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1995 WAKE VORTEX TESTING PROGRAM AT MEMPHIS, TN*

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ABSTRACT

This paper describes wake vortex field measurements conducted during August, 1995 at Memphis, TN. The objective of this effort was to record wake vortex behavior for varying atmospheric conditions and aircraft types. Wake vortex behavior was observed using a mobile continuous-wave (CW) coherent laser Doppler radar (lidar) developed at Lincoln Laboratory. This lidar features a number of improvements over previous systems, including the first-ever demonstration of an automatic wake vortex detection and tracking algorithm. An extensive meteorological data collection system was deployed in support of the wake vortex measurements, including a 150' instrumented tower, wind profiler/ RASS (radio acoustic sounding system), sodar and balloon soundings. Aircraft flight plan and beacon data were automatically collected to determine aircraft flight number, type, speed and descent rate. Additional data was received from airlines in post-processing to determine aircraft weight and model. Over 600 aircraft wakes were recorded over the one-month period during 29 traffic pushes. Preliminary results from the field measurement program are presented illustrating differences in wake vortex behavior depending on atmospheric conditions and aircraft type.

INTRODUCTION

Significant restrictions currently exist in the air traffic control system due to wake vortex considerations. Eliminating or reducing these restrictions would yield increased capacity, decreased delays and significant cost savings[1]. Current wake vortex separation standards are widely viewed as very conservative under most conditions. However, scientific uncertainty about wake vortex behavior under different atmospheric conditions remains a barrier to development of an adaptive vortex spacing system.

Wake vortex measurements have been conducted in the U.S. and elsewhere since the late 1960s[2].A number of sensors have been employed for wake vortex measurements, including CW lidar, pulsed lidar, anemometer lines and acoustic sensors. Early wake vortex measurements were often not accompanied by suitable atmospheric measurements. This deficiency became more apparent in 1985 with the publication of an approximate theory of wake vortex behavior relating circulation decay and descent rate to nondimensionalized atmospheric conditions (i.e., normalized to aircraft characteristics)[3].

More recent wake vortex field measurements were made during tower fly-by tests at Idaho Falls in 1990[4]. A major aim of this effort was to collect wake vortex, atmospheric and aircraft data under controlled conditions. A variety of wake vortex sensors were employed, including an instrumented tower, CW lidar, monostatic acoustic vortex sensing system (MAVSS) and an anemometer line. Atmospheric data was collected with a tethersonde, tower and and the flight profiles of the test aircraft were carefully controlled. While constituting the most comprehensive set of measurements to that time, the experimental protocol suffered from some deficiencies. Only three types of aircraft were studied (Boeing 727, 757 and 767), the aircraft made low passes instead of actually landing and data were collected on only two days for each type.

The objective of the field measurement program reported here was to collect wake vortex, atmospheric and aircraft data in an operational setting for diverse atmospheric conditions and aircraft types. This effort is part of a larger effort by NASA Langley Research Center in cooperation with the Federal Aviation Administration[5]. Initial field measurements were made for a one-month period during the fall of 1994 at Memphis, TN[6]. The second one-month fielding during August, 1995 is reported in this paper.

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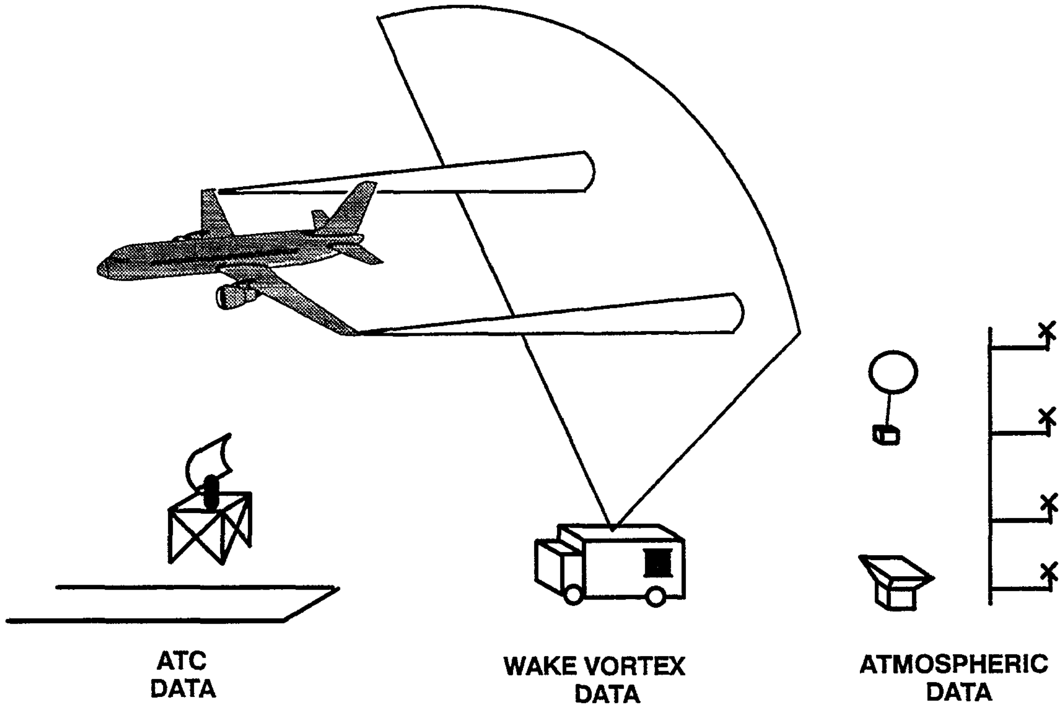

Figure 1. Memphis wake vortex field measurement system.

