DOT/FAA/ND-97-6
DOT-VNTSC-FAA-97-10

Office of Communications,
Navigation and
Surveillance Systems
Washington, D.C. 20591

Database of Ground-Based Anemometer Measurements of Wake Vortices at Kennedy Airport

Research and Special Programs Administration
John A. Volpe National Transportation Systems Center
Cambridge, MA 02142-1093

Final Report
July 1997

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

This document is available to the public
through the National Technical Information
Service, Springfield, Virginia 22161

U. S. Department of Transportation
Federal Aviation Administration

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
July 1997

3. REPORT TYPE AND DATES COVERED
Final Report
September 1994 - March 1995

4. TITLE AND SUBTITLE
Database of Ground-Based Anemometer Measurements of Wake Vortices at Kennedy Airport

5. FUNDING NUMBERS
FA727/A7072
DTRS-57-93-D-00070
TTD CH 5218

6. AUTHOR(S)
David Burnham* and Steve Abramson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Research and Special Programs Administration
John A. Volpe National Transportation Systems Center
Cambridge, MA 02142-1093

8. PERFORMING ORGANIZATION REPORT NUMBER
DOT-VNTSC-FAA-97-10

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Aviation Administration
Office of Communications, Navigation and Surveillance Systems
800 Independence Avenue, SW
Washington DC 20591

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FAA/ND-97-6

11. SUPPLEMENTARY NOTES
*Scientific & Engineering Solutions, Inc.
Orleans, MA

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the National Technical Information Service, Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A 700-foot array of horizontal and vertical single-axis anemometers was installed at New York's Kennedy Airport on 30-foot poles under the approach to Runway 31R. Although the original purpose for the anemometers was to track the lateral position of wake vortices, new processing algorithms were developed that permit assessment of vortex height and circulation. Data from more than 20,000 landings have been recorded and processed. This report documents the current state of algorithm development and provides processed data for other researchers to analyze.

14. SUBJECT TERMS
wake turbulence, wake vortices, ground-wind anemometers, airport wind measurements, airport turbulence measurements

15. NUMBER OF PAGES
32

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

PREFACE

One of the long-term goals of the United States Wake Vortex Program is to develop real-time, all-weather systems for measuring wake vortices. Ground-based anemometers qualify as real-time, all-weather vortex sensors but have previously not been able to measure vortex height and circulation. This report describes new processing algorithms that have had some success in extracting height and circulation values from such measurements and presents analyses of more than 20,000 landings at Kennedy airport.

The Federal Aviation Administration (FAA) Wake Vortex Program Manager, George C. (Cliff) Hay, has asked the John A. Volpe National Transportation Systems Center (Volpe Center) to make its extensive archives of wake vortex data available in electronic form for wake vortex research. This report documents the available ground-based anemometer data and makes it available on CD ROM to interested parties. The CD ROM can be obtained by contacting the Volpe Center library.

The authors would like to acknowledge the support of Leo Jacobs, who helped install and maintain the Kennedy test site, and David Hazen, who managed and validated the data files coming from the site and the surface observations. Both are employees of the System Resources Corporation. Jim Hallock of the Volpe Center reviewed the report and assisted in getting it published.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (ha) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

°C=5/9(°F - 32)

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

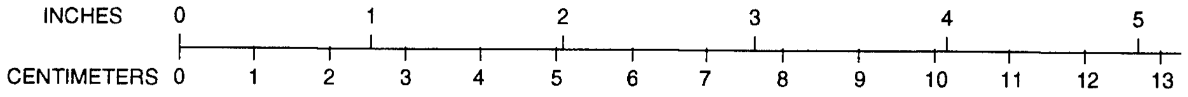
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

°F=9/5(°C) + 32

QUICK INCH-CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

Updated 8/1/96

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

In 1994, the John A. Volpe National Transportation Systems Center (Volpe Center) installed a ground-wind wake vortex tracking system[1] at New York's Kennedy Airport at the same Runway 31R approach region used for testing[2] in the 1970s. The new installation consisted[3] of an array of two-axis anemometers (vertical wind and crosswind). The headwind was also measured at the ends of the array. The data collection system operated automatically. Aircraft arrivals were detected automatically with noise monitors; each arrival generated a data files containing data until the next arrival or 180 seconds later, whichever came first.

The wake vortex data collected from September 1994 through June 1995 and in November 1996 will be presented in this report. The data collection was continuous during the first period with some missing blocks of data. The most significant missing data gaps are four weeks in December-January and one week in early March. For the second data collection period, the anemometer data collection system was operated concurrently with other manually operated wake vortex sensors; data are available for less than half the month. [Note that the system was installed[4] at the Memphis, TN, airport during the time between JFK tests (August 1995 to December 1995).]

The purpose of this report is to present preliminary results of the wake vortex measurements and to make the wake vortex data set available to other researchers. Chapter 2 describes the data collection, and Chapter 3 the data processing. Chapter 4 describes the databases provided on CD ROM, which can be obtained by contacting the Volpe Center Library (617-494-2306).

