PLANETARY BOUNDARY LAYER MEASUREMENTS FOR THE UNDERSTANDING OF AIRCRAFT WAKE VORTEX BEHAVIOR [*][†]

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1.   INTRODUCTION

Significant restrictions currently exist in the air traffic control system due to the potential dangers from the wake vortices of leading aircraft. Eliminating or reducing these restrictions would yield increased capacity, decreased delays and significant cost savings (Evans & Welch, 1991). The current wake vortex restrictions are normally very conservative, but may be insufficient under certain transient atmospheric conditions.

Since the late 1960s, many wake vortex measurements have been made in an attempt to observe, and understand wake vortex behavior. However, many of these experiments were either not accompanied by suitable atmospheric measurements, or they did not measure a wide range of aircraft types. Suitable atmospheric measurements are important because wake vortex behavior is thought to be strongly influenced by atmospheric conditions. Greene(1986) theorized that atmospheric turbulence, and thermal stratification affects the decay rate of the vortex. Recent modeling results have shown that vortex decay and descent rates are affected by vertical shear, while vortex motion is closely linked to atmospheric winds.

The wake vortex field measurement program at MIT Lincoln Laboratory is sponsored by NASA Langley Research Center, in cooperation with the FAA. The major focus of the program is to make simultaneous measurements of wake vorticies generated by aircraft landing at major airports with the atmospheric conditions associated with the vortices. To do this, Lincoln Laboratory has fielded a collection of meteorological instruments, and a CO_2 CW (Continuous Wave) lidar. To date, this system has been deployed at the Memphis International Airport during the fall of 1994 and the summer of 1995. In the future the system will be deployed at the Dallas/Fort Worth International Airport.

During the two one–month field measurements in Memphis, TN. almost 600 aircraft wakes were recorded by the CW lidar, for comparison with the atmospheric measurements. Of these 600 measurements, almost 100 of the measurements were from heavy aircraft, and 13 were from Boeing 757 aircraft. The remainder were primarily Boeing 727, McDonnell Douglas DC9 and MD80. All aircraft measured were on final approach with true air speeds between 60 and 80 meters per second.

2.   WAKE VORTEX SYSTEMS

Wake vortex measurements were performed by a van–mounted $10.6\mu m$ CO_2 Coherent CW lidar (Heinrichs et. al. 1995, 1996). The lidar typically was situated underneath the flight path of aircraft approaching the runway. Figure 1 shows the location of the lidar sites relative to the Memphis International Airport. Measurements were made from four sites around the airport; 36R_armory, 18L_tang, 27_tchulahoma, and 27_threshold. Each of these sites is situated at different distances from the touch down zone, so that vortices are measured at different initial altitudes.

3.   ATMOSPHERIC SYSTEMS

Atmospheric data were obtained from several sources. Some of these data sources are operational NWS or FAA systems, such as the Terminal Doppler Weather Radar (TDWR), the Automated Surface Observation Stations (ASOS), and the Low Level Windshear Alert System (LLWAS). However, most data sources were acquired and installed at the Memphis International Airport by Lincoln Laboratory or NASA Langley. These systems included a 150' instrumented tower, an atmospheric profiler, a Radio Acoustic Sounding System (RASS), sodars, an instrumented aircraft, and CLASS rawindsondes. Most of these instruments, installed by Lincoln Laboratory and NASA, were located between the two north–south runways at the southern end of the airport. The location is shown in figure 1. Each of these systems will be described in this section.

The 150' instrumented tower consists of two types of sensor packages: SAVPAKs and FLUXPAKs. Five SAVPAKs were mounted on the tower at 5, 10, 20, 30, and 42 meters to measure the standard atmospheric variables (temperature, humidity, and horizontal winds) at a 1 Hz sample rate. Two FLUXPAKs were mounted on the tower at 5 and 40 meters to measure the surface fluxes. The FLUXPAK consisted of a sonic anemometer sampling at a 10 Hz rate. A krpyton hygrometer was also located at the 5 meter altitude to measure the water vapor flux near the surface. The data were processed into one minute averages.

