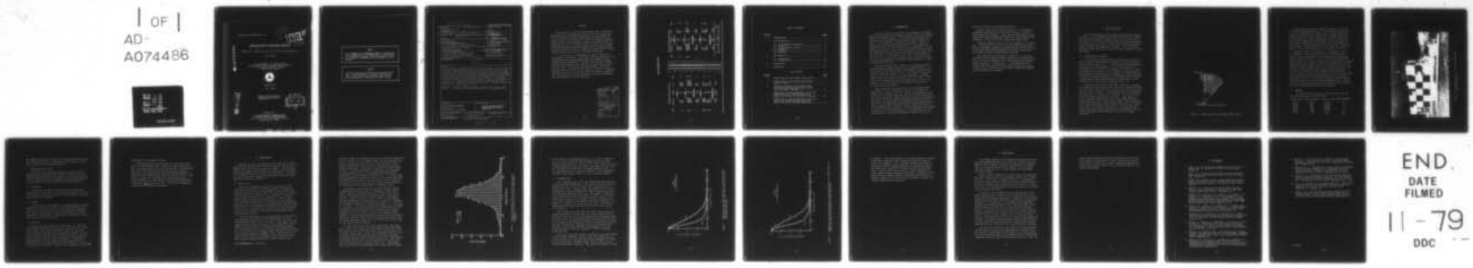
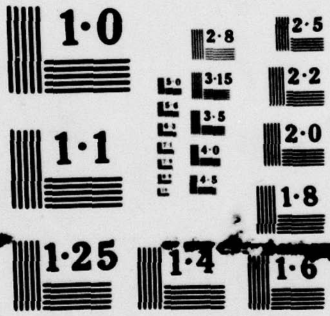
AD-A074 486 TRANSPORTATION SYSTEMS CENTER CAMBRIDGE MA F/G 1/1
VORTEX ADVISORY SYSTEM SAFETY ANALYSIS. VOLUME III. SUMMARY OF --ETC(U)
AUG 79 J N HALLOCK
UNCLASSIFIED TSC-FAA-79-20 FAA-RD-78-68-3 NL

1 OF 1
AD-
A074486



END
DATE
FILMED
11-79
DDC


1·0
2·8
2·5
3·15
2·2
5·0
3·5
2·0
1·1
4·0
4·5
1·8
1·25
1·4
1·6

(12)

REPORT NO. FAA-RD-78-68, III

SC

A063649

VORTEX ADVISORY SYSTEM SAFETY ANALYSIS

VOLUME III: Summary of Laser Data Collection and Analysis

J.N. Hallock

U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
Transportation Systems Center
Cambridge MA 02142

AUGUST 1979

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research and Development Service
Washington DC 20591

(19) 78-68-3

Technical Report Documentation Page

(18) **1. Report No.** FAA-RD-78-68, III

2. Government Accession No.

3. Recipient's Catalog No. (11)

(6) **4. Title and Subtitle**
VORTEX ADVISORY SYSTEM SAFETY ANALYSIS.
Volume III. Summary of Laser Data Collection and Analysis.

5. Report Date August 1979

6. ~~Performing Organization~~ Code (14)

(10) **7. Author(s)** J. N. Hallock

8. Performing Organization Report No. DOT-TSC-FAA-79-20, III

9. Performing Organization Name and Address
U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge MA 02142

10. Work Unit No. (TRAIS) FA905/R9111

11. Contract or Grant No.

(9) **13. ~~Type of Report and Period~~ Covered**
Final Report.
April-May 1979

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Aviation Administration
Systems Research and Development Service
Washington DC 20591

14. Sponsoring Agency Code

15. Supplementary Notes

(12) 26p.

16. Abstract

A Laser-Doppler velocimeter (LDV) was used to monitor the wake vortices shed by 5300 landing aircraft at a point 10,000 feet from the runway threshold. The data were collected to verify the analysis in Volume I of the safety of decreasing interarrival separations to three nautical miles between the outer marker and the runway threshold. Such reduced spacings would only be used when the Vortex Advisory System (VAS) indicated that wake vortices would not pose a threat to a following aircraft. The data show that vortex behavior, during times identified by the VAS, is commensurate with the goal of using uniform three-nautical-mile separations from the outer marker to touchdown regardless of leader or follower aircraft type.

Volume I: Analytical Model (160 pages) was published in Sep. 1978.
Volume II: Laser Data Collection and Analysis is in preparation.

17. Key Words
Vortex Advisory System
Aircraft Wake Vortices
Vortices
Laser-Doppler Velocimeter

18. Distribution Statement
DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	26	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

407 082 LB

PREFACE

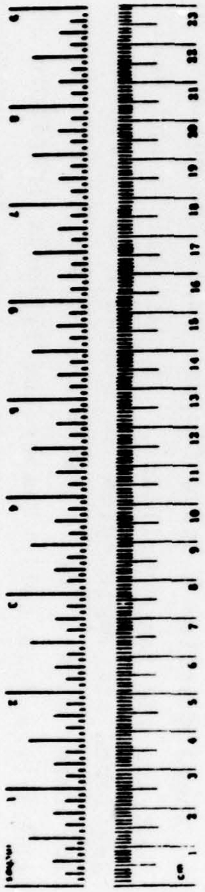
The concept of a Vortex Advisory System (VAS) evolved from the analysis of an accumulating wealth of vortex-tracking data. Tens of thousands of tracks demonstrated that the concept was viable; however, all the data were collected between the middle marker and the runway threshold. Before certifying the VAS for an operational test, the Flight Standards Service of the Federal Aviation Administration (FAA) requested that the region between the middle and outer marker be examined to determine its relative safety vortexwise for the use of decreased separations.

