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COMPARISON OF NUMERICAL MODEL SIMULATIONS AND SFO WAKE VORTEX WINDLINE MEASUREMENTS

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ABSTRACT

To provide quantitative support for the Simultaneous Offset Instrument Approach (SOIA) procedure, an extensive data collection effort was undertaken at San Francisco International Airport by the Federal Aviation Administration (FAA, U.S. Dept. of Transportation). During the time period from March 2000 to October 2002, wake vortex data was measured for over 260,000 landing aircraft. The data set includes wake vortex measurements from Small, Large, and Heavy category aircraft. The measurements consist of cross-runway wind speed recorded every two seconds from three windlines, comprised of a series of propeller anemometers on three-foot poles near the threshold of runways 28L and 28R. The resulting data set is being used to demonstrate the feasibility of SOIA and to guide the improvement of the wake vortex model in the FAA airspace simulation tool ASAT (Airspace Simulation and Analysis for TERPS). We show that a slightly modified version of the AVOSS (Aircraft VOrtex Spacing System) Prediction Algorithm (APA) produces lateral position predictions that agree well with the windline data. We also show that the data and the APA results agree with results produced by TASS (Terminal Area Simulation System), a numerical code developed by NASA. These comparisons between code and data provide an independent validation of the lateral transport estimates using windline sensors and give us increased confidence in both the data obtained from the windline sensors and our ability to predict vortex evolution using numerical simulations.

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1. INTRODUCTION

Due to the current wake turbulence rules imposed by the Federal Aviation Administration (FAA), airports having closely spaced parallel runways are restricted to using only one of the runways in bad weather. This reduction in runways from two to one results in a major loss of capacity and in increased air traffic delays. A well known example within the aviation community is the San Francisco International Airport (SFO).

Measurements of wake vortices from landing aircraft using three propeller anemometer-based windlines have been made by the FAA at SFO since March, 2000. This measurement campaign is part of an effort to provide support for an FAA proposal for improving airport capacity called Simultaneous Offset Instrument Approach (SOIA). Under SOIA, one aircraft makes a straight-in ILS approach to one runway and a second aircraft makes a localizer-type directional aid (LDA) with a glide slope instrument approach to the other runway. The LDA aircraft starts 3,000 ft horizontally from the ILS aircraft until under the clouds, then turns, and makes visual contact with the ILS aircraft before turning to make a visual approach to the second runway. The SOIA concept is designed to allow the use of parallel runways in lower ceiling and visibility conditions than currently allowed. The goal of SOIA is to reduce air traffic delays in bad weather, while maintaining the current safety level.

In SOIA operations at SFO, it is anticipated that both aircraft will be within a one-mile longitudinal separation from each other to minimize the effects of wake turbulence. In this paper, we will show comparisons only for the first 30 seconds after the aircraft passes the windline. We use 30 seconds since this time equates to a one-mile separation at a speed of 120 kt.

As part of investigating the feasibility of SOIA, it must be shown that the lateral transport of trailing vortices from aircraft landing on an upwind runway will not be a hazard to aircraft landing on the downwind runway that are following SOIA procedures. The SFO windline data are being used directly to examine the feasibility of SOIA, and they are also being used to guide the improvement of the trailing-vortex model in ASAT, a simulation tool used by the FAA to evaluate proposed Air Traffic Control (ATC) procedures such as SOIA. (ASAT stands for Airspace Simulation and Analysis for TERPS, where TERPS stands for Terminal Instrument Procedures.) In order to help select windline cases to be used in the ASAT trailing-vortex model improvement effort, we use simultaneous wind measurements from the Automated Surface Observing System (ASOS) at SFO.

Section 2 of this paper discusses the SFO windline and supporting data systems. A description of the numerical models is given in Section 3. Numerical simulations of SFO data will be shown in Section 4. A summary and conclusions is given in Section 5.

