REPORT NO. FAA-RD-76-58, I

JOINT US/UK VORTEX TRACKING PROGRAM AT HEATHROW INTERNATIONAL AIRPORT

Volume I: Executive Summary

J. N. Hallock
W.D. Wood

U.S. DEPARTMENT OF TRANSPORTATION
TRANSPORTATION SYSTEMS CENTER
Kendall Square
Cambridge MA 02142

MARCH 1976
FINAL REPORT

Prepared for

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

Technical Report Documentation Page

1. Report No. FAA-RD-76-58, I	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle JOINT US/UK VORTEX TRACKING PROGRAM AT HEATHROW INTERNATIONAL AIRPORT Volume I: Executive Summary		5. Report Date March 1976
		6. Performing Organization Code
7. Author(s) J.N. Hallock and W.D. Wood		8. Performing Organization Report No. DOT-TSC-FAA-76-11
9. Performing Organization Name and Address U.S. Department of Transportation Transportation Systems Center Kendall Square Cambridge, MA 02142		10. Work Unit No. (TRAIS) FA605/R6122
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington DC 20591		13. Type of Report and Period Covered Final Report April 1974 - January 1976
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

From May 1974 through June 1975 the approach region to Runway 28R at Heathrow International Airport was equipped with aircraft wake vortex tracking equipment. The vortices from approximately 13000 aircraft were monitored along with the attendant meteorological conditions. The joint US/UK project represents a major step in learning how vortices move and die in the terminal environment. An overview of the Heathrow project is given and it is shown how the project has significantly contributed to the capability to develop a vortex advisory system promising increased capacity through decreased aircraft separations.

17. Key Words Aircraft Wake Vortices, Vortices, Meteorology, Vortex Transport	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	34	

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

PREFACE

The Aircraft Wake Vortex Program has an overall objective to increase capacity at the major high density air terminals. The joint US/UK vortex tracking project at Heathrow International Airport was implemented as a planned and preliminary step.

The highly professional and cooperative manner in which the UK field site personnel operated and maintained the meteorological and vortex tracking sensors must be recognized; the data collected from their efforts has provided the most significant and complete data base in the vortex program to date. These data constitute the basis for the algorithm to be used in the first vortex advisory system, scheduled for installation at Chicago's O'Hare International Airport in the Spring of 1976. This system will use meteorological sensor inputs to determine when it is possible to decrease aircraft separations to 3 nautical miles for all classes of aircraft.

The Executive Summary Report provides an overview of the total Heathrow project and describes its significant contributions to the capability to develop vortex advisory systems promising increased capacity through decreased separations. It also briefly describes the project's accomplishments in increasing the overall scientific knowledge of vortex dynamics under various meteorological conditions. The report identifies other factors that may yield additional significant benefits from the Heathrow data and lead to further cooperative analyses. A final report detailing all the data and its interpretation will be available shortly.

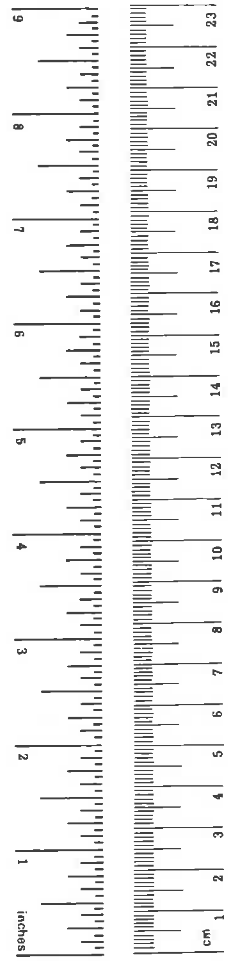
The valuable contributions of the UK project and the staff to the vortex program stands as another example of outstanding benefits derived from international cooperation on projects with common national objectives.

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

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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

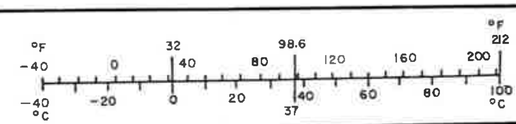


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

It has long been known that the wake from an aircraft can be sufficiently powerful to cause a serious disturbance to a following aircraft under certain conditions. This is especially true of light following aircraft and there have been numerous reports of light aircraft experiencing difficulty. It was realized, with the development of the B-747 and other wide-body aircraft, that the wake from such aircraft might be hazardous to following aircraft at the minimum spacings normally applied by the FAA Air Traffic Control (3 nautical miles), especially in the high density terminal areas where all of the aircraft are constrained to a fixed flight path and minimum separations are used to maintain capacity.

As a result of the foregoing realization, a large evaluation program was initiated in the United States to establish the theory of the behavior of wake turbulence and to measure its characteristics as seen under various meteorological and flight conditions. For a short period in early 1970, the FAA set the separation distance between a B-747 and a smaller, following aircraft at 10 nautical miles minimum. The National Air Traffic Services in the United Kingdom later imposed a minimum separation of 5 nautical miles behind a B-747. The regulation took account of the United States experience. This minimum separation distance was subsequently applied to smaller aircraft behind all wide-bodied large transport aircraft (the B-747, L-1011, DC-10, and C-5A). About this time, the Federal Aviation Administration in the United States imposed the same minimum separation (5 nautical miles) for smaller aircraft behind all aircraft capable of a gross takeoff weight in excess of 300,000 pounds (136,000 kilograms). Thus, in the United States, aircraft such as the stretched versions of the B-707 and DC-8 are grouped together with the B-747 and DC-10 and other large wide-bodied aircraft. In the UK the increased separation is given only behind the truly heavy wide-bodied aircraft such as the B-747, L-1011 and DC-10. Recently the division was formalized in the UK on the basis of a maximum take-off weight in excess of 375,000 pounds (170,000 kilograms).

From June 1970 onwards, unsolicited reports of possible wake vortex encounters were received by air traffic control officers at London Heathrow. Consequently, the United Kingdom Civil Aviation Authority instituted a program to gather information on wake behavior under operational conditions, and on the way various civil aircraft were affected by a wake vortex encounter. This program involved having pilots of both the aircraft experiencing the wake vortex encounter and the aircraft thought to have caused it, complete a detailed questionnaire. Where possible, the information was supplemented by data relating to weather conditions and aircraft spacings (from the Meteorological Office and Air Traffic Control Officers). It was possible, in some cases, to measure the degree of disturbance experienced by the affected aircraft by reference to the flight data recorder.