At the base of the 150' tower were located several soil sensors, a rain gauge, and a barometer. Although these data sources will not be used for direct comparison to wake vortex behavior, the data provided is useful for atmospheric column models. The soil sensors consisted of a soil temperature probe, as well as a soil moisture probe sampling at a 1 Hz rate. A total hemispherical radiometer, located at the base of the tower measured the incoming and outgoing radiation. The
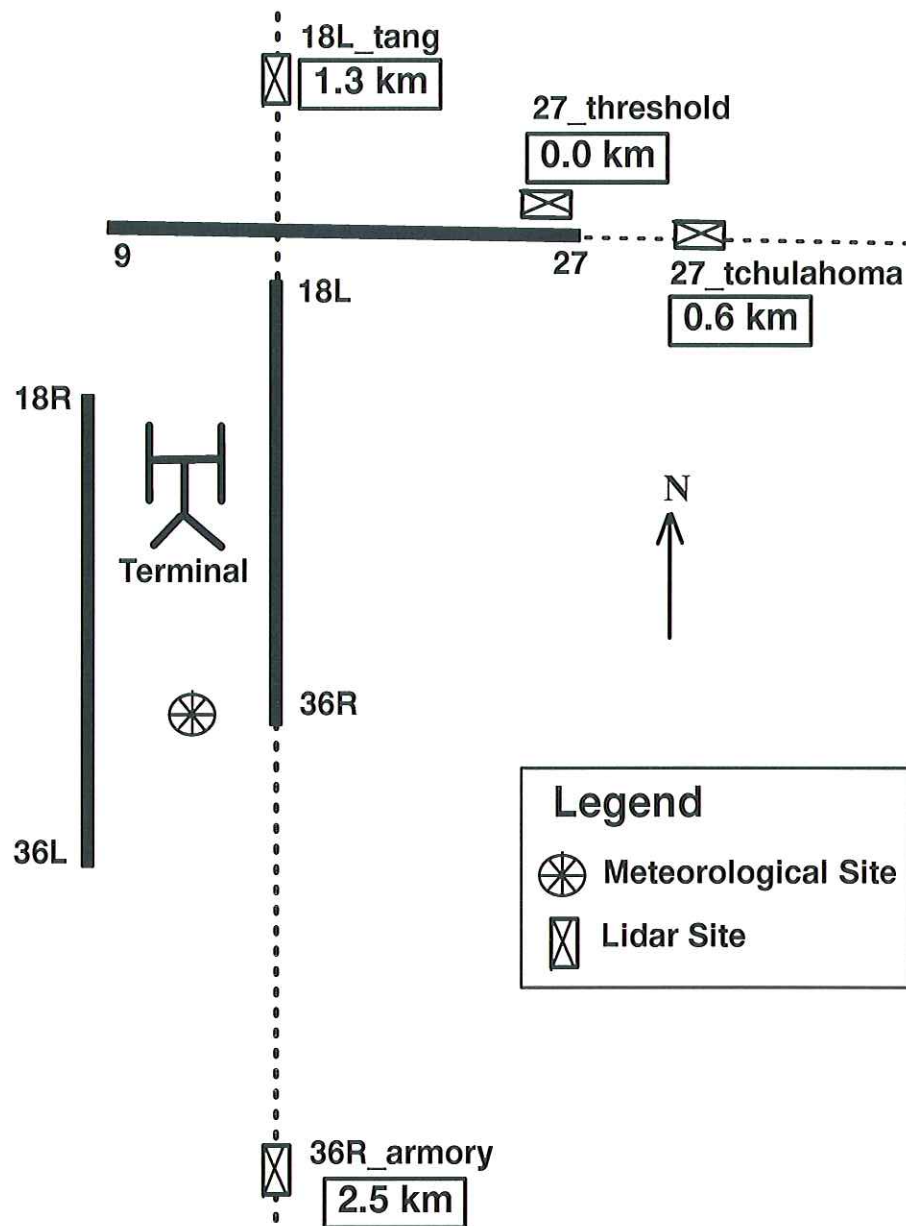
Figure 1. Location of Meteorological and Lidar Instrumentation at the Memphis International Airport.

barometer, and rain gauge were located at a 2 meter height. These data were also averaged for one minute.