It is a pleasure to acknowledge the many TSC people who contributed to this report. The laser system was operated by the Lockheed Missiles & Space Company under the guidance of John Fantasia and Ian McWilliams. Ian McWilliams and David Burnham developed and implemented the software to record and to analyze the laser data. Tom Sullivan and Eileen Magnant reduced the theodolite data collected by the Illinois Institute of Technology Research Institute. Last but not least, Berl Winston assembled the data into a data base and retrieved the various information in a form amenable to detailed analysis.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

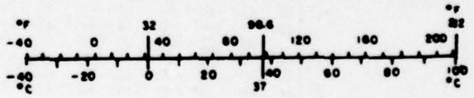


TABLE OF CONTENTS

ILLUSTRATIONS

1. INTRODUCTION

The Vortex Advisory System (VAS) was developed as an interim means for decreasing costly congestion delays in aircraft approach queues at the major airports. VAS evolved from the analysis of the behavior of the wake vortices from over 50,000 landing aircraft. It was found that vortices might present a threat to a following aircraft, but only during specific wind conditions. Most of the time, vortices do not pose a safety problem. The VAS indicates the vortex status to the controllers via colored lights: Red light means that the winds are such that vortices might present a threat to a following aircraft, and a Green light means that the winds are such that vortices will not pose a threat for interarrival separations of 3 nautical miles regardless of leader or follower aircraft type.

The vortex behavior data however, were collected in the region between the middle marker and the runway threshold. Over 82 percent of the landing accidents attributed to wake vortices occurred within this region (Ref. 1). The VAS advises when this region is safe with respect to a vortex encounter. Although some capacity gains may be realized if only this region is permitted to use reduced separation standards (Refs. 2 and 3), the utility of the VAS increases if the protected region can be extended to the outer marker.

Since applicable data did not exist, two approaches were undertaken. First, a probability analysis, the subject of Volume I of this report (Ref. 4), was done to calculate the relative safety of reduced separations out to the outer marker when the VAS indicated that reduced separations would be permitted near the runway. Such an analysis was undertaken because it was expected that the conditions that permitted reduced separations inside the middle marker would also permit reduced separations to be used inside the outer marker. The second approach, the subject of Volume II of this report which is in preparation and is summarized herein, concerns the gathering of appropriate data to verify the claims of the probability analysis.

Section 2 describes the data collection. A Laser-Doppler velocimeter (LDV) was used to track the vortices. A total of 5300 aircraft was recorded. A data base was constructed containing all the vortex information (trajectories and strengths), VAS information, aircraft positions, and general weather data.

Section 3 summarizes one facet of the analysis of the O'Hare data. The behavior of vortices in VAS-Red and VAS-Green conditions was examined; compared with VAS-Red conditions, the vortices in VAS-Green conditions dissipated more rapidly or moved away more rapidly from the extended runway centerline.

The conclusions are discussed in Section 4. No vortices persisted near the extended runway centerline in VAS-Green conditions for a time commensurate with a three-nautical-mile interarrival separation. On this basis, it is asserted that VAS-reduced separations should be safe; vortices should not present a hazard to any aircraft flying VAS-reduced separations between the outer marker and touchdown.

2. DATA COLLECTION

To verify the results of the probability analysis presented in Volume I, a Laser-Doppler Velocimeter (LDV) was used to monitor both the vortices shed by landing aircraft and the winds aloft. The behavior of the vortices (motion and decay) was disaggregated by aircraft type, VAS status (Red or Green), and meteorological condition (winds and atmospheric stability). The primary data sources are described briefly in this section; Volume II will have the details.

2.1 LASER-DOPPLER VELOCIMETER

An LDV involves the measurement of the Doppler spectrum of laser radiation backscattered by naturally occurring atmospheric aerosols (dust, pollen, etc.). The instrument incorporates means to transmit the laser radiation (a CO_2 laser operating at a wavelength of 10.6 microns) to the region of interest, to collect the backscattered radiation, and to photomix on a photodetector the backscattered radiation and a portion of the transmitted beam. A difference-frequency component, at the Doppler-shift frequency, is generated at the photodetector and is translatable into an along-optic-axis wind-velocity component (Refs. 5-8).

A profile of the line-of-sight wind in a plane is obtained by scanning the focal volume of the laser beam in range and angle. The focal-point scan pattern used to search for high altitude vortices is shown in Figure 1. The elevation angle is scanned back and forth at a rate of one scan per second. At the end of each scan, the range is stepped to a new value. Eight ranges are scanned from the highest range to the lowest range providing a scan through the vortices every eight seconds. This scan pattern gives high resolution velocity profiles of the vortices. When the vortices are directly above the LDV, the vortex velocity measurements have minimum contamination by the ambient wind; the wind is horizontal and therefore has little line-of-sight component.

