JET BLAST TEST PROGRAM

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FINAL REPORT

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DEFINITIONS AND ACRONYMS

Acoustic Sensor - A microphone.

Ambient Wind - The background wind.

Ambient+4-knots Threshold - A value of wind speed. 4 knots above the ambient wind.

Ambient+10-knots Threshold - A value of wind speed, 10 knots above the ambient wind.

CATER - Collection and Analysis of Terminal Records, a process of tabulating aircraft arrival and departure data.

Crosswind - That component of wind velocity blowing perpendicular to the runway.

CS9000 Campbell-Scientific Data Logger – A high speed data acquisition system.

DARC – Data Acquisition Retrieval System.

DAS – Data Acquisition System.

Data File - A file of data that may contain a number of aircraft run files.

DSDS – Data Storage and Display System.

FAA - Federal Aviation Administration.

Headwind - That component of wind velocity blowing parallel to the runway and into the nose of an aircraft.

Jet Blast Duration Time - The length of time from application of takeoff power by the pilot until the 1-second running average of the measured maximum values of jet blast velocity fall below some measurement threshold. The thresholds used during this study were 4 knots and 10 knots above ambient headwind.

Jet Blast Profile - The time history of the value of the Maximum Peak Jet Blast velocity for a single aircraft as measured at the Windline.

Maximum Jet Blast Velocity - The highest value of jet blast velocity measured at the Windline at each data acquisition time increment (0.1 second) for a single aircraft over the entire run file.

DEFINITIONS AND ACRONYMS (Cont.)

Met Station - The meteorological station which provides a independent measure of wind speed and direction at a location away from the Windline.

Mini-SODAR - A sonic system that measures wind speed and direction as a function of altitude up to approximately 200 meters.

Outlier - Aircraft whose jet blast duration time exceeds 90 seconds.

Peak Jet Blast Velocity - The highest value of jet blast velocity measured during a single aircraft departure.

Propeller Anemometers - A wind speed measurement device using Gill propeller anemometers.

Run File - All the data acquired relating to a specific aircraft departure.

RVMD – Remote Video Monitoring Display.

RWY – Runway.

Sonic Anemometers - A compact wind speed and direction measurement device using an ultrasonics signal between a transmitter and receiver in open air.

TWY – Taxiway.

VCC – Video Capture Computer.

VCS – Video Capturing System.

VMS – Video Monitoring System.

Volpe Center - Volpe National Transportation Systems Center.

Windline - The array of seven 50-foot poles each equipped with eight propeller anemometers and used for measuring wind speed in a direction perpendicular to the plane of the anemometer array. The anemometers are spaced 5 feet apart staring at the 10-foot height.

FOREWORD

The Jet Blast Test Project was undertaken by the Volpe Center to support the effort of the Port Authority of New York and New Jersey to safely increase efficiency at the John F. Kennedy International Airport (JFK).

This project was designed to measure the intensity and duration of the jet blast from Heavy aircraft departing RWY 13R in an effort to address specific jet blast constraints at the RWY 31L/4R area of the airport as stated in Order JFK7110.67D.

The authors realize that this project would not have been possible without the intensive effort of Kevin Clark, Yan Zhang, and Melanie Soares of the Volpe Center and Leo Jacobs, David Hazen, and Ralph Hoar of System Resources Corporation. We also wish to acknowledge the enthusiastic support of Julio Pereira, the Jet Blast Program Manager for the Port Authority of New York and New Jersey, John Farley of JFK Operations and also the Port Maintenance Department at JFK for their assistance in preparing the Test Site.

EXECUTIVE SUMMARY

Operational rules, as described in Order 7110.67D, have been implemented at Kennedy International Airport (JFK) to protect Large and Small aircraft arriving on RWY 4R against the potential jet blast hazards produced by a departing Heavy aircraft on RWY 31L. The current operational procedures require Heavy aircraft departing from RWY 31L to hold in position if an aircraft landing on RWY 4R is within 5 nautical miles from the RWY 4R threshold. Depending upon the arriving aircraft's landing speed, the departing aircraft may have to hold in position for as much as 120 seconds. This rule is intended to ensure that the arriving aircraft does not encounter the jet blast from the departing Heavy aircraft.

The JFK Jet Blast Project was intended to investigate jet blast behavior and to determine the actual length of time necessary for jet blast dissipation.

In May, 1999, under sponsorship of the Port Authority of New York and New Jersey with the cooperation of the Federal Aviation Administration (FAA), the Volpe Center began a Jet Blast measurement test program at JFK. The purpose was to determine how quickly jet blast effects decay over a distance equivalent to the separation of the departure point of RWY 31L from the centerline of RWY 4R, a distance of 760 feet. In June/July 1999, the Volpe Center installed a wind velocity measurement system (Windline) comprising an array of anemometers on seven 50 foot poles perpendicular to and centered on the extended centerline of RWY 13R at a distance of 760 feet from the end of RWY 13R. The anemometer poles were spaced 55 feet apart. Eight anemometers were installed on each pole at heights from 10 feet to 45 feet and spaced 5 feet apart.

The data collection period lasted from July 29, 1999 to October 31, 1999. The data collection took place remotely from the Volpe Center. The data consisted of aircraft identification, video recordings of the departing aircraft, and data files produced from the array of anemometers. All data collected were stored both at the Jet Blast Test Site and at the Volpe Center.

The primary objective of the analysis was to determine the duration of the jet blast from its creation at the aircraft until it decayed to some prescribed threshold at the Windline.

Jet blast data were captured and analyzed for 636 aircraft. The data for an additional 229 departures were not captured because crosswind conditions caused the jet blast to be displaced beyond the end of the Windline. Of the 636 aircraft used for the analysis, 114 were Boeing 747s and 397 were Boeing 767s.

Summary of Results

The results of this Jet Blast Test Program indicate that:

- The jet blasts from 100% of the aircraft analyzed decayed to within 10 knots of ambient headwind within 50 seconds;

- The jet blasts from over 100% of the aircraft analyzed decayed to within 4 knots of ambient headwind within 70 seconds;

- The size of the jet blast wind cross section at the Windline distance would allow use of shorter instrumented poles to monitor jet blast peak velocities.

- Taxiing aircraft that move into the departure hold position on the runway between 20 seconds and 60 seconds after the start of roll of the lead aircraft, will cause light jet blast turbulence at the 760-foot distance.

- Aircraft that cycle engines while holding at the runway departure position, will cause light jet blast turbulence at the 760-foot distance.

Conclusion

The test data show that the current procedure of holding Heavy departures on RWY 31L when arriving Large and Small aircraft are less than 5 nautical miles from RWY 4R threshold should be reviewed in an effort to reduce current separations.

Recommendations

- Procedures Modification – Based on the results of this test program, start a phased separations reduction program to 3 nautical miles, in steps of 1 nautical mile, while monitoring the wind field at the 31L/4R area.

- Install wind measurement instrumentation at the RWY 31L/4R area for measuring RWY 4R crosswinds to an altitude of 75 feet. The instrumentation could be a compact device similar to a Mini-SODAR (Sound Detection and Ranging) instrument that would not intrude into the FAR Part 77 surfaces or an array of monitoring sonic anemometers mounted on short poles. During actual Heavy departures from RWY 31L, both ambient wind and jet blast would be monitored in conjunction with Large and Small aircraft arrivals at RWY 4R under current and reduced separation rules.

- Encounter Simulation - Perform a simulation of aircraft encounters with jet blast under conditions similar to the 4R/31L runway configuration at JFK and use the simulation results and the collected jet blast database to explore further possible reductions in departure hold times.

1. INTRODUCTION

As airport traffic density increases, the need to safely improve airport efficiency has become an important issue for airport operators, airlines, and the Federal Aviation Administration (FAA). A particular problem exists when the threshold of a runway being used for arrivals lies on the extended centerline and in the near vicinity of a perpendicular departure runway. In some cases, under this type of configuration, a Heavy aircraft departure may be delayed so an arriving Small or Large aircraft will avoid a jet blast encounter. The applicable document is Order JFK7110.67D.

In order to determine whether some of the Heavy departure delay may be safely recovered under a particular runway configuration at Kennedy International Airport (JFK), a test program was conducted by the Volpe National Transportation System (Volpe Center) for the Port Authority of New York and New Jersey to measure jet blast duration times.

This report presents details of the test-site layout, data collection and data processing procedures and the results from the jet blast data collected from August 1999 to October 1999. Section 2 provides background information. Section 3 describes the technical approach taken to collect data. Section 4 describes the data collection and data processing procedures. Section 5 provides a discussion of the results of the data. Section 6 discusses modeling and characterization and Section 7 provides conclusions and recommendations.

2. BACKGROUND

2.1 JFK RWY 31L/4R OPERATIONAL PROCEDURE

At JFK Airport, Heavy aircraft departing on RWY 31L are held in position if Small or Large aircraft arriving on RWY 4R are within 5 nautical miles from the threshold of RWY 4R.

The distance between the threshold of RWY 31L and the centerline of RWY 4R is approximately 760 feet and the RWY 31L extended centerline crosses RWY 4R approximately 700 feet from its threshold as shown in Figure 2-1. Depending upon the heavy aircraft's arrival speed, this may cause the departing aircraft to be held in position for a period of at least 120 seconds. This departure delay is employed in order to prevent jet blast of the Heavy aircraft departing RWY 31L from interfering with the Small or Large aircraft arriving on RWY 4R.

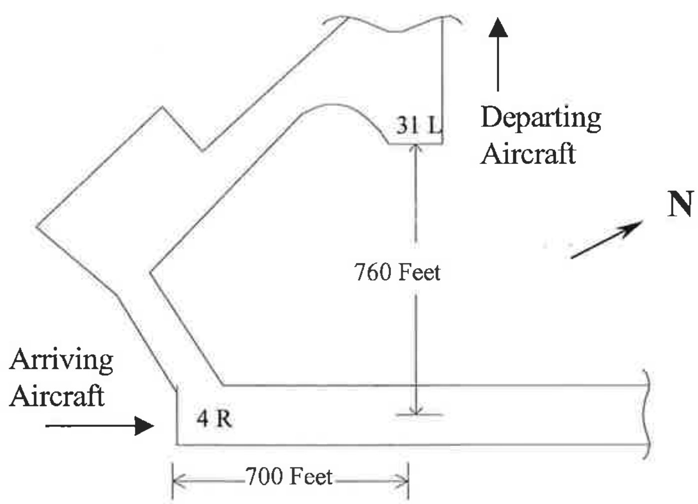


Figure 2-1. RWY 31L/4R Region at JFK

2.2 JET BLAST TEST I

In November 1996, the Volpe Center conducted preliminary jet blast testing at JFK Airport funded by the FAA. Since it was not feasible to install an instrumentation system at the RWY 31L/4R area to make jet blast duration measurements, a test site was established on the approach path to RWY 13R. The Windline system deployed consisted of three fiberglass poles, 30 feet in height and spaced 55-feet apart with the middle pole located on the extended RWY 13R centerline, with headwind propeller anemometers located at the 7-, 14-, 21-, and 28-foot positions on each pole. The poles were located 760 feet from the end of RWY 13R which corresponds to the distance of the RWY 4R centerline from the end of RWY 31L. The results obtained and presented in a Draft Final Report[1] to the FAA and the Port Authority of New York and New Jersey were as follows:

- Peak jet blast velocities measured at the Windline were less than 50 knots.
- Jet blast duration, defined as the length of time for the jet blast to return from its maximum value to within 10 knots of the ambient headwind on RWY 4R, was on the order of 50 seconds or less.
- Variations in the time between a departing pilot's receipt of a clear-to-depart signal from the tower and the beginning of the takeoff roll were significant.
- Ambient wind conditions had a significant impact on the jet blast magnitude, duration, and location.

Based on the initial data, the following recommendations were made:

- The Windline array of three anemometer poles was inadequate for complete and efficient assessment of the jet blast characteristics. At least two additional poles should be added to each end of the current array.
- The initial data indicated that for some aircraft, the current 28-foot anemometer poles were not capturing the maximum jet blast winds. A portable 50-foot tower should be used to establish the true maximum jet blast winds and the height at which they occur.

The results of the testing were presented to the FAA and the Port Authority of New York and New Jersey. Based on the conclusion that the prospects were good for reducing delays at the RWY 31L/RWY 4R area, the Port funded the Volpe Center to conduct a more comprehensive jet blast test program implementing the instrumentation improvements recommended in the earlier report.

3. JFK JET BLAST INSTRUMENTATION

The Jet Blast Test configuration comprised two separate but linked test sites. The Windline and data acquisition instrumentation were located at the JFK Jet Blast Test Site. Monitoring and control of the data acquisition process were conducted remotely from the Volpe Center Remote Control Site.

3.1 JFK JET BLAST SITE

3.1.1 JFK Jet Blast Test Site Location

The Jet Blast Test Site was established at a location 760 feet from the end of RWY 13R since it was not feasible to install an extensive instrumentation system at the RWY 31L/4R area. The location of the Jet Blast Test Site at JFK is depicted in Figure 3-1.

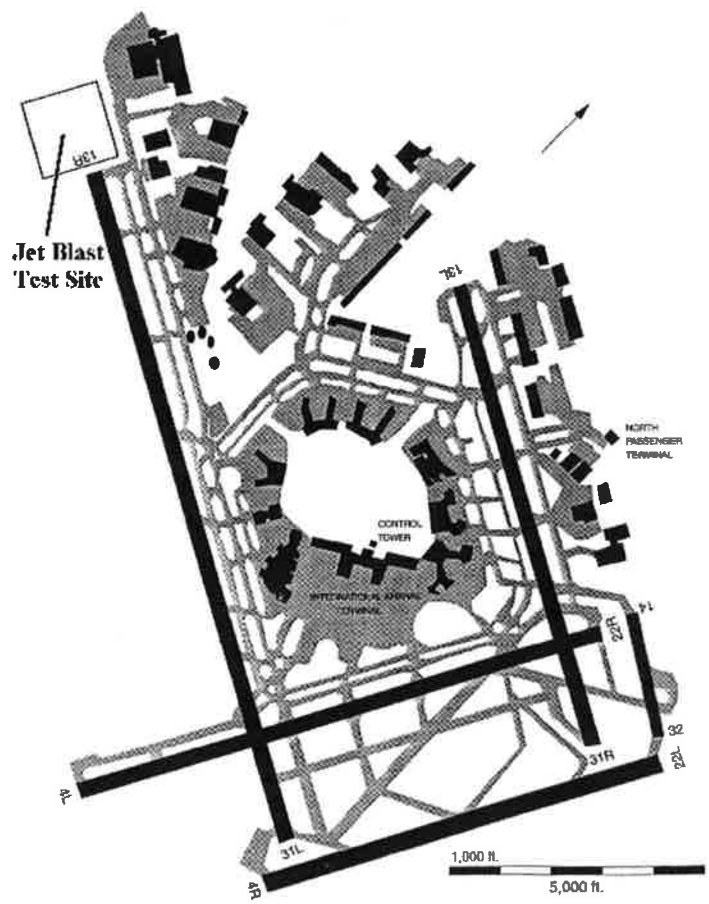


Figure 3-1. Jet Blast Test Site Location

3.1.2 JFK Jet Blast Test Site Instrumentation

The JFK Jet Blast Test Site consisted of the Windline and the Data Acquisition System. Figure 3-2 is a schematic of the JFK Jet Blast Test Site.

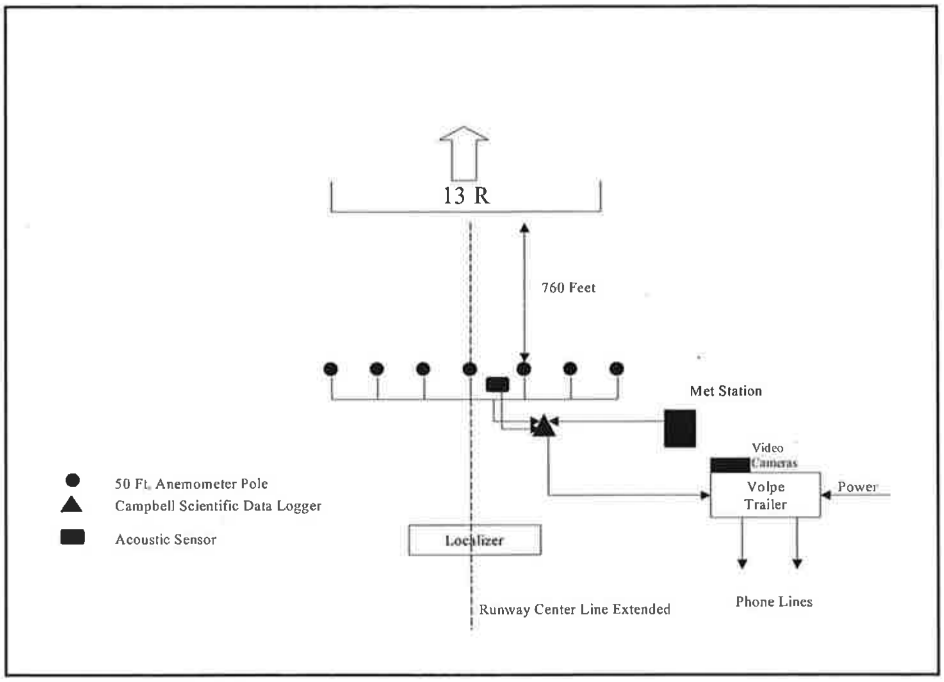


Figure 3-2. JFK Jet Blast Test Site Schematic

3.1.3 Windline

The instrumentation used to collect jet blast data consisted of propeller anemometers, an acoustic sensor, a meteorological station, and a data acquisition system. The primary sensors used to collect data were propeller anemometers. The Windline consisted of seven 50-foot fiberglass poles, spaced 55-feet apart and centered on and perpendicular to the RWY 13R extended centerline. For jet blast measurement, each pole was equipped with eight propeller anemometers spaced 5 feet apart starting at the 10-foot height and were aligned parallel to the RWY 13R extended centerline to measure head wind and tail wind. Each pole was fitted with a red obstruction light mounted on top. In order to obtain information on the effect of ground plane reflections of jet blast winds, the end and centerline poles were equipped with additional anemometers for measurement of vertical wind. Anemometers for measuring crosswind were mounted on the end and center poles. The vertical wind and crosswind anemometers were mounted at the 27.5-foot height. Meteorological data, ambient wind speed and direction were obtained from a Meteorological (Met) Station placed off to the side of the Windline. Figure 3-3 is a photograph of the JFK Jet Blast Test Site.

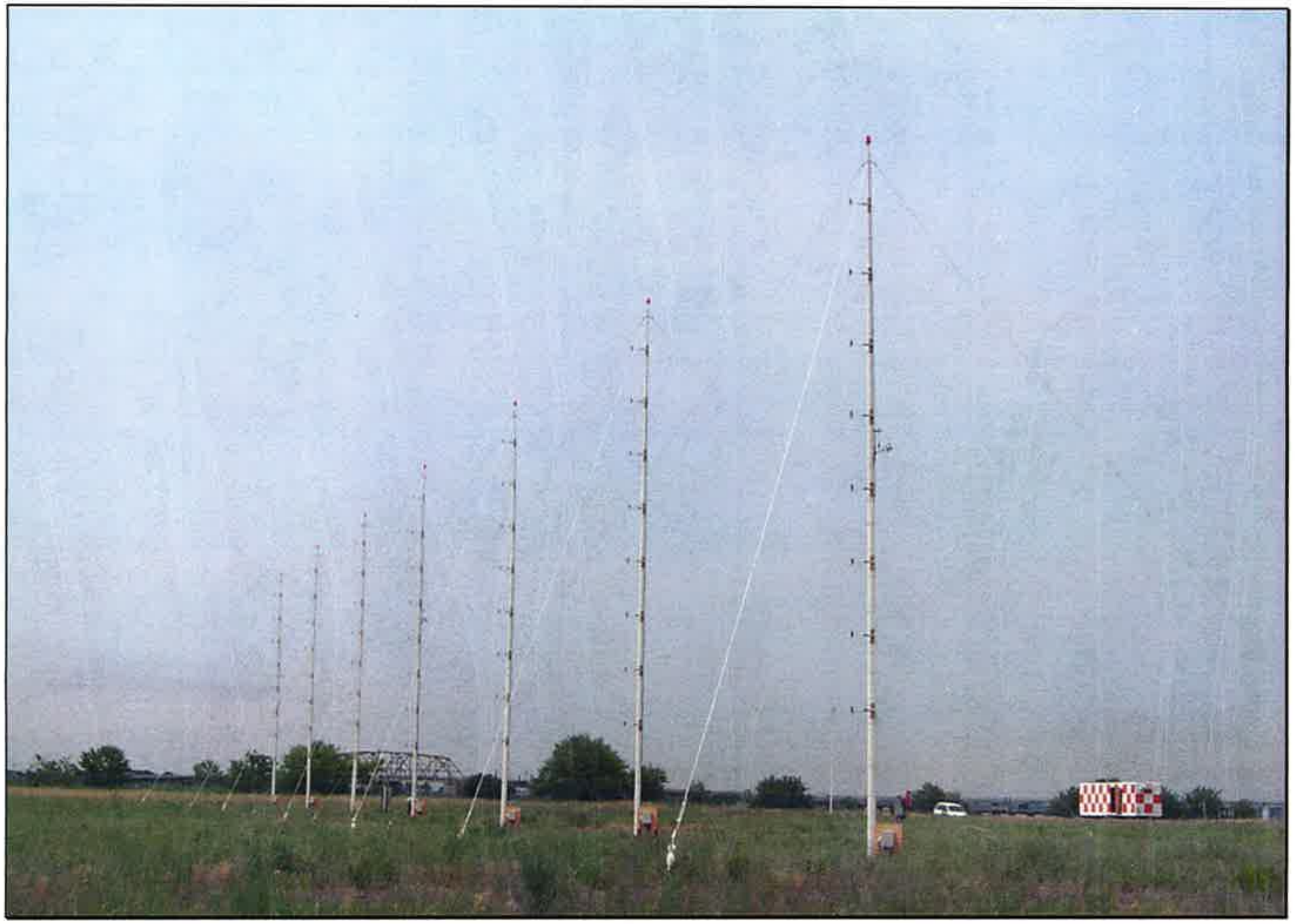


Figure 3-3. JFK Jet Blast Test Site

Data from the Windline and the Met Station were collected on a Campbell Scientific CS-9000 data logger located at the Windline. Windline and Met station data were sampled at 10 Hz. The sampled data was transferred, via fiber optic cable, to the Data Acquisition System (DAS) located in the Jet Blast trailer.