2. DATA COLLECTION

2.1 DATA DIGITIZATION

2.1.1 Sensor Descriptions

Table 1. Sensors Recorded

Sensors	Units	Number	Total Channels
Two-Axis Anemometers	m/s	17	34
Three-Axis Anemometers	m/s	2	6
Temperature	°C	1	1
Humidity	%	1	1
Noise	0.1 volt	1	1
TOTAL		22	43

The sensors listed in Table 1 were digitized by four Campbell Scientific data acquisition systems (CSDAS #n, n=1-4). CSDAS #1-3 report in low-resolution binary format (two bytes per channel). CSDAS #4 reports in ASCII format. The first three CSDAS sample the sensors at 10 Hz and report two-second averages every two seconds. Since the three CSDAS may not be synchronized, the data acquisition system prefixes the second the message was detected (to hundredths of a second) in standard Campbell low resolution format. Since the message channels are scanned every half second, the actual resolution on the message time tags is only 1/2 second (not the 1/18 second resolution of the computer clock). The wind units are meters/second. The aircraft noise units are 0.1 volts.

Table 2. Anemometer Pole Locations

Pole	Distance (ft) from Runway Centerline	Distance (ft) from Middle Marker	Height(ft)	Number Axes
01	-350	400	30	3
02	-300	400	30	2
03	-250	400	30	2
04	-200	400	30	2
05	-150	400	30	2
06	-100	400	30	2
07	-50	400	30	2
08	0	400	30	2
09	50	400	30	2
10	100	400	30	2
11	150	400	30	2
12	200	400	30	2
13	250	400	30	2
14	300	400	30	2
15	350	400	30	3
16	0	450	30	2
17	50	450	30	2
18	0	200	30	2
19	50	200	30	2
20	100	415	14	2
21	100	420	7	2
22	100	425	3.5	2

In 1994-1995, all anemometers were installed at approximately 30-foot height on 19 fiberglass poles at locations given in Table 2. In 1996, three shorter poles were added near Pole 10. The three-axis anemometers measure crosswind, vertical wind and headwind. The two-axis anemometers measure crosswind and vertical wind. The sign convention is defined with respect to a pilot landing on Runway 31R; positive lateral distances and crosswinds are toward the pilot's right hand. The distances from the middle marker are toward the runway. The temperature, relative humidity and aircraft noise sensors were installed near the runway centerline on the main anemometer line, 400 feet from the middle marker.

The single-axis propeller anemometers were manufactured by the R. M. Young Company with a current Model No. of 27106R. The four-bladed propellers are made of black polypropylene, have a distance constant of 2.7 meters and a starting speed of 0.5 m/s, and have an approximate cosine wind response. The calibration of each anemometer was checked for nominal response (17.2 m/s per volt).

The aircraft detector consisted of a horn-type loudspeaker aiming upward toward the arriving aircraft. A drain hole was drilled in the horn to allow water to drain out. In the wintertime, the mount of the horn was covered with plastic to keep out rain and snow. The horn was mounted on the runway side of the plywood box housing the CSDAS, which was located near Pole 9; in this location, the aircraft noise was somewhat blocked from the horn until the aircraft was directly overhead and thus should provide a sharply rising noise signature for landing aircraft. The signal from the horn loudspeaker was amplified and rectified to produce the noise signal that was digitized.

The original horn loudspeaker was low cost and failed part way through the test. The drain hole was also ineffective in some cases and water collected in the horn and froze. More reliable operation was experienced when a higher quality horn speaker, specifically designed for microphone use, was installed and carefully protected with a plastic cover. Considerable aircraft arrival data was lost in December 1994 through March 1995 (see Table 5) because of these problems.

2.1.2 Parameter Names

Table 3 describes the 1994-1995 channel assignment. The 3 or 4 character codes assigned to each sensor are included. The anemometer axes are labeled Cnn, Vnn or Hnn, where nn refers to the pole number and C, V or H refer to crosswind, vertical wind or headwind, respectively. The names of the standard deviation parameters are obtained by prefixing a "T" for turbulence, e.g., TVnn. Note that, according to Monin-Obukhof similarity theory, TVnn is a better indication of atmospheric turbulence in the boundary layer than TCnn or THnn, which are influenced by large scale eddies which affect the wind direction.

Since space was available in the output format for CSDAS #3, standard deviations were calculated on the 20 samples in the 2-second average for the 2-second averaged data in channels 1-7. These standard deviations were found to be very small (less than half the one-minute standard deviation for vertical wind components and less than one third the one-minute standard deviation for horizontal wind components) and have been excluded from all subsequent analyses.