2. OVERVIEW OF THE SFO DATA COLLECTION EFFORT

SOIA operational procedures have been designed to eliminate the possibility of a wake encounter and to provide both enhanced safety and runway throughput. In order to demonstrate that the SOIA procedure is safe as designed, an extensive data collection effort was undertaken at SFO. During the time period from March 2000 to October 2002, wake vortex data was measured for over 260,000 landing aircraft. This wake vortex data was taken over all seasons and all weather, 24-hours per day when the system was operating. The data set includes wake vortex measurements from Small, Large, and Heavy category aircraft.

Figure 1 shows an aerial view of SFO in the top plot and a schematic view of SFO on the bottom plot, and shows the locations of runways 28L and 28R. The centerlines of 28L and 28R are separated by 750 feet. Three windlines were installed near the thresholds of these runways. The locations of the windlines are shown in Figure 2. Windline 1 extends beyond the outside edges of 28L and 28R, while Windlines 2 and 3 are limited to between the runways. Each windline contains a row of 3-foot high poles, 25 ft apart, in a line perpendicular to the runways. On the top of each pole is a propeller anemometer to measure the crosswind of both the background atmosphere and of the vortex-driven flow (Figure 3). At each end of Windline 1 is a 20-foot high pole with a 3-axis propeller anemometer on top (Figure 4).

The crosswind measurements from the anemometers were averaged for 2 sec before being recorded. These data were used to estimate the lateral positions of the vortices generated by the landing aircraft.[1] Data in this paper is shown only from Windline 1.

3. DESCRIPTIONS OF THE NUMERICAL MODELS

3.1. The APA Model

The APA model (AVOSS Prediction Algorithm, where AVOSS stands for Aircraft VOrtex Spacing System[2]) is an engineering, numerical model of the behavior of

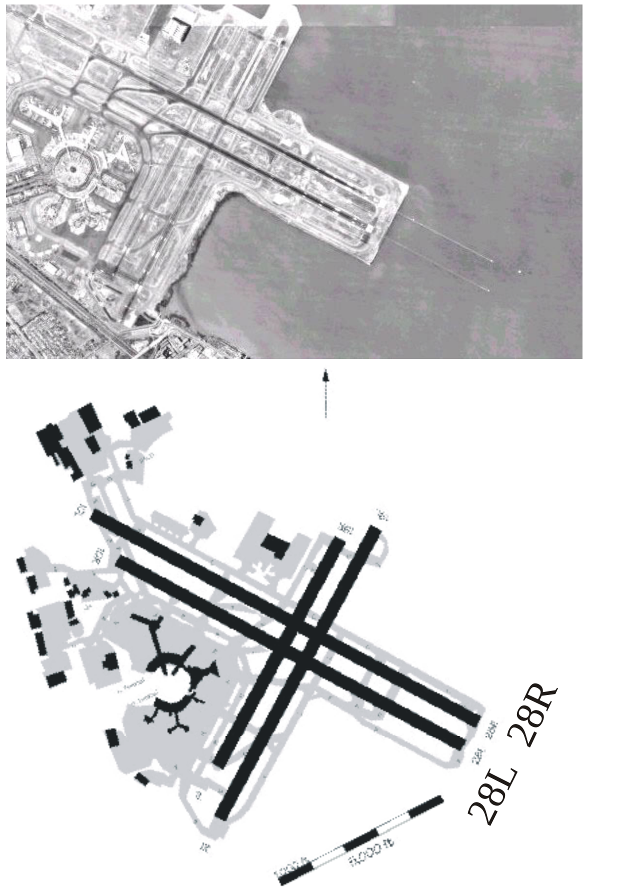

Figure 1. Aerial view of SFO (top) and a schematic view of SFO (bottom) showing the locations of runways 28L and 28R.