3.1.4 Data Acquisition System

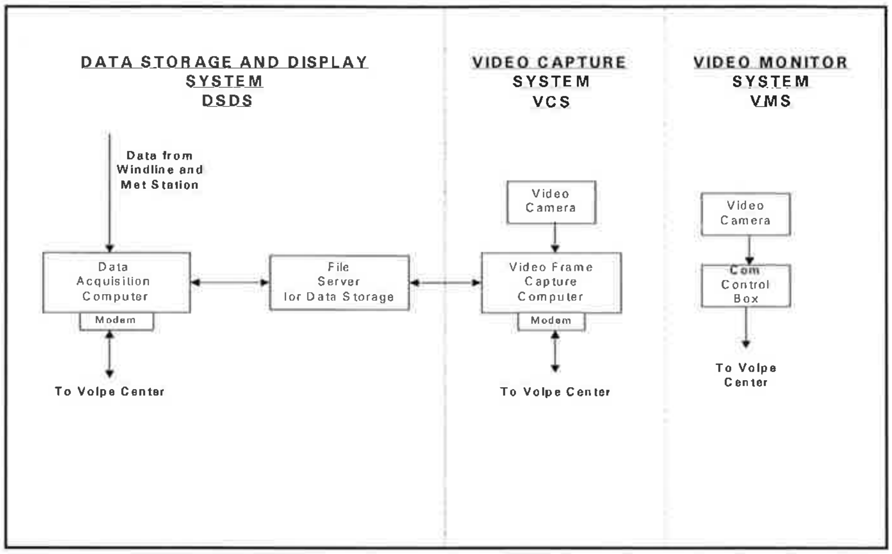


Figure 3-4. JFK Data Acquisition System Block Diagram

The DAS, located in the Jet Blast trailer, consisted of the Data Storage and Display System (DSDS), a Video Monitoring System (VMS) and the Video Capturing System (VCS). A block diagram of the DAS is shown in Figure 3-4.

The DSDS received data through a fiber optic interface from the CS 9000 data logger located at the Windline. The data, which is the formatted Windline and Met Station data, was stored in the DSDS in ASCII format. A display of the data, either locally or remotely, in a strip chart type format, could be obtained by selecting the appropriate software module from a menu on the DSDS.

The Video Capturing System (VCS), which consisted of a video camera, a computer, and software for capturing and storing a video frame, was used to assist in identifying aircraft type. The video camera was aimed directly at the intersection of TWY PD and RWY 13R in order to capture a profile of the departing aircraft.

A Video Monitoring System (VMS) was installed to enable monitoring and data collection activities to be conducted from the Volpe Center Remote Control Site. The VMS consisted of a video camera and a video converter. The video converter transferred video data via phone line from the Jet Blast Test Site to the Volpe Center Remote Control Site.

3.1.5 Volpe Center Remote Control Site

The remote control site was located at the Volpe Center in Cambridge, Massachusetts and is depicted in Figure 3-5.

Figure 3-5. Volpe Center Remote Control System

The remote control system consisted of the Data Acquisition Retrieval Computer (DARC), the Video Capture Computer (VCC), and the Remote Video Monitoring Display (RVMD). The remote control system allowed the test operators to control remotely the systems located at JFK. Figure 3-6 displays the system configuration.

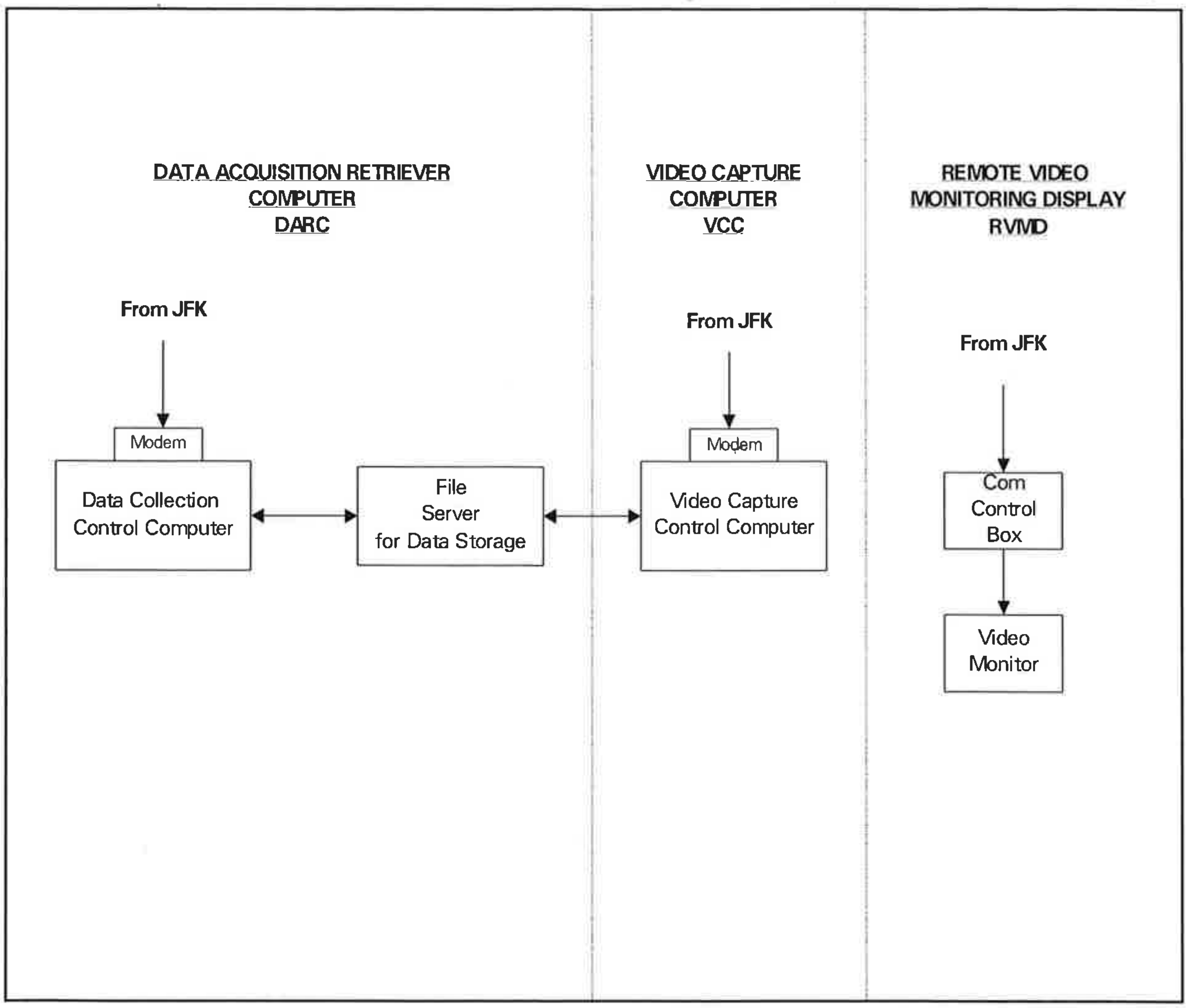


Figure 3-6. Volpe Center Remote Control System Block Diagram

The DARC was linked to the DSDS at JFK via modem using the remote control software PC Anywhere.[R] This enabled the Test Director to monitor in real-time the output of the CS 9000 data remotely.

The VCC was linked to the VMS at JFK via modem. Digital images of aircraft departing from RWY 13R were captured and stored on a data storage unit located at JFK. The aircraft location was determined by viewing the RVMD.

The RMVD, which consisted of the remote monitoring control box and a video monitor, received video data from the VMS at JFK via phone line at a transfer rate 26 kbps. The received video data was displayed at the Volpe Center on the video monitor and recorded on a VCR. This enabled the Test Director to view in real time the airport operations on RWY 13R and to play back video for closer inspection.

4. DATA COLLECTION AND PROCESSING

4.1 DATA COLLECTION METHODOLOGY

During the test period, RWY 13R was monitored remotely through a video monitor at the Volpe Center Remote Site for departure traffic. The typical daily period for monitoring RWY 13R for departure traffic was 0800 to 2000 hours. Once it was determined that traffic was running steadily, the data collection procedures commenced and continued until departure traffic ceased or until darkness prevented video monitoring.

The two computers at the Volpe Center Remote Site were used to remotely control (1) the Data Acquisition System computer and (2) the Video Capturing System computer. The Test Director was able to remotely control the data acquisition process, monitor the sensors and collect run files. The run files were stored at the Jet Blast Test Site, at the Volpe Center's data collection site, and data storage cartridges. With the VMS, the test director was able to view, in real time, traffic at RWY 13R. The video data was recorded and stored at the Volpe Center.

To identify the aircraft type, a digital image of the aircraft was taken and stored as the aircraft entered the active runway. The aircraft type and the time of departure roll were entered into the Jet Blast Test data log. Once an aircraft was detected entering the active runway, the Jet Blast run file began. The Jet Blast run file contained data from the 56 headwind anemometers, 3 crosswind and 3 vertical wind anemometers, an acoustic sensor, and the Met station. Ideally, the run file is initiated at least 10 seconds prior to take-off roll and terminated when the winds return to ambient conditions. Because of the number and frequency of aircraft using RWY 13R for departure, occasionally a single run file may contain multiple aircraft departures.

To supplement the aircraft identification information provide by the video image capturing, CATER (Collection and Analysis of Terminal Records) data files were obtained from Aviation Data Systems, Inc.

The data collection period was from July 29, 1999 to October 31, 1999.

The CATER data was received on October 15, 1999. Prior to that, since it had not yet been determined that the CATER data would be available, jet blast data collection was limited to daylight hours because of the video method of aircraft identification.

4.2 DATA PROCESSING

Processing of the data involved conversion of the acquired data to a form that could be used for analysis of jet blast properties and statistics. To accomplish this, the following data processing objectives were established:

- Capture the jet blast profile,
- Identify the ambient headwind,
- Identify the ambient crosswind,

- Identify the maximum jet blast velocity,
- Identify the jet blast duration to 4 knots above ambient, and
- Identify the jet blast duration to 10 knots above ambient.

For purposes of data processing, ambient crosswind is defined as the average wind speed in a direction perpendicular to the extended RWY 13R centerline for the 10 seconds prior to detection of take-off jet blast at the Windline. Ambient headwind is defined as the average wind speed in a direction parallel to the extended RWY 13R centerline for the 10 seconds prior to detection of take-off jet blast at the Windline. The jet blast duration is the amount of time between when the pilot applies takeoff thrust and when the resultant jet blast returns to a predetermined threshold above ambient headwind at the Windline.

Each data file contains the date of the run file, time, the anemometer wind speed in knots for each anemometer, the Met Station wind speed in knots, and the Met station wind direction in compass heading, and acoustic data in millivolts. Data files were collected continuously at a 10 hertz rate independent of whether there was a jet blast or not.

A number of data files collectively form a Jet Blast run file for a specific departing aircraft. The number of data files included in a run file is defined by the jet blast duration time plus 10 seconds of ambient measurement prior to start of aircraft departure roll. The start and end of a run file was determined by the Test Director in real time by appropriate computer keystrokes or offline by partitioning a large multi-aircraft jet blast data file. Although the original file may contain data from many jet blasts, because of the rate and quantity of aircraft departures, it is essential to extract and isolate individual jet blast files, called run files, based on the time of departure. Since all the data were time tagged and detailed logbook entries were maintained, extracting and isolating individual aircraft jet blast files was a relatively simple process. The Jet Blast run files were converted to, and stored as, spreadsheet files.

To create jet blast duration plots from the spreadsheet files, a software process was developed to select, for each 0.1 second interval of the run file, the maximum velocity value existing anywhere on the Windline array of fifty-six anemometers. This was done for the entire time period of the run file. A smoothing process, effectively a low pass filter, was then employed that generated a 1-second running average of the maximum velocity averages. This is a customary method used to average out small calibration variations between anemometers. An example of a duration plot using 0.1 second (10 hertz) data is shown in Figure 4-1. A plot using the same data but employing a 1-second running average is shown in Figure 4-2. The plot in Figure 4-2 using the 1-second running average does not affect the measurement of jet blast duration time nor materially affect peak jet blast velocity.

From the resultant plots, the jet blast duration time, t_d, that is, the time for the jet blast to decay to some threshold value relative to ambient headwind was determined graphically. For each run file, jet blast duration time t_d was measured to threshold values of 4 knots and 10 knots above ambient headwind. In the final version of this plot, called simply the jet blast run time plot, t=0 was set at 5 seconds prior to the arrival of the jet blast to account for jet blast transport time. The threshold lines which appear in Figure 4-2 also appear in the final versions of the run time plots.

It should also be noted here that the run time plots also afforded an opportunity to chronicle the various methods of thrust control pilots used to accelerate their aircraft during takeoff.

A frequently used capability of the data reduction system was the creation of run time plots for each anemometer in the Windline array. This allowed detailed investigation of the interaction of the jet blast with the Windline array including exploration of the extent and characteristics of the jet blast volume at the Windline.

The peak jet blast velocities for each aircraft were extracted from the run time plots.

Run time plots for all the jet blast data used in the analysis are contained in a CD-ROM described in Appendix A2. An MS Excel spreadsheet containing a summary of the data for each run time plot is also contained in the CD-ROM and described in Appendix A2.

The velocity of the ambient headwind was determined by averaging the values of the maximum velocity measured on the headwind anemometers in each data file for the 10 seconds prior to each aircraft departure. The ambient headwind was also investigated in terms of any longer term effects caused by repetitive departures of Heavy aircraft. In other words, absent of any aircraft departures, the ambient headwind would reflect the effect of natural meteorological processes. However, during the periods of high runway departure activity, some increase of the ambient headwind as measured at the Windline might be expected, and indeed does occur, as Large or Heavy aircraft are moving into the departure and hold position while at the same time other Large or Heavy aircraft are on their takeoff roll thereby creating and maintaining a higher level of ambient headwind than would otherwise be present. A method for viewing this effect is shown in Figure 4-3. By concatenating run files, longer term trends in headwind magnitude growth can be observed and measured. The run file shown in Figure 4-2 also appears, in compressed form, in Figure 4-3 and is highlighted with a box around the aircraft type.

Windline poles 1, 4, and 7 were equipped with crosswind anemometers at the 27.5-foot height. The velocity of the ambient crosswind was determined by averaging the values measured by the crosswind anemometers for the 10 seconds prior to each aircraft departure.

Met station crosswind and headwind information was used primarily for verification purposes.

