be 50 feet. The reasoning is that for the aircraft under consideration, a vortex at such a distance will have no significant impact on the motion of the aircraft.

3.1.2 **Maximum acceptable vortex lateral travel**: Based upon the value obtained in 3.1.1, the maximum acceptable vortex lateral position is: 750′ - 50′ = **700 feet**.

3.1.3 **Initial vortex position**: the vortex generation point is approximated as π/4 of the generator wing semi-span. From Figure 2.3.1, the vast majority of Large aircraft landing on runway 28L are B737 (wingspan 112.6 feet), A319-321 (wingspan 111.8 feet) and MD88 (wingspan 107.1 feet). Averaging these wingspans gives an average Large wake category aircraft wingspan of 110.5 feet. Therefore, the vortices of interest (generated by the right wing of the leading aircraft) originate at a distance of approximately: 110.5 · ½ · π / 4 = **43.4 feet** from runway 28R centerline.

3.1.4 **Original vortex travel distance**: The data presented in Figure 9 of Reference 2 indicates that no vortices traveled as far as 725 feet from the centerline of runway 28R in 28 seconds. In order to reach such a location, a vortex will have to travel a distance equal to 725 feet less the initial location distance where the vortex has been generated or: 725′ – 43.4′ = **681.6 feet**.

3.1.5 **Maximum acceptable vortex travel distance**: Since the vortex under consideration has been generated at a location of 43.4 feet and it might travel to a distance of up to 700 feet, the maximum acceptable travel distance is 700′ – 43.4′ = **656.6 feet**.

3.1.6 **Average lateral transport velocity of vortex**: Using the original travel distance of 681.6 feet (3.1.4) and a time of 28 seconds (Reference 2 for Large aircraft) an average lateral transport velocity can be obtained: 681.6 / 28 = **24.3 feet per second** (FPS). This is conservative in that it is greater than the 10 kt crosswind limit for the SOIA procedure (plus vortex self-induced lateral speed) and allows for the wind at the runway to be somewhat greater than measured at the ASOS location.

3.1.7 **Time calculation**: The transport time to the “maximum acceptable vortex lateral position” (that is the time it took the vortex to be transported a distance of “Maximum acceptable vortex travel distance”) can be calculated as 656.6 / 24.3 = 27.0 [Sec]. Since the lateral transport speed was conservative (high), also this time can be considered to be conservative (i.e., in real life the vortex will travel the “maximum acceptable vortex travel distance” in a longer time).
3.1.8 Determination of operational window far end, based upon the speed of the trailing aircraft: Shown in Table 3.1.1.

Table 3.1.1: Large Aircraft Operational Window Length versus Trailing Aircraft Ground Speed (Based on 27.0 second wake transport time)

<table>
<thead>
<tr>
<th>Ground Speed (Knots)</th>
<th>Operational Window (NM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>0.97</td>
</tr>
<tr>
<td>135</td>
<td>1.01</td>
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<tr>
<td>140</td>
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<tr>
<td>145</td>
<td>1.09</td>
</tr>
<tr>
<td>150</td>
<td>1.12</td>
</tr>
<tr>
<td>155</td>
<td>1.16</td>
</tr>
<tr>
<td>160</td>
<td>1.20</td>
</tr>
</tbody>
</table>

3.2 Extent of Operational Window Following a Heavy Aircraft

The same methodology will be applied to determine the extent of the operational window behind a heavy wake category aircraft.

**NOTE:** The numbers shown in the following section have been rounded to one decimal point. However, the calculations have been done using entire floating numbers.

3.2.1 Minimum acceptable vortex lateral distance: This value has been chosen to be 50 feet. The reasoning is that for the aircraft under consideration, a vortex at such a distance will have no significant impact on the motion of the aircraft.

3.2.2 Maximum acceptable vortex lateral travel: Based upon the value obtained in 3.1.1, the maximum acceptable vortex lateral position is: 750’-50’ = **700 feet**.

3.2.3 Initial vortex position: the vortex generation point is approximated as $\pi/4$ of the generator wing semi-span. From Figure 2.3.1, the vast majority of Heavy aircraft landing on runway 28L are B747 (wingspan 211.4 feet), B767 (wingspan 170.3 feet), B777 (wingspan 199.9 feet) and A340 (wingspan 208.1 feet). Averaging these wingspans gives an average Heavy wingspan of 197.5 feet. Therefore, the vortices of interest (generated by the right wing of the leading aircraft) originate at a distance of approximately: $197.5 \cdot \frac{1}{2} \cdot \pi / 4 = 77.6$ feet from runway 28R centerline.