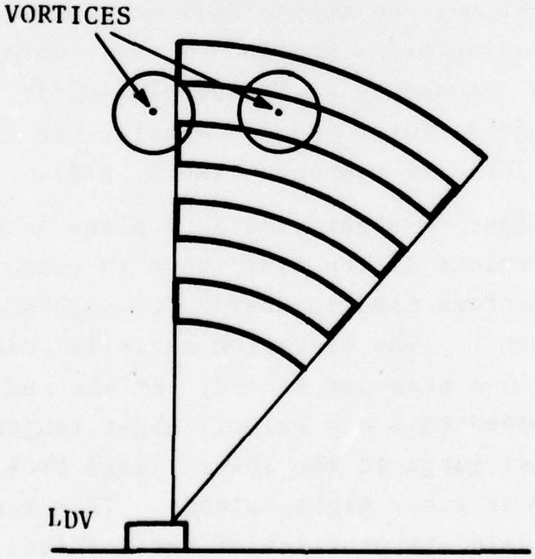


FIGURE 1. STEPPED ARC SCAN FOR PROBING VORTEX PAIRS

Figure 2 shows the mobile FAA/TSC LDV housed in a 24-foot, 2-1/2-ton, detachable body truck. The system was deployed initially under the approach to runway 27R at O'Hare; the lack of traffic, in particular the lack of B-747s, prompted moving the system during April 1978 to the approach region of runway 14R. The truck was approximately 10,000 feet from the threshold of runway 14R. For the three-degree glide slope, the centerline of the Instrument Landing System (ILS) glide-slope beam is approximately 575 feet above the ground at the location of the LDV.

Doppler spectra are processed by a minicomputer system in the LDV truck. The largest Doppler shift (and hence, the largest line-of-sight velocity) is interpreted as the maximum vortex tangential velocity. At TSC a similar minicomputer was used to track the vortices by following the location of the largest Doppler shifts, one from each side of the vortex center, and to calculate vortex strengths using the vortex velocity field. When there was little crosswind, the vortices could be monitored for as long as two minutes as they descended toward the ground. Strong crosswinds rapidly blew the vortices out of the scan region and distorted the vortex signature when the vortices were no longer above the LDV. The crosswind component at the height of the vortices was also extracted from the Doppler data. The LDV data thus yielded the location and strengths of the two vortices and the crosswind component every eight seconds.

2.2 AIRCRAFT

The vortices from 5300 aircraft were recorded by the LDV. The type and numbers are listed below:

AIRCRAFT TYPE	NUMBER RECORDED	AIRCRAFT TYPE	NUMBER RECORDED
B-727	2334	L-1011	63
DC-9	1092	C-130	9
DC-10	587	KC-135	8
B-707	489	VC-10	1
B-737	263	CV-440	1
DC-8	236	F-100	1
B-747	216		
		TOTAL	5300