The majority of incidents occurred at or near Heathrow Airport and on final approach to the same runway. In some cases the encounter took place very near to the ground. Incidents were reported from a wide variety of aircraft pairs, and it was found that the heaviest jets (B-747 and L-1011) caused 40% of all incidents, in spite of the fact that they constituted only about 12% of all traffic at Heathrow during peak periods. After consideration of the incident reports and consultation with the appropriate operations groups, the separation distance in the United Kingdom was increased from 5 nautical miles to 6 nautical miles behind wide-bodied jets for light aircraft on the approach. The rule, promulgated in March 1974 to run on an experimental basis for one year, has since been extended indefinitely.

It has been calculated that at this time, using 6 nautical mile separations instead of 5, the reduction in airport capacity with the Heathrow traffic mix would be about 5%, at peak periods. This would be expected to increase significantly in time because of traffic increases. Airports like Chicago's O'Hare International, Atlanta's William B. Hartsfield International, and Los Angeles' International are operating near their capacity limits now.

There was therefore a strong incentive to establish those meteorological conditions during which the aircraft wake was not likely to persist in the approach corridor. The increased separations would then be necessary only when the probability of a wake vortex encounter was high.

A program for collecting pertinent data has been under way in the United States for some time. In 1973, two vortex data collection sites were established: the John F. Kennedy International Airport in New York and the Stapleton International Airport in Denver, Colorado. The test sites were instrumented to track vortices shed by landing aircraft and to record the ambient meteorological conditions. The landing zone was monitored because this is potentially the most dangerous region as all aircraft must follow essentially the same path to execute a landing. In a homogeneous, quiet atmosphere the vortex pair will descend to an altitude of approximately half a wingspan and then begin to move apart parallel to the ground. However, in the presence of winds the vortices are affected by the wind; the induced separation motion near the ground can be cancelled by the motion due to a cross-wind so that one vortex stalls (dwells) in the flight path of a following aircraft. Several effects modify the behavior of vortices near the ground; wake behavior is somewhat unpredictable due to turbulence-stimulated distortion and instabilities, and one vortex might rise in a wind shear. In addition, the transport and life of a wake vortex are directly affected by the wind magnitude and direction and the turbulence level.

Before the close of the Stapleton International Airport test site in November, 1973, the vortices from over 7000 landing aircraft were monitored. The J.F. Kennedy International Airport site, which has been used as a test bed for the development of vortex sensors and the collection of vortex dynamic behavior data, is still in operation.

There has been close liaison between the UK Civil Aviation Authority (CAA) and the Federal Aviation Administration (FAA) on wake vortex research for some years. They jointly agreed in late 1973 that it would be beneficial if equipment similar to that tested at Denver and New York could be installed at Heathrow for a defined test program. The test program would afford the opportunity to expand significantly the vortex track and meteorological data base under new and varied environmental conditions, to correlate reported vortex incidents (reports which could not be obtained in the United States) with measured vortex and meteorological conditions, and to track vortices from a number of aircraft rarely seen in the United States, e.g., Trident, Viscount, A-300B, and the Concorde. In view of the increased spacings being applied behind the heaviest jets at Heathrow, the results of such a program would be particularly valuable in assessing those conditions under which the rules might be relaxed and therefore in determining if significant capacity gains might be possible under relaxed rules.

The CAA and FAA have agreed to jointly develop technology, techniques, and systems concepts to increase runway capacities while avoiding wake vortex hazards. It was considered that use of the FAA wake vortex data collection system by the CAA would encourage and foster development of civil aeronautics and air commerce by providing further knowledge of the effects of wake turbulence on airport capacity. A formal lease agreement was therefore approved in February, 1974, to run for a period of six months. Under the agreement, the FAA delivered a wake vortex data collection system to Heathrow Airport. The system included an instrumentation van, meteorological towers, acoustic and ground wind sensor equipment, associated electronics, necessary interface equipment, cabling, etc. The FAA also provided a team to assist in the installation of the equipment at Heathrow and to familiarize the UK CAA personnel in its operation and maintenance. The CAA provided personnel to perform the installation of the equipment and a team to operate and maintain the equipment throughout the duration of the lease agreement. The time period was extended by mutual agreement from six months to one year because of the outstanding quality of the data obtained by the CAA test team. The vortex track, meteorological and incident report data collected by the CAA were sent to the Transportation Systems Center (TSC) in Cambridge, Massachusetts, for computer processing and analysis. The results of this analysis were periodically verbally reported to the CAA and an overall detailed report of the entire joint test program and its results is forthcoming. The detailed report will include all data summaries, analyses performed, analytical results, conclusions derived, and intended uses of the results. This Executive Summary serves as an interim report and demonstrates the great usefulness of the joint project. The report also supports the fact that further effort is warranted based both on the excellent quality of the data and indications from the currently completed analysis.

2. TEST SITE SENSORS AND DATA

Of the six active runways of Heathrow, Runway 28R was chosen for the installation of the equipment because sufficient land and facilities were available in the threshold area and, since the prevailing wind at Heathrow is between southwest and west, a significant number of landings would be monitored.

The equipment was installed during March and April 1974 and became fully operational in May 1974. Data collection continued through June 1975. The vortex tracking instruments were emplaced on two baselines (see Figure 1) sited perpendicularly to the extended runway centerline, 1475 feet (450 meters) and 2400 feet (732 meters) from the runway threshold. The outer baseline (see Figure 2) comprised an array of single-axis Gill propeller anemometers spaced 50 feet (15 meters) apart on either side of the centerline out to 300 feet (91 meters) and then every 100 feet (30 meters) out to 800 feet (244 meters). To ensure minimum disturbance to existing facilities, the anemometer line was aligned parallel to a fence along Cranford Lane. The inner line (see Figure 3) consisted of a row of similar anemometers extending out to 600 feet (183 meters), and a bistatic pulsed-acoustic radar system developed by the Department of Transportation, Transportation Systems Center. The inner line was positioned just to the east of the ILS localizer aerial for Runway 10L, and tests confirmed that the equipment did not interfere with the localizer beam.

Two pressure sensors were used to detect the passage of an aircraft over each baseline. A motion picture camera mounted on the inner baseline monitored the approach of each aircraft. Two meteorological towers were installed on the inner baseline, one approximately 900 feet (274 meters) north of the runway centerline (height of 32 feet (10 meters)) and one approximately 800 feet (244 meters) south of the centerline (height of 50 feet (15 meters)). Both towers were instrumented at two levels with three-axis Gill propeller anemometers to measure wind components.