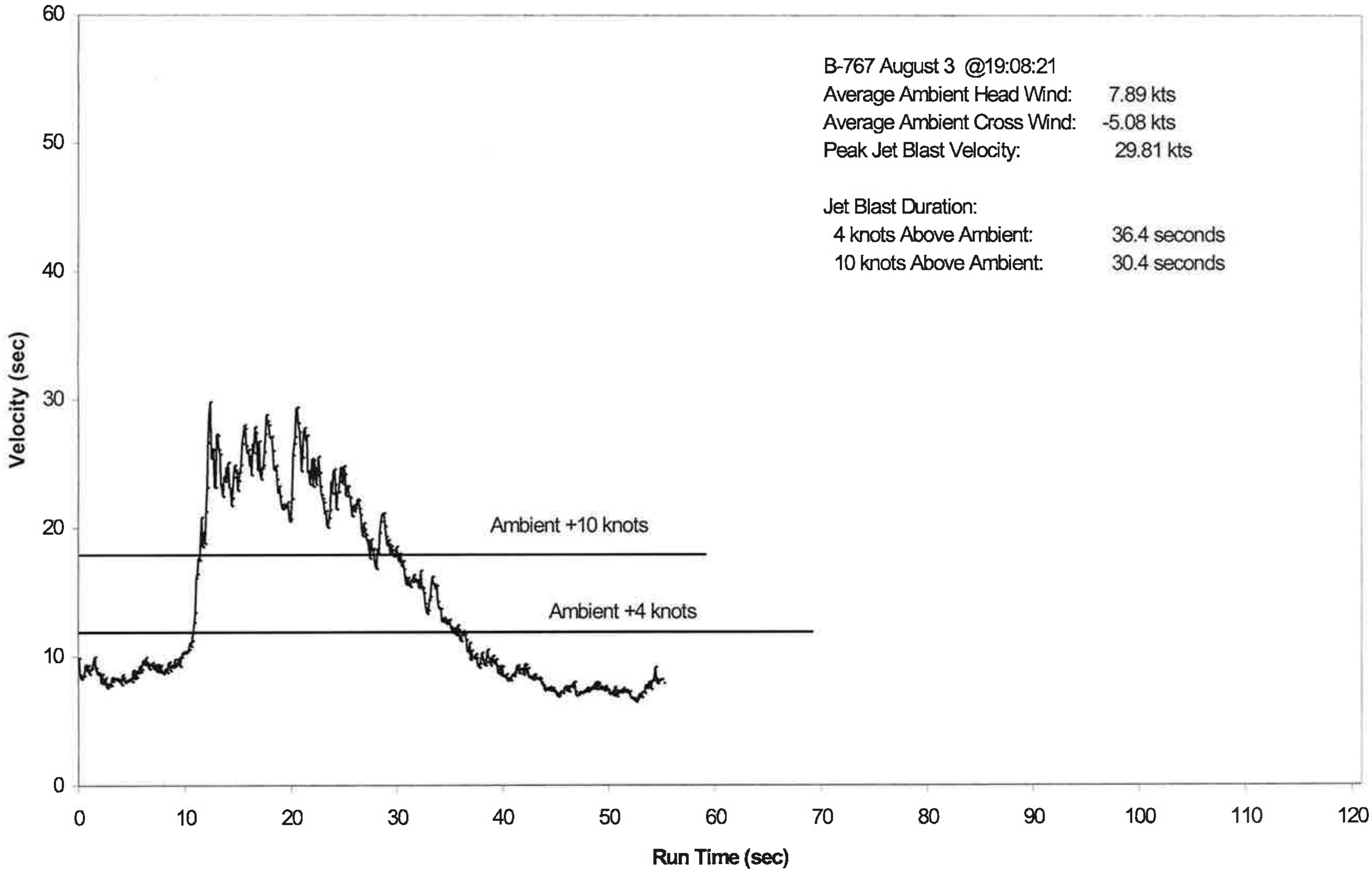


Figure 4-1 Jet Blast Profile 10-Hz Data Rate

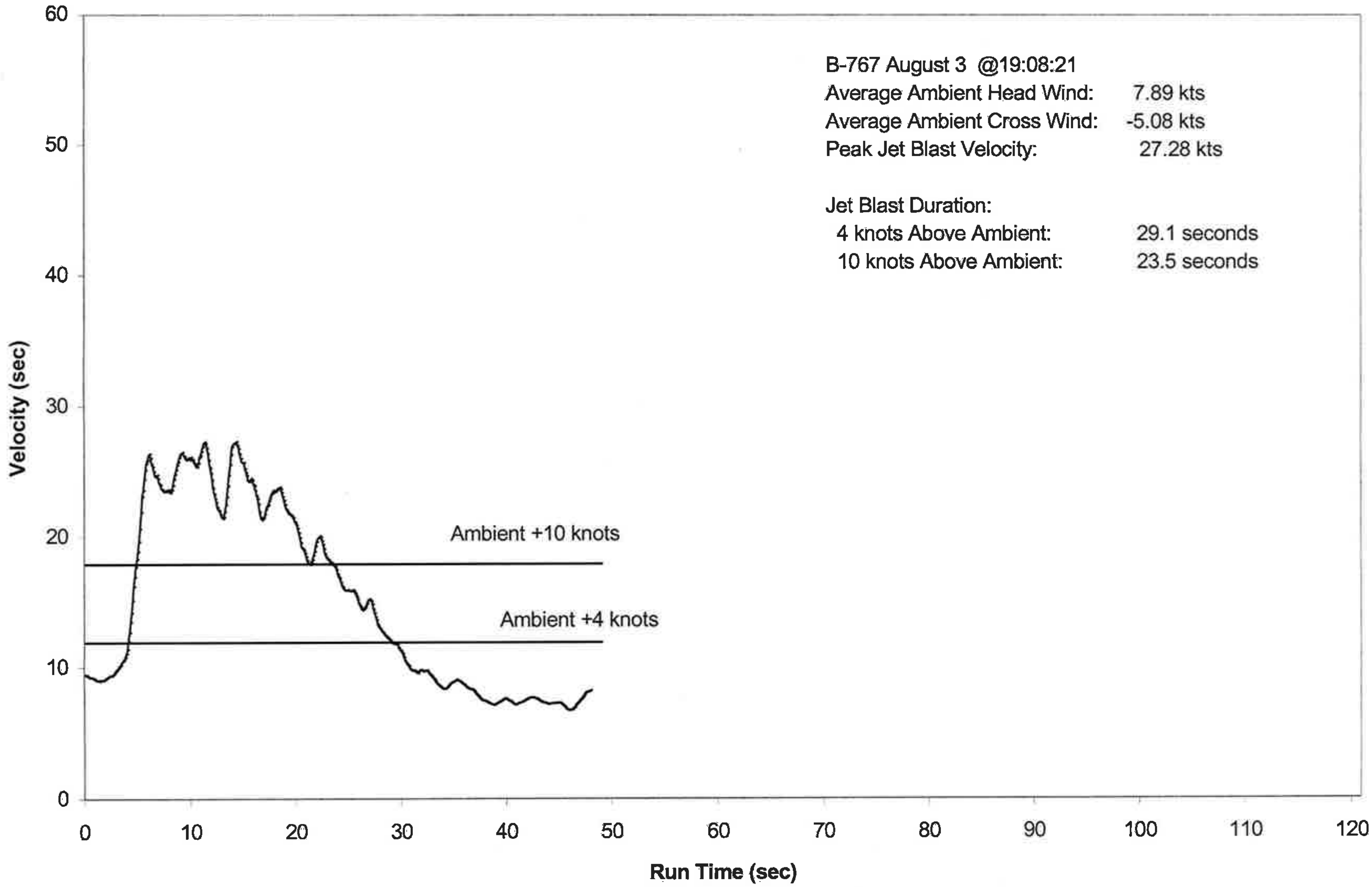


Figure 4-2 Jet Blast Profile 1-sec Running Average

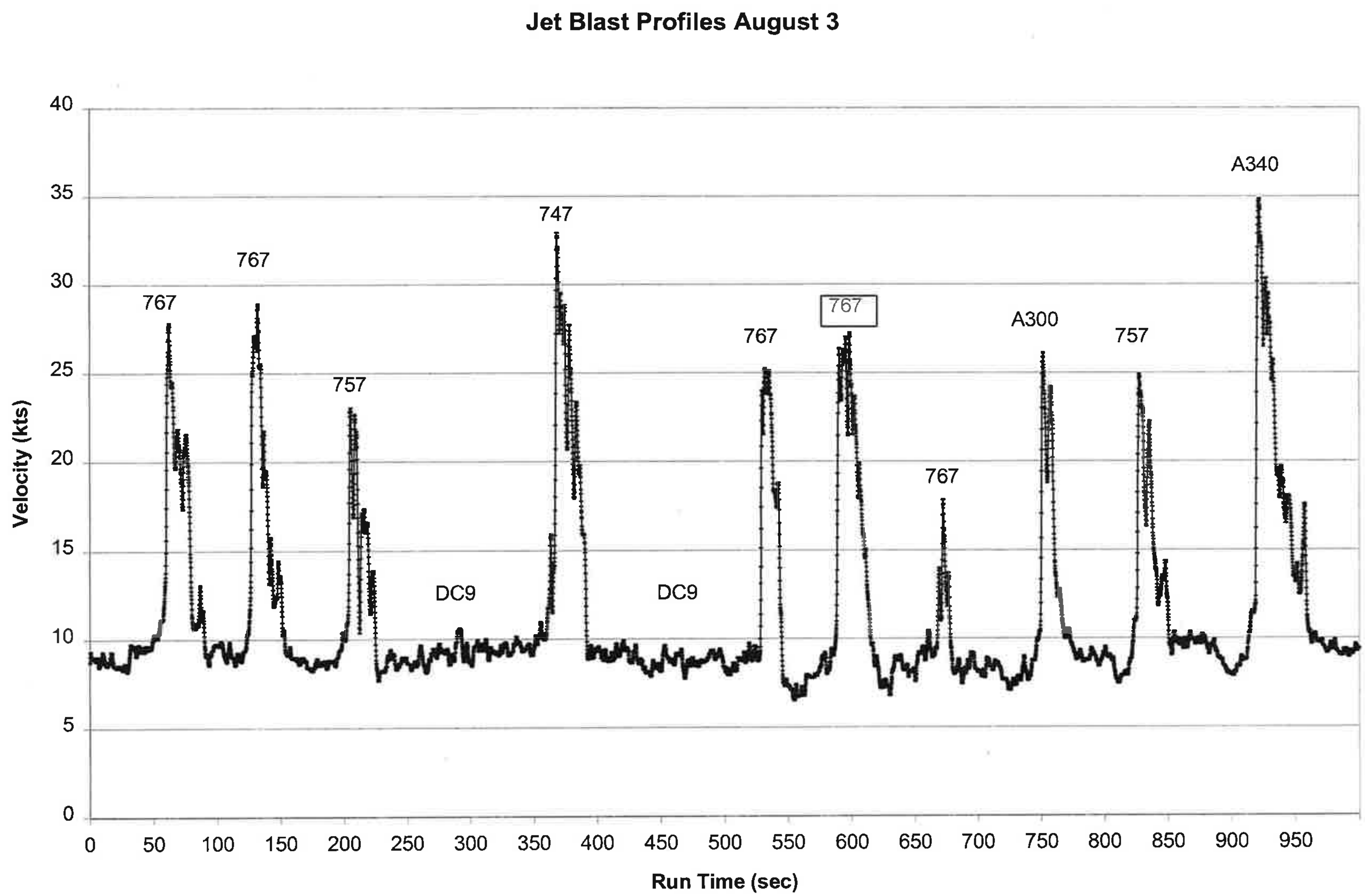


Figure 4-3. Concatenated Jet Blast Run Files

5. JET BLAST DATA ANALYSIS

The purpose of this Jet Blast Test Program has been to determine jet blast duration for a number of Heavy aircraft at a distance of 760 feet behind the generating aircraft. This distance corresponds to the distance between the departure point of RWY 31L and the centerline of the perpendicular runway, RWY 4R. Heavy aircraft are those with a maximum certificated weight over 255,000 lbs. The jet blast duration, t_d, is defined as the time between the application of take-off thrust by the pilot and when the measured speed in the jet blast stream from a departing Heavy aircraft decays below some defined threshold as measured at a distance of 760 feet behind the end of RWY 13R.

5.1 DATA ANALYSIS PROCESS

5.1.1 Initial Analysis

The basic analysis plot used is called a jet blast duration run time plot, an example of which is shown in Figure 5-1 which is a run time plot of a Boeing 767 aircraft departure. The plot is divided into five elements. The first element, labeled A, is the 5-second period that represents the time for the jet blast to arrive at the Windline after the pilot has applied takeoff thrust. During this period and the previous 5 seconds, ambient headwind and crosswind measurements were obtained for this particular run file in order to obtain an estimate of ambient wind. The next element, labeled B, is where the jet blast thrust rises to its peak value as the pilot increases the thrust to an initial takeoff level, releases the brakes, and begins to proceed down the runway. The third element, labeled C, is the decay of the jet blast. Once the aircraft begins accelerating, the increasing separation distance between the aircraft and the Windline results in a decrease of the measured jet blast velocity at the Windline.

Figure 5-1 also contains horizontal gridlines for identifying where the 4-knot and 10-knot threshold lines were drawn for this run. Element D is the measurement point for the duration time at the 10-knot threshold. Element E is the measurement point for the duration time at the 4-knot threshold. From this plot, the jet blast duration can be read directly on the time axis by determining the point on the curve where the jet blast velocity makes its last excursion below the threshold line. The defined jet blast duration, t_d, is the sum of the transit time for the jet blast to reach the Windline (5 seconds), the time to reach maximum jet blast velocity, and the time until the jet blast decays to some threshold value. In the Figure 5-1 plot, for a threshold of 4 knots above ambient headwind, the duration time is 31 seconds; for a threshold of 10 knots above ambient headwind, the duration time is 25 seconds.

All the duration run time plots were initially analyzed the same way in order to obtain values of peak jet blast velocity, duration times to 4- and 10-knot thresholds, ambient headwind, and ambient crosswind. This allowed for creating a variety of scatter plots for demonstrating the variability of jet blast duration time for all Heavy aircraft including B757s. From this database, scatter plots were derived for each aircraft type. In all the scatter plots, the measured jet blast duration times are plotted against other parameters to determine whether any dependency exists. As stated previously, two duration times (time to 4-knots threshold and time to 10-knots threshold) were measured for each departing aircraft that was in the data analysis set.

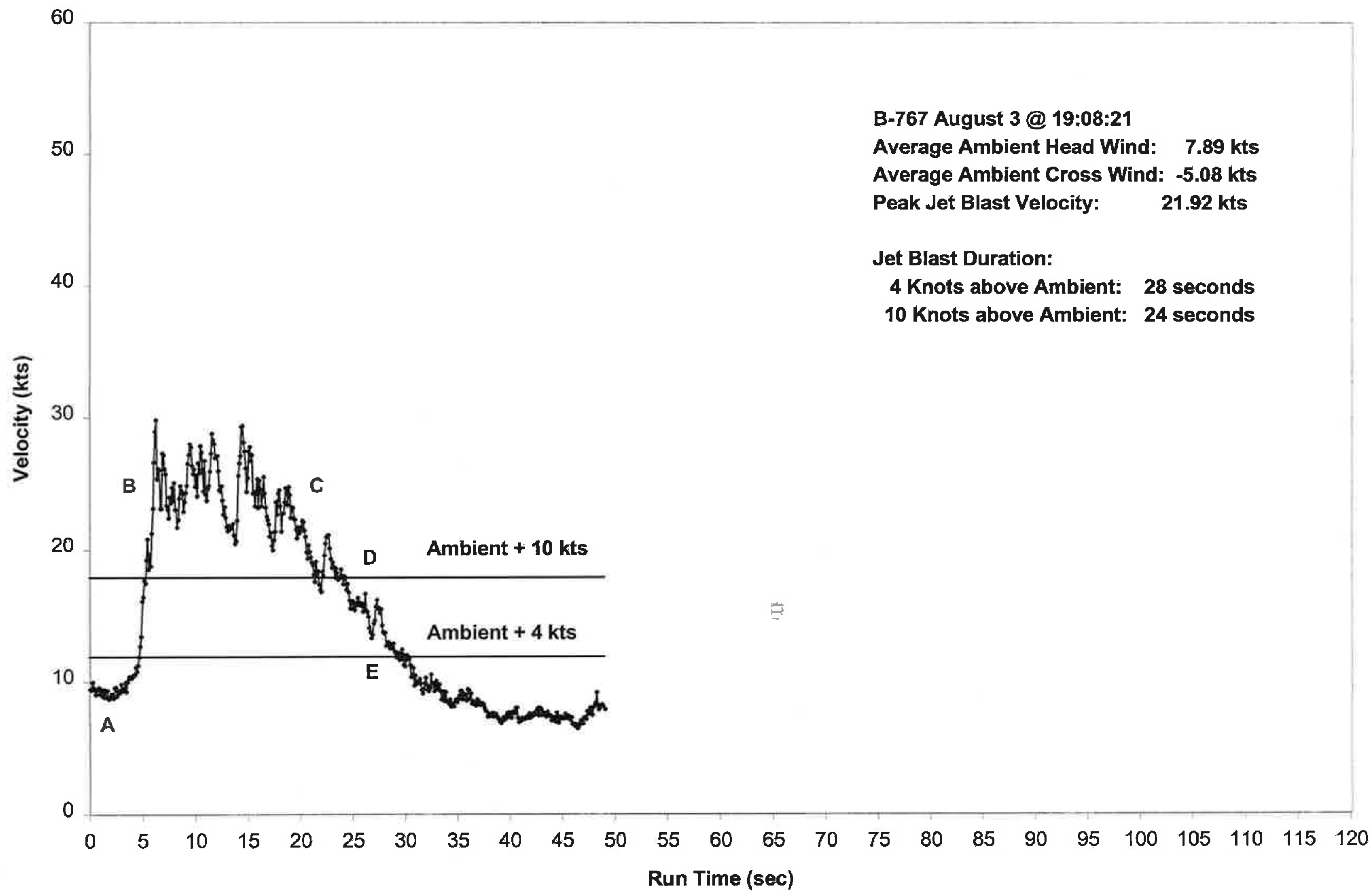


Figure 5-1. Sample Jet Blast Duration Profile

Table 5-1 is a listing of all the aircraft that made up the aircraft population for this test program. As shown in Table 5-1, approximately 56% of the total number of data runs were disqualified from inclusion in the data analysis sets. There were a number of run files where no discernible jet blast was detected. In addition, there were a number of run files where the jet blast, although discernible, did not survive the duration time measurement at the 10-knot threshold. There are three reasons for this effect. First, under high crosswind conditions, the jet blast is blown downwind to the extent that there is only a slight encounter with the Windline or misses the Windline entirely. Second, some aircraft began their takeoff roll while making the turn onto the runway. Coupled with moderate and high crosswinds, the jet blast provided low values of velocity at the Windline. Third, some aircraft turned onto the runway from a taxiway further down the runway.

Table 5-1. Jet Blast Test Program Aircraft Population

Aircraft	Data Runs	Data Analysis Set
A-330	6	3
A-340	10	7
B-747	159	114
B-757	95	41
B-767	780	397
B-777	27	18
DC-10	21	18
L-1011	13	11
MD-11	29	27
Total	1140	636

Since the primary emphasis in the Jet Blast Test Program is to study the duration times, the disqualifications had no effect other than reducing the aircraft population. A listing of the specific aircraft included in the data analysis sets are contained in a spreadsheet on the CD-ROM described in Appendix A2.

For all the aircraft that were included in the data analysis sets, an initial measurement of jet blast duration time was made. A scatter plot of jet blast duration time versus peak jet blast velocity was generated from this data and is shown in Figure 5-2 for a 4-knot threshold and Figure 5-3 for a 10-knot threshold to provide an initial view of the distribution of duration times.

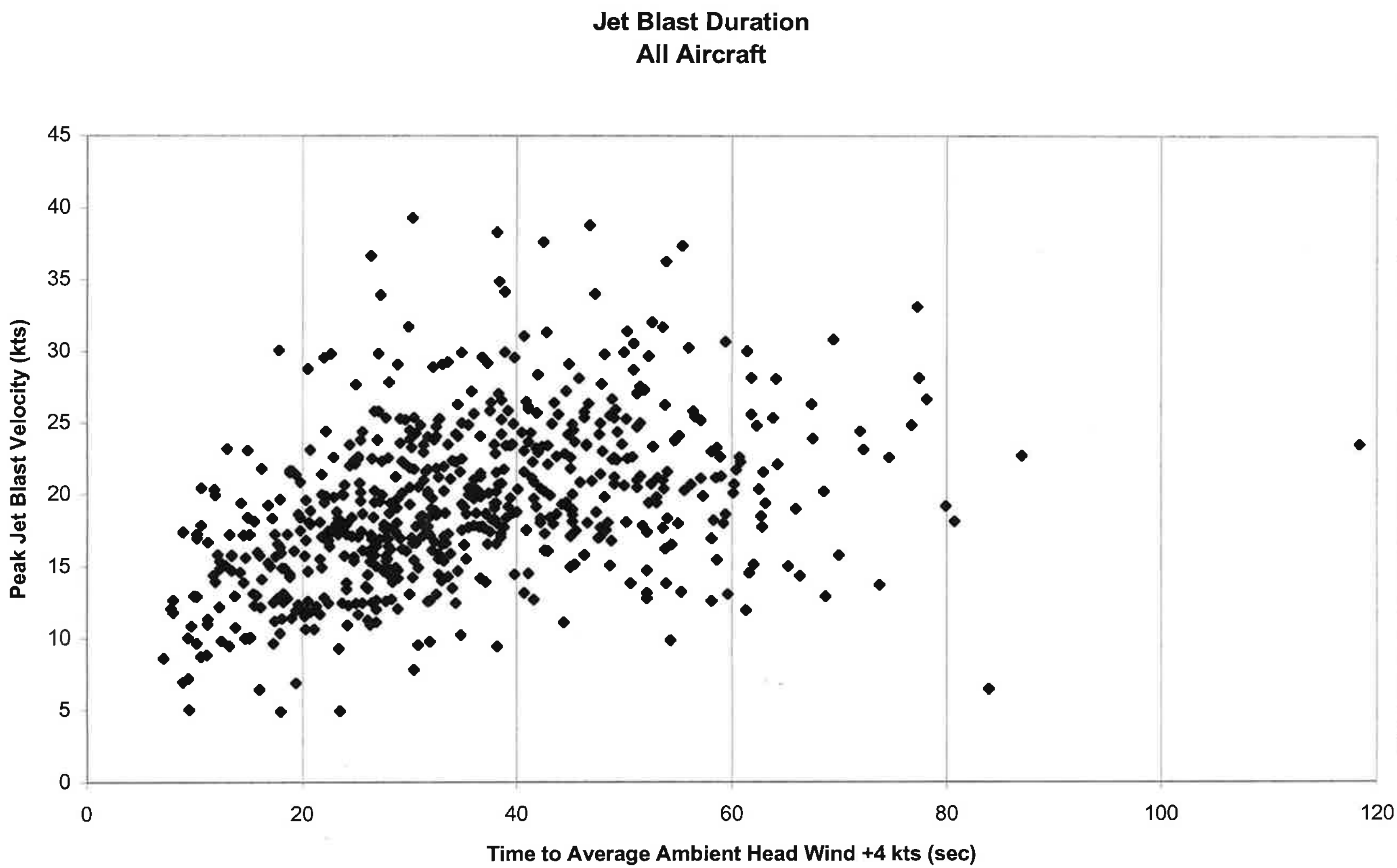


Figure 5-2 Initial Analysis Scatter Plot For Ambient Headwind +4-kt Threshold

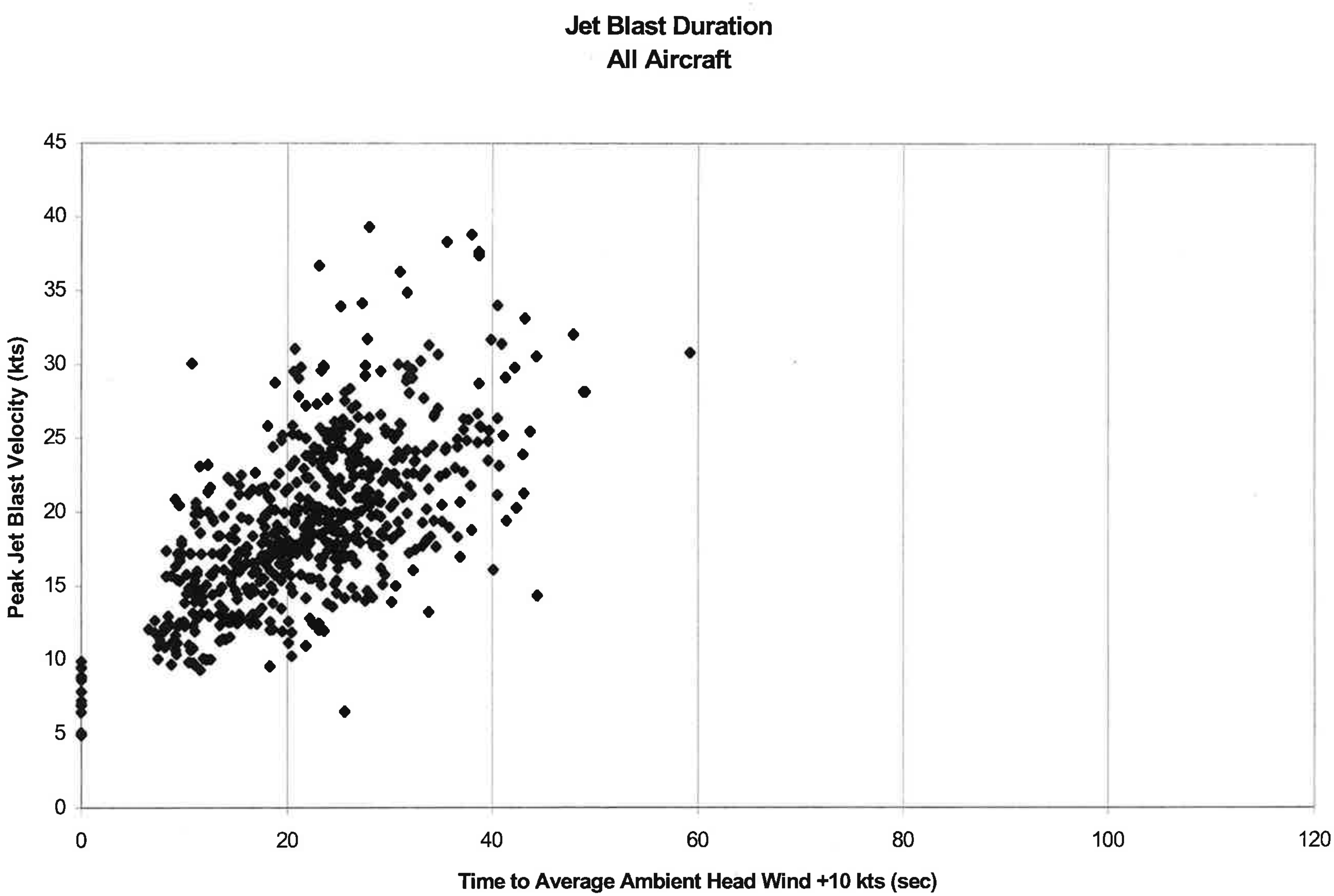


Figure 5-3 Initial Analysis Scatter Plot for Ambient Headwind +10-kt Threshold

From those initial views, all those aircraft with duration times greater than 70 seconds were reviewed in detail and compared to similar aircraft types with a duration time less that 70 seconds.

In order to validate the magnitudes of the peak jet blast velocity measurements and the jet blast duration times, a review of relevant available information was conducted. A simple analysis of jet blast duration time was also carried out at the Volpe Center as part of this test program. The discussion of this modeling and characterization effort is discussed in some detail in Section 6 of this report. The results show that the magnitudes of the various measurements are in general agreement with the magnitudes predicted.