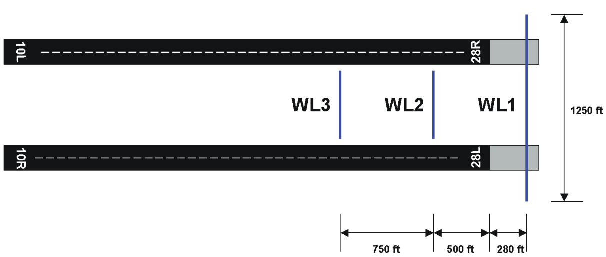

Figure 2. Positions of the three windlines relative to runways 28L and 28R.

Figure 3. Close-up view of Windline 1 showing the 3-foot high poles and the propeller anemometer on top of each pole.

Figure 4. Photograph of a twenty-foot pole with a 3-Axis anemometer on top and the Sodar (located 750 feet to the left of Runway 28L Centerline).

aircraft trailing vortices subject to atmospheric effects and interaction with the ground. The model is intended to provide real-time predictions for use in operational systems such as AVOSS and air traffic simulation systems such as ASAT (Aircraft Simulation and Analysis for TERPS). The APA model divides vortex evolution into three phases: out of ground effect (OGE), near ground effect (NGE) and in ground effect (IGE).

For the OGE phase, APA utilizes an enhanced version of a formulation developed by Greene[3], and later modified by Sarpkaya[4]. In the NGE and IGE phases, a point vortex formulation is adopted. For NGE, the effect of the ground is modeled by two image vortices, and for the IGE phase, additional vortices are used to model the generation of secondary vorticity by the interaction of the primary vortices with the ground.

Input data required by APA are the initial height, separation distance, and descent speed of the vortices, and vertical profiles of crosswind, temperature, and eddy dissipation rate in the atmosphere. Output parameters from the model are circulation, height, and lateral position for each primary vortex as a function of time. APA requires only a small fraction of a second to simulate a typical landing scenario. Considerable effort has been devoted to comparing APA simulation results with aircraft measurements.[5, 6]

3.2. The TASS Model

The TASS model (Terminal Area Simulation System) is a numerical model developed at NASA Langley Research Center by Dr. Fred Proctor that solves equations describing three-dimensional, compressible, non-hydrostatic flow.[7] TASS has been used to simulate the evolution of trailing aircraft vortices.[8-10] A large-eddy simulation (LES) formulation is used by TASS to include the effects of sub-grid scale turbulence. These effects are modeled by a conventional first-order closure scheme that has been modified to include stratification and rotation effects. TASS can be run as a two-dimensional model, which was used for the simulations reported here.

The ground boundary formulation used by TASS is an important feature that enhances its ability to simulate wake vortex behavior near the ground. This formulation is based on Monin-Obukhov similarity theory, with the sub-grid stress at the ground determined locally from the wind speed, the surface roughness, and the local thermal stratification.

4. NUMERICAL SIMULATIONS OF SFO DATA

4.1. APA Predictions vs Ensemble Data

The aircraft trailing-vortex model in ASAT currently uses the APA model to predict the lateral transport of the wake vortices. The APA model was validated primarily using vertical transport and circulation data, and, therefore, needs to be further validated for lateral motion predictions. We have used a slightly modified APA model to predict the lateral transport of wake vortices at SFO. We have validated the model using a subset of SFO windline data, some of which is shown in the following figures. To determine the relevant windline data to be used in the comparisons to the numerical predictions, we binned the SFO arrivals by aircraft type, ASOS crosswind, and ASOS headwind. We then compared the numerical predictions to the appropriate bin for the aircraft and environmental conditions used in the numerical model.

Figure 5 shows a schematic drawing of an aircraft landing on runway 28R and another aircraft landing on runway 28L. The planes are landing from right to left, and the wake vortices are shown trailing behind the aircraft and over Windline 1. Figure 5 shows the wake vortices as they would appear with little or no crosswind, where a crosswind is defined as a component of the wind blowing in a direction perpendicular to the runways. Including a crosswind will have the effect of making the vortex tracks in Figure 5 move in the direction of the wind.

Figure 5. Schematic drawing of aircraft landing on 28R and 28L and the trailing wake vortices.