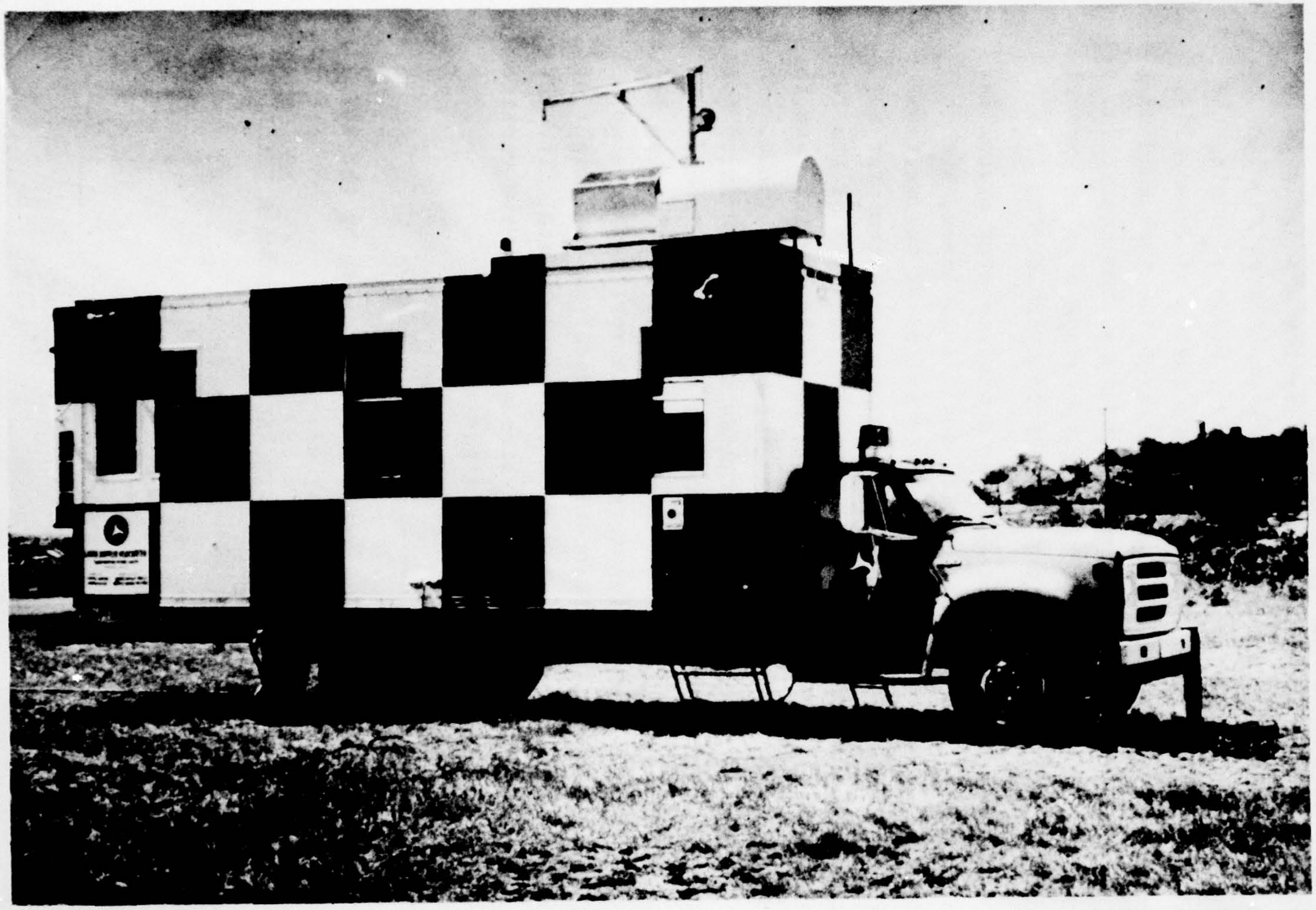


FIGURE 2. FAA/TSC MOBILE LASER-DOPPLER VELOCIMETER HOUSED IN TRUCK

Two hundred forty-three of these cases were discarded as the LDV data exhibited anomalies. Apparently the LDV scanner was sticking at one of the elevation-angle limits.

2.3 VORTEX ADVISORY SYSTEM

The ambient wind conditions measured by the VAS and the Red/Green status condition were recorded. Using the time code (day:hour:minute:second) of the passage of the aircraft over the LDV, the VAS data tapes were searched to find the attendant VAS wind and status for correlation with the vortex behavior.

2.4 THEODOLITE

A theodolite was emplaced near the runway threshold and pointed up the glide slope. As the aircraft passed over the LDV, the azimuth and elevation of the aircraft were logged. Data for 2368 aircraft were recorded.

2.5 WEATHER

To characterize the atmosphere, a pyranograph and an acoustic sounder were deployed at O'Hare. The pyranograph monitors the cloud cover by measuring the solar and sky insolation; knowing the cloud cover allows one to assess the atmospheric stability. The acoustic sounder monitors the heights of atmospheric structure fluctuations and inversion layers.

2.6 DATA BASE

All the data were compiled in a data base. For each flyby the following information was obtained: aircraft type, VAS tape and run number, LDV tape and run number, time code, aircraft lateral position and height at the location of the LDV, VAS winds near the runway threshold, VAS status (Red or Green), crosswind aloft measured by the LDV, inversion height(s) (if present), pyranograph output, general weather conditions (precipitation, gustiness, etc.), and position and strength versus age of each vortex detected by the LDV. The data were assembled on a NOVA 800®

minicomputer for subsequent analysis.

A second data base was constructed for correlating winds aloft with VAS-measured winds. Winds aloft were measured by the LDV at altitudes of 400, 600, 800, and 1000 feet. These measurements were made primarily when aircraft were not landing on runway 14R. The comparison of LDV and VAS-measured winds is required to verify the crosswind model developed in Volume I. The data base consists of time code, VAS-averaged winds near the runway threshold, VAS status (Red or Green), and averaged winds at the four altitudes above the LDV. The data were assembled on a DECsystem-10® computer for analysis.

3. DATA ANALYSIS

When the test plan was devised for the collection of vortex behavior data using the LDV, the concept was to verify the various models used in the VAS safety analysis, Volume I. The detailed analysis in Volume II* will address the suitability of the models, but the emphasis herein will be on the final results. In particular, this section will examine the persistance of vortices under VAS-Red and VAS-Green conditions.

3.1 SAFETY ZONE

Since it was expected that the vortices would move away (laterally and vertically) or dissipate before a following aircraft arrived, the LDV data were analyzed in terms of how soon the vortices exited a "safety zone." The safety zone is a region with no height restriction (i.e., vortex descent is ignored), centered on the extended runway centerline. If both vortices from a preceding aircraft have exited the safety zone, either by moving out or by dissipating, it is asserted that a following aircraft will not be significantly influenced by the vortices of the first aircraft. The safety zone is an artificial region defined to assist in the analysis of the data and the dimensions were conservatively selected.

The safety zone concept was used extensively in the analysis of the vortex data collected in the middle marker to runway threshold region (Refs. 9-11). The width of that safety zone was established by using two criteria. First, a measurement program conducted by TSC at Denver's Stapleton International Airport (Ref. 11) showed that 3σ or 99.7 percent of all landing aircraft are within 50 feet of the extended runway centerline in the region from the middle marker to touchdown. Most of the aircraft involved in these tests were conducting visual approaches during clear weather; instrument approaches should be much closer.