A further look at Figure 5-2 and Figure 5-3 indicates a general dependence of duration time on peak measured jet blast velocity. Since this apparent dependency has no effect on jet blast duration time measurements and their subsequent use in determining distributions of the measurements, an analysis of this effect is deferred to Section 6, Modeling and Characterization.

Scatter plots of jet blast duration time versus ambient crosswind, jet blast duration time versus ambient headwind, jet blast duration time versus time of day, and jet blast duration time versus day of year were also developed but no dependencies were detected.

5.1.2 Detailed Analysis

Based on the initial analysis including a review of the data distribution shown in Figure 5-2, a detailed analysis was then conducted to determine if there were any special circumstances that led to prolonged jet blast duration times (i.e. > 70-seconds) in some of the cases.

The first data files investigated were those for the four extreme Outliers with duration times exceeding 80 seconds. The first run file analyzed was that of an MD11. The second run file analyzed was that of a B747. The criteria used for analyzing these outliers can also be applied to the remaining two outliers, a B767 and an L1011.

The second set of data files reviewed were those corresponding to aircraft with duration times between 65 seconds and 80 seconds.

A further modification of the jet blast duration times was made through a consistent application of the 5-second jet blast transport time.

As a point of reference, a histogram, showing the distribution of duration times prior to detailed analysis, is shown in Figure 5-4.

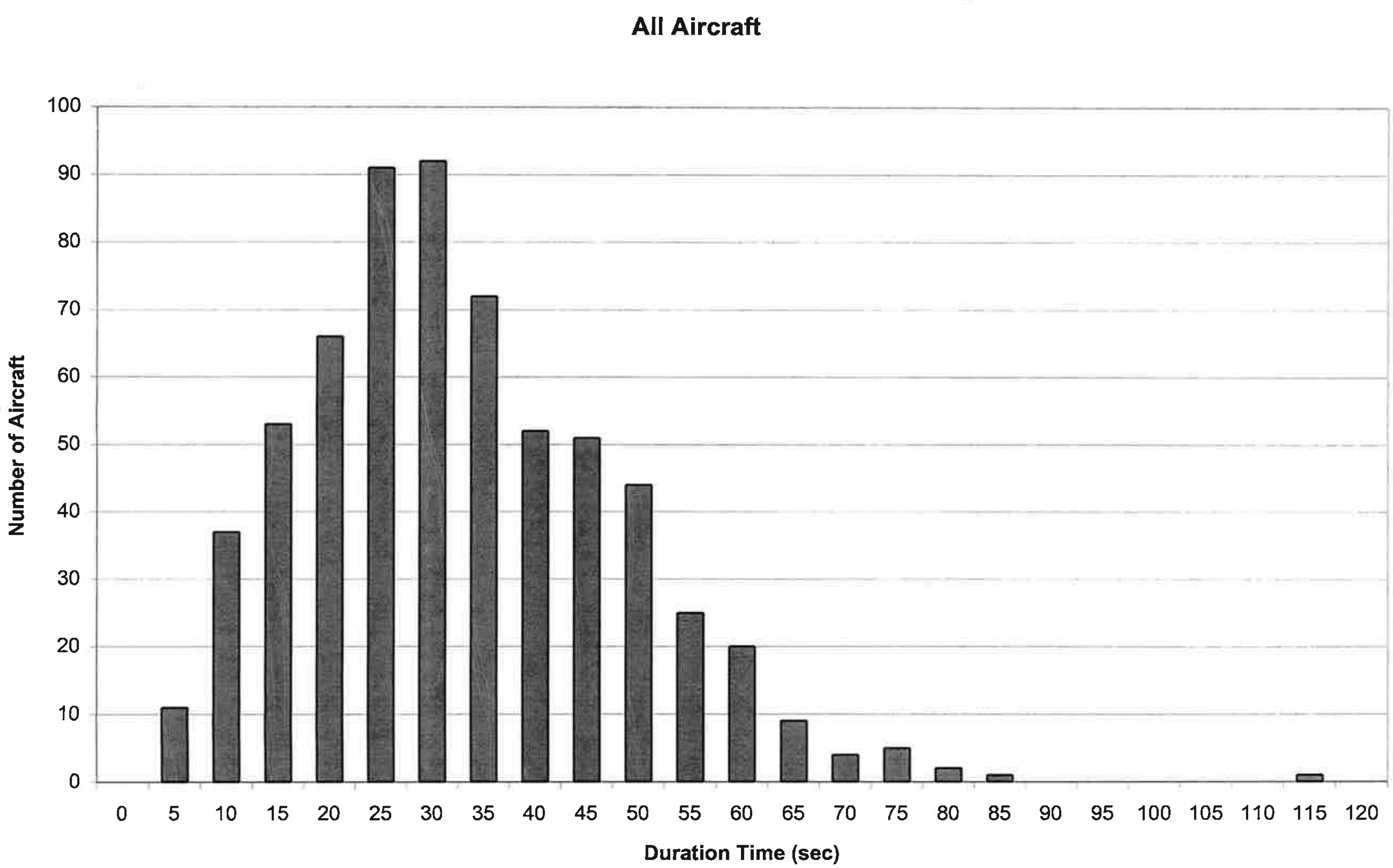


Figure 5-4 Histogram of Duration Times Prior to Detailed Analysis

80-sec+ MD11 Outlier

Figure 5-5 is the run time plot of the MD11 Outlier aircraft. It can be seen that the initial jet blast decay begins at approximately 27 seconds and, after the appearance of two brief bursts of headwind labeled F and G, continues to 75 seconds. The headwind stabilizes for about 10 seconds and then, at H, rises to a value of approximately 17 knots and maintains that value for 20 seconds before it decays to ambient.

In viewing the video replay of the MD11 departure, another aircraft, a B767, moves along the taxiway leading to the departure position shortly after the MD11 starts its takeoff roll. The B767 begins its turn onto the runway at approximately the 37-second mark. This event is labeled F in Figure 5-5. This action corresponds to an increase in jet blast velocity at that point that is maintained for some 9 seconds. This is attributed to the detection of the jet blast from the B767's starboard engine. Starting at time of 51 seconds, the B767 begins the last phase of the turn. This final phase of turning corresponds to the second increase in jet blast velocity, labeled G in Figure 5-5, which then decays as the B767 adjusts its alignment. This is attributed to the detection of the jet blast from the B767's Port engine or both. Since the jet blast velocities of the following B767 add to the jet blast velocities of the preceding B747, decomposition of the velocity profile into components attributable to each of the contributing aircraft was possible with a high level of confidence. An acoustic sensor, located at pole 4 along the extended centerline of RWY 13R, gave the first clues of the possible causes of the long jet blast duration time for the MD11.

The reason for the rise in jet blast velocity labeled H in Figure 5-5 is not so clear. There is an abrupt end to the acoustic signal that corresponds to the decay into ambient of the jet blast wind at 75 seconds. However, following that, there is a steady increase in noise that is inconsistent with the MD11 departure, which by then is airborne and, assuming a moderate acceleration of 6-feet/second,[2] is at least 15,000 feet from the departure position. Alternatively, if the following B767, already at the departure point, ran up its engines and maintained that low thrust level for a short period, then that would explain the behavior of the data.

Based upon a review of all the pertinent data, the conclusion is that the apparent long jet blast duration time was due to circumstances unrelated to the Outlier MD11 and that the duration time for the outlier MD11 is reduced to 50 seconds. Although the duration time of the MD11, using a 4-knot threshold, was changed to 50 seconds, even some of that period might be attributable to the B767's actions.

The results of the MD11 analysis led to a general approach to the analysis of all the long duration time jet blasts. During departure pushes, following aircraft often moved into departure positions within 20 seconds of the start of the takeoff roll of the preceding aircraft. Since there were other aircraft in the >70-seconds jet blast duration time category, whose duration time profile exhibited the same characteristics, they were also reviewed and where appropriate, the duration times were adjusted accordingly.

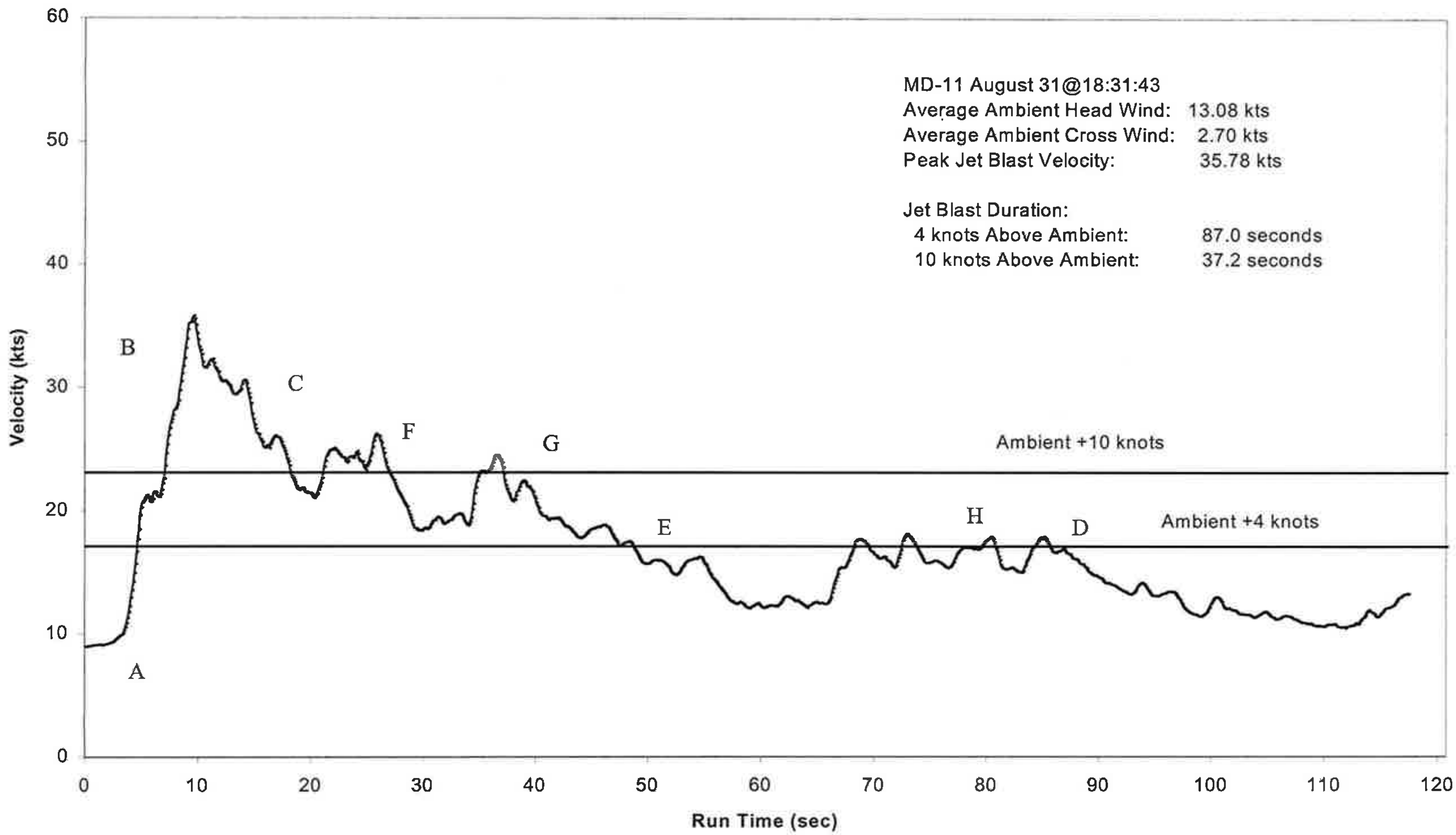


Figure 5-5. MD11 Outlier Jet Blast Duration Profile

80-seconds+ B747 Outlier

Figure 5-6 is the run time plot of the B747 Outlier aircraft. It can be seen that the detection of headwind ostensibly associated with the jet blast does indeed last a long time as it decays into ambient turbulence. The measured duration time to 4 knots above ambient threshold is 118 seconds. Using a 10-knot threshold, the duration time is 40 seconds. Clearly, by applying the criterion that the duration time is measured to the last excursion of the jet blast through the 4-knot threshold, the duration time measured is technically correct. It should be noted that the turbulence toward the end of the jet blast decay, from the 60 seconds point on, appears in short 3-second gusts varying up to 3 knots above and below the 4-knot threshold.

In reviewing the video of this particular departure, apart from the observation and measurement of gusting ambient winds, there were three unusual elements observed:

1. The first element was the apparent slowness of the aircraft in its departure acceleration. For comparison purposes, a concatenated plot of a number of aircraft departures before and after the B747 Outlier is shown in Figure 5-7. The B747 Outlier under question has been highlighted. By comparison with the duration times of the other aircraft represented in the plot, particularly with respect to the other B747 in the plot, the B747 Outlier duration time is noticeably longer. One explanation of the slower departure is that, since the B747 Outlier was an Asian Rim country aircraft, possibly with a significant load, the pilot chose to make use of the long runway to get airborne.

2. The second element was the appearance of a DC9 aircraft that started turning into the departure position at approximately 26 seconds after the B747 started it takeoff roll and completed its turn at the 41 seconds mark. As is often the case, some final maneuvering of the DC9 took place until it reached the final hold position. This was discovered by monitoring the video replay of the departure events. This is a situation similar to that which was described in the previous section relative to the MD11 Outlier. The jet blast velocities from the two aircraft are additive, that is, the velocities generated by the DC9 in turning into the RWY 13R departure position and hold added to those velocities generated by the departing B747 and detected by the Windline.

3. The third element was the appearance of a Tower Air B747 (TA-B747) along TWY Q apparently on its way to the Tower terminal located at the end of TWY QD. The TA-B747 appears in the video on TWY Q, approximately 3270 feet from TWY QD, approximately 239 seconds prior to the defined start of the run file of the Outlier B747. The entrance to TWY QD is approximately 850-feet from the RWY 13R extended centerline. The extended centerline of TWY QD is perpendicular to the extended RWY 13R centerline and is nearly coincident with the Windline. Therefore, the end pole of the Windline, pole 7, would be approximately 685 feet from an aircraft turning into TWY QD. A jet blast coming from an aircraft turning into and traveling along TWY QD would register on the Windline instrumentation both as crosswind and headwind components.

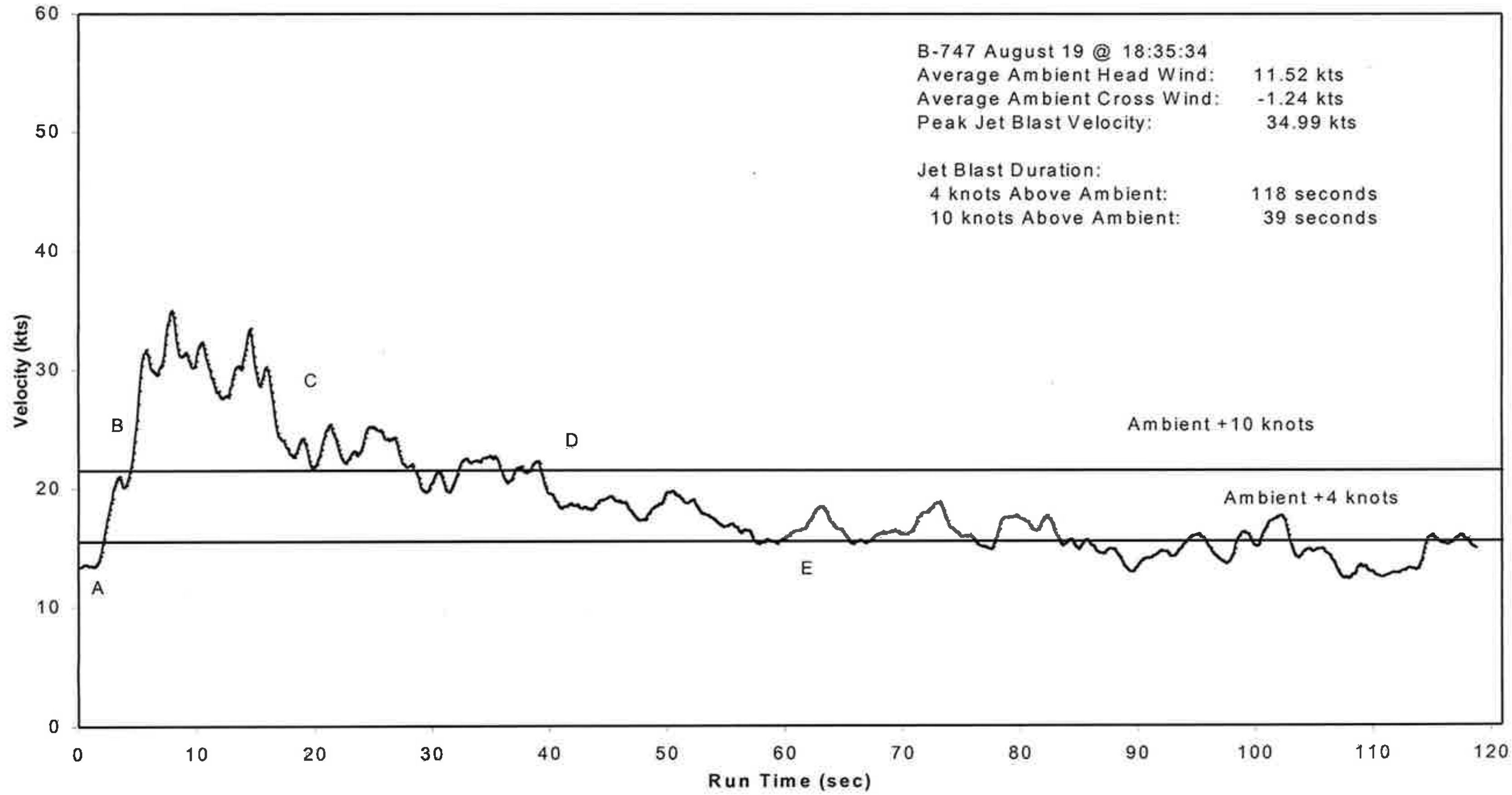


Figure 5-6. B747 Outlier Jet Blast Duration Profile

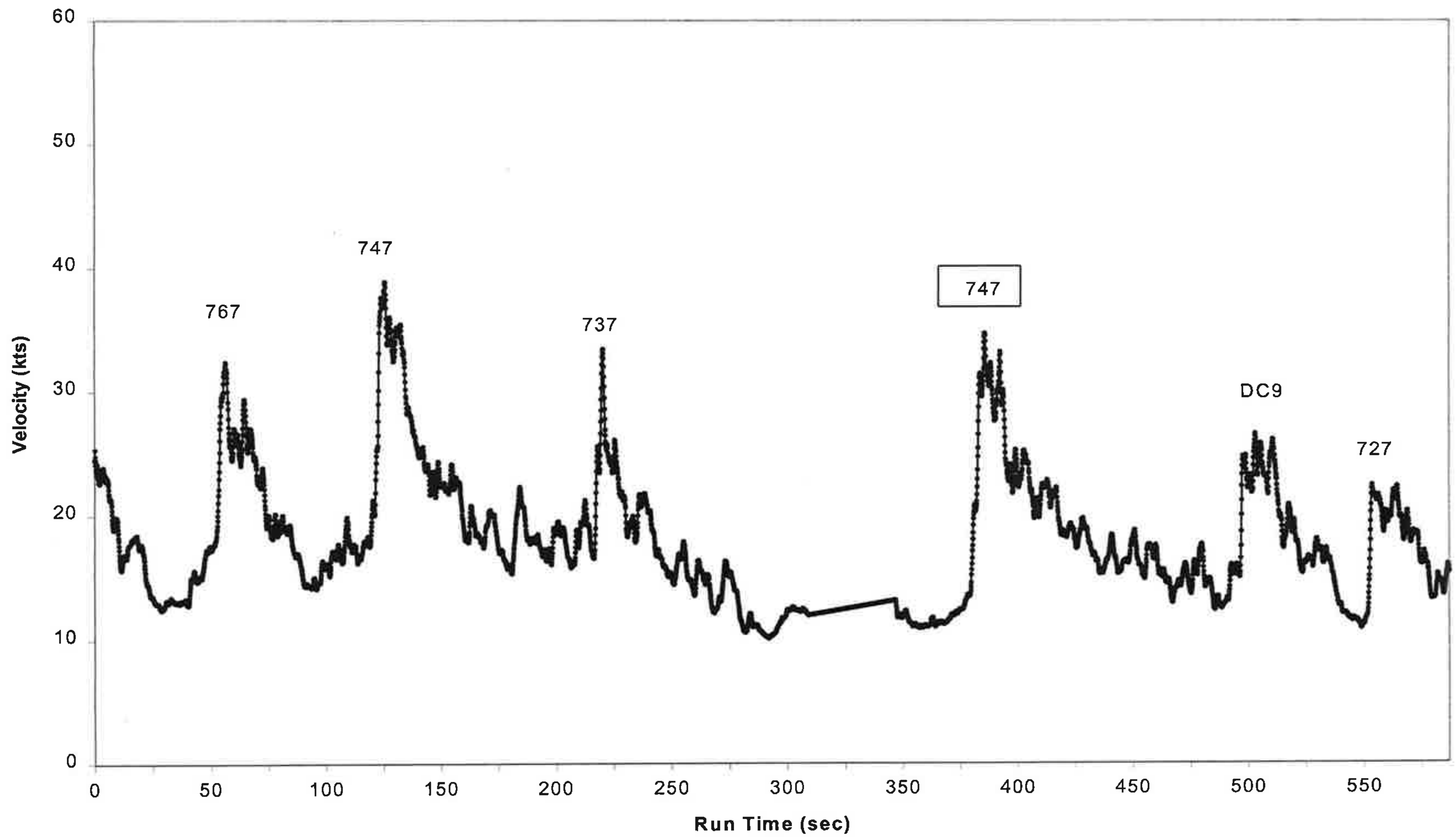


Figure 5-7. Multi-Departure Jet Blast Duration Profiles Surrounding B747 Outlier

There is no way of determining with certainty that the timing of the arrival of the TA-B747 at the mouth of TWY QD and its subsequent movement along TWY QD occurred simultaneously with the departure of the Outlier B747. However, had it occurred simultaneously, that would account for the variability of the Outlier B747 duration profile starting at point E as shown in Figure 5-6.