DATA COLLECTION SYSTEM

The elements of the Memphis field measurement program are summarized in Figure 1. These elements include wake vortex measurements, atmospheric measurements and aircraft data collection.

Wake Vortex Measurements

Wake vortex measurements were performed by a van–mounted 10.6 μm CO_2 CW lidar[7]. The lidar measures line–of–sight velocities in a plane perpendicular to the flight path in order to characterize vortices generated by approaching or departing aircraft. An algorithm was developed to allow the lidar to automatically recognize, track and characterize wake vortices[8]. Various lidar scanning strategies are employed to study wake vortices generated in, near and out of ground effect.

Lidar Design

The lidar design (Figure 2) is similar to those used in previous work, but with some significant improvements. First, the master oscillator is offset in frequency from the local oscillator by 10 MHz in order to resolve positive and negative frequencies. Second, the design features a fully digital signal processing system which offers greater flexibility than the analog techniques previously used.

The lidar utilizes a 33 cm aperture which provides an effective range resolution of a 6 m at 100 m range. The range resolution increases as the square of the distance and the maximum measurement range is roughly 300 m. The maximum sweep rate is in excess of 180°/s, but typical scan rates are closer to a 50° sweep in 1 s (including acceleration and deceleration).

The lidar data is sampled at a 40 MHz rate to yield an effective +/–50 m/s velocity bandwidth. FFT (Fast Fourier Transform) processing is performed on the raw data. FFT length is selectable, with a typical FFT consisting of 128 velocity data points, corresponding to a velocity resolution of 0.8 m/s. The FFTs are accumulated to generate averaged velocity spectra at nominally 300 Hz and sent to a Sun workstation for archiving and further processing.

Automatic Detection and Tracking Algorithm

The Sun workstation carries out the task of recognizing, tracking and characterizing wake vortices from the lidar data. The first step in this process is to perform feature extraction on the averaged spectra, such as peak finding. The extracted spectral features are then used to locate vortex cores, which are then tracked. The vortex tracking data is fed back to the lidar scan and focus control circuits. Once the core location is determined, the vortex circulation can be estimated

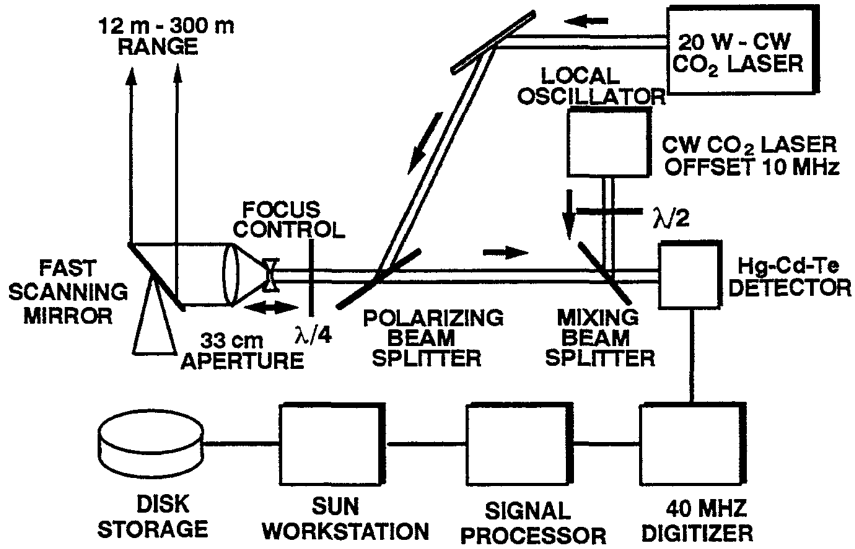

Figure 2. Wake vortex detection lidar design.