Trailing vortices generated by the aircraft as they pass over the sensing equipment produce distinctive wind variations which can be detected and measured. By noting when a particular anemometer

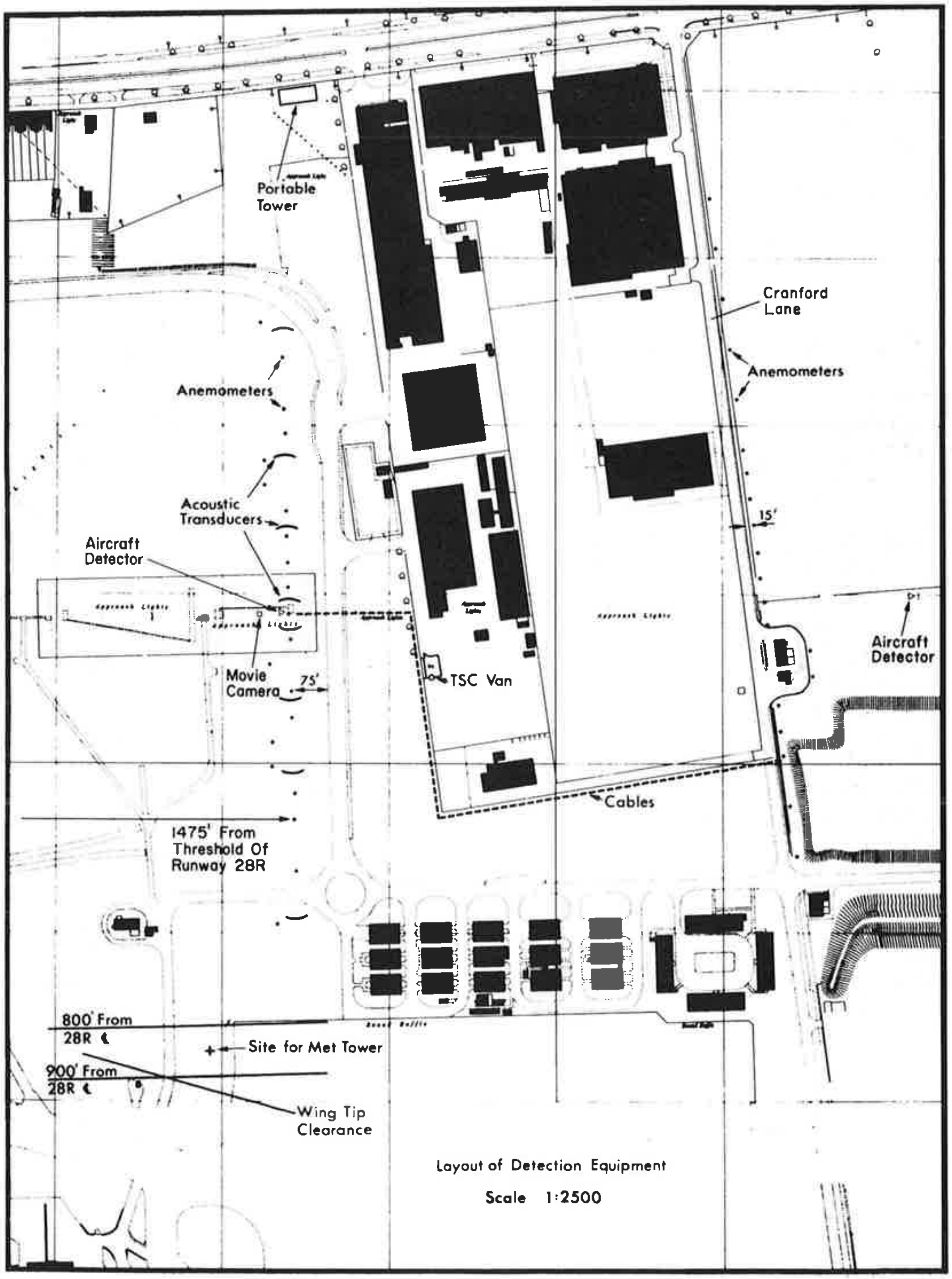


Figure 1. The site layout of the equipment on the approach to Runway 28R at Heathrow

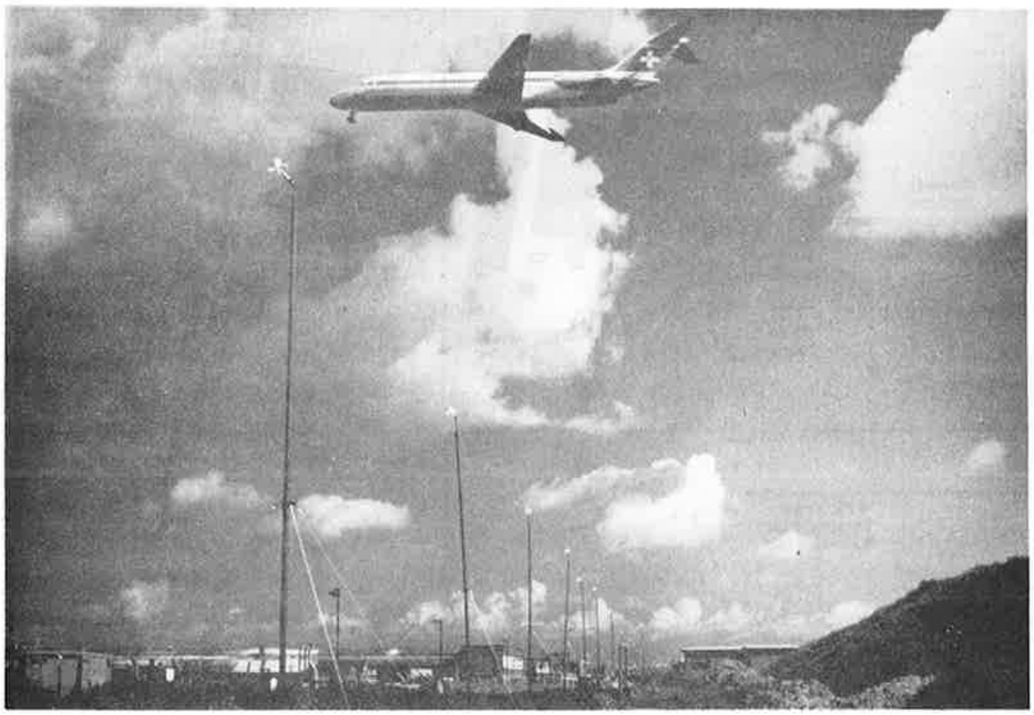


Figure 2. The outer baseline at Heathrow showing the Gill propeller anemometers mounted on 21-foot (6.4-meter) poles

Figure 3. The inner baseline at Heathrow showing the Gill propeller anemometers mounted on 11-foot (3.4-meter) poles and the pulsed acoustic parabolic antennas

in an array shows the greatest deviation from the ambient wind signal, it is possible to fix the horizontal displacement of the two vortices from the extended runway centerline. The bistatic pulsed-acoustic system uses time differences (within a transmitter/receiver pair system) between a pulse propagated along the ground and that portion of the pulse refractively scattered by the organized motion in a vortex core, to locate a vortex. After five months of operation the pulsed-acoustic system was dismantled as little additional information was gained from the data.