Based upon a review of all the pertinent data, the conclusion is that the apparent long duration time was due to circumstances unrelated to the Outlier B747 jet blast; therefore the duration time for the Outlier B747 is reduced to 59 seconds. This value corresponds to the time of the first excursion of the Outlier B747 profile below the 4-knot threshold.

65-seconds to 80-seconds Outliers

After a review of the video replays of the departures of the aircraft in the 65 seconds to 90 seconds Outlier region, it was clear that aircraft turning onto the runway while the preceding aircraft was on its takeoff roll created not only a measurable jet blast velocity at the Windline, but the jet blast velocities added. This effectively obscured the normal jet blast decay of the departing aircraft. The analysis concerning the MD11 Outlier applies. A conservative estimate of the jet blast velocity of the departing aircraft was extracted and used as its characteristic value for the scatter plots and the statistics.

The aircraft below the 65-second duration time were not further analyzed using this method although they might benefit from it.

5-seconds Jet Blast Transport Time

All the jet blast duration times were further adjusted to include the 5-second time period required for the initial jet blast to reach the Windline. In many cases the initial determination of the jet blast duration time included an extended period, often > 15 seconds, for the initial blast to reach the Windline. In reviewing the video replays, and using B727 aircraft as a guide, the 5-second period was verified.

5.1.3 Detailed Analysis Results

The results of the detailed analysis, using a 4-knot threshold, are shown in the scatter plot of jet blast duration time versus peak jet blast velocity in Figure 5-8. Table 5-2 lists the final distribution of jet blast duration times, the percentage of the population in each time segment, and the cumulative percentage. Figure 5-9 is a histogram representation of the data in Table 5-2.

Table 5-2. Final Distribution of Jet Blast Duration Times for 4-kts Threshold

Duration Period	Number	% Population	Cumulative %
0-sec to 10-sec	11	1.73	1.73
10+-sec to 20-sec	90	14.15	15.88
20+-sec to 30-sec	159	25.00	40.88
30+-sec to 40-sec	169	26.57	67.45
40+-sec to 50-sec	114	17.92	85.37
50+-sec to 60-sec	74	11.64	97.01
60+-sec to 70-sec	19	2.99	100

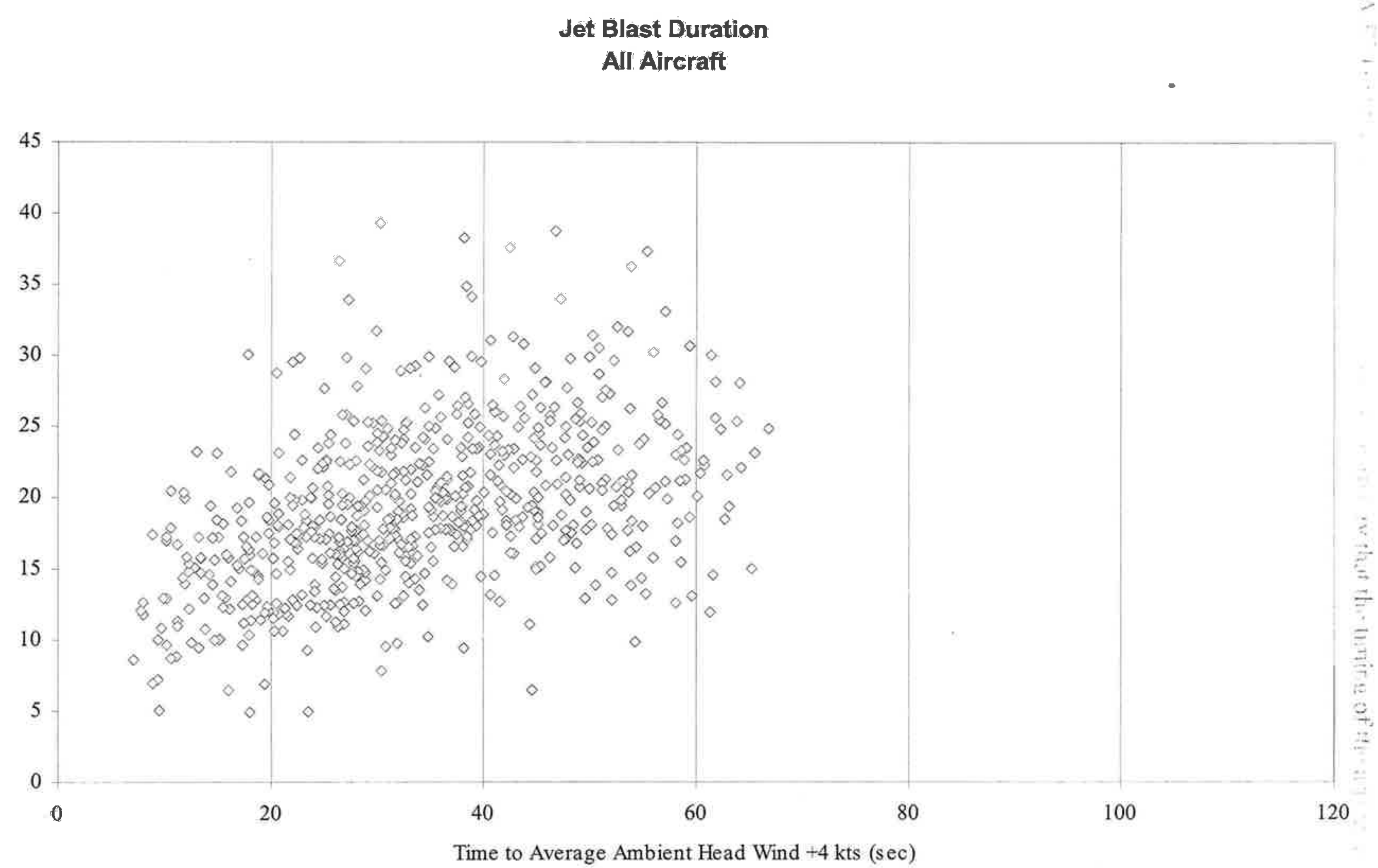


Figure 5-8. Detailed Analysis Scatter Plot for Ambient Headwind +4-kt

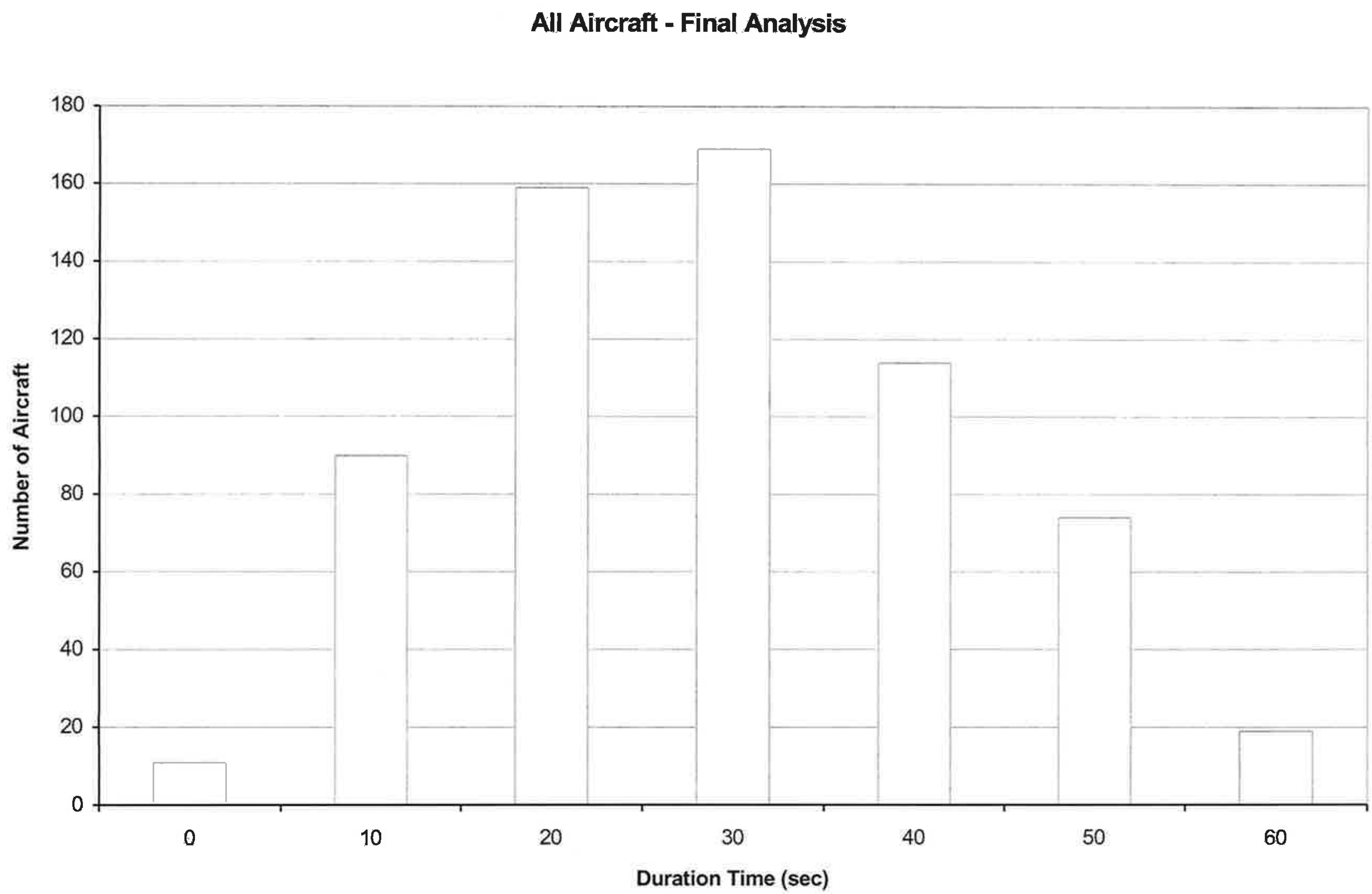


Figure 5-9 Histogram of Data in Table 5-2

6. MODELING AND CHARACTERIZATION

Investigations were conducted into the available analytical and simulation information concerning maximum jet blast velocities, expected jet blast duration times and effects of variations in measured peak jet blast velocities on duration times.

6.1 Peak Jet Blast Velocity Predictions

As a first approximation, the expected jet blast velocities encountered at the Windline can be estimated from computer-model predictions of the exhaust velocity as a function of distance and height for various aircraft. For example, in the jet-blast-maximum-speed/distance plots[2] in Figure 6-1, the curve for full takeoff thrust predicts that at 600 feet behind a B747, the blast speed is approximately 65 mph (56.5 knots). This speed is maintained from ground level to approximately 40-feet above the runway surface. Similar curves[3] predict that the horizontal extent of the blast will be over 125 feet on each side of the RWY 31L centerline. Applying the information from Figure 6-1 to the jet blast test configuration, at 760 feet behind a 747 at full takeoff thrust the jet blast velocity is approximately 55 mph (47.8 knots).

Morris[4] has developed a model for calculating jet blast velocity at a fixed position initially 70-feet behind a 747 aircraft as it accelerates for take-off. He estimates a constant aircraft acceleration of 7.92-feet/second^2, an absence of headwind, and a maximum value of jet blast velocity at the 70-foot fixed position of 620-ft/sec (365.8 knots). Based on this analysis the accelerating aircraft is approximately 760-feet from the initial position after 13 seconds. This corresponds to the distance of the Windline from the departure point in the JFK test configuration. Under those circumstances, the maximum jet blast velocity would be approximately 55 ft/sec (32.5 knots).

A useful comparison of the relative blast magnitudes from various aircraft is contained in Table 6-1. Data in this table were obtained from plots[3] similar to Figure 6-1. For the 747-400, for example, at Breakaway Thrust, the jet blast speed drops below 100 mph (87 knots) approximately 100 feet behind the aircraft. At full Takeoff Thrust, however, that speed is exceeded out to 460 feet behind the aircraft.

Table 6-1. Distance Along Centerline (ft) Where Jet Blast Falls below 100 MPH

RCRAFT TYPE	BREAKAWAY THRUST	TAKEOFF THRUST
777-200	0	410
747-400	100	460
737-300	20	190
737-200	30	140
757-200	40	470
767-300	80	470
747-100	50	410

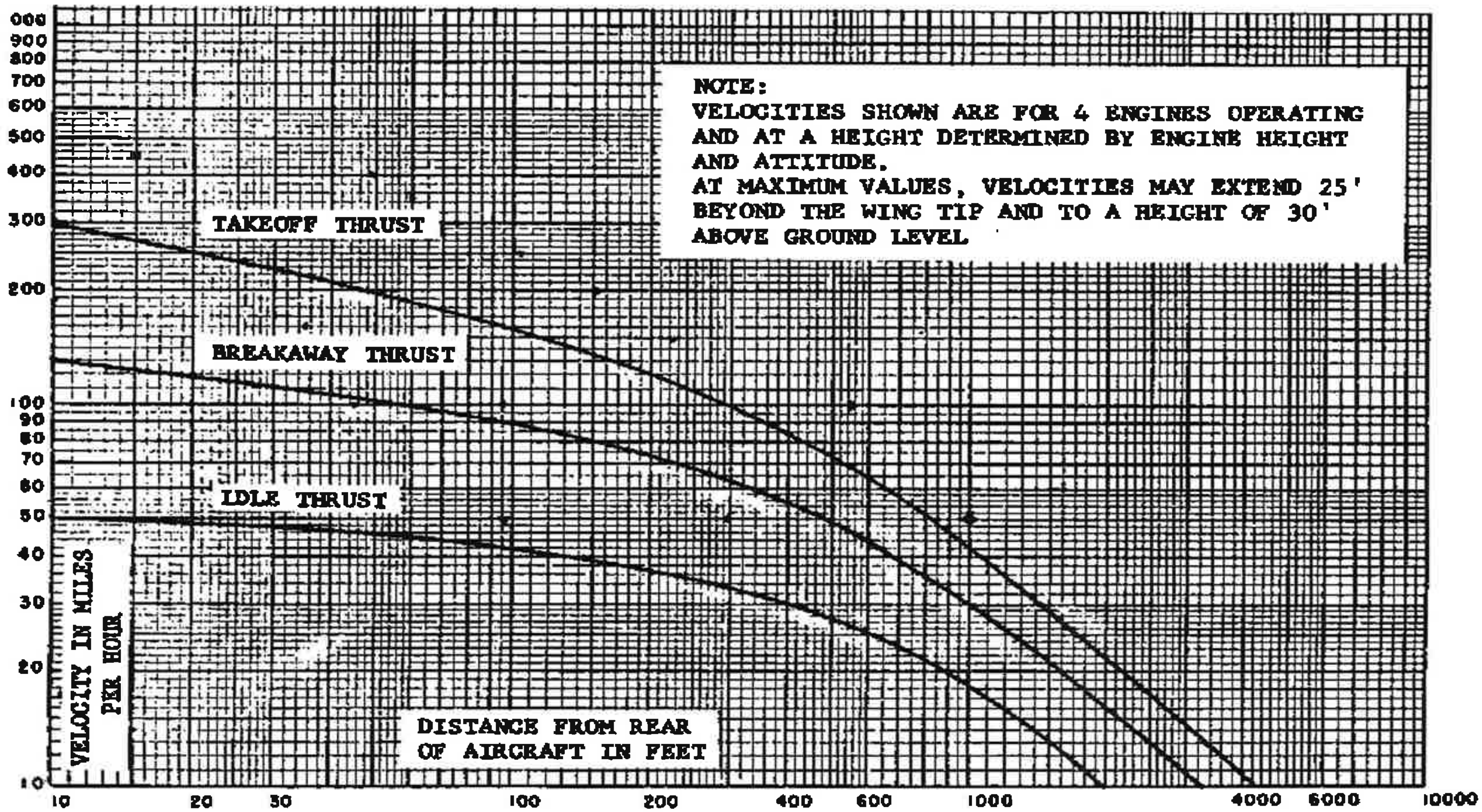


Figure 6-1. Velocity Distance Curves for Boeing 747

These computer generated predictions for Takeoff Thrust contain no surprises but do show that a newer and larger aircraft, such as a B777, does not necessarily produce a stronger blast at a given distance than a smaller, older aircraft such as a B757.

6.2 Jet Blast Duration Time Predictions

Referring to Figure 6-1, at a distance of 4300 feet behind the departing B747, the maximum jet blast velocity is estimated to be 10 mph (8.7 knots). At an acceleration of 8 ft/sec^2, the velocity of the aircraft at the 4300-foot point is approximately 256 ft/sec (151 knots) which is close to the rotation velocity of the aircraft. The aircraft reached the rotation point in 32 seconds. This suggests that the jet blast velocity measured at the Windline distance falls below the 4-knot threshold value in less than 60 seconds including an additional 5 seconds that must be added to account for the initial jet blast transport time from the aircraft to the Windline.

A model of jet blast decay, but with some simplifying assumptions, was developed at the Volpe Center by Zhang[5] as part of this program. The detailed description of this model is included on the CD-ROM discussed in Appendix A2. Three simplifying assumptions were made: first, an aircraft acceleration value of g/4 was used; second, the maximum jet blast velocity from a departing B777 as measured at the Windline while the aircraft was stationary at the end of the runway would be used as the starting value for decay estimating purposes; and third, that the acceleration of the aircraft during the takeoff run was constant. As the aircraft proceeded down the runway, the measured value maximum at the Windline would decrease. The result of this modeling appears in Figure 6-2. Included in Figure 6-2 for comparison purposes is a jet blast duration profile for a departing Boeing 777. Assuming that the jet blast speed of 42 mph (36.5-knots) measured at the Windline was the maximum within the jet blast volume and an aircraft acceleration of 8 ft/sec^2, the predicted values of the jet blast speed as the aircraft accelerates away from the Windline compare well with the measured values at the lower speeds. The jet blast velocity, according to the model should decay to the 4-knot threshold in approximately 20 seconds. An additional 5 seconds must be added to account for the initial jet blast transport time from the aircraft to the Windline. The total jet blast duration time is 25 seconds. This estimate for jet blast duration is close to the measured value. The departure of the predicted value from the measured value at the higher speeds is due to Windline effects discussed in more detail in the next section.

Morris[4] also calculates the rate of decay of the maximum velocity of the jet blast at a fixed point, namely 70 feet behind the departing aircraft when it starts its takeoff roll. Again, using his calculated maximum jet blast velocity at 13 seconds, which corresponds to a fixed position 760 feet behind the departing aircraft, his estimate of the time to decay to 6.8 ft/sec (4 knots) is approximately 27 seconds. Again, an additional 5 seconds must be added to account for the initial jet blast transport time from the aircraft to the Windline. The total jet blast duration time is 32 seconds compared to the measurements made during the Jet Blast Test Program. Both the Morris and Zhang model predictions resulted in values of jet blast duration that were half of the measured values. The difference is probably due to the thrust application process practiced by pilots. In the B747 Outlier analysis, the conclusion was that the pilot accelerated the aircraft more slowly than pilots of other B747 aircraft. During the summer months, this might be

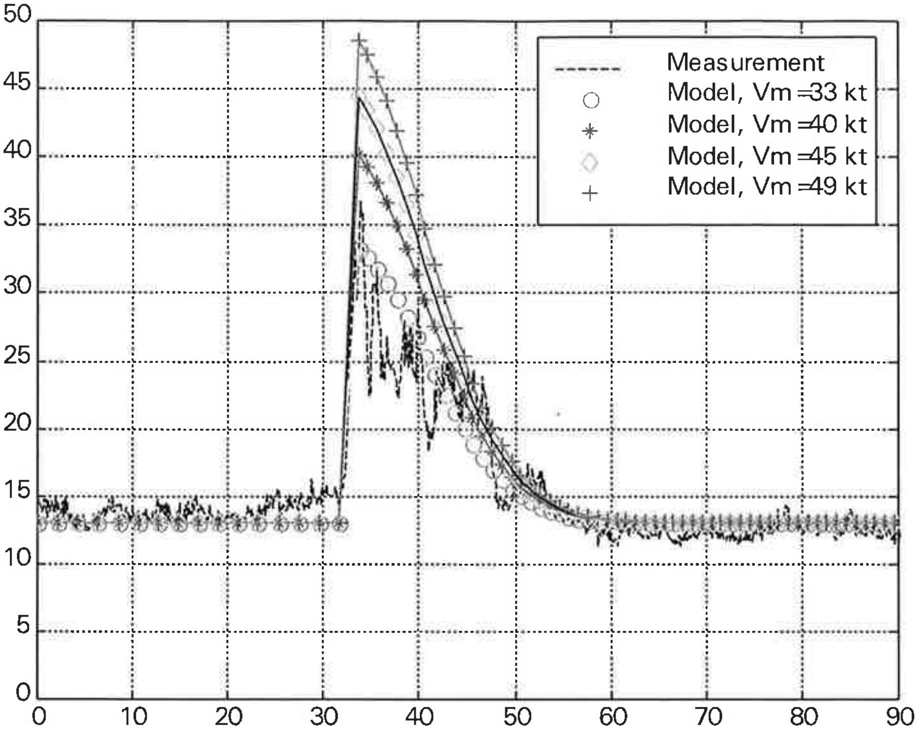


Figure 6-2. Velocity Decay Predictions from Zhang's Model

expected where large aircraft loads are involved. In general, perhaps the acceleration values selected by the modelers were underestimated. In any case, the models' predictions were useful in establishing reference values.