Figure 6 shows all Windline 1 measurements for B-737 landings for near-zero crosswind (crosswinds between -0.5 kt and 0.5 kt) and near-zero headwind (headwinds between -1 and 1 kt) conditions. For these parameters, there were 1,351 B-737 landings in the database. Since the landings took place on both runways, we calculated the median lateral transport and the 10th and 90th percentiles for each vortex on each runway. For this figure and following figures, we have overlaid these lateral transport results from runway 28R over the results from runway 28L (cf. Figure 5). Thus, in Figure 6, the gray solid lines are the medians of the windline measurements of vortex lateral position vs. time after the passage of the aircraft over the windline. There are two solid gray lines for the median transport for the starboard vortex, one for the starboard vortex from 28R and one for the starboard vortex from 28L. There are also two solid gray lines for the median transport for the port vortex. The dashed gray lines show the 10th and 90th percentiles of the observed lateral motion.

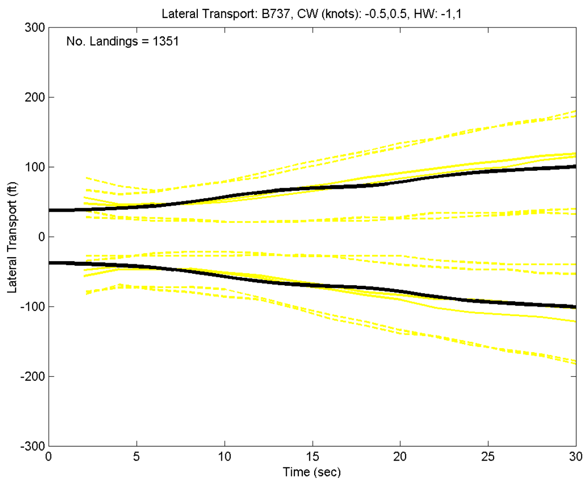

Figure 6. Comparison of windline observations of trailing-vortex lateral motion for 1,351 Boeing-737 landings at SFO in near-zero crosswind and near-zero headwind with APA predictions. The solid gray lines represent the medians of the windline observations for the 1,351 landings. The dashed gray lines show the 10th and 90th percentiles of the observed lateral motion. The solid black lines in the figure are predictions from the modified APA algorithm. Note the good comparison between the APA predictions (black lines) and the medians of the windline measurements (gray lines).

Note in Figure 6 that the solid gray lines and the dashed gray lines nearly overlay each other. This means that the vortex evolution on runway 28R is nearly identical to the vortex evolution on runway 28L, as expected.

The black lines in Figure 6 are predictions from the modified APA algorithm. Note the good comparison between the APA predictions (black lines) and the median of the windline measurements (the gray lines). For the port vortex, the root mean square (rms) difference between the APA predictions and the windline medians is 7.6 ft. For the starboard vortex, the rms value is 8.8 ft. Thus, the APA model is simulating the lateral transport of the aircraft vortices quite well.

Figure 7 shows data similar to Figure 6 for 615 landing B-757 aircraft for the same near-zero crosswinds and near-zero headwinds as in Figure 6. Again, the data for runway 28R nearly overlays the data from runway 28L. Also, the APA predictions, shown as the solid black lines, agree well with the median lateral transport from the windlines. In this case, the rms difference between APA and the windline measurements is 6.5 ft for the port vortex and 5.0 ft for the starboard vortex.

Figure 8 shows data similar to Figure 6 for 320 landing B-747 aircraft for the same near-zero crosswinds and near-zero headwinds as in Figure 6. As in Figures 6 and 7, the data for runway 28R nearly overlays the data from runway 28L and the APA predictions agree well with the median lateral transport from the windlines. The rms difference between APA and the windline measurements is 7.2 ft for the port vortex and 7.9 ft for the starboard vortex.