3.2.4 Original vortex travel distance: The data presented in Figure 11 of Reference 2 indicates that no vortices traveled as far as 800 feet from the centerline of runway
In order to reach such a location, a vortex will have to travel a distance equal to 800 feet less the initial location distance where the vortex has been generated or: 800’ – 77.6’ = 722.4 feet.

3.2.5 **Maximum acceptable vortex travel distance**: Since the vortex under consideration has been generated at a location of 77.6 feet and it might travel to a distance of up to 700 feet, the maximum acceptable travel distance is 700’ – 77.6’ = 622.4 feet.

3.2.6 **Average lateral transport velocity of vortex**: Using the original travel distance of 722.4 feet (3.2.4) and a time of 28 seconds (Reference 2 for Heavy aircraft) an average lateral transport velocity can be obtained: 722.4 / 28 = 25.8 [FPS]. This is conservative in that it is greater than the 10 kt crosswind limit for the SOIA procedure (plus vortex self-induced lateral speed) and allows for the wind at the runway to be somewhat greater than measured at the ASOS location.

3.2.7 **Time calculation**: The transport time to the “maximum acceptable vortex lateral position” (that is the time it took the vortex to be transported a distance of “Maximum acceptable vortex travel distance”) can be calculated as 622.4 / 25.8 = 24.1 [Sec]. Since the lateral transport speed was conservative (high), also this time can be considered to be conservative (i.e., in real life the vortex will travel the “maximum acceptable vortex travel distance” in a longer time).

3.2.8 Determination of operational window far end, based upon the speed of the trailing aircraft: Shown in Table 3.2.1.

<table>
<thead>
<tr>
<th>Ground Speed (Knots)</th>
<th>Operational Window (NM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>0.87</td>
</tr>
<tr>
<td>135</td>
<td>0.90</td>
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<td>145</td>
<td>0.97</td>
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<td>155</td>
<td>1.04</td>
</tr>
<tr>
<td>160</td>
<td>1.07</td>
</tr>
</tbody>
</table>

4.0 **Results and Conclusions**

The results of this reevaluation are conservative in that they are based on the worst case conditions measured at SFO over a multi-year period. The operational window as calculated was determined by a few instances when the crosswind component at the
runway was greater than 10 knots at a time when the ASOS measured crosswinds were 10 knots or less. All of these instances occurred when visual approaches were being conducted. Weather conditions for SOIA operations typically include lower winds/crosswinds and, therefore, could result in a larger operational window. Thus the risk of a wake encounter when exceeding the limits of the operational window specified in this report depends on the weather conditions and in particular on the crosswind.

Based upon the analysis of actual wake vortex data collected at SFO, the results of the study indicate the following:

1. The operational wake protection zone window for aircraft following a Large wake category aircraft ranges from 0.97NM to 1.20NM corresponding to a ground speed range of 130 knots to 160 knots for the trailing aircraft.

2. The operational wake protection zone window for aircraft following a Heavy wake category aircraft ranges from 0.87NM to 1.07NM corresponding to a ground speed range of 130 knots to 160 knots for the trailing aircraft.

3. The increased length of the operational window might allow the ceiling minimum to be reduced to 1600 feet, particularly for weather conditions typical of SOIA operations.

4. A trailing aircraft that is outside the operational window will not necessarily encounter a wake vortex. The risk of encountering a wake vortex increases with distance outside the operational window, particularly when trailing a Heavy aircraft as shown in Figure 3.0.1. Figure 3.0.1 represents worst case conditions when crosswinds (as measured by the airport ASOS) are at the maximum SOIA limit. These data were taken during times when visual approaches were being conducted and would be less likely to occur under typical SOIA weather conditions.

5. It may be difficult for trailing aircraft with an approach speed significantly less than that of the leading aircraft to remain within the operational window. For these slower and typically smaller trailing aircraft, one or more of the other wake mitigation strategies should be considered.

The prior report [1] identified three wake mitigation strategies:

1) Ensure that the lead aircraft is not a Heavy, B757, or a Large followed by a Small.

2) The lead aircraft approaches the downwind runway.

3) The trailing aircraft stays within an “operational window” behind the lead aircraft.

References