Table 3. 1994-1995 Data Acquisition System Channel Assignments, Parameter Names

Channel	CSDAS #1		CSDAS #2		CSDAS #3		CSDAS #4	
0	ID=1		ID=2		ID=3		ID=4	
	Main Baseline, 400 ft from MM							
	Crosswind		Vertical Wind					
1	-300 ft	C02	-300 ft	V02	A/C Noise	ACNO	Temperature	TMPC
2	-250 ft	C03	-250 ft	V03	Cross -350 ft	C01	Rel. Humid.	HUMD
3	-200 ft	C04	-200 ft	V04	Vert -350 ft	V01		
4	-150 ft	C05	-150 ft	V05	Head -350 ft	H01		
5	-100 ft	C06	-100 ft	V06	Cross 350 ft	C15		
6	-50 ft	C07	-50 ft	V07	Vert 350 ft	V15		
7	0 ft	C08	0 ft	V08	Head 350 ft	H15		
8	50 ft	C09	50 ft	V09	50 ft Cross, 200 ft baseline	C19		
9	100 ft	C10	100 ft	V10	50 ft Vert, 200 ft baseline	V19		
10	150 ft	C11	150 ft	V11	Std Dev Ch 1	VACN		
11	200 ft	C12	200 ft	V12	Std Dev Ch 2	SC01		
12	250 ft	C13	250 ft	V13	Std Dev Ch 3	SV01		
13	300 ft	C14	300 ft	V14	Std Dev Ch 4	SH01		
	Baseline 450 ft from MM							
14	0 ft	C16	0 ft	V16	Std Dev Ch 5	SC15		
15	50 ft	C17	50 ft	V17	Std Dev Ch 6	SV15		
	Baseline 200 ft from MM							
16	0 ft	C18	0 ft	V18	Std Dev Ch 7	SH15		

Table 4 shows the change in channel assignments for 1996. In addition to the data from poles 20, 21 and 22, an additional headwind anemometer (H09) was added near the runway centerline,

Table 4. 1996 Data Acquisition System Channel Assignments, Parameter Names

Channel	CSDAS #1		CSDAS #2		CSDAS #3		CSDAS #4	
0	ID=1		ID=2		ID=3		ID=4	
			Main Baseline, 400 ft from MM					
	Crosswind		Vertical Wind					
1	-300 ft	C02	-300 ft	V02	A/C Noise	ACNO	Temperature	TMPC
2	-250 ft	C03	-250 ft	V03	Cross -350 ft	C01	Rel. Humid.	HUMD
3	-200 ft	C04	-200 ft	V04	Vert -350 ft	V01		
4	-150 ft	C05	-150 ft	V05	Head -350 ft	H01		
5	-100 ft	C06	-100 ft	V06	Cross 350 ft	C15		
6	-50 ft	C07	-50 ft	V07	Vert 350 ft	V15		
7	0 ft	C08	0 ft	V08	Head 350 ft	H15		
8	50 ft	C09	50 ft	V09	50 ft Cross, 200 ft baseline	C19		
9	100 ft	C10	100 ft	V10	50 ft Vert, 200 ft baseline	V19		
10	150 ft	C11	150 ft	V11	Head 50 ft	H09		
11	200 ft	C12	200 ft	V12	Vert. 100 ft	V20		
12	250 ft	C13	250 ft	V13	Vert. 100 ft	V21		
13	300 ft	C14	300 ft	V14	Vert. 100 ft	V22		
	Baseline 450 ft from MM							
14	0 ft	C16	0 ft	V16	Cross 100 ft	C20		
15	50 ft	C17	50 ft	V17	Cross 100 ft	C21		
	Baseline 200 ft from MM							
16	0 ft	C18	0 ft	V18	Cross 100 ft	C22		

2.2 DATA ACQUISITION

The primary data acquisition system (DAS) is hosted in an industrial PC and was derived from an available weather acquisition system. The DAS accepts data from up to 32 serial ports. The DAS software operates under the Desqview multitasking environment. The DAS operating information is specified in a configuration file, which defines the message format and storage requirements for each serial channel.

2.2.1 Equipment Layout

The four CSDAS were located in a small shelter near the middle of the anemometer array to minimize cable lengths. The DAS was installed in a trailer located near the end of the anemometer array and was one node in a Novell Netware computer network. The network permitted real-time analysis of the data from the anemometer array.

The following four sections describe the various files recorded by the DAS. The third one was used for the wake vortex data analyzed in this report.

2.2.2 Raw Wake Vortex Data Storage

The daily data file is named "WMmmDdd.Yyy," where the capital letters are fixed in the file name and mm is the month, dd is the day and yy is the year. This file stores one-minute data blocks and is saved on both the local DAS hard drive and the network fileserver. The configuration file used each day is copied to a file named "XMmmDdd.Yyy." Because of the amount of two-second averaged data, the complete WM file for one day contains more than 4 Mbytes. To reduce this file size by eliminating uninteresting data, two options were specified for the amount of data saved in the WM file: (a) all data, or (b) the minute before and four minutes after each aircraft arrival, which was detected by measuring aircraft noise near the middle of the main anemometer array.

2.2.3 Meteorological Data Storage

A secondary data acquisition program receives each one-minute data block as a mail message (under Desqview) from the primary data acquisition program. It saves the non-binary data as received, but processes the two-second binary data into one-minute means and standard deviations, which are stored as ASCII. The meteorological file is named DMmmDdd.Yyy and stores all one-minute data blocks for the day. It is recorded on both the local hard drive and the network fileserver. The configuration file for this file is named CMmmDdd.Yyy and was generated by manually editing the file XMmmDdd.Yyy rather than by automatic computer processing, since it was fixed for long periods of time.