The site was manned during normal working hours whenever Runway 28R was in use for landing operations. A total of 12,950 landings were monitored during the test period. Table 1 lists the number of each aircraft type recorded along with a tally of the number of "good data" landings. "Good data" means that no data of consequence were lost due to an instrument malfunction. Ninety-six percent of the recorded data were good.

TABLE 1: RECORDED DATA

AIRCRAFT TYPE	NUMBER OBSERVED	GOOD DATA
Trident	3947	3838
DC-9	1149	1115
B-707	1133	1097
Viscount	1021	962
BAC-111	895	863
B-727	895	874
B-747	811	791
B-737	810	768
DC-8	389	381
VC-10	325	314
HS-125	293	205
Caravelle	254	247
GA	201	187
A-300	129	125
B-720	82	81
IL-62	74	73
L-1011	73	73
Mystere	66	52
TU-134	64	60
Herald	60	60
F-27	60	57
Vanguard	52	51
CV-990	51	49
Gulfstream II	46	34
DC-10	30	30
HS-748	25	20
Learjet	7	7
IL-18	2	2
DC-6	2	2
Unknown	2	2
Concorde	1	1
Electra	1	1
	12,950	12,422

3. ANALYSIS OF THE DATA

3.1 SAFETY ZONE

Since vortices usually move away or dissipate before a following aircraft arrives, the vortex track data were analyzed in terms of how soon the vortices exit a "safety zone". The safety zone is a region with no height restriction, centered on the extended runway centerline. If both vortices from a preceeding aircraft have exited the safety zone, either by moving out or by dissipating, then 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 was deliberately selected to be conservative.

The width of the safety zone was established by using two criteria. First, a measurement program conducted by TSC at Denver's Stapleton International Airport showed that 3σ or 99.74% of all landing aircraft are within 50 feet (15 meters) 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. Second, six-degree-of-freedom aircraft-vortex encounter simulations done at TSC and elsewhere have indicated that if the fuselage of any aircraft is at least 100 feet (30.5 meters) 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 (30.5-meter) 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 (15+30.5 or 45.5 meters) 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 (61 meters) and yet both may be within the safety zone. Furthermore, the vortex may have been generated by an aircraft whose vortices will not affect the following aircraft, e.g., a HS-125 followed by a B-747, and 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.

3.2 RESIDENCE TIMES

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 or may have decayed to an undetectable level. Figure 4 shows the probability of a vortex remaining in the safety zone longer than any given time. For example, 16% of the data collected on the outer baseline at Heathrow yielded a vortex in the safety zone in excess of 60 seconds. Figure 4 is a composite of all the aircraft and meteorological conditions. The difference between the two curves, that is, between the two baselines, can be directly attributed to the higher turbulence caused by the winds which emanated from the direction of the B-747 hangars near the outer baseline. The higher turbulence caused the vortices on the outer baseline to decay more rapidly than those on the inner baseline when the winds were from the south. No discernable differences between the curves were seen when the winds were from the north.

Crosswind magnitude plays an important role. Figure 5 shows the probability of a vortex remaining in the safety zone in the presence of various crosswinds. Eighty seconds represents an aircraft-to-aircraft spacing of less than three nautical miles at the approach speeds of most modern aircraft. On the basis of Figure 5 it is reasonable to predict that wake vortices are unlikely to be troublesome at Heathrow when there are crosswinds greater than 5 knots. The crosswind was greater than 5 knots for about 45% of the landings monitored during the data collection.

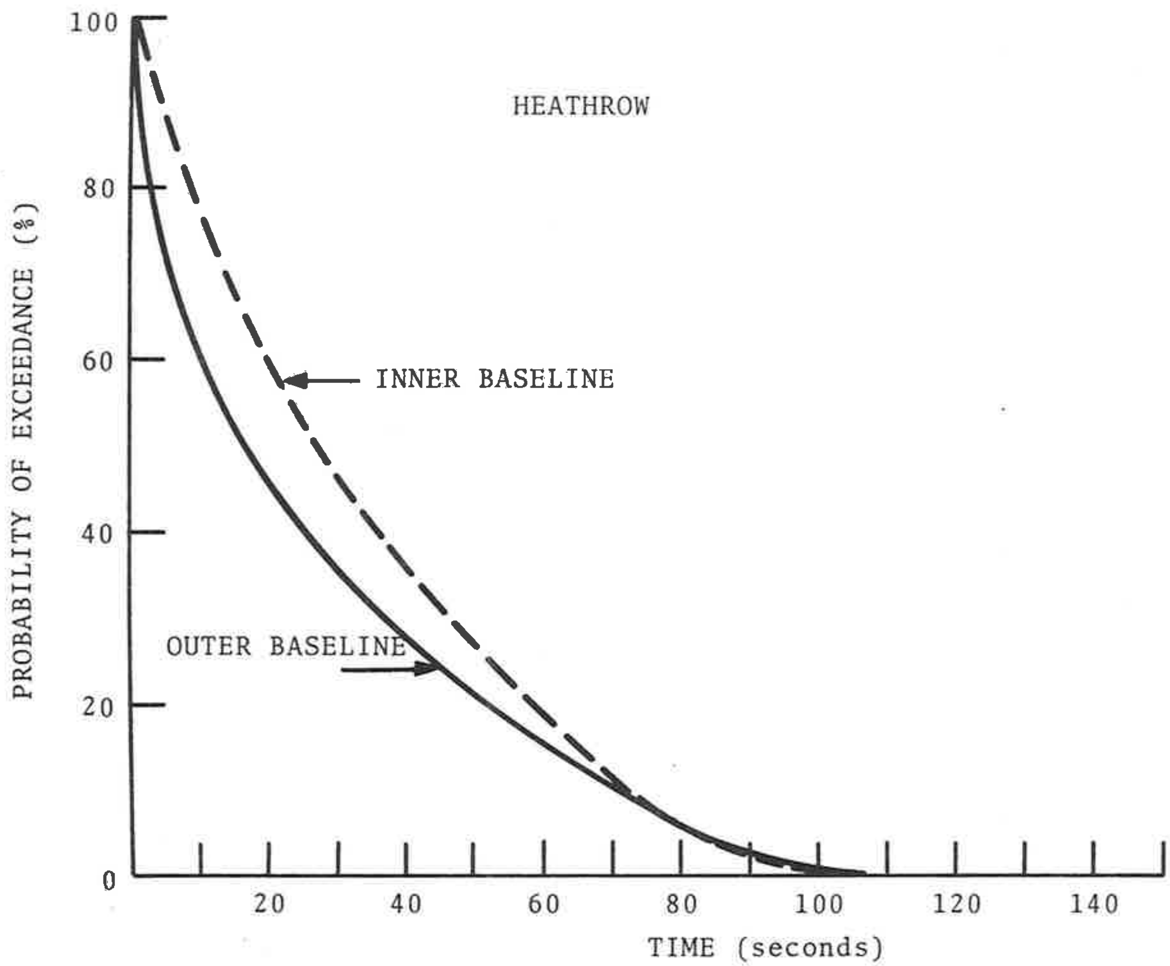


Figure 4. The probability measured at the two baselines for a vortex to remain in the safety zone longer than any given time