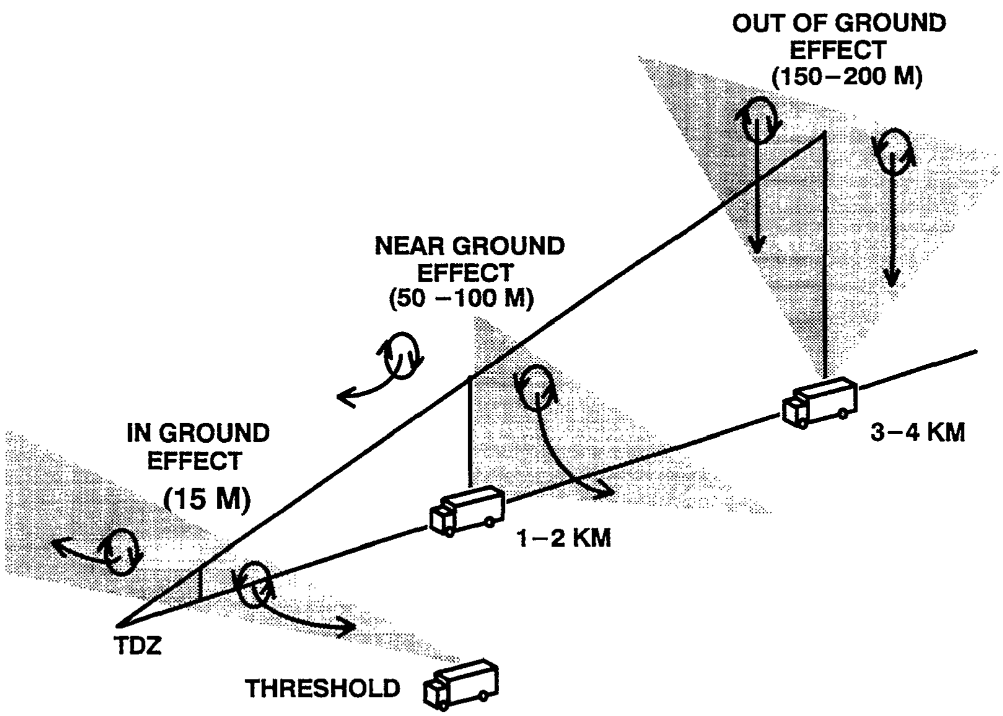

Figure 3. Lidar scanning strategies.

Scan Strategies

Figure 3 summarizes the scan strategies used to make the wake vortex measurements. The scan strategies are used to measure vortices out–of–ground effect (OGE), near ground effect (NGE) and in ground effect (IGE). The onset of ground effect occurs at an altitude of approximately half the generating aircraft wingspan. As illustrated in the figure, vortices tend to descend downwards above this level and to diverge horizontally below it.

Atmospheric Measurement System

Atmospheric data were obtained from several sources. An instrumented tower was erected on the airport to collect temperature, humidity, winds and other data needed to characterize the atmosphere near the surface. Balloon soundings were made to collect this data above the tower level. A profiler/RASS and sodar were also installed.

Figure 4 illustrates the atmospheric measurement system. A 150' tower was erected on the airport between the two main runways. This tower has two types of sensor packages: SAVPAKs and FLUXPAKs. Five SAVPAKs were used to collect temperature, humidity and 2D (horizontal) winds at a 1 Hz rate. Two FLUXPAKs were used to measure temperature and 3D (horizontal & vertical) winds at a 10 Hz rate at the base and top of the tower.

Additional instruments near the tower base include a total net radiometer, barometer and soil temperature/moisture probes. The data from the tower and other sensors are collected by an ASTER Data Acquisition Module (ADAM) developed by the National Center for Atmospheric Research (NCAR). The ADAM communicates via Ethernet with a Sun workstation located in a shed some 500' south of the tower location.

The Sun workstation performs processing on the data from the ADAM, such as computing temperature, and momentum fluxes from the FLUXPAK data. Besides communicating with the ADAM, the Sun workstation also interfaces to a Radian Profiler/RASS. The Sun archives the atmospheric data to a large disk and provides communication with the main Lincoln Laboratory network via a modem connection. The communications capability is used to remotely access the data and monitor sensor health.

Aircraft Data Collection

Air traffic control (ATC) data was obtained to determine the aircraft type, position and speed. This data is in the form of aircraft beacon reports and flight plans. Additional data was acquired from air carriers to determine the weight of the aircraft on takeoff or landing. This data also included the aircraft model number within the aircraft type.

Post–Processing System

The wake vortex data processing system is currently being developed as outlined in Figure 5. Due to the diverse nature of the data sources, extensive post–pro-