---

*To be published at a later date.

Second, six-degree-of-freedom aircraft-vortex-encounter simulations done at TSC (Ref. 12) and elsewhere (Ref. 13) have indicated that if the fuselage of any aircraft is at least 100 feet from the center of any vortex, the aircraft will not experience an unacceptable disturbance. This claim is supported by limited flight test data. The 100-foot figure is conservative and represents the most dangerous case of a light general aviation aircraft approaching a vortex formed by a wide-body jet. The exact figure obviously depends on the characteristics of the vortex generating/encountering aircraft pair. Thus, the safety zone was selected to extend 50 + 100 or 150 feet on both sides of the extended runway centerline for the middle marker to touchdown region.

The concept is now extended to the final approach segment. A theodolite was deployed near the threshold of runway 14R at O'Hare; whenever an aircraft passed over the LDV, the lateral offset of the aircraft from the extended runway centerline was measured. Figure 3 shows the results, which are in agreement with the measurements reported in Refs. 4, 14, and 15. Assuming the navigation deviation is normally distributed, $\sigma = 52$ feet and $3\sigma = 156$ feet. (The positive mean lateral offset of 17 feet might be attributed to the observation that over three-quarters of the landings on 14R were conducted with a southwesterly crosswind component; the +17 feet shows a bias to fly somewhat upwind.) Adding the 100-foot closest approach distance to the 3σ navigation deviation, the safety zone at the LDV location (10,000 feet from the runway threshold) extends 156 + 100 or 256 feet on both sides of the extended runway centerline.

If both vortices are clear of the safety zone, they cannot pose a threat to a following aircraft landing on the same runway. Note that the size of the safety zone is very conservative; even if both an aircraft and a vortex from a preceding aircraft are in the safety zone at the same time, the vortex may have decayed sufficiently that it could not affect the aircraft. Additionally, the aircraft and the vortex can be separated by as much as 200 feet and yet both may be within the safety zone. Furthermore, the vortex may have been generated by an aircraft whose vortices