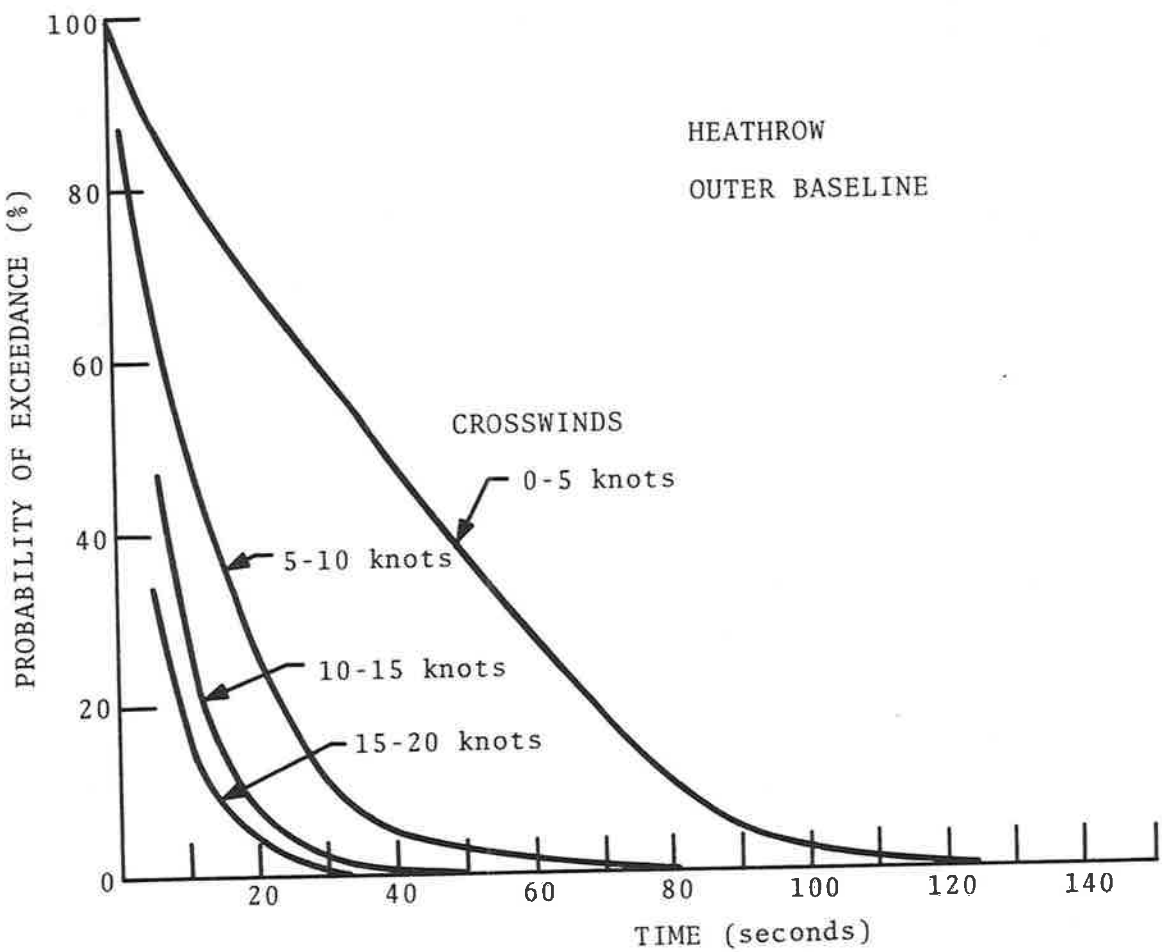


Figure 5. The probability of a vortex remaining in the safety zone longer than any given time for various crosswind components

Generating aircraft type also plays an important role on the longevity of a vortex. Figure 6 shows the probability of a vortex remaining in the safety zone as a function of the residence time for three aircraft: the HS-125, the Trident and the B-747. The wide-body jets make up the significant portion of the older residence time cases.

3.3 WIND CRITERION

One method for regaining or increasing the capacity of an airport would be to determine those times during which all separations could be safely decreased to 3 nautical miles. It would be expected that such times are dependent on the wind velocity, as crosswinds in excess of 5 knots at Heathrow appear to alleviate the wake vortex problem. To pursue the appropriate wind conditions, data on the heavy aircraft whose vortices had a residence time in excess of 80 seconds were segregated from the data base. The United States definition of heavy aircraft was used. However, as shown in Table 2, 103 of the 113 cases would be attributed to the heavy category in both the US and UK nomenclatures.

Figure 7 shows the measured wind velocities for the 113 heavy aircraft which had residence times greater than 80 seconds. The open circles represent vortices with 80-90-second residence times and the solid circles represent vortices with greater than 90-second residence times. (A ground speed of 135 knots means that 3 nautical miles is equivalent to 80 seconds.) Any number of geometrical patterns could have been used to enclose the data points, but a convenient pattern with a low enclosed area is the ellipse shown in Figure 7. The semi-major axis (headwind or tailwind axis) is 12 knots and the semi-minor axis (crosswind) is 5.5 knots. Although the data points shown are for the long-lived (residence times in excess of 80 seconds) cases detected at the outer baseline, the same ellipse also encloses the long-lived cases detected at the inner baseline. In addition, the ellipse encloses the long-lived cases detected in both the Stapleton and Kennedy International Airport data collection programs.

The calculation of the 3 nautical miles separation involves an assumption of the ground speed of the aircraft which will vary by ±12 knots across the major axis of the ellipse. Using the actual ground speed for the aircraft involved, however, does not alter the dimensions of the ellipse.