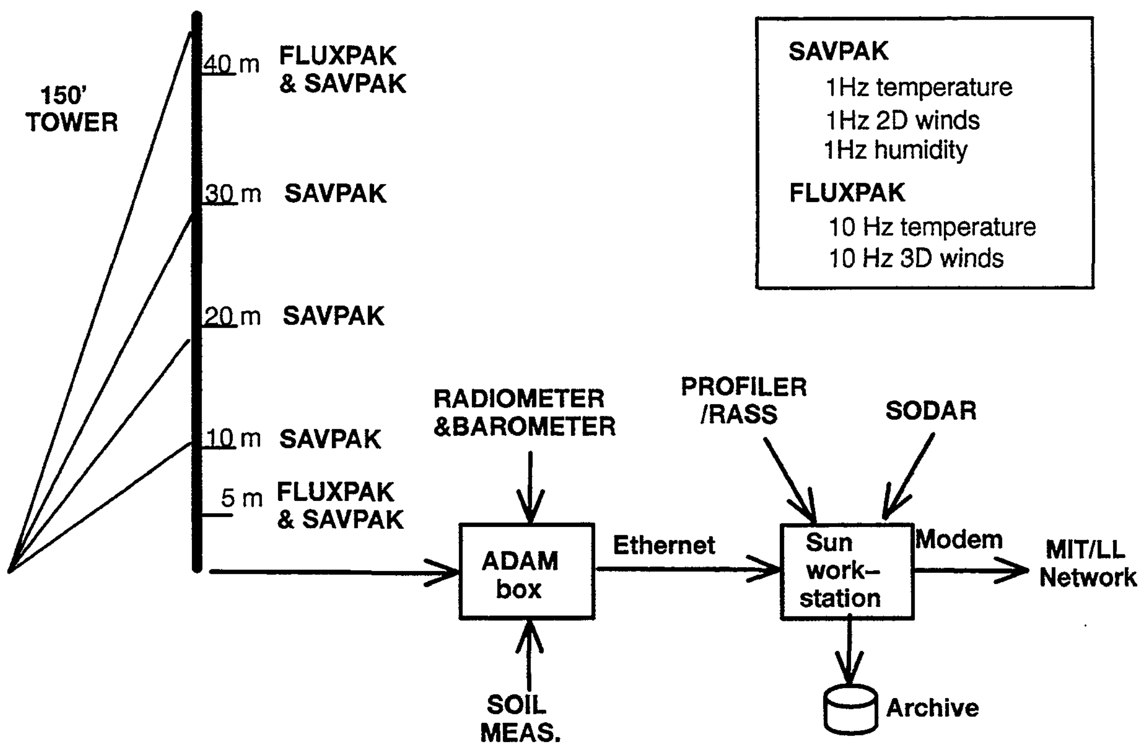

Figure 4. Atmospheric measurement system

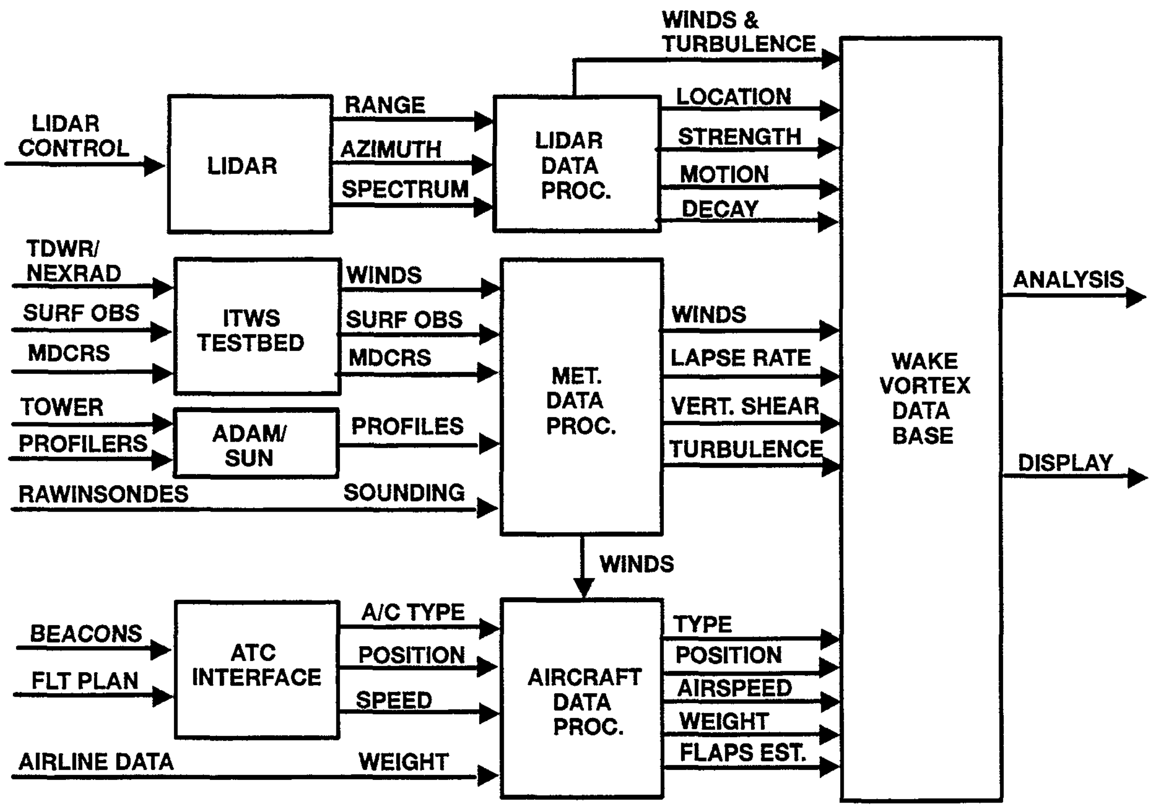

Figure 5. Post–processing system.

cessing will be required to analyze and correlate the data.

Preliminary lidar data processing (e.g., computing vortex circulation, core motion, wind profiles, etc.) is performed during real–time data gathering to allow quick–look analysis of the data and to facilitate data gathering. Post–processing techniques are currently being developed to generate vortex location, strength, motion and decay.

The meteorological processing combines data from the tower, profilers, rawinsondes, surface observations and other data. Techniques are being developed to generate profiles of temperature, winds and turbulence vs altitude. These profiles will then be used to compute the lapse rate, vertical wind shear and turbulence levels for each lidar measurement.

The aircraft beacon and flight plan data are processed to determine the aircraft type, ground speed, glideslope and position with respect to the runway. Winds data from the meteorological processing are combined with the ground speed to determine the airspeed of the generating aircraft. Weight data from airlines are combined with this information.

All of this information will be combined in a wake vortex data base which draws together the wake vortex, atmospheric and aircraft data for each event. The data processing is being designed to facilitate automated processing and dissemination of the wake vortex data set.

FIELD MEASUREMENTS

The 1995 field measurement program was conducted at the Memphis International Airport from July 31st through August 29th. Figure 6 depicts the locations of the runways and lidar sites. Also shown is the location of the meteorological site, including the 150' instrumented tower situated between the parallel runways.