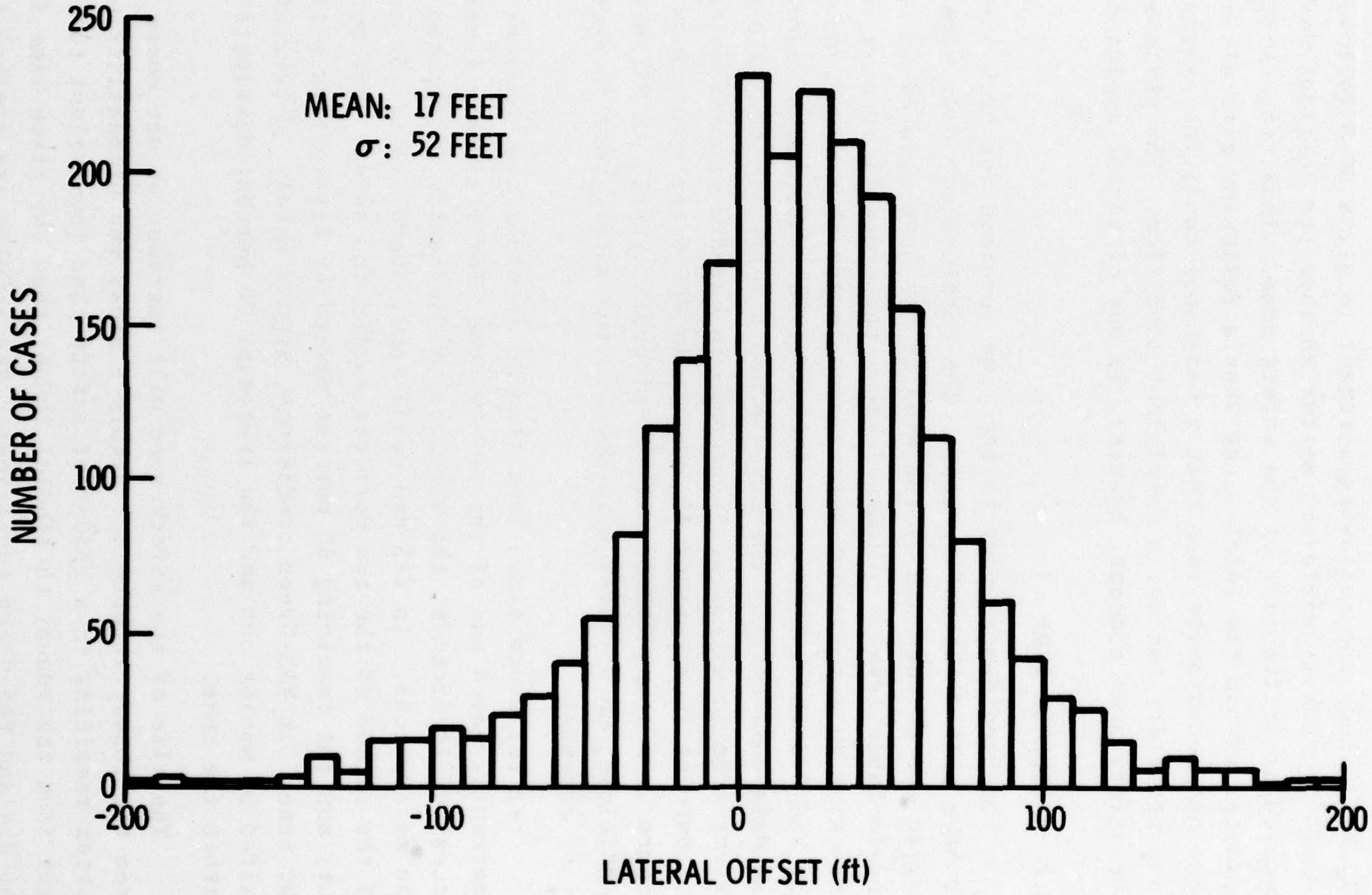


FIGURE 3. THEODOLITE-MEASURED LATERAL OFFSET FROM LOCALIZER CENTERLINE FOR AIRCRAFT 10,000 FEET FROM RUNWAY THRESHOLD

will not affect the following aircraft (e.g., a DC-9 followed by a B-747); then it would not matter whether the vortices have decayed or drifted out of the safety zone. Thus, the existence of a vortex within the safety zone when a following aircraft arrives does not necessarily mean that a hazardous condition exists. It is a necessary but not a sufficient condition. The philosophy of the safety zone concept, however, is one of vortex avoidance.

3.2 RESIDENCE TIME

The "residence" time is the time required for both vortices to have exited the safety zone. The vortices may have been transported out of the zone by the wind or may have decayed to an undetectable level. Figure 4 shows the probability of a vortex remaining in a ±250-foot safety zone longer than any given time for VAS-Red and VAS-Green conditions. For example, 17 percent of the data collected by the LDV yielded a vortex in the ±250-foot safety zone in excess of 40 seconds in VAS-Red conditions, and 2.5 percent in excess of 40 seconds in VAS-Green conditions. The figure is a composite of all the aircraft types. In VAS-Green conditions, no vortices were seen in the safety zone in excess of 60 seconds!

For residence times less than 20 seconds, the vortices predominantly moved out of the safety zone; for residence times in excess of 20 seconds, the vortices predominantly dissipated within the safety zone. In VAS-Red conditions, approximately 50 percent of the second of the two vortices exited the safety zone by moving out, and the remaining 50 percent exited by dissipating within the zone. In VAS-Green conditions, approximately 30 percent exited by moving out and the remaining 70 percent dissipated within the zone.

The size of the safety zone will increase as one moves farther from the runway threshold. Figure 5 shows the probability of a vortex remaining in a ±330-foot safety zone (equivalent to 13,200 feet from the runway threshold) longer than any given time for VAS-Red and VAS-Green conditions. The results are similar to those