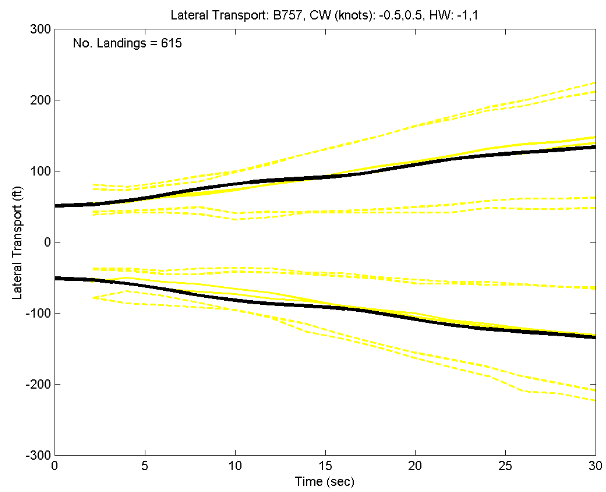

Figure 7. Similar to Figure 6, only for 615 B-757 aircraft landing in near-zero crosswind and near-zero headwind.

Figures 6, 7, and 8 taken together show that the APA model agrees well with the ensemble averages of wakes from B-737, 747, and 757 aircraft under low wind conditions.

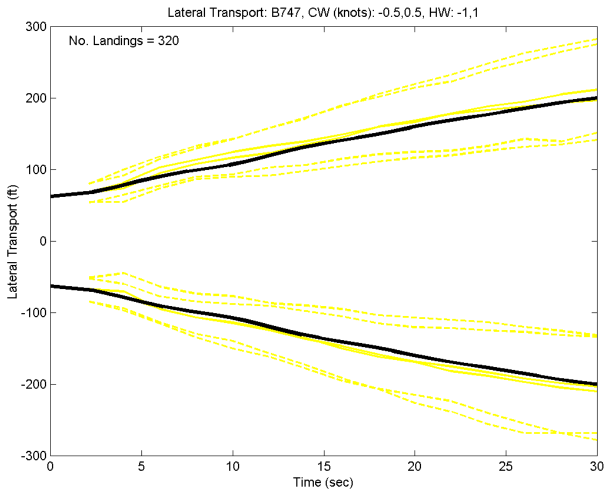

Figure 8. Similar to Figure 6, only for 320 B-747 aircraft landing in near-zero crosswind and near-zero headwind.

4.2. APA and TASS Predictions vs Individual Landings

In addition to comparing numerical predictions to ensemble data, we have also compared APA and TASS to single landings. Three of those landings will be shown here.

Figure 9 shows data from a B-737 landing on runway 28R on September 25, 2001 in a crosswind of -5.0 kt (crosswind blowing from 28R to 28L). The windline data is shown by the triangles with black lines joining them, the prediction of the APA model is shown by the light gray lines, and the predictions from the TASS model are shown by the dark gray lines. The APA and TASS predictions have been shifted in time to account for the fact that the initial vortices in the numerical simulations are already rolled up into a counter-rotating vortex pair, while in the real world, this rollup takes several seconds. In the comparisons in Figures 9 to 11, we shifted the numerical predictions by 4 to 6 seconds. In Figure 9, the maximum difference between either numerical prediction and the windline data is just over 50 ft at a time of 30 sec.

Figure 10 shows similar data to Figure 9 for a B-757 landing on runway 28R on September 25, 2001 in a crosswind of -6.7 kt. The maximum difference between either numerical prediction and the windline data is approximately 60 ft at a time of 22 sec.