There were the five lidar locations used during the 1995 deployment: Armory, TANG, Tchulahoma, Winchester and 27 Threshold. The Armory site was located 3.0 km south of the 36R runway touch down zone (TDZ) at the Tennessee National Guard Armory on Holmes Road. This was therefore an OGE site with aircraft passing over at nominally 150 m on approach. The TANG site, located at the Tennessee Air National Guard facil-

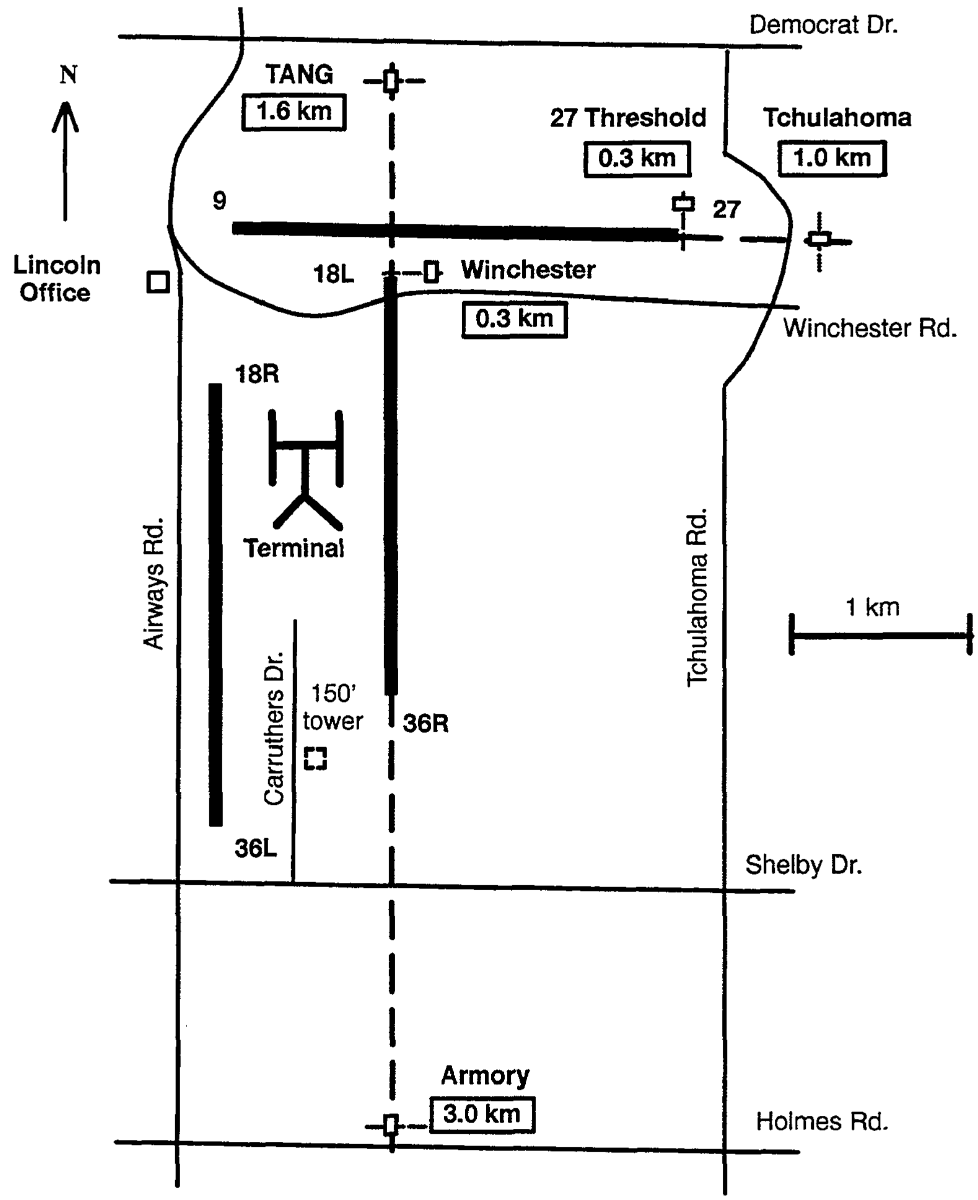

Figure 6. Memphis airport lidar sites with distances to touchdown zone for 1995 deployment.

ity, was 1.6 km north of the runway 18L TDZ and therefore an NGE site with the aircraft passing over at 80 m. The Tchulahoma site, located 1.0 km east of the runway 27 TDZ, was also an NGE site with the aircraft passing over at nominally 50 m. The two IGE sites were Winchester and 27 Threshold, located at the runway 18L and runway 27 thresholds, respectively. Aircraft passed over these sites at nominally 15 m (i.e., 0.3 km from the touch down zone).

Wake vortex measurements were made for 664 aircraft for 29 traffic pushes on 20 days as summarized in Table 1. Measurements were attempted for a greater number of days, but only those pushes for which useful data was gathered are listed here. The reason that data could not be gathered was generally because landings were occurring on a different runway than anticipated. It also should be noted that not all measurements were of equal quality and that a smaller number (perhaps 400) will be included in the final data set.