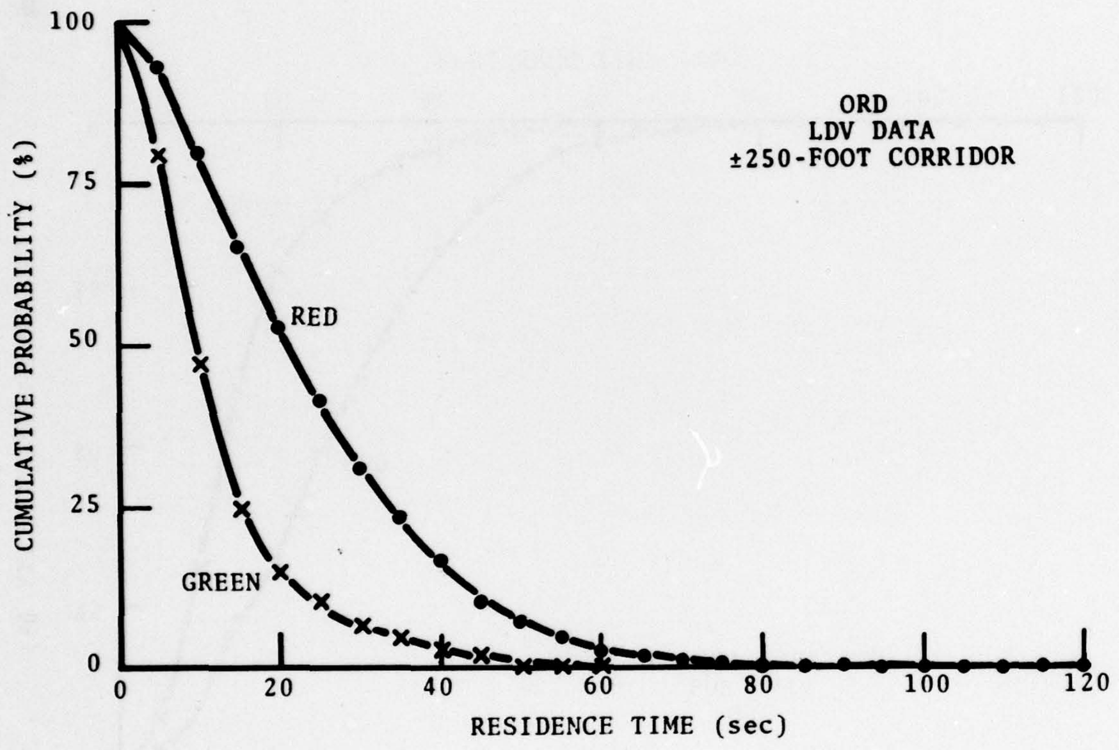


FIGURE 4. PROBABILITY OF VORTEX REMAINING IN ±250-FOOT SAFETY ZONE LONGER THAN ANY GIVEN TIME DURING VAS-RED AND VAS-GREEN CONDITIONS

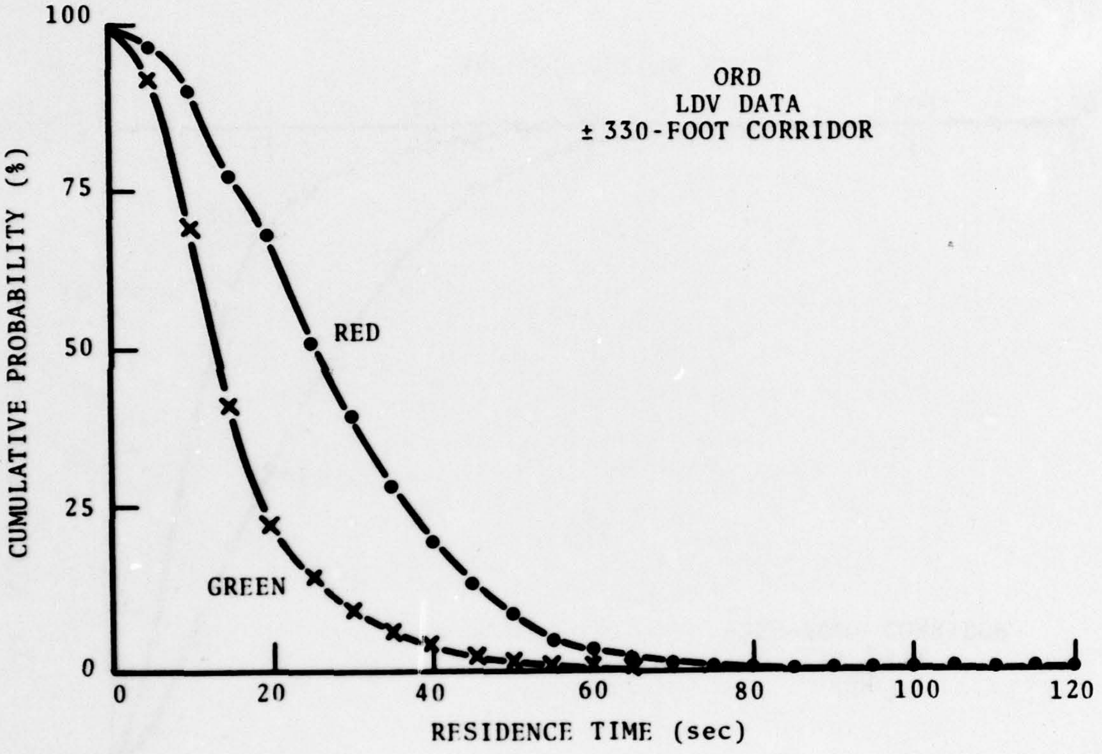


FIGURE 5. PROBABILITY OF VORTEX REMAINING IN ±330-FOOT SAFETY ZONE LONGER THAN ANY GIVEN TIME DURING VAS-RED AND VAS-GREEN CONDITIONS

in Figure 4. One vortex resided in the safety zone for 62 seconds in VAS-Green conditions, but no vortex was found for times in excess of 65 seconds. For a ±410-foot corridor (equivalent to 16,400 feet from the running threshold), no vortex was found in the safety zone in excess of 70 seconds during VAS-Green conditions. Larger safety zones (and hence, larger equivalent distances from the runway threshold) could not be studied due to the range-elevation scanner parameters employed in the LDV data collection. However, no vortices were ever observed in excess of 80 seconds during VAS-Green conditions.

4. CONCLUSIONS

The original intent of the LDV data collection was to verify the various analytical models of the vortex, aircraft, and wind behavior used in Volume I. However, the thrust of this summary report has been the observed vortex behavior itself, particularly the correlation of the vortex behavior with the VAS-Red or VAS-Green status.

Eighty seconds represents an aircraft-to-aircraft spacing of less than 3 nautical miles at the approach speeds of most modern aircraft. On the basis of Figures 4 and 5, it is reasonable to assert that wake vortices are unlikely to pose a safety threat in the outer to middle marker regions when the VAS status is Green. No vortices were ever monitored by the LDV in excess of 70 seconds during VAS-Green conditions!