To measure the atmosphere above the tower height, several remote sensing instruments were installed, periodic rawindsonde launches were performed, and an instrumented aircraft was operated by NASA Langley. The remote sensing instruments consisted of a profiler/RASS, and a sodar, both located within 600 feet of the 150' tower.

The NASA Langley Radian LAP–3000 profiler/ RASS was installed at the meteorological site. The profiler is capable of measuring winds from 100 meters to 5 kilometers with a vertical resolution of 100 meters, and a 30 minute update rate. The profiler sampled the wind data for 25 minutes, allowing five minutes for RASS operations.

During the two deployments, three different sodars were used to measure the winds in the lower altitudes. During the 1994 deployment, a Remtech PA2 was operated at a 10 minute averaging period, and a vertical resolution of 20 meters. The Remtech PA2 performed very well in the high noise environment of the airport. In 1995, a Aerovironment M2000 was located at the Lincoln/NASA meteorological site. The M2000 measured winds from 40 to 500 meters in 10 meter increments. The M2000 was set to use a ten minute averaging period. Also in 1995, an Aerovironment M4000 mini–sodar was operated by the DOT Volpe Center at the 27_tchulahoma site. The M4000 measured winds from 5 to 200 meters in five meter increments, with an averaging period of one minute. The M2000 performed poorly in the high noise environment

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of the airport, and experienced interference with the Radian RASS. However, the M4000 worked well in the high noise environment.

During the deployments, rawindsonde launches were performed before and after the lidar data collection periods from a small shelter 500' south of the instrumented tower. Typical lidar data collection periods ranged from 90 minutes to 180 minutes depending on air traffic activity in the Memphis area. All launches were coordinated with the Memphis ATC facility. The rawindsonde used the Vaisala RS–80 Loran based sonde, and communication and processing equipment designed and operated by the University of Massachusetts at Lowell Meteorology Department. The sonde provided data in 2–3 second intervals, and a 10 second average was computed from these measurements for the temperature, pressure, and humidity data which corresponded to an altitude interval of roughly 50 meters. Due to resolution limitations of the Loran system, wind data were averaged for 60 second intervals, output at 10 second periods.

During the deployments, meteorological data from the tower, sodar, profiler/RASS, and rawindsonde were stored in ASCII files on disk. Each evening the data was transferred to Lincoln Laboratory's host computer, and made available via ftp for NASA Langley to download. During post–processing, all meteorological data is quality edited prior to comparison with vortex behavior data.

Finally, during each of the deployments, NASA Langley Research Center operated an instrumented aircraft to measure the atmospheric conditions on the approach and departure corridors to the airport. The aircraft measured, temperature, pressure, winds, humidity, as well as many aircraft parameters, such as position, altitude, roll, etc. Data collected from the aircraft along the approach or departure path was averaged in to vertical bins of 10 meter resolution. Depending upon the flight path chosen by the air crew and ATC, the aircraft profiles ranged from the surface to 300 meters above the ground level.

4.   ATMOSPHERIC DIAGNOSIS

In order to compare the atmospheric data with the wake vortex behavior, atmospheric profiles must be created from all of the available data sources. These profiles must have enough vertical resolution to demonstrate the fine scale features that may influence wake vorticies. Also, the profiles must have sufficient time resolution to detect noticeable changes in vortex behavior during transitions times. However, it is important that artificial features are not created in the profiles that do not exist in the real atmosphere.

To accomplish this task, a truthing tool was developed with the Interactive Development Language (IDL) to display all of the available meteorological data, and allow the human truther to point–and–click at various values and create a profile. It was discovered that in order for a human truther to develop faith in the profiles he/she is creating, that the truther needs to have enough information about the time history of the input data sources, as well as information about the future changes in the atmosphere. This was complicated by the various update rates of the sensors.