6.3 Windline Array Effects

Several effects on the measurements were attributed to the finite length of the Windline and the separation between Windline poles. These effects are discussed in detail in the following sections.

6.3.1 Crosswind Effects

The crosswind component of the ambient wind may displace the jet blast winds significantly from the extended runway centerline. A demonstration of the effect of the crosswind component on the jet blast is shown in Figure 6-3. These histograms show the distribution of jet blast speeds, when the maximum jet blast speed is measured at each of the seven Windline poles. The sequence of three histograms reading from the top histogram to the bottom histogram demonstrate the effect of increasing crosswind velocity on where the maximum jet blast velocity is measured. In the bottom histogram, the crosswind is of sufficient magnitude to effectively move the jet blast completely off the Windline. In each of the histograms, the crosswind is blowing left to right corresponding to a crosswind perpendicular to the RWY 13R extended centerline in the direction from Windline pole 1 to Windline pole 7.

This effect occasionally prevented obtaining valid jet blast data.

6.3.2 Effects of Peak Jet Blast Velocity on Duration

The Windline is a somewhat coarse sensor array. The headwind anemometers are spaced 5 feet apart vertically to a height of 45 feet. The Windline poles themselves are spaced 55 feet apart horizontally. It was expected, as a result of the earlier jet blast test effort, that the jet blast at the Windline would extend from ground level to approximately 70 feet in height. Given this size, there was a high likelihood that velocities measured by the anemometers on a given pole would be close to the peak velocity. At issue is what the effect would be on jet blast duration time if the peak velocity was not that which was measured. This effect was compounded by the crosswind effect discussed in Section 6.3.1.

From the scatter plots of jet blast duration versus peak velocity from Figure 5-2 and Figure 5-3, there is a subtle relationship between the two parameters. In reviewing the literature available on jet blast characteristics, it became clear that a simple consolidated acceleration model was necessary in order to determine the nature of any relationship between the peak velocity of the jet blast and its measured duration. Zhang[5] developed such a model based on an 8-ft/sec^2 aircraft acceleration, computer-generated estimates[2] of jet blast velocity at a short distance behind the engine nozzle, and the peak velocity and decay profile measured for a B777 run.

Referring once again to Figure 6.2, a number of additional profiles appear on the plot. These resulted from exercising the model for several additional peak jet blast velocities. The result shown in Figure 6-2 shows a barely perceptible change in jet blast duration time. The change in jet blast duration time from the model calculations appears in Figure 6-4 the relative changes in duration time as a function of higher values of peak jet blast velocity. If the measurement of jet blast peak velocity was 35 knots, but the actual value was 45 knots, from Figure 6-4, the difference in the duration time would be approximately 1.5 seconds. This suggests that for high values of peak jet blast velocity, small differences between measured values and actual values would not result in significant increases in jet blast duration time. However, when the magnitude of the measured value is low, then duration times will be unreliable. This would have little effect on the long duration time portion of the scatter plots shown in Figure 5-2 and Figure 5-3. The primary effect would be to increase some of the lower magnitude measured duration times. There is no basis for believing that all or any duration times would increase beyond the 70-seconds line.

These modeling results also add credence to the observation that there appears to be a subtle relationship between the peak jet blast velocity and duration time.

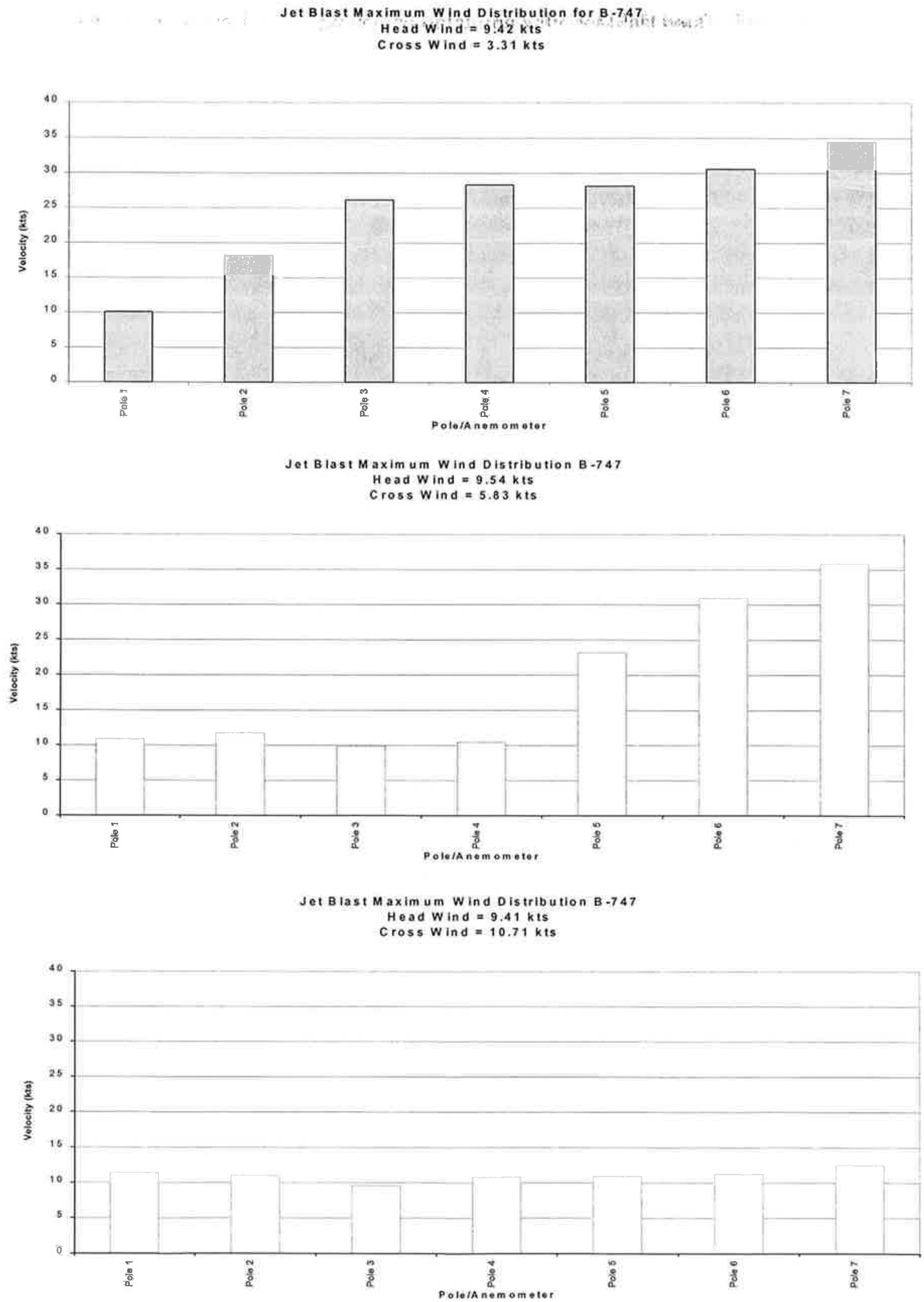
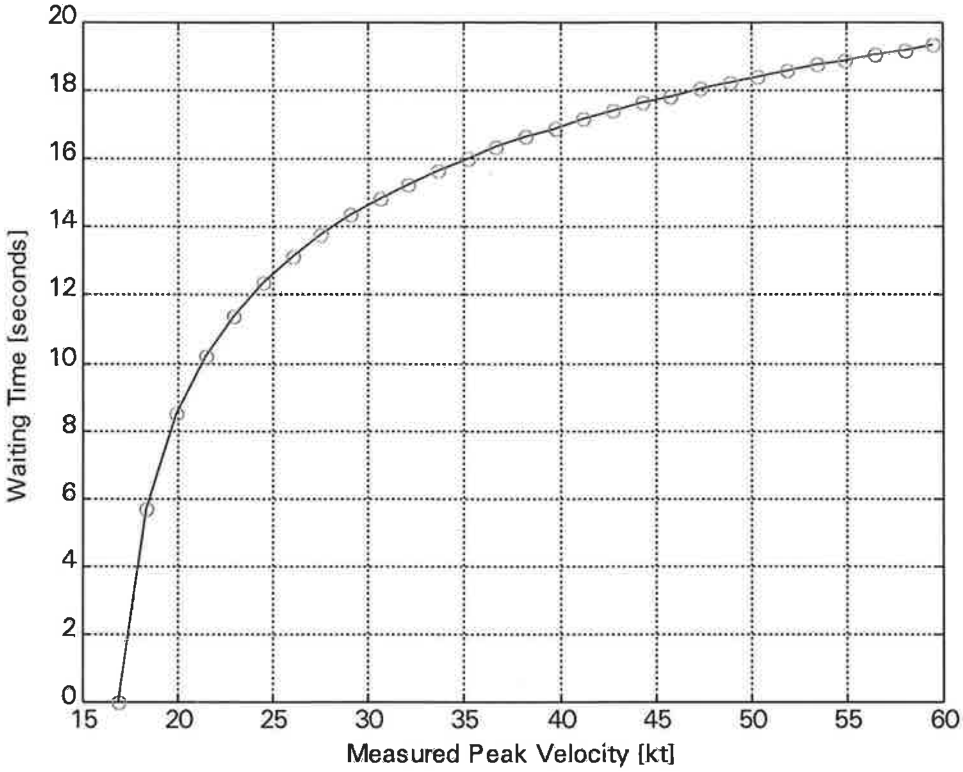


Figure 6-3. Influence of Crosswind on Intersection of Jet Blast and Windline



6-4. Effect of Peak Jet Blast Velocity on Duration Time

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY OF RESULTS

The results of this Jet Blast Test Program indicate that:

- The residual jet blast remaining after 60 seconds is no worse than that of an idling B747 waiting for departure;
- The jet blasts from 100% of the aircraft analyzed decayed to within 10 knots of ambient headwind within 50 seconds;
- The jet blasts from 100% of the aircraft analyzed decayed to within 4 knots of ambient headwind within 70 seconds;
- The size of the jet blast wind cross section at the Windline distance would allow use of shorter instrumented poles to monitor jet blast peak velocities.
- Taxiing aircraft that move into the departure hold position on the runway between 20 seconds and 60 seconds after the start of roll of the lead aircraft, will cause light jet blast turbulence at the 760-ft distance.
- Aircraft that cycle engines while holding at the runway departure position will cause jet blast turbulence at the 760-ft distance.

7.2 CONCLUSION

The test data show that the current procedure of holding Heavy departures on RWY 31L when arriving Large and Small aircraft are less than 5 nautical miles from RWY 4R should be reviewed in an effort to reduce current separations.

7.3 RECOMMENDATIONS

- Procedures Modification - Start a phased separation reduction program to 3 nautical miles in steps of 1 nautical mile while monitoring the wind field at the 31L/4R area.
- Install wind measurement instrumentation at the RWY 31L/4R area for measuring RWY 4R crosswinds to an altitude of 75 feet. The instrumentation could be a compact device similar to a Mini-SODAR (Sound Detection and Ranging) instrument that would not intrude into the FAR Part 77 surfaces or an array of monitoring sonic anemometers mounted on short poles. During actual Heavy departures from RWY 31L, both ambient wind and jet blast would be monitored in conjunction with Large and Small aircraft arrivals at RWY 4R under current and reduced separation rules.

- Encounter Simulation - Perform a simulation of aircraft encounters with jet blast under conditions similar to the 4R/31L runway configuration at JFK, and use the simulation results and the collected jet blast database to explore further possible reductions in departure hold times.

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3. Jet Engine Wake and Noise Data from Boeing Company Airplane Group Reports, "Airplane Characteristics for Airport Planning" 1969 – 1995.
4. Morris, P. J. "A Simple Model of Jet Blast" private communication, 1996.
5. Zhang, Y. "A Simple Fluid Dynamics Model For Jet Blast Velocity Distribution Formulation," Private Communication, January, 2000.

Appendix A1. Scatter Plots by Aircraft Type

Appendix A1 contains the summary scatter plots for all the aircraft whose jet blast duration times were analyzed during the test period and scatter plots by aircraft type.

Figures A1.1 and A1.2 are summary plots of jet blast duration time for all aircraft as a function of average ambient headwind using a 4-knot threshold and a 10-knot threshold, respectively.

Figures A1.3 and A1.4 are summary plots of jet blast duration time for all aircraft as a function of peak jet blast velocity using a 4-knot threshold and a 10-knot threshold, respectively.

Figures A1.5 and A1.6 are summary plots of jet blast duration time for all aircraft as a function of average crosswind using a 4-knot threshold and a 10-knot threshold, respectively.

The remaining plots in Figures A1.7 through A1.24 are by aircraft type with jet blast duration time plotted as a function of average ambient head wind for both the 4-knot and 10-knot thresholds. The following are the aircraft types in the order that they appear:

- A330 – Figures A1.7 and A1.8
- A340 – Figures A1.9 and A1.10
- B747 – Figures A1.11 and A1.12
- B757 – Figures A1.13 and A1.14
- B767 – Figures A1.15 and A1.16
- B777 – Figures A1.17 and A1.18
- DC10 – Figures A1.19 and A1.20
- L1011 – Figures A1.21 and A1.22
- MD11 – Figures A1.23 and A1.24

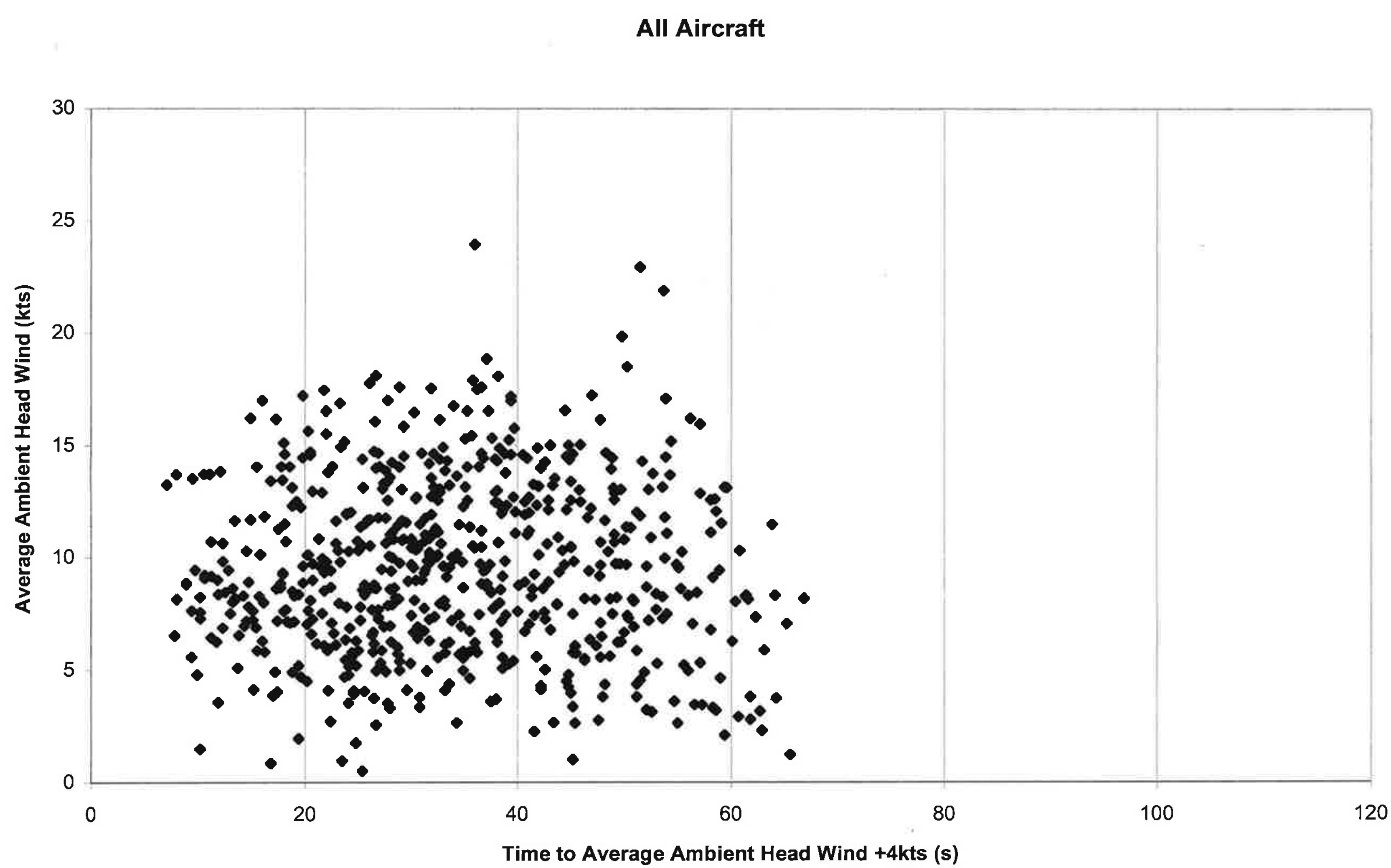

All Aircraft
Average Ambient Head Wind (kts)
30
25
20
15
10
5
0
0
20
40
60
80
100
120
Time to Average Ambient Head Wind +4kts (s)

Figure A1.1

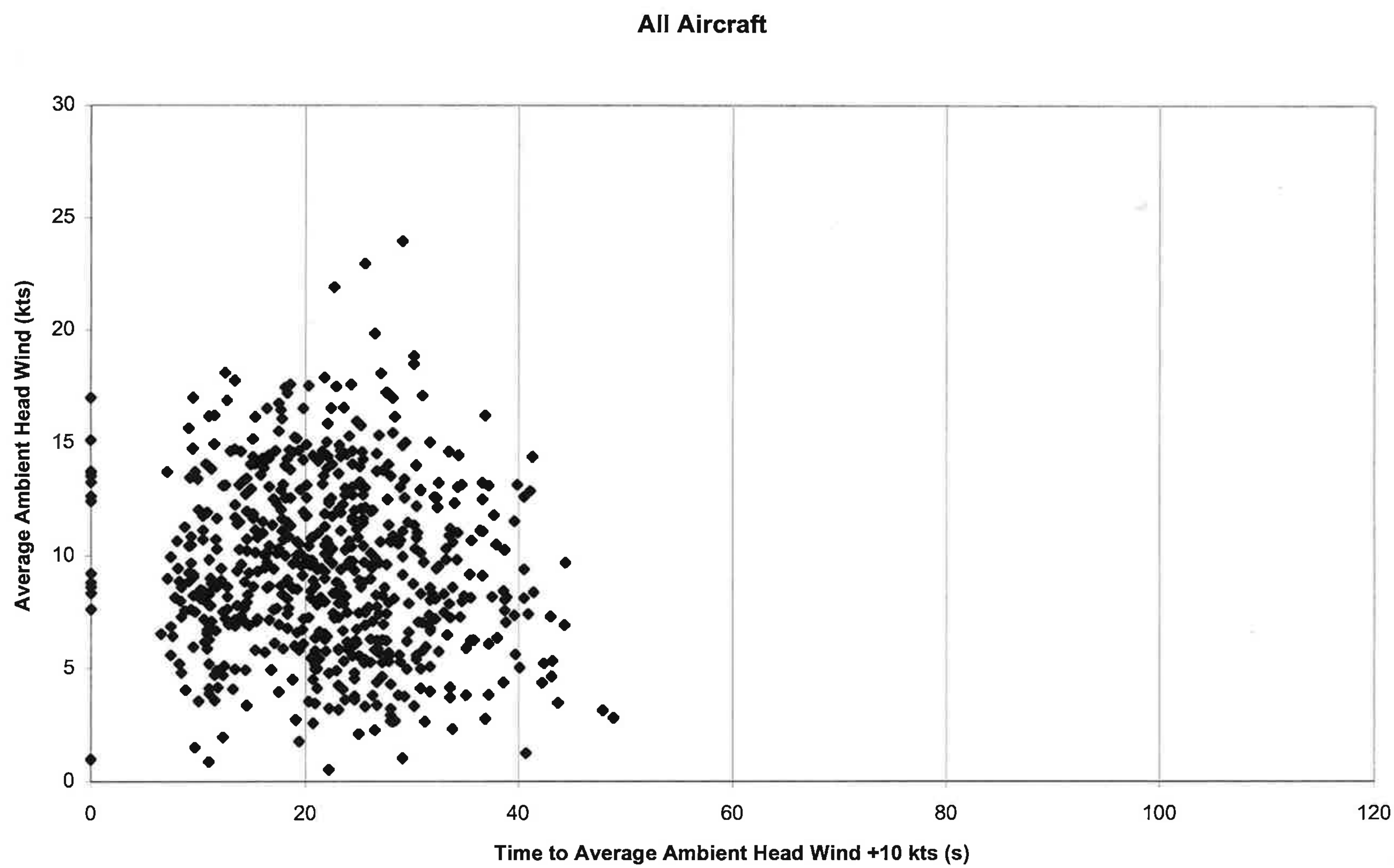

All Aircraft
30
25
20
15
10
5
0
Average Ambient Head Wind (kts)
0
20
40
60
80
100
120
Time to Average Ambient Head Wind +10 kts (s)