2.2.4 Wake Vortex Run

Each wake vortex run file is named "RMmmDdd.nnn," where the capital letters are fixed in the file name and mm is the month, dd is the day and nnn is the number of the aircraft arrival for that day. The start of run is defined by the two-second average of aircraft noise reaching a peak (i.e., noted by a decrease in the next two-second average) that is above a detection threshold. The start of the next run is suppressed for 16 seconds to prevent multiple triggers on the same aircraft (more likely on a 13L departure than a 31R arrival because of the higher altitude). The run file records two-second data blocks from ten seconds before the arrival until the next arrival or until 180 seconds has elapsed since the start of run. Note that some early 1994 run files started recording at the start of run rather than ten seconds before.

2.2.5 Real-Time Analysis

The data collection program also outputs three files to the network fileserver that can be used for real-time analysis.

2.2.6 Clock Time

The data collection clock time was defined by the clock on the fileserver. This clock was set for GMT. However, a PC's clock can drift significantly and the actual time was observed to err by as much as 20 minutes. This time drift was not documented, but could affect comparisons with other sources of data. In 1996 an attempt was made to synchronize all data sources with GPS time.

2.3 KNOWN SENSOR FAILURES

The known sensor failures are:

1. During the period when the data collection system was down (December 16, 1994 - January 13, 1995), anemometer V08 vibrated loose and fell off its pole.
2. On February 25, 1995 pole 09 fell down, thereby disabling C09 and V09.
3. On February 26, 1995 V02 seized up and stopped working. It had earlier showed signs of a high starting threshold.

These failures were corrected on March 9 - 10, 1995.

3. DATA PROCESSING

3.1 WAKE VORTEX ALGORITHMS

3.1.1 Input Data

The ground-based anemometer system measures the vertical and crosswind components with an array of anemometer poles laid out on a baseline perpendicular to the aircraft flight path. Pole spacing is 25 or 50 feet. Pole height is 10 or 30 feet. Two-second averages are stored for analysis.

3.1.2 Traditional Algorithm

3.1.2.1 Vortex Location, Ambient Crosswind

The traditional algorithm assigns the vortex positions to the position of the anemometers measuring the maximum and minimum crosswind. As an extension to the traditional algorithm, the median wind may give a reasonable estimate of the ambient crosswind even in the presence of wake vortices.

Input:

Crosswind c_i at pole lateral positions x(i), i = 1, n (n = number of poles)

Calculate:

Max crosswind c_{max} at pole i_{max}, Minimum crosswind c_{min} at pole i_{min}

Median crosswind c_{med}

Output:

Max Vortex: position $x_{max} = x(i_{max})$, crosswind c_{max}

Min Vortex: position $x_{min} = x(i_{min})$, crosswind c_{min}

Median crosswind c_{med}

Saving the maximum and minimum crosswinds is also an extension of the traditional algorithm.

3.1.2.2 Vortex Tracking

Start Track: The algorithm should start only when the vortex crosswind can be distinguished from the ambient turbulence. The vortex trajectory starts when the difference between the vortex crosswind and the median crosswind is less than a limiting value c_{lim}, e.g., $|c_{max} - c_{med}| < c_{lim}$. Ultimately the choice for c_{lim} should be based on the ambient crosswind turbulence. If the crosswind turbulence is measured in the ten seconds prior to aircraft arrival, this approach has problems with the residual effect of the vortices from the previous landing. The simpler approach of using a fixed value for c_{lim} (e.g., 2 m/s) is more reliable, but will give problems in turbulent conditions.

Stop Track: The simplest stopping algorithm stops the tracking when the difference between the median wind and the vortex wind is below a certain value, perhaps 1 m/s. A value below the starting limit will follow a vortex longer once it has been detected. This algorithm is blind to normal vortex behavior and needs to be augmented with an algorithm that determines when the vortex goes off the end of the array. Such an algorithm will prevent misidentifying the secondary vortices of the other vortex.

Off End of Array: The only algorithm implemented so far has limitations for vortices that change their direction of motion but otherwise appears to give reasonable results. It allows the vortex location to be assigned to the end of the array for 1.5 times the time it spent at the next to last location:

1. See if vortex is in next to last position, count the number of data samples *n* until its location changes.

2. End the track 1.5**n* samples later.

Position Jump: The traditional method of ending a vortex track to see when the vortex location jumps to a distant location, such as more than three poles away.

3.1.2.3 Limitations

The main limitation of the traditional algorithm is that it gives no information on vortex height and vortex circulation. It also makes no use of the vertical wind information.

Memphis[4] Application: The application of the traditional algorithm to the Memphis ground-wind anemometer data is complicated by the different pole heights (10 feet rather than 30 feet in the middle of the array). In general, the ambient winds are smaller at 10 feet than at 30 feet. It is suggested that the ten-foot crosswinds be scaled up by a factor f to approximate the winds at 30 feet. The algorithm can then be applied as normal. The best choice for the factor f will have to be determined by trial to see how well the vortices are tracked.