TABLE 2: HEAVY AIRCRAFT OBSERVED AT HEATHROW

AIRCRAFT TYPE	NUMBER OBSERVED	NUMBER LONG-LIVED*	PERCENT LONG-LIVED*
B-747	791	95	12.0
DC-10	30	3	10.0
L-1011	73	5	6.8
DC-8-61/62/63	31	1	3.2
VC-10	325	9	2.8
B-707-320/420	60	0	0.0
	1310	113	

*Residence time in excess of 80 seconds.

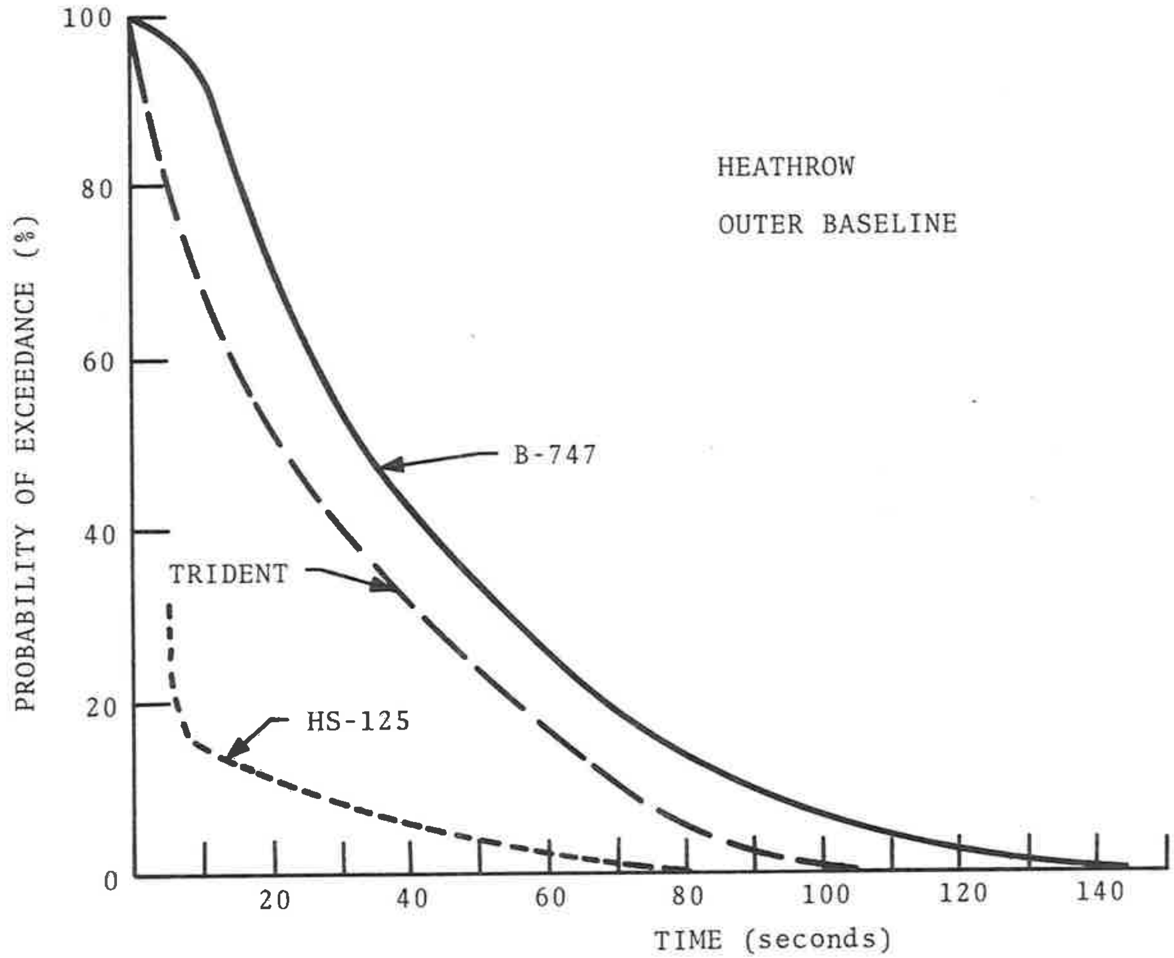


Figure 6. The probability of a vortex remaining in the safety zone longer than any given time for various aircraft types