Figure A1.2

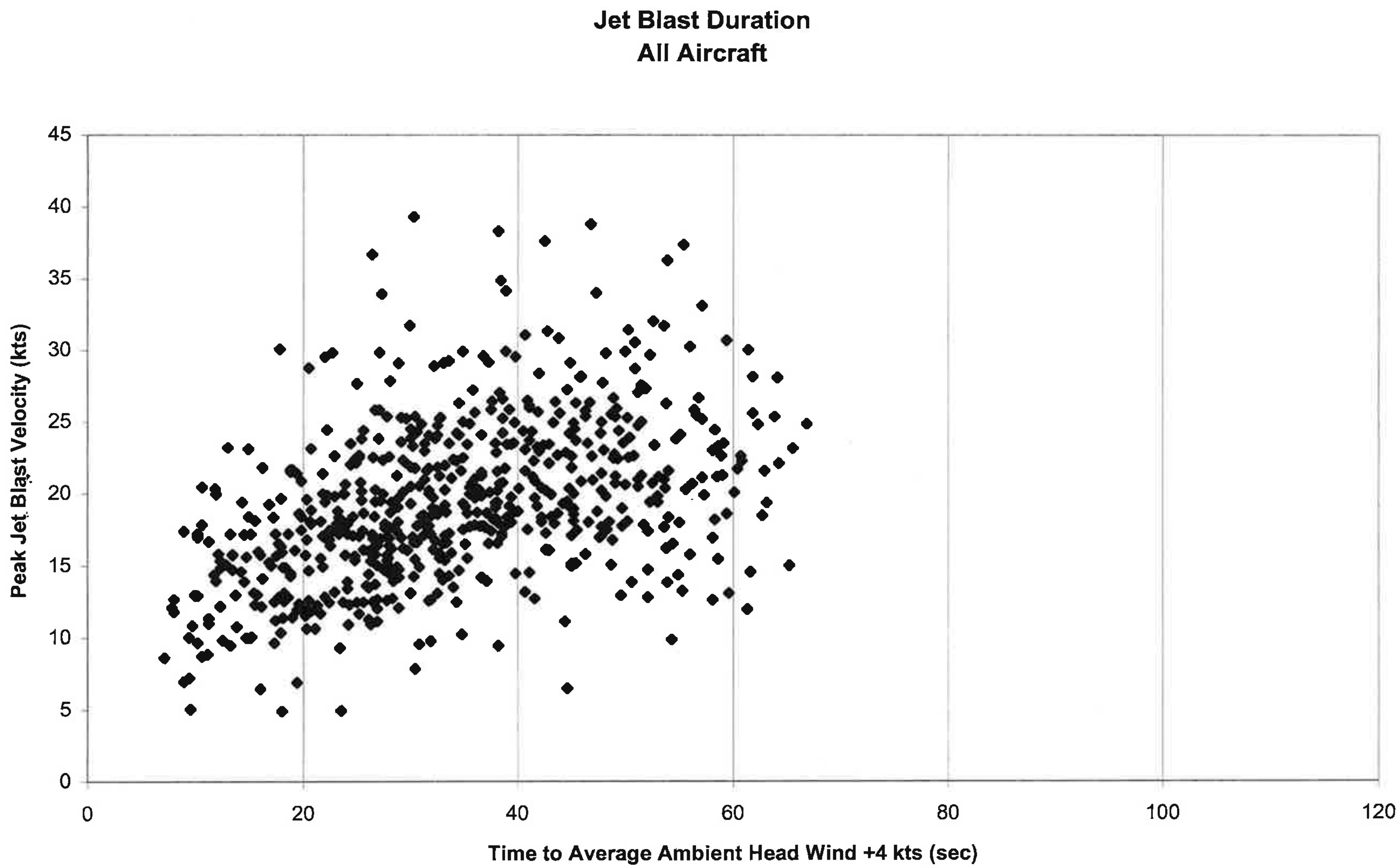

Jet Blast Duration
All Aircraft
Peak Jet Blast Velocity (kts)
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
Time to Average Ambient Head Wind +4 kts (sec)

Figure A1.3

Jet Blast Duration
All Aircraft

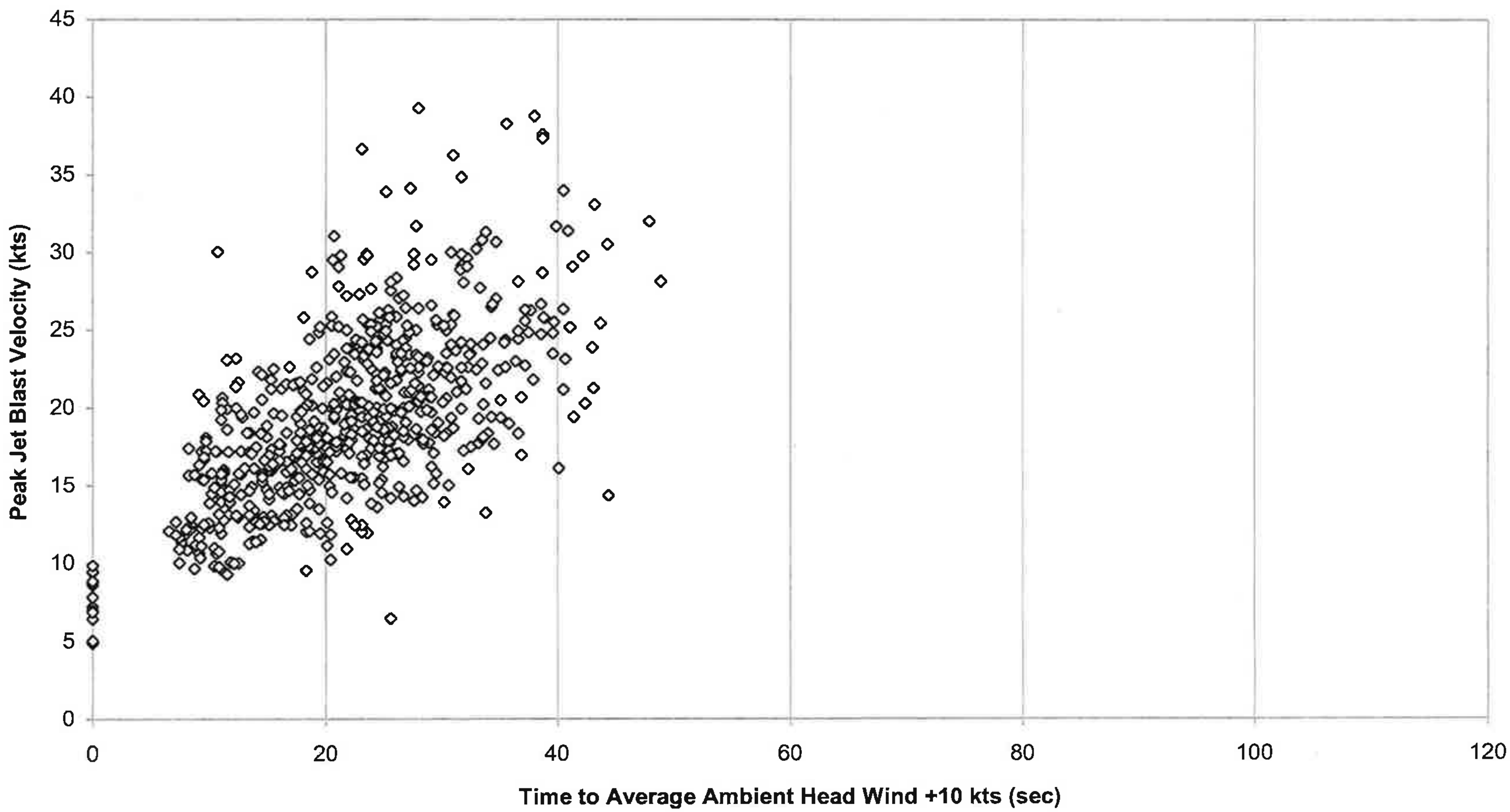


Figure A1.4

All Aircraft

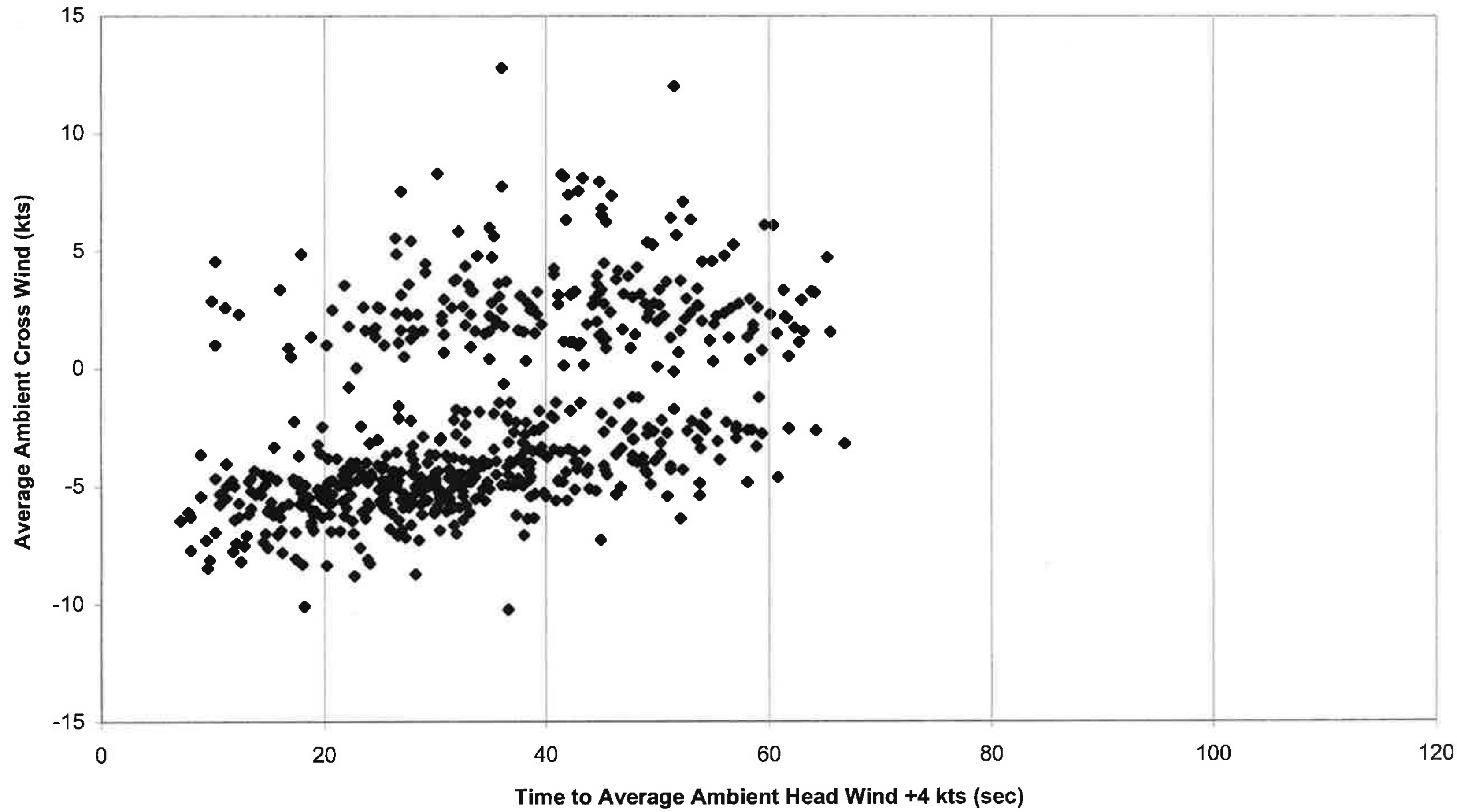


Figure A1.5

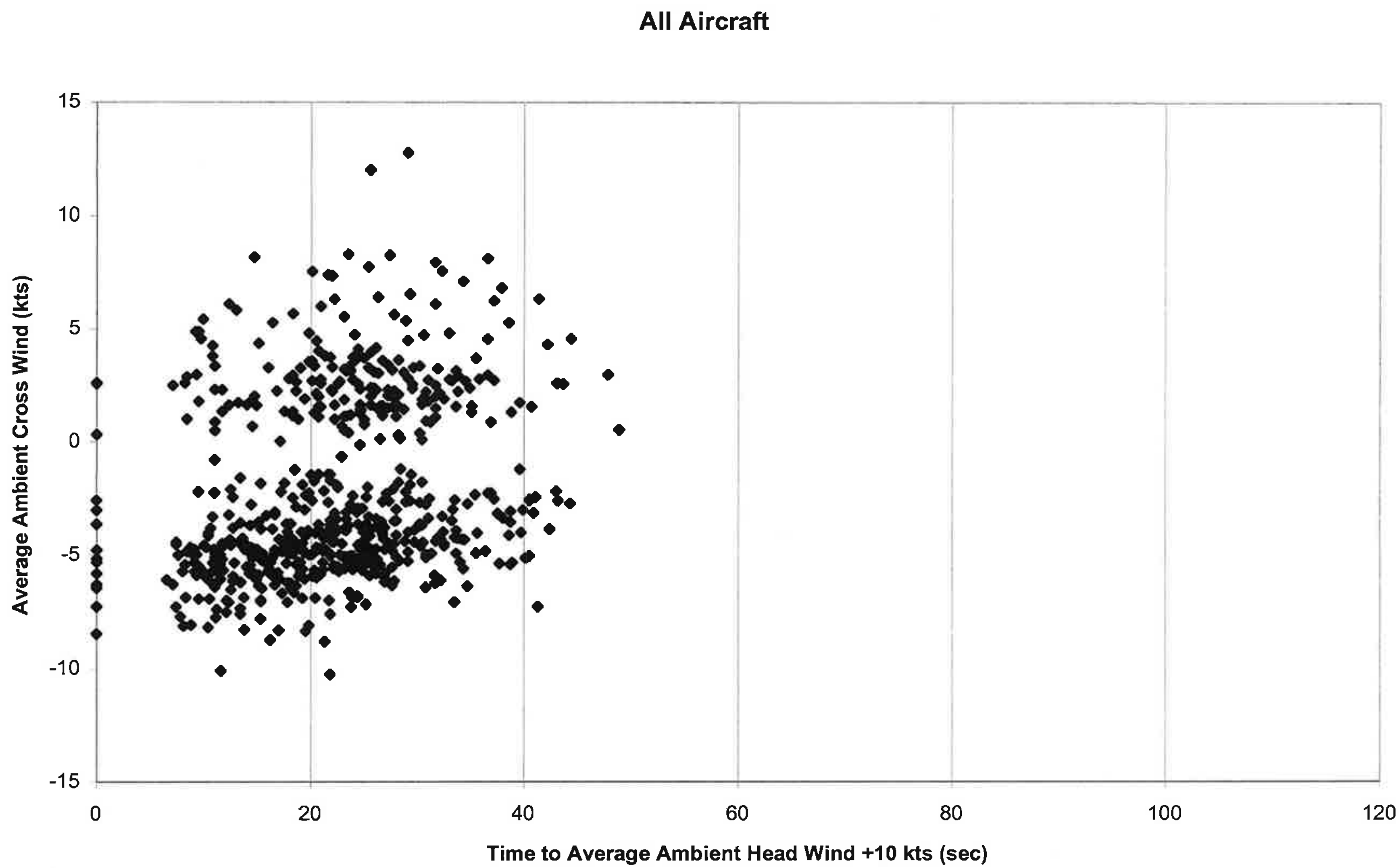

All Aircraft
15
10
5
0
-5
-10
-15
Average Ambient Cross Wind (kts)
0
20
40
60
80
100
120
Time to Average Ambient Head Wind +10 kts (sec)

Figure A1.6

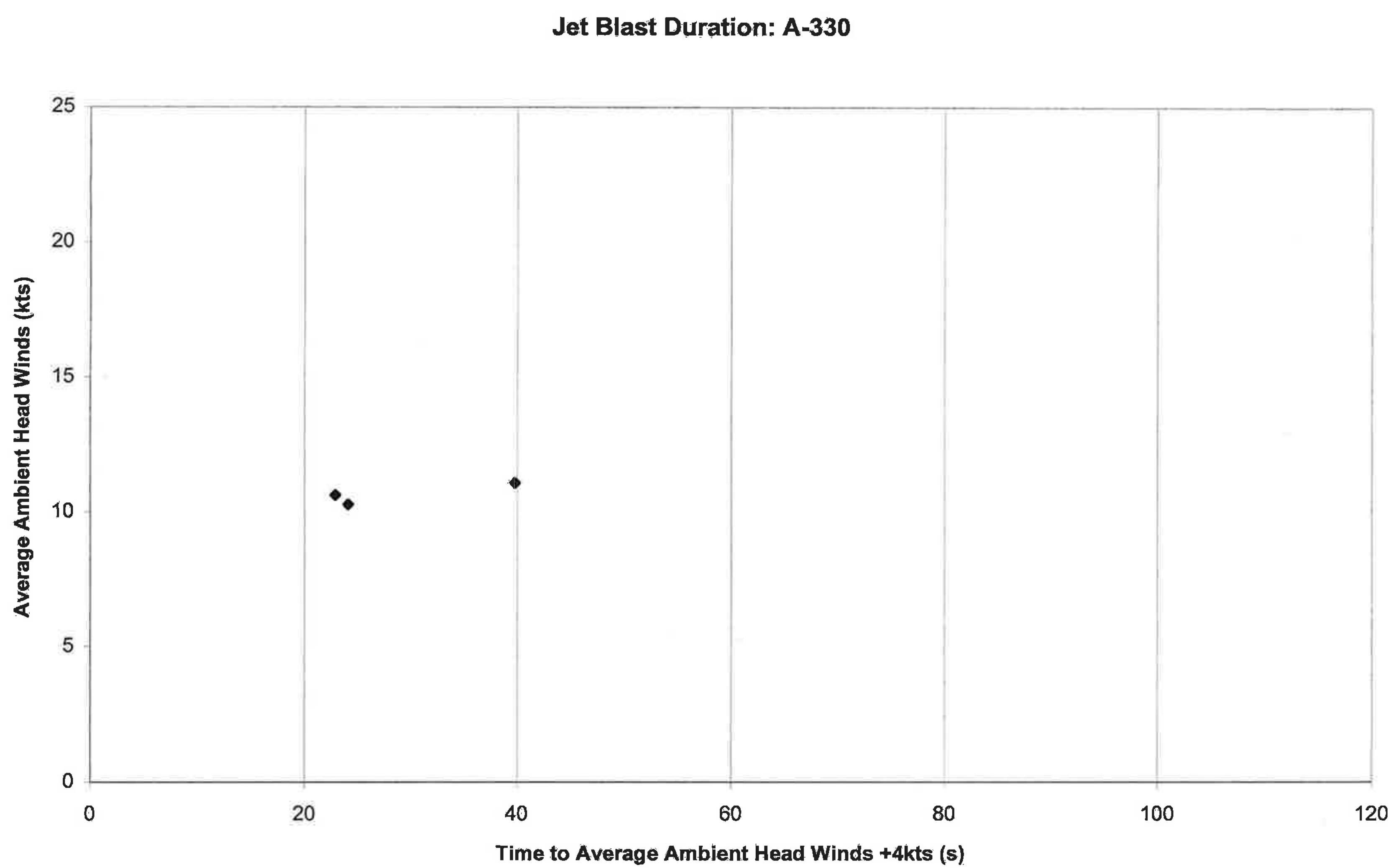

Jet Blast Duration: A-330
25
20
15
10
5
0
Average Ambient Head Winds (kts)
0
20
40
60
80
100
120
Time to Average Ambient Head Winds +4kts (s)

Figure A1.7

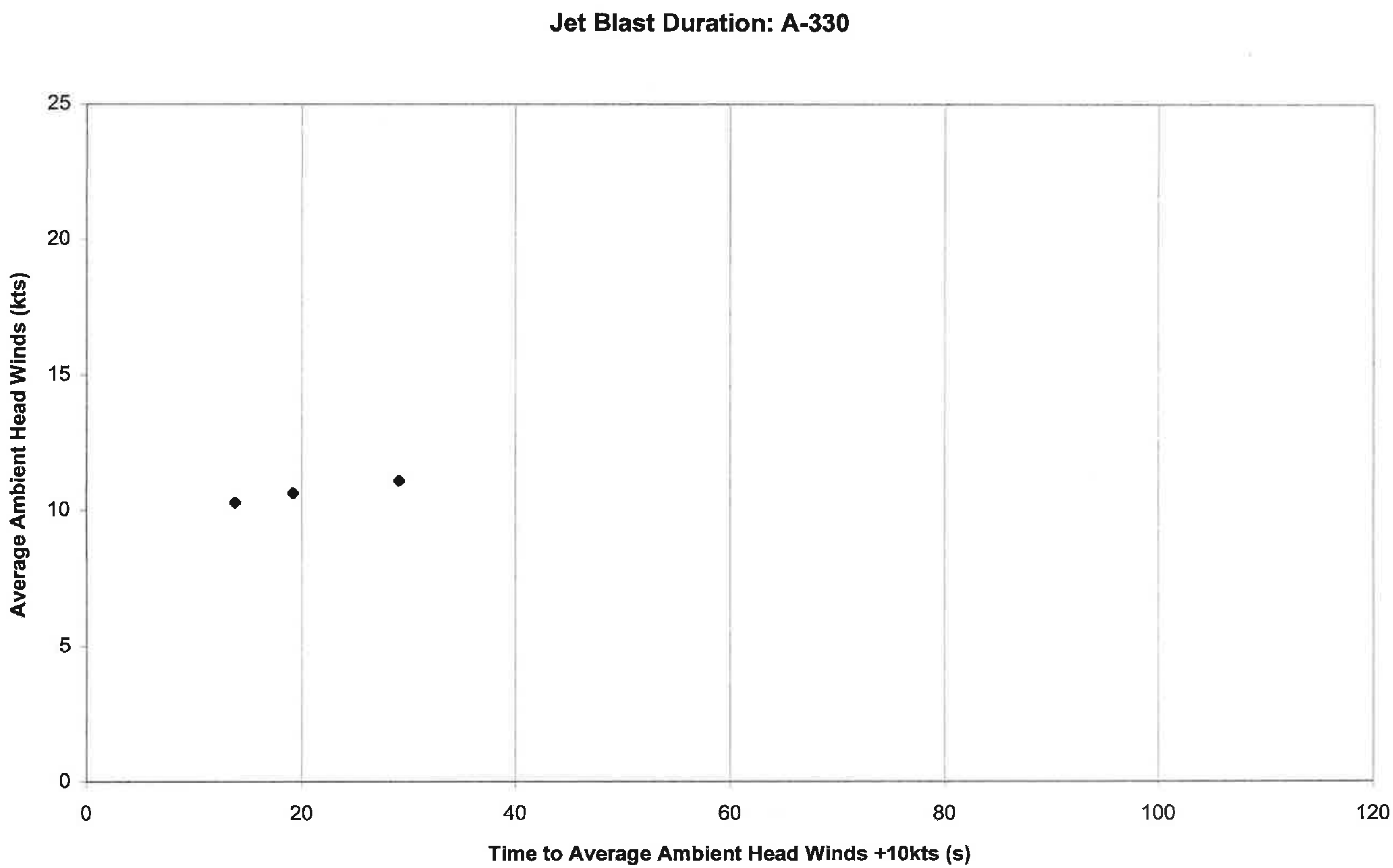

Jet Blast Duration: A-330
Average Ambient Head Winds (kts)
25
20
15
10
5
0
0
20
40
60
80
100
120
Time to Average Ambient Head Winds +10kts (s)