3.1.3 Image Vortex Model

The image vortex model accounts for the fact that the vertical wind must be zero at the ground. This boundary condition can be assured if the vortex flow field is computed from the real vortex above the ground (circulation = Γ, lateral position = X, height = $Z > 0$) and an image vortex (circulation = $-\Gamma$, lateral position = X, height = $-Z$) located below the ground. Figure 1 shows the geometry of this calculation. Note that a positive circulation rotates in the counterclockwise direction. Define $G = \Gamma/2\pi$; then the vortex tangential velocity = G/(vortex radius) as long as the point of interest lies outside the vortex core. G is positive for the max vortex and negative for the

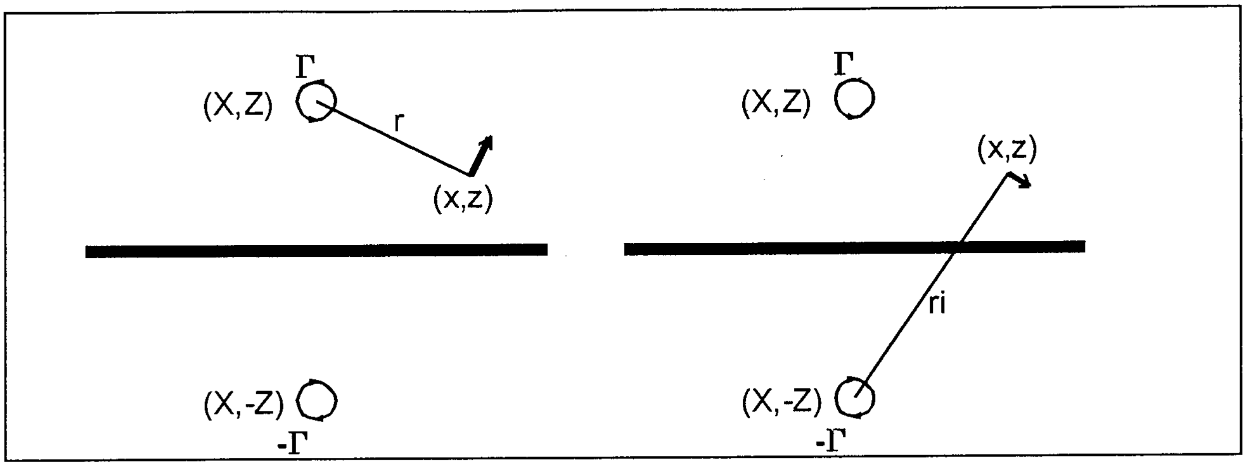


Figure 1. Velocity Contributions from Real Vortex (left) and Image Vortex (right)

min vortex. Derive the wind components at position (x,z) from the real vortex (see left plot in Figure 1):

Distance from real vortex center = r = sqrt$[(z-Z)^2+(x-X)^2]$; Tangential velocity = G/r

z component = (G/r) (x-X)/r = G(x-X)/r^2

[Note x-X is positive in Figure 1, z component is positive]

x component = -(G/r) (z-Z)/r = -G(z-Z)/r^2

[Note z-Z is negative in Figure 1, x component is positive]

The corresponding results for the image vortex (see right plot in Figure 1) are:

Distance from image vortex center = ri = sqrt$[(z+Z)^2+(x-X)^2]$; Tangential velocity = G/ri

z component = (-G/ri) (x-X)/ri = -G(x-X)/ri^2

[Note x-X is positive in Figure 1, z component is negative]

x component = (G/ri) (z+Z)/ri = G(z+Z)/ri^2

[Note z+Z is positive in Figure 1, x component is positive]

Combining the velocity components from real and image vortices gives the vortex velocity at lateral position x and height z:

Vertical component: $W(x,z,X,Z,G) = G(x-X)\{1/[(z-Z)^2+(x-X)^2]-1/[(z+Z)^2+(x-X)^2]\}$

Cross component: $U(x,z,X,Z.G) = G\{(z+Z)/[(z+Z)^2+(x-X)^2]-(z-Z)/[(z-Z)^2+(x-X)^2]\}$

For multiple vortices the wind components from each are simply added. The mean ambient crosswind is simply added to the vortex crosswinds. The mean ambient vertical wind is zero.