It can be seen from Table 1 that wake vortex data was gathered at a variety of sites and under a variety of atmospheric conditions. There were four different traffic pushes: morning (7–8 a.m.), noon (12–1 p.m.), evening (6–7 p.m.) and FedEx (11 p.m.–1 a.m.). There were five morning, eleven noon, eight evening and five FedEx pushes. Generally measurements were attempted for two pushes on days when the lidar van remained in the same site or one push on days when the lidar van was moved to a different site. There were five IGE, ten NGE and fourteen OGE pushes.

Table 2 summarizes the aircraft types sorted by time of day and distance from touchdown. The aircraft types observed included B747, MD11, DC10, A300, A310, B757, A320, B727, MD80, B737, DC9, F100 and a variety of smaller aircraft. A total of 73 heavy, 430 large jet and 161 other aircraft were observed during the field measurement period.

Table 1. Memphis 1995 Wake Vortex Case List (preliminary)

Date	Push	Location	Type	Time	Aircraft	Weather	Winds
8/6/95	Noon	TANG	NGE	1715–1830	24	Cloudy	WSW 8kts
'''''''	Evening	'''''''	NGE	2150–0020	26	Storm	SE 8 kts
8/7/95	Evening	TANG	NGE	2340–0020	14	Ptly cldy	SSE 6 kts
8/8/95	Noon	TANG	NGE	1700–1830	23	Clear	SSW 8 kts
'''''''	Evening	'''''''	NGE	2320–0030	15	Clear	SSW 5 kts
8/9/95	Evening	Winchester	IGE	2150–2300	5	Ptly cldy	S–E(GF)
8/10/95	Noon	Armory	OGE	1650–1710	1	Ptly cldy	W 5 kts
'''''''	Evening	'''''''	OGE	2300–2350	13	Mstly cldy	Light & var.
'''''''	FedEx	'''''''	OGE	0400–0600	37	Ptly cldy	Light SE
8/11/95	Noon	Winchester	IGE	1700–1820	5	Ptly cldy	Light SW
8/12/95	Morning	Armory	OGE	1220–1330	22	Clear	Calm
'''''''	Noon	'''''''	OGE	1750–1830	9	Ptly cldy	Light SW
8/14/95	FedEx	Armory	OGE	0325–0605	57	Clear	S 5 kts
8/15/95	FedEx	Armory	OGE	0300–0600	60	Clear	Light S
8/17/95	Noon	TANG	NGE	1900–1935	5	Clear	Calm
8/18/95	Morning	Tchulahoma	NGE	1230–1310	14	Clear	Calm
'''''''	Noon	'''''''	NGE	1700–1820	20	Clear	Calm
8/19/95	Morning	Tchulahoma	NGE	1230–1310	21	Hazy	Calm
'''''''	Noon	'''''''	NGE	1630–1815	23	Clear	Light & var.
8/23/95	Evening	Armory	OGE	2230–0015	20	Clear	N 10 kts
'''''''	FedEx	'''''''	OGE	0330–0625	55	Clear	NE 6–8 kts
8/24/95	FedEx	27 Threshold	IGE	0345–0545	49	Clear	ENE 5 kts
8/26/95	Morning	27 Threshold	IGE	1215–1320	21	Hazy	NNE 4–7 kts
'''''''	Noon	'''''''	IGE	1720–1810	16	Clear	ENE 11 kts
8/27/95	Evening	Armory	OGE	2330–0040	19	Clear	N 10 kts
8/28/95	Noon	Armory	OGE	1650–1920	18	Clear	Light NE
8/28/95	Evening	Armory	OGE	2225–0030	27	Clear	NE 10 kts
8/29/95	Morning	Armory	OGE	1230–1320	20	Clear	E 7 kts
8/29/95	Noon	Armory	OGE	1650–1850	25	Clear	E 7 kts
				Total Aircraft	664		

Table 2. Memphis 1995 aircraft types sorted by traffic push.

Date	Push	Loca-tion	Alt (m)	DC10 MD11	A300 A310	757	A320	727	DC9 MD80	Other	Total
8/26/95	Morning	27 Thr.	15				1		8	12	21
8/18/95	Morning	Tchula.	50			1	1		6	6	14
8/19/95	Morning	Tchula.	50				1	2	5	13	21
8/12/95	Morning	Armory	150			1	2	2	10	7	22
8/29/95	Morning	Armory	150			1	2	2	12	3	20
8/11/95	Noon	Winch.	15							5	5
8/26/95	Noon	27 Thr.	15			1		2	5	8	16
8/18/95	Noon	Tchula.	50			1		2	4	13	20
8/19/95	Noon	Tchula.	50			1	1	2	2	17	23
8/6/95	Noon	TANG	80			1	2	2	16	3	24
8/8/95	Noon	TANG	80		1	1	2	1	10	8	23
8/17/95	Noon	TANG	80				2	1	2		5
8/10/95	Noon	Armory	150		1						1
8/12/95	Noon	Armory	150				1		4	4	9
8/28/95	Noon	Armory	150			1	4	1	7	5	18
8/29/95	Noon	Armory	150								25
8/9/95	Evening	Winch.	15						1	4	5
8/6/95	Evening	TANG	80			1	3		15	7	26
8/7/95	Evening	TANG	80			1	3	2	8		14
8/8/95	Evening	TANG	80				2	2	7	4	15
8/10/95	Evening	Armory	150						7	6	13
8/23/95	Evening	Armory	150			1	3	1	8	7	20
8/27/95	Evening	Armory	150				3	1	14	1	19
8/28/95	Evening	Armory	150				1		13	13	27
8/24/95	FedEx	27 Thr.	15	4	1			42	1	1	49
8/10/95	FedEx	Armory	150	7	3			22		5	37
8/14/95	FedEx	Armory	150	10	9			31		7	57
8/15/95	FedEx	Armory	150	9	10	1		31	1	8	60
8/23/95	FedEx	Armory	150	9	7			31		8	55
				40	32	13	37	182	176	184	664