In Volume I, the existence of two unresolved issues (the model describing the crosswinds aloft was unproven and its derivation required somewhat inconsistent assumptions, and a possible problem might have been introduced by comparing two conservative estimates of the probability of a hazardous-vortex encounter) prompted an alternative analysis which showed the safety of VAS-reduced spacings for Heavy and for Large aircraft following Heavies. The analytical proof of the safety for Small aircraft following a Heavy or Large aircraft relies on the favorable resolution of the two issues. However, the fact that no vortices were ever monitored by the LDV in excess of 70 seconds (equivalent to about a 2.6-nautical-mile separation between aircraft) during VAS-Green conditions demonstrates that 3-nautical-mile spacings should be safe for all aircraft pairs under VAS-Green conditions.

Data were not collected in the vicinity of the outer marker, but the normal increase in wind magnitude with altitude in conjunction with the mitigation of the hazard of a vortex encounter at increased altitude support the contention that 3-nautical-mile separations should be safe under VAS-Green situations. Since the higher winds attendant with VAS-Green conditions cause vortices to dissipate or translate out of harm's way within 80 seconds, the VAS may be safely used to reduce separation standards to a uniform three nautical miles for all aircraft between the outer marker and touchdown.

5. REFERENCES

1. Gupta, V.P., "Vortex-Related Accidents Over the Ten-Year Period 1964-73," FAA-EM-75-6, April 1975, Mitre Corp., McLean, VA.

2. Avant, A.L., "Procedural Feasibility of Reduced Spacings Under VAS Operation at O'Hare," MTR-7415, May 1977, Mitre Corp., McLean, VA.

3. Keeffe, B.E., "Vortex Advisory System Simulation of Chicago O'Hare International Airport," FAA-RD-78-76, July 1978, National Aviation Facilities Experimental Center, Atlantic City, NJ.

4. Hallock, J.N., "Vortex Advisory System Safety Analysis, Volume I: Analytical Model," FAA-RD-78-68, I, Sep. 1978, Transportation Systems Center, Cambridge, MA.

5. Huffaker, R.M., Jeffreys, H.B., Weaver, E.A., Bilbro, J.W., Craig, G.D., George, R.W., Gleason, E.H., Marrero, P.J., Reinbolt, E.J., and Shirey, J.E., "Development of a Laser Doppler System for the Detection, Tracking, and Measurement of Aircraft Wake Vortices," FAA-RD-74-213, Mar. 1975, NASA Marshall Space Flight Center, Huntsville, AL.

6. Bilbro, J.W., Jeffreys, H.B., Weaver, E.A., Huffaker, R.M., Craig, G.D., George, R.W., and Marrero, P.J., "Laser Doppler Velocimeter Wake Vortex Tests," FAA-RD-76-11, Mar. 1976, NASA Marshall Space Flight Center, Huntsville, AL.

7. Brashears, M.R., Lawrence, T.R., and Zalay, A.D., "Mobile Laser Doppler System Checkout and Calibration," FAA-RD-77-48, I and II, June 1977, Lockheed Missiles and Space Company, Huntsville, AL.

8. Burnham, D., Hallock, J., McWilliams, I., Fantasia, J., and Winston, B., "Measurement of Aircraft Wakes at 250-Meter Altitude with a 10.6-Micron CW Laser Doppler Velocimeter," In: Proceedings of the Electro-Optics/Laser 1978 Conference, Boston, MA, 1978, p. 354-357.

9. Hallock, J.N. and Wood, W.D., "Joint US/UK Vortex Tracking Program at Heathrow International Airport, Volume I: Executive Summary," FAA-RD-76-58, I, Mar. 1976, Transportation Systems Center, Cambridge, MA.

10. Hallock, J.N., Winston, B.P., Burnham, D.C., Sullivan, T.E., McWilliams, I.G., and Wood, W.D., "Joint US/UK Vortex Tracking Program at Heathrow International Airport, Volume II: Data Analysis," FAA-RD-76-58, II, Nov. 1977, Transportation Systems Center, Cambridge, MA.

11. Hallock, J.N. and Eberle, W.R. (editors), "Aircraft Wake Vortices: A State-of-the-Art Review of the United States R&D Program," FAA-RD-77-23, Feb. 1977, Transportation Systems Center, Cambridge, MA.

12. McWilliams, I.G., "Hazard Extent about Aircraft Trailing Wake Vortices--Analytic Approach," In: Proceedings of the Aircraft Wake Vortices Conference, FAA-RD-77-68, June 1977, Transportation Systems Center, Cambridge, MA, p. 23-30.

13. Tinling, B.E., "Estimation of Vortex-Induced Roll Excursions Based on Flight and Simulation Results," In: Proceedings of the Aircraft Wake Vortices Conference, FAA-RD-77-68, June 1977, Transportation Systems Center, Cambridge, MA, p. 11-22.

14. Clay, L.E., DeLong, R.C., and Rockafellow, R.I., "ILS Flight and Ground Data from Unusual Events Recording System in a Commercial 737 Aircraft," FAA-RD-72-113, Nov. 1972, Technology Inc., Dayton, OH.

15. Carter, H.L., "Revalidation of the Data Base Used in Establishing the Criteria for Simultaneous ILS Approaches to Parallel Runways," Letter Report--Subprogram No. 150-502, May 1970, Federal Aviation Administration, Washington, DC.

330 copies