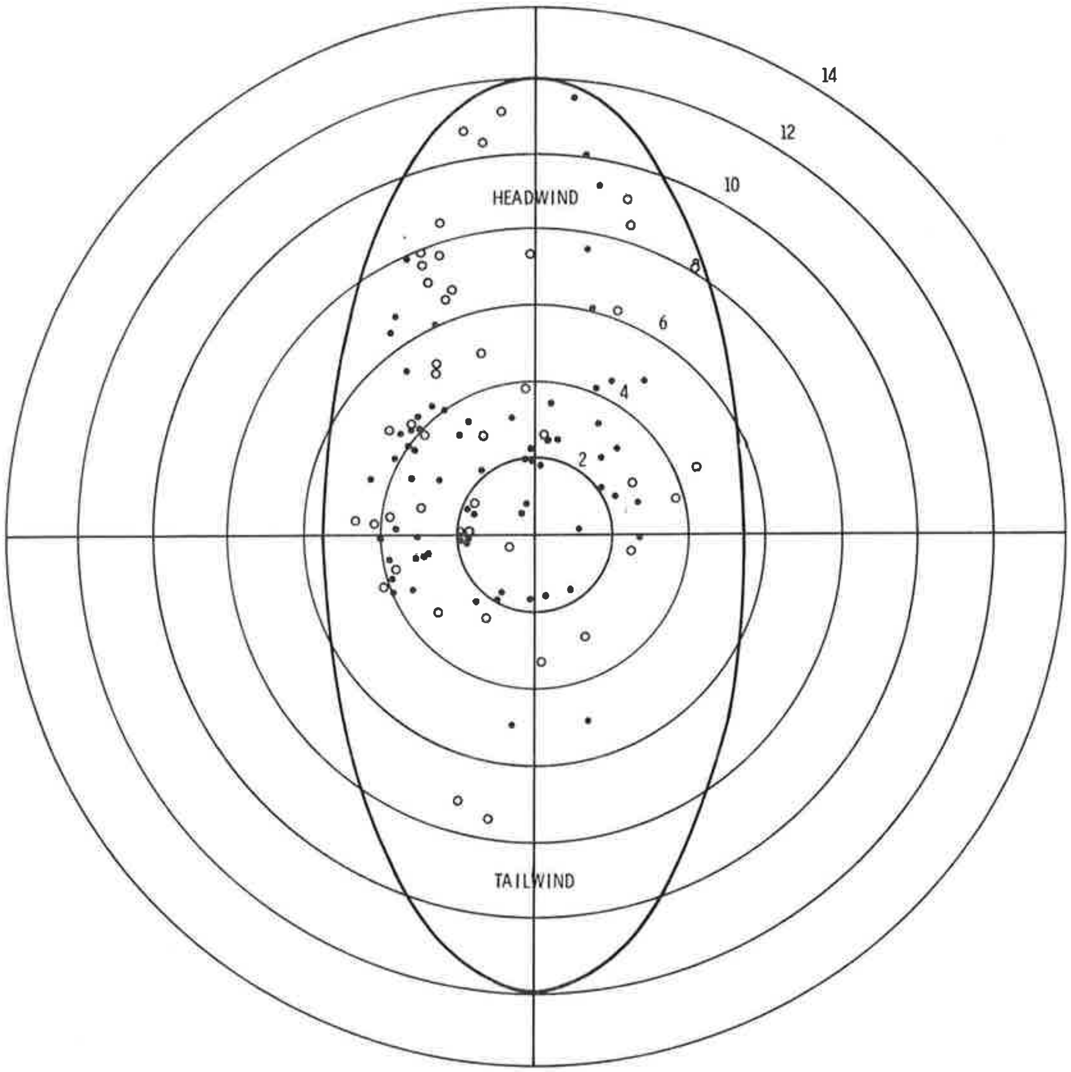


Figure 7. The wind conditions (in knots) which led to residence times in excess of 80 seconds for the heavy category of aircraft. (Open circles are the 80-90-second cases and solid circles are the in-excess-of-90-second cases)

Thirty-one of the long-lived cases were detected during tailwind conditions, 81 during headwinds, 80 with crosswinds from the north, and 33 cases with crosswinds from the south. For the 1310 heavy aircraft observed at Heathrow (Table II) 198 occurred during tailwinds, 1112 during headwinds, 649 with a crosswind component from the south, and 661 with a crosswind component from the north. Thus, the probability of having a long-lived case (for the heavy category only) is 31/198 or 0.157 during tailwind operations, 80/1112 or 0.072 during headwind operations, 33/649 or 0.051 for the crosswind from the south, and 80/661 or 0.121 for a crosswind from the north. With the wind conditions measured during the Heathrow data collection, the chance for observing a long-lived case during tailwind operations was 2.2 times greater than in headwind operations. (A ratio of 4.1 was found in the Stapleton-Kennedy tests.) The chance for observing a long-lived case was 2.4 times greater with a crosswind from the north than for a crosswind from the south. The crosswind anomaly is attributed to the presence of many buildings to the south of the extended runway centerline which induce turbulence into the wind, thus causing more rapid decay of the vortices. A preliminary study of the decay of the vortices tracked at Heathrow supports the induced-turbulence contention.

To determine a measure of the effectiveness of incorporating the ellipse into a wind-criterion system which allowed all possible separations at Heathrow to be 3 nautical miles, the ellipse was overlaid on a Heathrow wind rose. The wind rose was not the wind rose which would be obtained from the airport meteorological office, but rather one compiled by recording the one-minute averaged winds as an aircraft passed over the vortex tracking equipment in the approach to Runway 28R during normal working hours. Fifty-five percent of the time the winds were outside the ellipse and, accordingly, the separations could have been reduced to 3 nautical miles. Using only the wind data obtained when a B-747 landed on 28R, 51% of the following aircraft could have been spaced safely 3 nautical miles behind the B-747. The calculations serve only to indicate the possible benefit of a wind-criterion system as the percentages were obtained by using data from the Heathrow environment (meteorology and aircraft mix) and assuming the use of US rules and procedures.

It must be noted that just because winds are measured to be within the ellipse does not mean that every vortex will remain in the safety zone for 80 seconds or more. It is only a necessary condition for vortices to linger. The overly conservative dimensions of the safety zone, the ignoring of aircraft types, the ignoring of vortex decay due to atmospheric turbulence or the non-stability of the atmosphere, etc., all contribute to restricting the times when the separation standards could be decreased. Research should provide additional criteria to shrink the size of the ellipse. If the winds are outside the ellipse, then it is completely justifiable to reduce separations to a standard 3 nautical miles.

3.4 INCIDENT REPORTS

Although vortex-related incidents were reported, only one incident was reported in the vicinity of the vortex tracking apparatus. On 29 May 1974 a Trident reported a 15-degree roll (the on-board flight data recorder indicated a 10-degree roll) just prior to touchdown on Runway 28R. The motion picture camera located on the inner baseline recorded the rolling motion of the Trident and indicated that the roll began about 1800 feet (550 meters) from the runway threshold. The preceding aircraft was a B-707 which passed over the tracking equipment 101 seconds ahead of the Trident. The data, however, showed that the B-707 vortices were in excess of 300 feet (91 meters) south of the flight path of the Trident. But at the time of the roll the meteorological instrumentation recorded a wind shift - a low-level wind shear. Apparently, the wind shear caused the Trident to roll in the same manner that a mild vortex encounter would have affected the Trident.

3.5 ONGOING STUDIES

A number of other, statistically based, studies are currently under way and the results will be included in the final detailed report:

A. Meteorology Study--Comparisons between the winds measured by the two towers and the winds reported by the air traffic controller will establish the site dependency of wind measurement systems. This will be very important if any capacity increasing system based upon wind measurement is to be implemented. The average shear for the Heathrow site and the meteorological characterization of the site (surface roughness factor and friction velocity) will be determined.

B. Vortex Decay--The probability of a vortex decaying to a negligible strength will be determined as a function of wind velocity. The roles of vortex transport and decay within the safety zone will be elucidated, as will the consequences of these roles on the design of vortex avoidance systems.

C. Prediction--The ability to predict conditions warranting a decrease in aircraft separations will be investigated.

D. Ellipse Buffer Zone--The elliptical wind criterion cannot be directly used in a capacity gaining system without adding a buffer zone about the ellipse. When winds are in the buffer zone, the controller can be warned that either the conditions will eventually require the use of standard separations or the use of 3 nautical miles for all aircraft. If the wind velocity is determined to be within the ellipse, a red light would be displayed and the usual separations enforced; if the wind velocity is determined to be outside the ellipse, a green light would be illuminated indicating that a 3 nautical mile separation could be used for all aircraft. When the winds are near the edge of the ellipse without a buffer zone the lights could alternate rapidly between red and green. The necessary logic will be developed in terms of a buffer zone about the ellipse allowing the gradual change of conditions from green to red with sufficient warning to avoid unnecessary aircraft waveoffs or missed approaches.

E. Building Effects--As noted in the previous sections, the nearby buildings often induced sufficient turbulence to cause premature decay of the vortices. The effect will be examined quantitatively in terms of aircraft dependence, wind velocity, and the position of the ultimate demise of the vortices.