PRELIMINARY RESULTS

Analysis of the 1995 field measurements is still in progress, however, some preliminary results will be presented. The first results compare the wake vortex behavior for DC9 aircraft for the morning and noon pushes on 8/12/95, as shown in Figure 7. As seen from the figure, the vortices persist much longer for the morning push than the noon push. It can be seen that the vortices are generated well out of ground effect in regions with similar stability. However, the turbulence is much more substantial at noon than in the morning, suggesting that this caused the decreased vortex lifetime.

Figure 8 shows a similar comparison between two pushes at the same time of day but at different locations. Both were FedEx pushes but the 8/15 push was at the Armory and the 8/24 push was at the 27 Threshold site. The results are shown for B727 aircraft. It can be seen that the vortices measured at the Armory were generated well out of ground effect, while the vortices at 27 Threshold were generated in ground effect. It can be seen that the decay rate for the 27 Threshold aircraft was much higher than the Armory aircraft, suggesting that vortices generated in ground effect may be more short-lived. Note that the vortex generated in ground effect actually rises instead of sinking.

FUTURE WORK

The field measurement program is planned as a multi-year effort. Future work will concentrate on analysis of the Memphis '95 data set. Additional field measurements are also planned.

SUMMARY

A comprehensive field measurement program has been conducted for automated collection of wake vortex, atmospheric and aircraft data in an operational airport environment. Measurements were made for a one-month period during August, 1995 at the Memphis International Airport. Wakes were observed for over 600 aircraft during 29 traffic pushes. Data was gathered at five sites ranging from 0.3 km to 3.0 km from the runway touchdown zone during morning, noon, evening and FedEx pushes. A variety of aircraft types were observed, including heavy jets, large jets, turboprops and other aircraft. Preliminary results were presented comparing wake vortex behavior for different atmospheric conditions and aircraft types.

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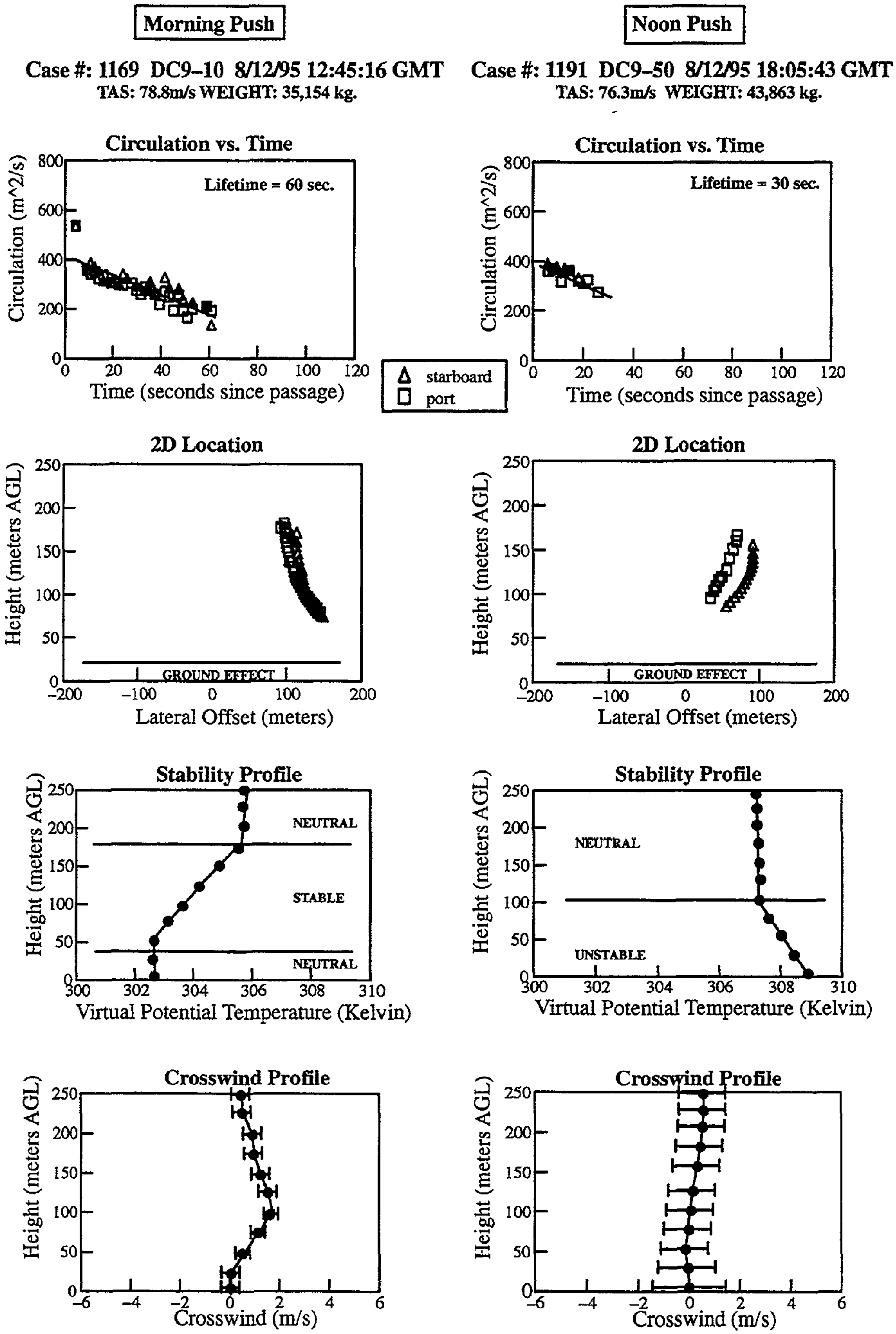