Wake vortex modelers at NASA Langley Research Center determined that in order to fully understand the effects of the atmosphere on wake vortex behavior, the atmospheric variables must be resolved down to ten meters vertical resolution with a five minute update rate. With the large time averaging of the profiler/RASS, it was decided to perform time interpolation on these input data sources. A simple linear interpolation was used to estimate the parameters in between the time steps of these data sources.

The rawinsonde data provided special problems for the creation of the profiles. First, the launches only occurred at the beginning and end of the data collection periods. Second, the rawindsonde reports the data in 10 second time steps, which do not correlate to fixed altitudes. Finally, the rawindsonde vertical resolution is much greater than the 5 meters required by the wake vortex modelers. Interpolation was performed to the rawindsonde data in both time and height to acquire the desired vertical resolution of 10 meters, and time resolution of five minutes.

Figure 2 is a plot of the data sources available for August 16, 1995, at 05:20Z, and the human truthed profile shown by the continuous line. During the truthing process, the meteorologist must consider such things as averaging period of the different sensors, sensor quality and reliability, and influences of the local terrain. In this case, it is believed that the tower best represents the temperature and humidity from the surface to 50 meters, and the rawinsonde, after interpolation, best represents these variables from 50 meters to 400 meters. The instrumented aircraft supports the structure of the atmosphere, however, there appears to be a bias between the aircraft and sonde data. The RASS is believed to be providing accurate data above 300 meters, but below this altitude, the sensor is questionable. The winds profile, in this case, is believed to be best represented by the tower near the surface, with an excellent agreement between the aircraft, and the profiler above 50 meters.

5.   COMPARISON OF WAKE VORTEX AND ATMOSPHERIC DATA

The next step in the analysis process is to begin comparing the wake vortex data, collected by the CO_2 lidar, and the human truthed profiles. Figure 3 is a collection of plots to help understand the influence of the meteorology on the vortex pair. The figure shown, is from an Airbus A310 aircraft crossing over the lidar at 05:20:53Z. The meteorological data from figure 2 was used to create the human truthed profiles shown in figure 3. This case is representative of the roughly 100 heavy aircraft measured during the deployment.