3.1.4 Least-Square Fit to Vortex Pair

The least-square fit is carried out by:

1. Estimating the initial vortex positions (X,Z) and circulations (Γ) for the vortices (one or two) being tracked and estimating the ambient crosswind C.
2. Calculating the vertical w(i) and horizontal u(i) winds at each anemometer location (x(i),z(i)) using the estimated vortex and ambient wind parameters:

$$w(i) = W(x(i),z(i),X_{max},Z_{max},G_{max}) + W(x(i),z(i),X_{min},Z_{min},G_{min})$$

$$u(i) = C + U(x(i),z(i),X_{max},Z_{max},G_{max}) + U(x(i),z(i),X_{min},Z_{min},G_{min}$$

3. Calculating the sum of the squares of the differences between the estimated (w(i), u(i)) and measured (v_i, c_i) vertical and crosswind components:

$$\text{Sum} = \Sigma\ (i=1,N)\ [(w(i)-v_i)^2 + (u(i)-c_i)^2].$$

4. Varying the initial estimates until the sum of the squares is minimized.

The least-square method works best if the parameters have more or less independent effects on the difference between the measured and calculated values. The vortex height and circulation do not meet this criterion since the maximum vortex wind is proportional to the ratio of circulation to height. Therefore, this ratio is taken as one of the parameters to fit. The specific parameter used is: $vm = \Gamma/\pi z$, which is approximately the maximum vortex crosswind. The height z is used as the other parameter; given vm, it then specifies the spacial width of the vortex crosswind profile.

The initial values are taken from the traditional tracking algorithm:

$X = x_{min}$ or x_{max},	Initial increment = 8 meters
Z = 30 meters	Initial increment = *0.2
$vm = c_{min}-c_{lim}$ or $c_{max}-c_{lim}$	Initial increment = *0.2
Crosswind = c_{med}	Initial increment = 0.7 m/s

Two ways are used to vary the parameters, a constant increment or a fractional increment. The type and initial size of the increment are listed above. After the minimum sum of squares is found for the initial increments, the size of the increment is reduced by a factor of two and the process is repeated. After the third increment reduction, the best fit parameters are accepted as the fit. The parameters are varied in turn up or down by one increment. If a lower sum of squares is achieved, then the new value of the parameter is kept. The parameters are passed through many times until no parameter is changed. If too many passes through the parameters (30) are taken before the minimum is achieved, the fitting process is abandoned as unsuccessful.

A general least-square fit routine is used based on the following structure for N parameters:

```
typedef struct {

        float best[N]; /* best parameters so far */

        float trial[N]; /* parameter values to used for calculating wind values */

        float inc[N];  /* size of increment */

        int mode[N]; /* mode = 0 fraction, mode = 1, add */

        int use[N];  /* 1 if parameter used in fit, 0 if not */

        } Fit_Params;
```

The sum of the squares of the differences are calculated by a routine:

```
        float sumsq(Fit_Params*,Wind_Data*,int mode);
```

where the Wind_Data structure (for 1994 JFK site only) is:

```
typedef struct {

        float cross[19];        /* Crosswind:  Main Baseline -350 ft to + 350 ft,
                                               Baseline farther from runway 0, 50 ft
                                               Baseline closer to runway    0, 50 ft */

        float vert[19];         /* Vertical wind, same locations as crosswind */

        float head[2];          /* Headwind -350, +350 ft */

        float age[3];           /* Vortex Age each Campbell Message */

        float noise;            /* Aircraft Noise */

        float pole_x[19];       /* Lateral Position of Pole */

        float pole_y[19];       /* Longitudinal position of Pole */

        float pole_z[19];       /* Height of pole */

        } Wind_Data;
```

It contains both anemometer locations and wind values. Depending upon the mode, the routine uses the measured wind values to return the sum of the squares of the errors, or puts the calculated wind values into the Wind_Data arrays. Note that the Wind_Data structure must be broken up to use the more general structures that will work with either JFK or MEM data according to the configuration files: POLES.DAT and SENSORS.DAT.

Note that the pole height differences at Memphis do not, in principle, affect the least-square fit algorithm. The calculations of the vortex flow simply take the height into account. The initial estimate for vortex lateral position is the only problem.

3.1.5 Least-Square Fit Including Secondary Vortices

When a vortex is located far enough from the end of the anemometer array, it is possible for the anemometer array to detect opposite-sign secondary vortices (caused by the interaction of the primary vortices with the boundary layer), they can be added to the fitting process, thereby allowing up to four vortices. The secondary vortices are initially located 25 meters outside the primary vortex and given a vm value of -0.4*(primary vm) and a height of 30 meters. No criteria for rejecting secondary vortices has been determined. However, it is clear that when the secondary vortex lies on top of the primary vortex, it simply subtracts from the circulation of the primary vortex.

The program pltfit4 carries out the fitting process for secondary vortices.

3.1.6 Classical Vortex Trajectory Model

The image model described above does not consider the dynamics of vortex motion. It can be integrated to give classical motion where vortices created at spacing b' descend toward the ground at speed G/b' and then separate and propagate laterally at height b'/2. This model does not account for the interaction of the vortices with the boundary layer, but should give an approximate estimate for the early life of the vortices with the assumption of no circulation decay.

3.1.7 Least-Square Fit to Classical Vortex Motion

The classical model for vortex motion was used to fit the signals of two vortices from age 2 seconds up to a maximum age of 12-48 seconds. The following parameters are fit:

Constant circulation

Height at last time step (converted to initial height)

Lateral positions at last time step (converted to initial separation)

Lateral position at time zero

Average lateral transport speed

Crosswind at anemometer height

The initial values are estimated by fitting the vortex data at the last time step to two vortices with equal and opposite circulations, equal heights, separate lateral positions and an ambient crosswind at anemometer height. The initial average lateral transport speed assumes that the initial aircraft position is on the centerline. The vortex locations are then integrated backwards in time to the time zero values of height and vortex separation.