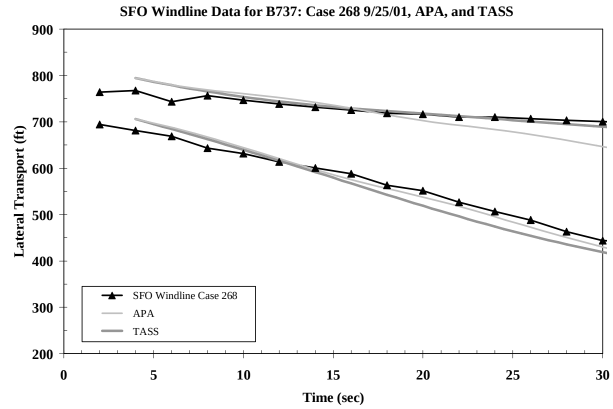

Figure 9. Comparison of the APA model (light gray lines) and TASS (dark gray lines) with windline data (triangles with black lines) for Case 268 on September 25, 2001. The aircraft is a B-737 landing on runway 28R in a crosswind of -5.0 kt (crosswind from 28R to 28L).

Figure 11 shows similar data to Figure 9 for a B-747 landing on runway 28L on September 25, 2001 in a crosswind of -5.0 kt. In this run, the port vortex migrates off the end of the windline at a time of approximately 19 sec. In this figure, both numerical predictions follow the windline data very closely. The maximum difference between either numerical prediction and the windline data is around 15 ft at a time of 30 sec.

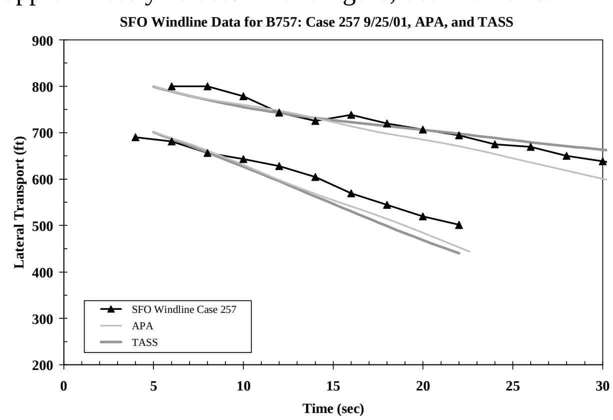

Figure 10. Similar to Figure 9 only for Case 268 on September 25, 2001. The aircraft is a B-757 landing on runway 28R in a crosswind of -6.7 kt (crosswind from 28R to 28L).

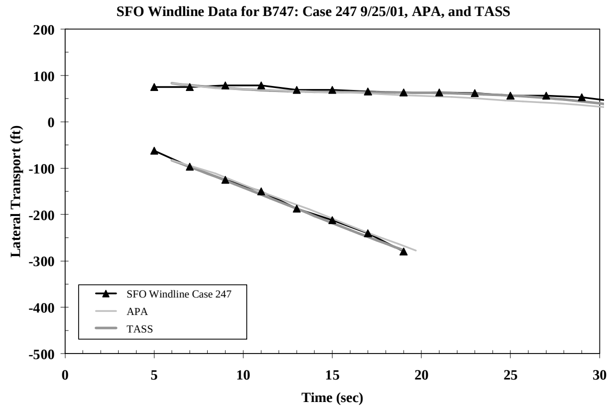

Figure 11. Similar to Figure 9 only for Case 247 on September 25, 2001. The aircraft is a B-747 landing on runway 28L in a crosswind of -5.0 kt (crosswind from 28R to 28L). The port vortex migrates off the end of the windline at a time of approximately 19 sec.

5. SUMMARY AND CONCLUSIONS

The APA numerical code predicts quite well the lateral transport of vortices in ground effect for near-zero wind conditions (Figures 6-8). With the addition of crosswind, the prediction is still good, but not as good, at least for the 737 and 757 cases shown here. The TASS simulations are reasonably similar to the IGE APA simulations, indicating that the ground effect model in each code is capable of predicting aircraft vortices, at least for the aircraft and environmental parameters shown here.

The comparison of the APA and TASS code predictions to the windline data for the B-747 case shown in Figure 11 is quite remarkable in that the maximum error in the code predictions to the windline data is around 15 ft. We are hopeful that improvements to the model will yield more comparisons that look like this figure.

ACKNOWLEDGEMENTS

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