On the left side of the figure, the vortex parameters are plotted as a function of time. The top left plot, shows the lateral position (Y–location) of the aircraft starboard and port vortices relative to the lidar van. The port and starboard vortex position and strength information is for a lidar scan in a plane perpendicular to the flight path. The aircraft crossed the lidar at approximately 85 meters, to the right side. The vortices slowly moved towards the lidar, or in a negative direction. The
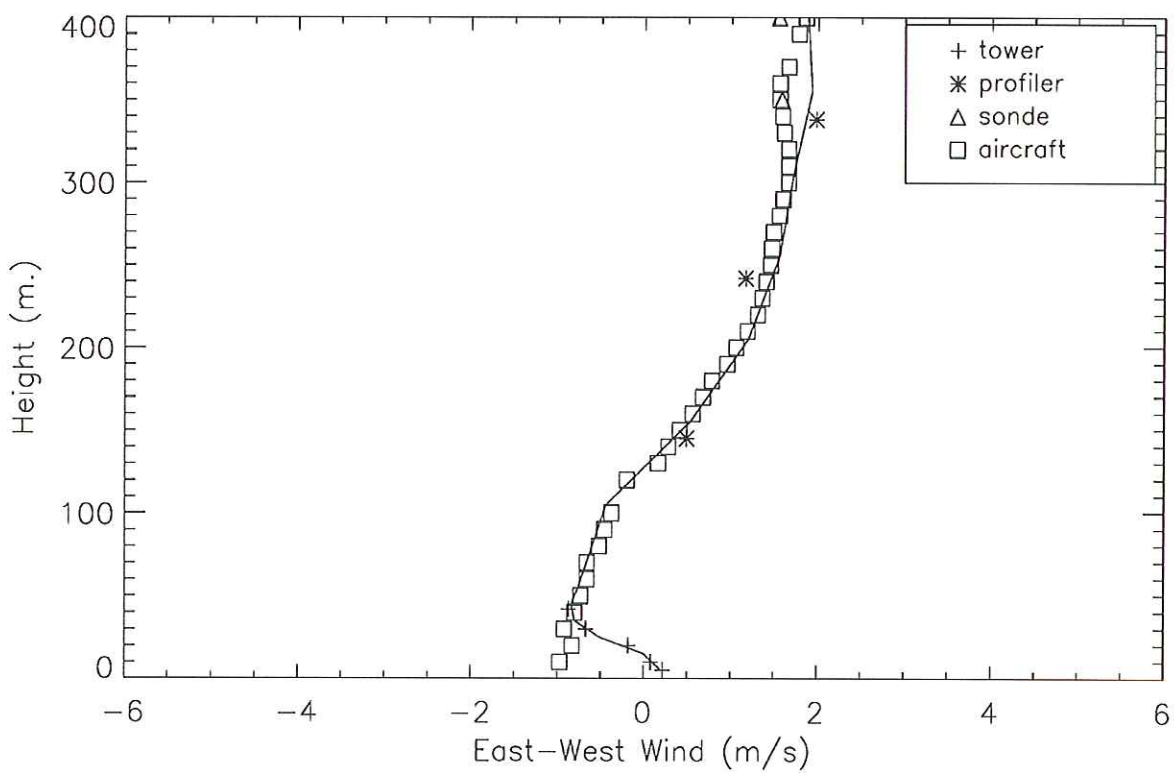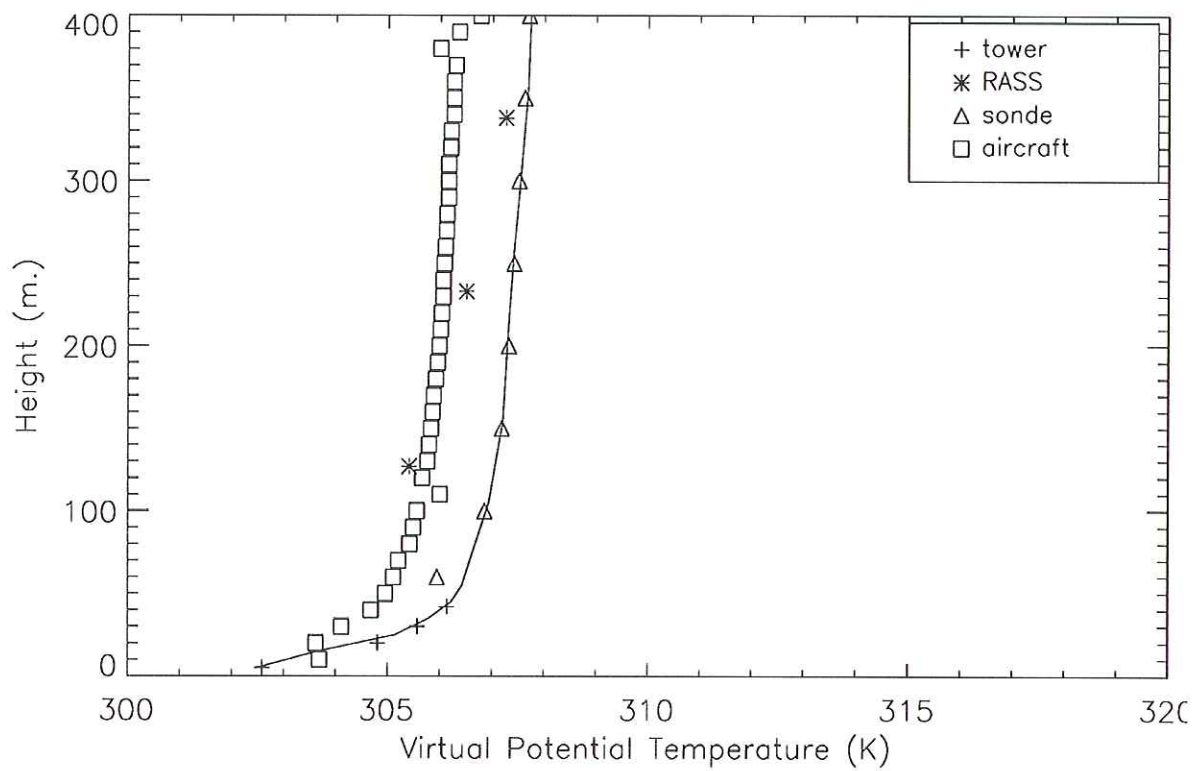
Figure 2. Meteorological data collected on August 16, 1995 at 05:20Z, and the human truthed profile.
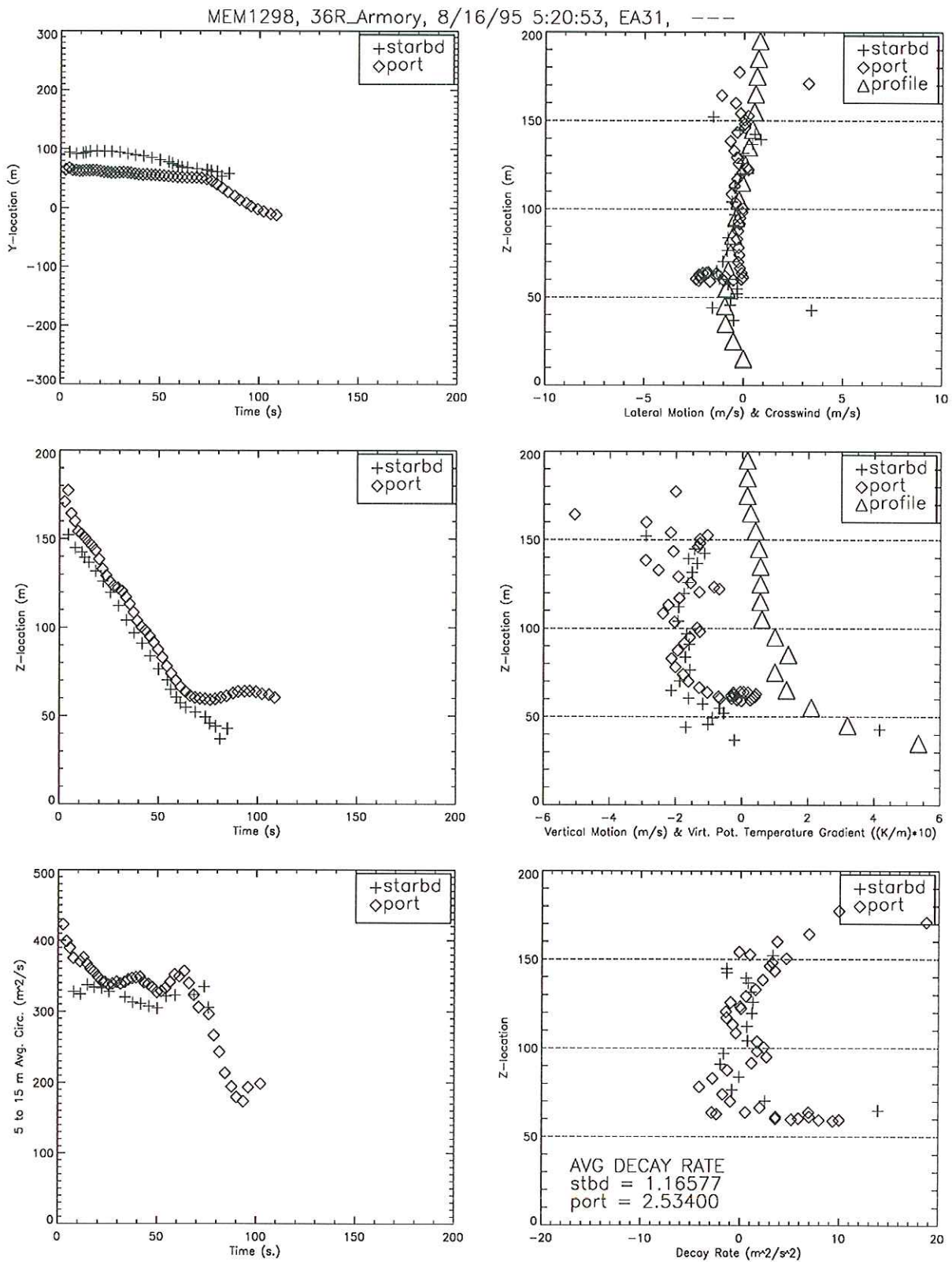
Figure 3. Comparison of Wake Vortex data and meteorological data for an Airbus A310 on August 16, 1995 at 05:20Z at the Memphis International Airport.