The wind data errors are then calculated for all included vortex ages and the squares of the errors are summed. The initial parameters are varied until the best fit is obtained. This process has just been implemented and tested on some JFK data. The results to date are plausible, but not convincing. Note that the aircraft weight is proportional to the product of the initial spacing and the initial vortex separation. The initial heights should be about equal to the glideslope position for most runs.

3.2 VORTEX PARAMETERS

The fitted vortex parameters are generated and output by a program called GOUTFIT. Currently, GOUTFIT used 2.0 m/s vortex crosswind to start tracking and 1.0 m/s to stop tracking. A position jump of more than three poles also ends the track. The output file is called VTX.TXT and is in comma-separated format. The filename is used to identify the run. The vortex is identified by a number (0 for min vortex, 1 for max vortex). The vortex age and vortex induced crosswind are included. The fitted parameters of lateral position, height and circulation are included. If a least-square fit to the vortex could not be made, the record is not saved. Each output record is coded with a one-character code to specify why it was saved. The following sections describe the codes and suggest possible uses for the records.

3.2.1 Times - T

The records are saved for integral multiples of 10 seconds, starting at 20 seconds. These records might be used, for example, to select vortices that are stalled near the runway centerline at age 60 or 80 seconds.

3.2.2 Last Point - L

The last point indicates the vortex life time within the array and places an upper limit on the times for the other codes.

3.2.3 Maximum Velocity Point - M

The maximum velocity typically occurs when each vortex is closest to the ground and hence is most readily measured by the ground-based anemometers.

3.2.4 Paired Maxiumum Velocity Points - B,A

For some purposes it is useful to have equal-age data when both vortices are low. The B code selects the time of the maximum sum of the crosswinds for the two vortices. The A code goes back in time from the B code to the point where the sum of the two crosswinds is less than 80 percent of the maximum value.

The B and A code data can be used to integrate the vortex image motions back to age zero (as in Section 3.1.7) using the dynamic image model. The initial parameters given will be the mean lateral motion (assuming the aircraft was on the runway centerline), the vortex spacing and the vortex height. The vortex separation and circulation values can be combined to estimate the aircraft mass.

3.2.5 Vortex Crosswind Limits - 3,4,6,8

For decay studies it may be useful to define vortex lifetimes that are relatively unaffected by atmospheric turbulence. Such lifetimes would permit the influence of turbulence on lifetime to be studied. As a first cut toward such lifetimes, the last time was recorded where the vortex crosswind remained above four threshold values, 4.0, 3.0, 2.0, and 1.5 m/s. These lifetimes are indicated by a code value equal to twice the threshold value (8, 6, 4, and 3, respectively). Note that vortex crosswind lifetimes are made before the vortex tracking algorithms are applied; consequently, the record will be missing if the vortex track is terminated by going off the end of the array before the crosswind drops below the threshold.

3.2.6 All Times - t

The program GOUTFIT saves only selected data points for two reasons:

1. To reduce the size of the data file, and
2. To facilitate subsequent data analysis.

For some purposes, however, it is useful to have all the valid data points. The program GOUTALL generates an output file called VTXALL.TXT which contains all the valid data points. The code character is "t."

3.3 AIRCRAFT DETECTION

Many of the aircraft detections are not caused by landing aircraft. Possible sources for false detections are:

1. Departures - since the departures are typically higher than the arrivals, the noise signature for departures should be longer than for landing.
2. Transmission errors between CSDAS and DAS - Since transmission errors are rare, they show up as an anomalous noise burst lasting for only one two-second average. The aircraft noise was assigned to the first data channel of a message to reduce the chance for transmission errors affecting the aircraft detection.
3. Other noise sources - thunder, trucks, etc.

An aircraft detection validation algorithm was designed to deal with the first two sources of false detection (note that the noise level is slightly negative under quiet conditions and the noise detection threshold is normally set for 2.0 units):

1. Reject detection if next two-second average noise after noise peak is negative (transmission error).

2. Reject detection if two-second average noise two samples after noise peak is greater than 0.15 times the peak noise (reject departures).

3. If recorded data start ten seconds before arrival, integrate (i.e., sum) the aircraft noise peak from 8 seconds before until 8 seconds after the arrival. The program GACNOIS saves both peak noise and summed aircraft noise. It also saves the last vortex age in the file, which is useful for selecting runs with enough data to be interesting.

Comparisons of the list of validated vortex detections using this algorithm with other lists of aircraft arrivals show that this algorithm rejects some valid arrivals.

3.4 METEOROLOGICAL PARAMETERS

3.4.1 Characterize Run

In addition to validating the aircraft noise detections, the program GACNOIS also processes the parameters listed in a file SAVE.DAT to characterize the meteorological conditions of the run. The program processes up to thirty data points (first minute of run) to determine the mean and standard deviation of the parameter. The outputs of GACNOIS are saved in a file named AC.TXT which has comma separated variable format. The normal contents of SAVE.DAT are the three wind components on each end of the anemometer array (H01, C01, V01, H15, C15 and V15).