F. Aircraft Effects--Vortices from a number of different aircraft types have now been tracked. The similarities and differences of the vortices will be investigated to determine possible groupings of aircraft types based upon the characteristic motion of their vortices.

These studies have also provided some valuable information. For example, the approach ground speeds of about half of the aircraft landing on Runway 28R were measured. This has provided data for the calculation of the variation and the effect of the longitudinal wind component. In addition, aircraft-to-aircraft spacings (separations) near the runway threshold have been determined as a by-product of the method used to record the vortex track data.

4. APPLICATIONS OF THE HEATHROW DATA

Using the Heathrow data a wind criterion (ellipse) has been defined which indicates the conditions during which vortices persist in a safety zone. It was evident from the meteorological data that there could be significant periods of time during which the wind magnitude and direction were outside the elliptical criterion and the safety zone would be clear of vortices for all aircraft at separations of 3 nautical miles. Since high density terminals have a significant number of heavy jets in their traffic mix, an advisory system can be designed to compare measured wind data to an algorithm (ellipse) and advise the air traffic controller when separations for all aircraft could be reduced to three nautical miles. This would increase the airport capacity. Chicago's O'Hare International Airport is the highest density airport in the United States, and an advisory system is being implemented there for evaluation purposes. The capacity gain that might be evidenced at O'Hare would indicate the value of the advisory system. It would also indicate the compatibility of such a system with the current air traffic control system and the effect on the work load of controllers in high density traffic situations during both IFR and VFR conditions.

Evaluation of the data from Heathrow and JFK indicated the necessary meteorological measurements that were required for the algorithm and the location requirements for the meteorological towers. Applying that information to O'Hare, it was determined that six meteorological towers with wind direction and magnitude sensors at the fifty-foot (15-meter) level would be adequate. The wind magnitude and direction data is directly inputted to a microprocessor which digitizes and formats the data. A digital data transmitter sends the formatted digital data over phone lines to a matching digital data receiver in the control tower room. Each of the six receivers inputs the meteorological data into a single microprocessor where a comparison is made with the ellipse algorithm and the current vortex conditions in the approach corridor of each landing runway is determined. The microprocessor outputs the conditions to a display in the common IFR room and also the

Tower Cab: a green light "3" if separations may be reduced to three miles for all aircraft or a red light "3456" if separations must be those currently specified for each class of aircraft.

As a by-product of the advisory system, the actual wind conditions (wind magnitude, direction and gust level) existing at the approach end of each landing runway is continuously updated on digital displays by the microprocessor. The availability of the actual wind parameters at the approach or departure end of the runway is expected to be a real asset to pilots in planning their approaches as the Heathrow and JFK data indicated significant differences between the center field reading and that measured by the vortex meteorological sensors near the approach corridor.

The vortex advisory system at O'Hare is only for operational evaluation. Separation standards will not be changed. Co-located instrumentation consisting of several arrays of groundwind anemometer sensors (identical to those used at Heathrow) will be used to track vortices to determine if the vortices are out of the safety zone in a time less than that associated with a three mile separation whenever the green light is on. The instrumentation system continuously records the aircraft type, the meteorological parameters, the output of the microprocessor ("green" or "red"), and the ground wind sensor array output. This data is to be shipped to TSC for processing and evaluation of the system performance. The meteorological and ground wind sensor data will be analyzed in a manner similar to that used for the Heathrow data. A comparison between the instrumentation data and the algorithm will be used to determine the margin of safety and the number of false alarms and system errors, if any, so that algorithm modifications may be made prior to use of the advisory system in the air traffic control system. Evaluation will include analysis of the lead time necessary to change from the three mile separation to the standard "3456" separations as well as of the effect this lead time has on altering approach spacings or runway usage configurations. Impact on controller workload and an assessment of the benefits provided by the advisory system to the controller will also be considered.

The vortex advisory system is a first step in increasing capacity at the major high density terminals. It relies solely on being able to reduce approach spacings when the winds are high enough and in a proper direction. It is anticipated that the capacity gains may be significant at an airport such as Chicago that has high wind conditions. The benefits may be slight at an airport such as Miami International that in general has very light winds. The analysis of test results of such a system is crucial to any decision to commit such a system into the National Airspace System.

5. CONCLUSIONS AND RECOMMENDATIONS

The growing demand on international airports has raised pressure for increasing airport capacity. A significant gain is possible through reduced approach separation times. Lack of knowledge about the life-cycle of wake vortices generated by today's large aircraft has mandated relatively large separation distances for following aircraft and, until now, set a limit to safe runway capacities. The joint US/UK Vortex Tracking Project at London's Heathrow Airport represents a major step in overcoming the obstacles set up by vortices in the approach area to increasing capacities by reduced separations. Analysis of Heathrow data indicates that there are wind conditions which predictably remove vortices as a limiting factor to separation distance reduction and thus to increasing airport capacity.

The analysis has shown that a wake persists in the safety zone for 80 seconds or longer for only about 5% of the time and these times occurred only with crosswinds of less than 5 knots. A time interval of 80 seconds represents a spacing of less than three miles for the approach speed of most modern aircraft. On the basis of the test results, it would appear to be reasonable to predict that wake vortices are unlikely to be troublesome at Heathrow for crosswinds greater than 5 knots.

Using the Heathrow data, an elliptical wind criterion has been defined which can be used to determine when separations can be uniformly set at 3 nautical miles. A vortex advisory system is being implemented at the Chicago O'Hare International Airport; the operation of the system is based on comparing the winds with the elliptical wind criterion. The suitability tests at O'Hare will establish the utility of the vortex advisory system.

Consideration should be given to the possibility of making even greater gains than are provided by the use of a simple elliptical criterion based on persistence and wind speed alone. The strength of the vortex is of fundamental importance in determining the impact on the following aircraft. Utilization of vortex strength and decay have not been considered in the advisory system but there are indications that significant gains are possible by taking advantage of these two parameters. The strength and decay of the vortices from stretched versions of the DC-8 and B-707 are being studied in the United States. Possibly these types can be eliminated from the US heavy category of aircraft as has been done in the UK. Further, the use of a complete predictive model which considers vortex transport and decay as a function of time, meteorological conditions (including turbulence and atmospheric stability) and aircraft type could be included in a system that might provide variable spacings in a fully automated environment as is eventually planned with metering and spacing.

Much work remains in the analytical area and in the design of fully automated systems, e.g., a completely automated Wake Vortex Avoidance System. Further analysis and studies using the Heathrow data are warranted and recommended. However, that is only the first step in arriving at a full solution to the problems of capacity reductions arising from the present methods of avoiding wake vortices on landing approaches.