middle–left plot, shows the altitude (Z–location) of the vortices relative to the lidar. The aircraft crossed the lidar at approximately 160 meters. The vortices descended at roughly a constant speed of 1.8 m/s. Finally, the bottom–left plot shows the strength estimates for the vortices. The strength is computed as the average circulation from 5 meters to 15 meters from the center of the vortex. The initial theoretical circulation for this aircraft, given a wingspan of 43.9 meters, a weight of 112,493 kg., and a true air speed of 74.9 m/s was 308 m^2/s. The theoretical circulation assumes an isolated vortex. The increased circulation estimates from the plot is due to the presence of the second vortex.

On the right side of the figure, the vortex behavior, and atmospheric conditions are plotted as a function of height. The top–right plot shows the crosswind component and the lateral motion of the vortex. At this time, the crosswind component was very weak, with winds ranging from zero near the ground, to a negative crosswind of 1 m/s at 40 meters, to a positive crosswind of 1 m/s at 200 meters. The most important observation from this data, is that the vortex motion while out of ground effect is closely linked to the crosswind component of the ambient wind. This would suggest that an accurate understand of the crosswind component, may provide accurate predictions of the vortex position relative to the runway centerline.

The middle–right plot shows the virtual potential temperature gradient and the vertical motion of the vortices. From this, it can be seen that there is a neutrally stable layer above 100 meters AGL, with a stable layer below 100 meters, increasing in strength closer to the ground. Both the port and starboard vortex descended at an initial descent rate of 1.8 m/s. The port vortex slowed, then bounced at approximately 60 meters above the ground. A strong stable layer was present at this altitude, and may have been a factor in the decrease in descent rate.

The bottom–right plot shows the decay rate of the vortices. The average decay rate of the port vortex was 2.5 m^2/s^2, however, the vortex decayed rapidly when it descended into the stable layer. This would suggest that the descent into the stable layer affected the decay rate of the vortex. In this case, the negative decay rates (vortex growth) is believed to be due to measurement error.

6.   FUTURE WORK

After two successful field deployments at the Memphis International Airport, the instrumentation will be moved to the Dallas/Fort–Worth International Airport during the winter of 1997. At DFW the suite of meteorological instruments will be expanded to include multiple sites on airport. Additionally a small 30' instrumented tower will be added, as well as two more sodars owned and operated by Lincoln Laboratory or NASA. Other possible improvements include the addition of a Remtech RASS, and improvements in current instrumentation systems. Several operational NWS and FAA radars are present in the DFW area that can be used to further enhance the atmospheric profiles.

At the DFW airport, the Lincoln Laboratory Wake Vortex Program will be working in conjunction with the NASA Langley Aircraft VOrtex Spacing System (AVOSS) program to predict adaptive aircraft spacing from in–situ measurements. This will include providing all of the atmospheric data to the AVOSS program in realtime, as well as the measured wake vortex position and strength estimates.

Analysis of the Memphis data will continue with an emphasis on generating bulk statistics from all of the data cases collected.

7.   SUMMARY

This paper described a comprehensive method of collecting meteorological and wake vortex data in an operational airport environment. A method to analyzing the meteorological data for creation of atmospheric profiles was discussed. An example of the meteorological and wake vortex data was shown. Results for this case show that the lateral motion of the wake vorticies is closely linked to the crosswind component from the atmospheric winds. Also, the data shown supports the theory that the descent rate and decay rate of the vortex can be influenced by the atmospheric stability. Future work will include more detailed analysis, as well as moving the instrumentation suite from Memphis to the Dallas/Fort–Worth International Airport in the winter of 1997.

8.   REFERENCES

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