For the purpose of assessing the validity of the ground-based anemometer measurements, the crosswind standard deviations, TC01 and TC15, are probably the most relevant, since variations in crosswind directly affect the vortex tracking algorithm. Since the wake vortices may reach the end of the array and affect the TC values, a way of estimating the ambient crosswind variance is to take the minimum value (MinTC) of TC01 and TC15. This algorithm is applied as a Paradox script after the AC.TXT file is imported into a Paradox database.

3.4.2 Selected Wind Parameters

For some analyses it is useful to extract some of the wind parameters from the run files. The program GWINDOUT extracts the thirty measurements (one minute) starting at aircraft detection for the parameters listed in file SAVE.DAT. The comma-separated output is contained in the file WIND.TXT.

4. DATABASES

This chapter describes the databases on the CD ROM.

4.1 RAW RUN FILES - 1994-1995 TEST

Table 5 lists the number of aircraft arrival files by month during the period September 1, 1994 to June 28, 1995. The valid runs were determined by running GACNOIS (Sections 3.3 and 3.4.1). The low turbulence runs were selected to have data for at least 80 seconds and a MinTC value (Section 3.4.1) less than 0.3 m/s. A second set of runs with 0.3 m/s ≤ MinTC< 0.5 m/s was generated to test the utility of the processing algorithms for somewhat higher turbulence levels.

Table 5. 1994-1995 Wake Vortex Runs

Month	Run Files	Valid Runs	Low Turbulence Runs
Sep-94	3,790	3,012	647
Oct-94	4,055	2,768	1012
Nov-94	3,911	3,333	523
Dec-94	1,444	1,108	276
Jan-95	1,231	1,146	86
Feb-95	1,416	1,312	308
Mar-95	2,775	2,512	444
Apr-95	5,362	3,616	503
May-95	6,427	3,488	1076
Jun-95	5,198	2,648	632
Total	35,609	24,669	5,507

4.2 RAW RUN FILES - 1996 TEST

Table 6 lists the runs by day for the 1996 test. The same algorithms were used as for Table 5.

Table 6. 1996 Wake Vortex Runs

Month	Run Files	Valid Runs	Low Turbulence Runs
11-Nov	79	58	2
12-Nov	297	222	24
13-Nov	179	138	20
14-Nov	284	204	43
15-Nov	218	144	12
16-Nov	148	89	52
17-Nov	278	189	121
18-Nov	227	119	102
19-Nov	347	220	102
20-Nov	375	229	74
21-Nov	311	182	40
Total	2,744	1,794	592

4.3 STRUCTURE OF DATABASES

Table 7 lists the fields for the run databases which are called ACF. Table 8 lists the format for the vortex databases. Only low-turbulence cases were processed and are called VTXTC_P3 (VTXTC_P5 for the runs with 0.3 m/s ≤ MinTC < 0.5 m/s).
The database files were generated in Paradox version 4.5. These databases are linked by the file number. Enough fields are keyed (indicated by asterisk) to uniquely identify each record. The type of parameter is indicated as A for ASCII, S for 16-bit signed integer, and N for floating point number.

The databases are provided in both Paradox form (extension DB) and the equivalent ASCII form (extension TXT).

Table 7. Fields for Run File ACF

Field Name	Field Type
File Name	A13*
Year	S*
Month	S*
Day	S*
Hour	S*
Minute	S*
Peak Noise	N
Noise Sum	N
H01	N
TH01	N
H09	N
TH09	N
H15	N
TH15	N
C01	N
TC01	N
C15	N
TC15	N
V01	N
TV01	N
V15	N
TV15	N
MinTC	N

Table 8. Fields for Vortex Files VTXTC_P3

Name	Type	Units
File Name	A13*	ASCII
Code	A1*	ASCII
Vortex	S*	0 or 1
Age	S*	sec
Max Crosswind	N	m/s
Lateral Position	N	m
Height	N	m
Circulation	N	$m^2/$

REFERENCES

1 Sullivan, T. E. and Burnham, D. C., "Ground Wind Sensing System Calibration Tests," Report No. FAA-RD-80-13, February 1980, Transportation Systems Center, Cambridge, MA.

2 Hallock, J. N. and Eberle, W. R., editors, "Aircraft Wake Vortices: a State-of-the-Art Review of the United States Program," Report No. FAA-RD-77-23, February 1977, Transportation Systems Center, Cambridge, MA.

3 Abramson, S. and Burnham, D. C., "Ground-Based Anemometer Measurements of Wake Vortices from Landing Aircraft at Airports," AGARD-CP-584 Conference Proceedings, The Characterization & Modification of Wakes from Lifting Vehicles in Fluids, 20-23 May 1996, Trondheim, Norway, November 1996, pp. 13-(1-7).

4 Burnham, D.C. and Abramson, S., "Wind Data from Memphis Airport," Report No. DOT/FAA/ND-97-5, June 1997, Volpe National Transportation Systems Center, Cambridge, MA.