Figure 7. Wake vortex and meteorological data for morning and noon pushes on 8/12/95 at Memphis (note: atmospheric profiles interpolated manually from tower, lidar, sodar, profiler & sonde data).

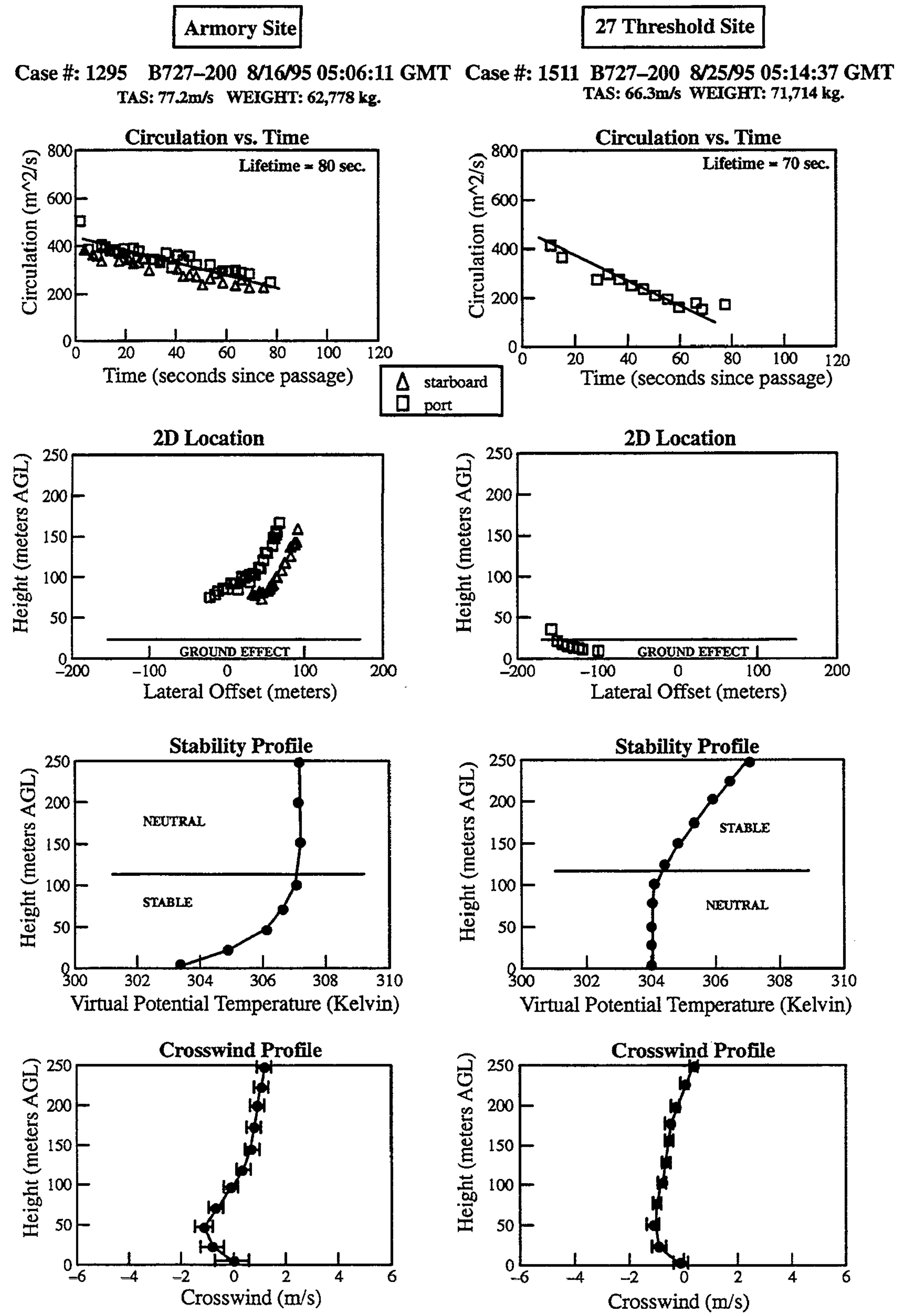

Figure 8. Wake vortex and meteorological data for FedEx pushes on 8/15/95 and 8/24/95 at Memphis (note: atmospheric profiles interpolated manually from tower, lidar, sodar, profiler and sonde data).