Figure A1.8

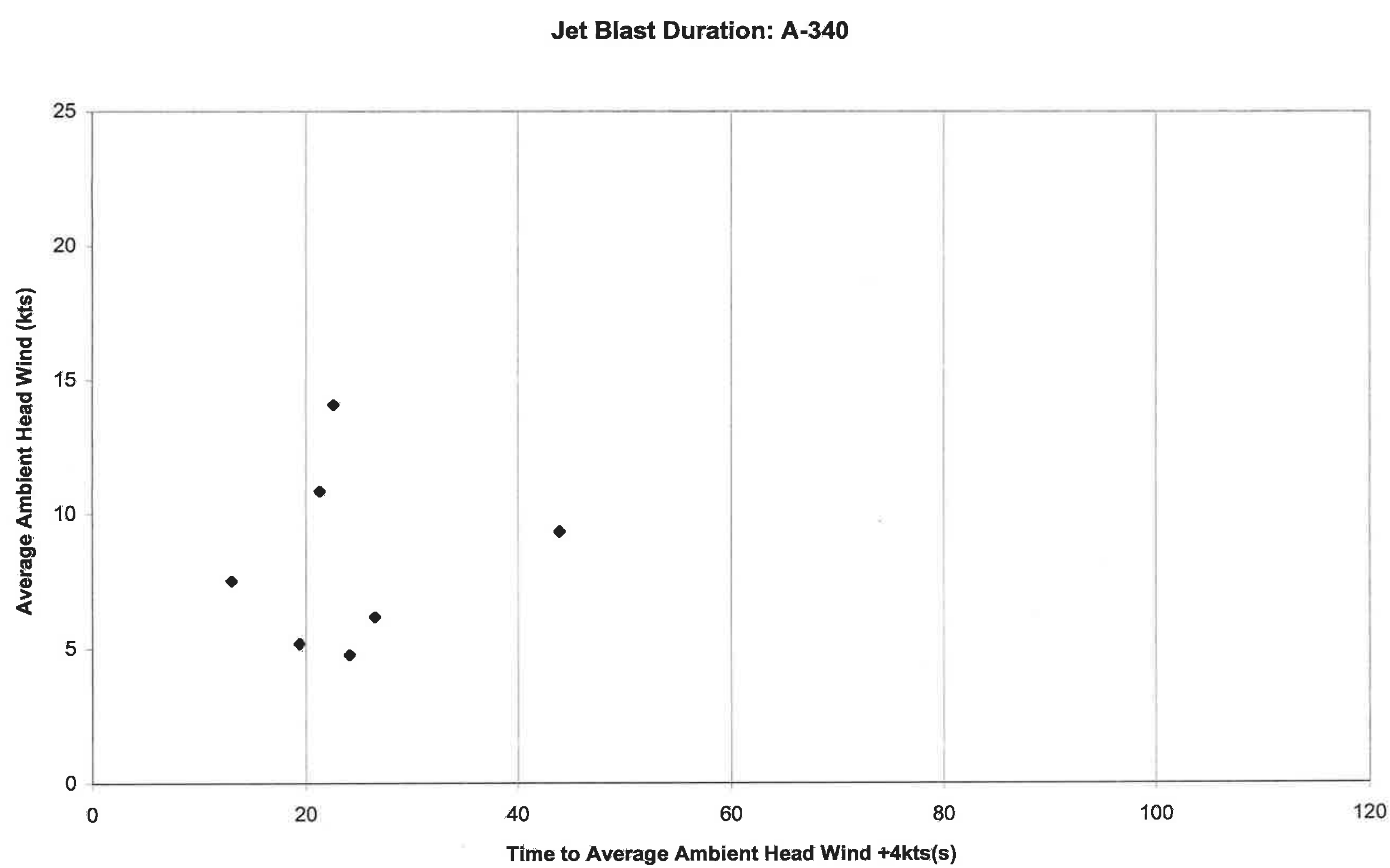
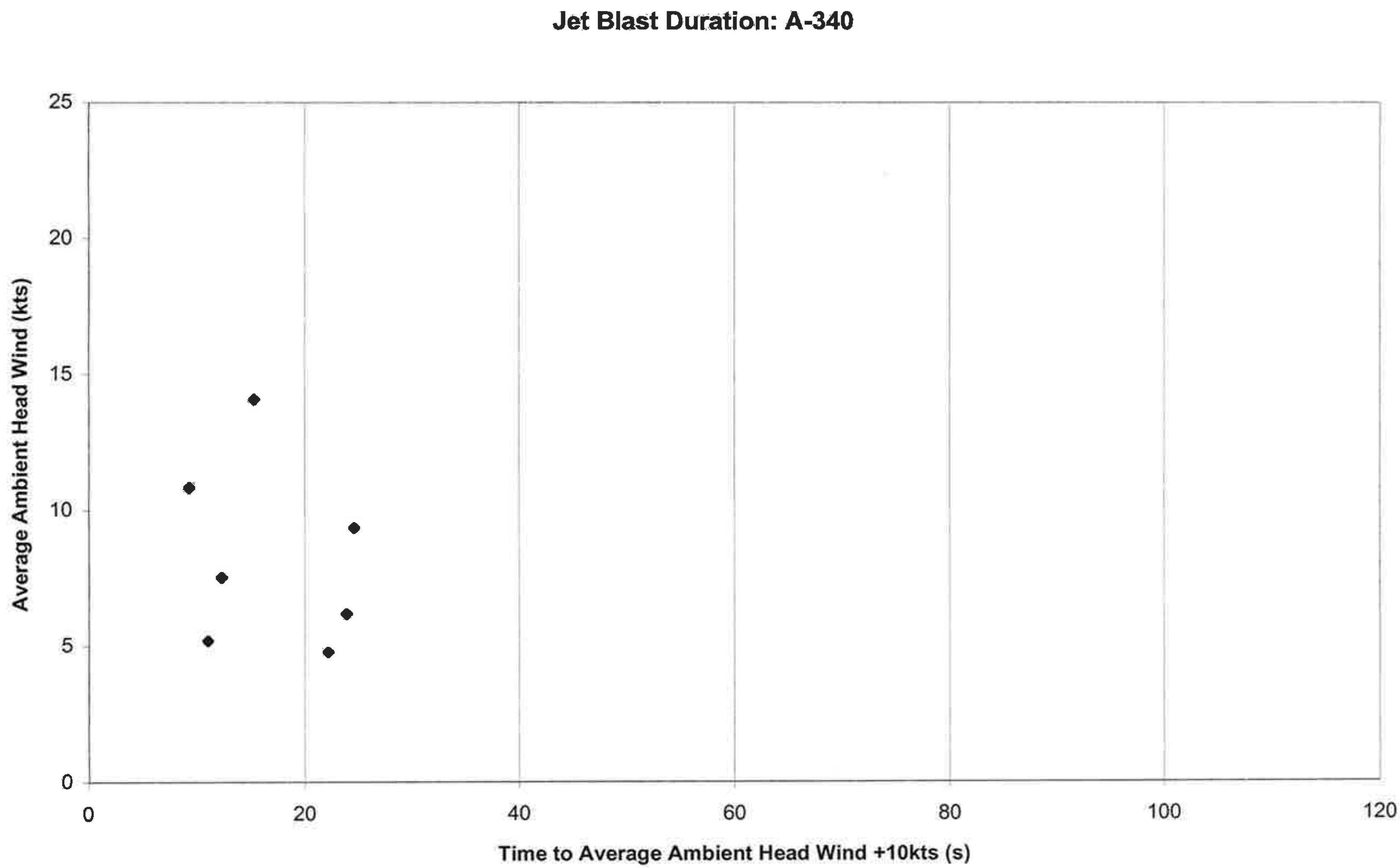

Jet Blast Duration: A-340
Average Ambient Head Wind (kts)
25
20
15
10
5
0
0
20
40
60
80
100
120
Time to Average Ambient Head Wind +4kts(s)

Figure A1.9



Jet Blast Duration: A-340
Average Ambient Head Wind (kts)
25
20
15
10
5
0
0
20
40
60
80
100
120
Time to Average Ambient Head Wind +10kts (s)

Figure A1.10

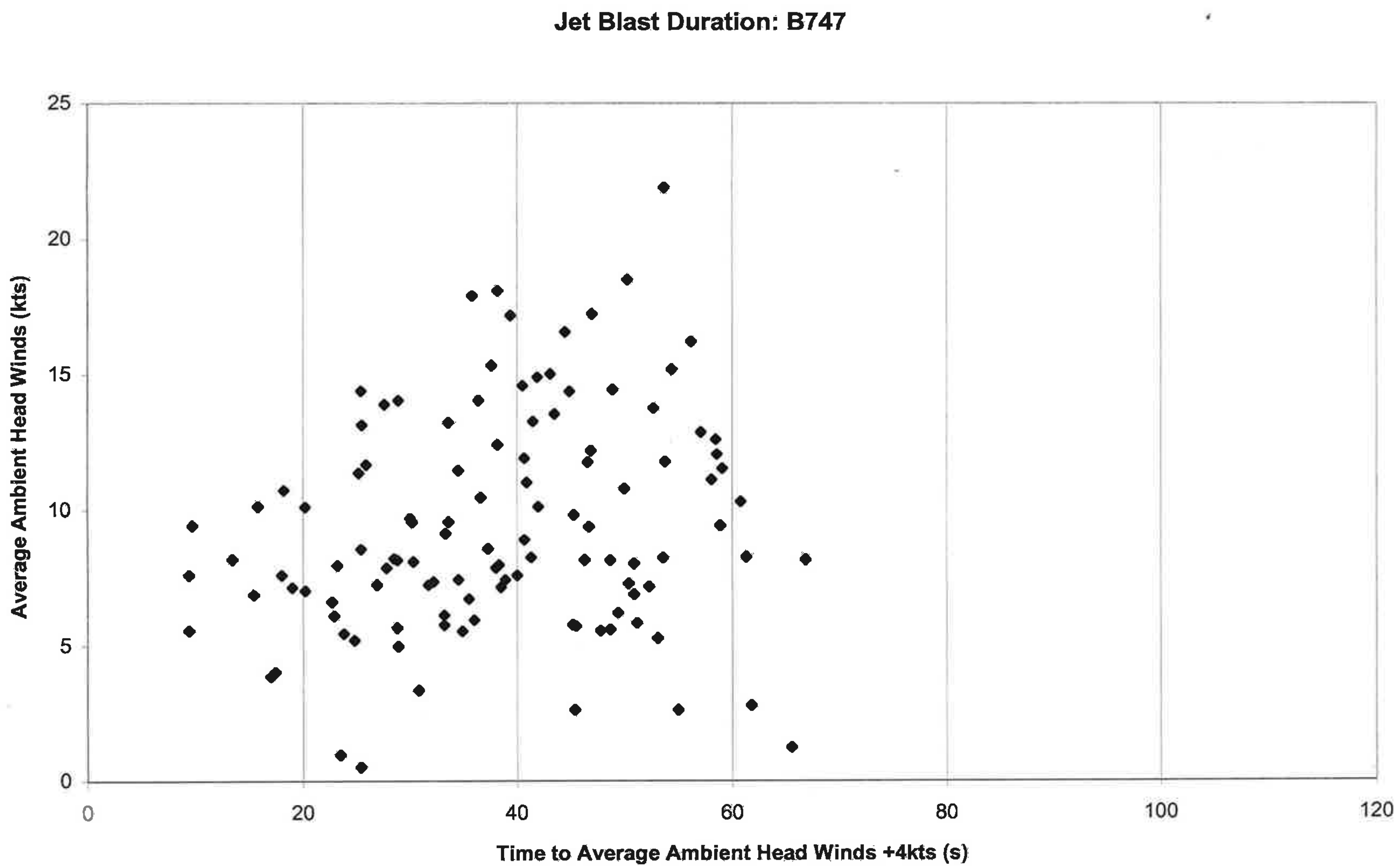

Jet Blast Duration: B747
Average Ambient Head Winds (kts)
25
20
15
10
5
0
0
20
40
60
80
100
120
Time to Average Ambient Head Winds +4kts (s)

Figure A1.11

Jet Blast Duration: B747

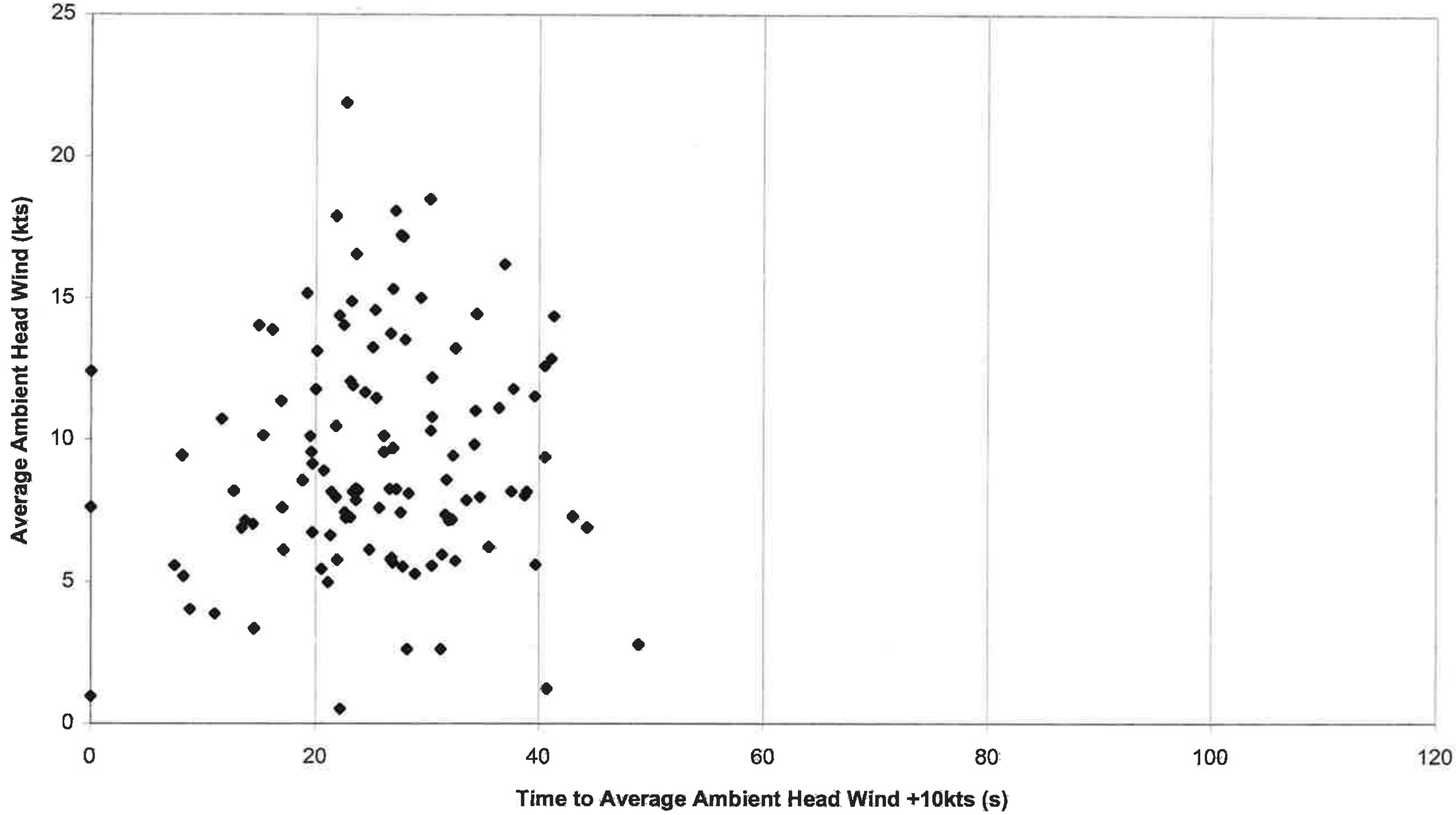


Figure A1.12

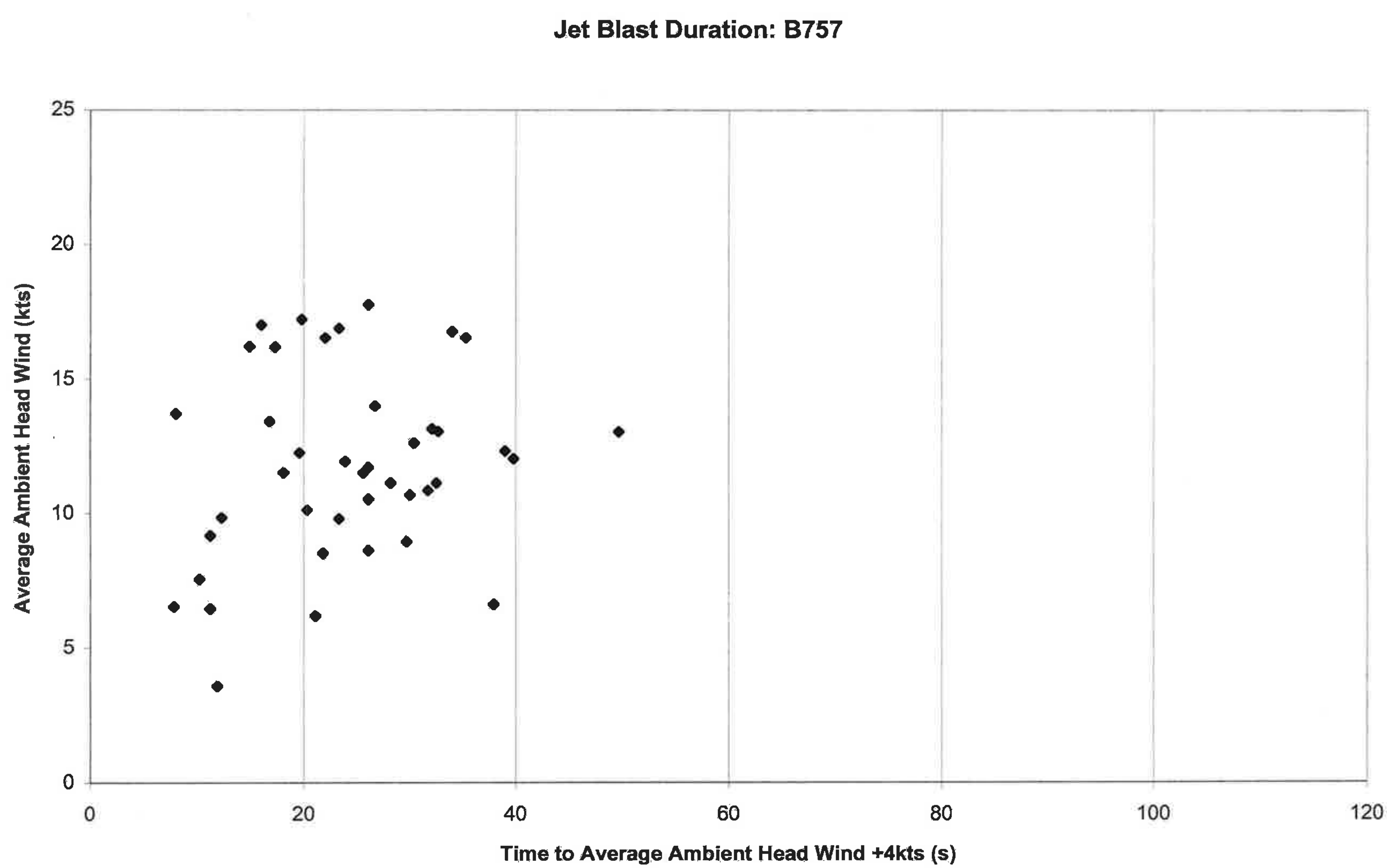

Jet Blast Duration: B757
Average Ambient Head Wind (kts)
Time to Average Ambient Head Wind +4kts (s)
0
5
10
15
20
25
0
20
40
60
80
100
120

Figure A1.13

Jet Blast Duration: B757

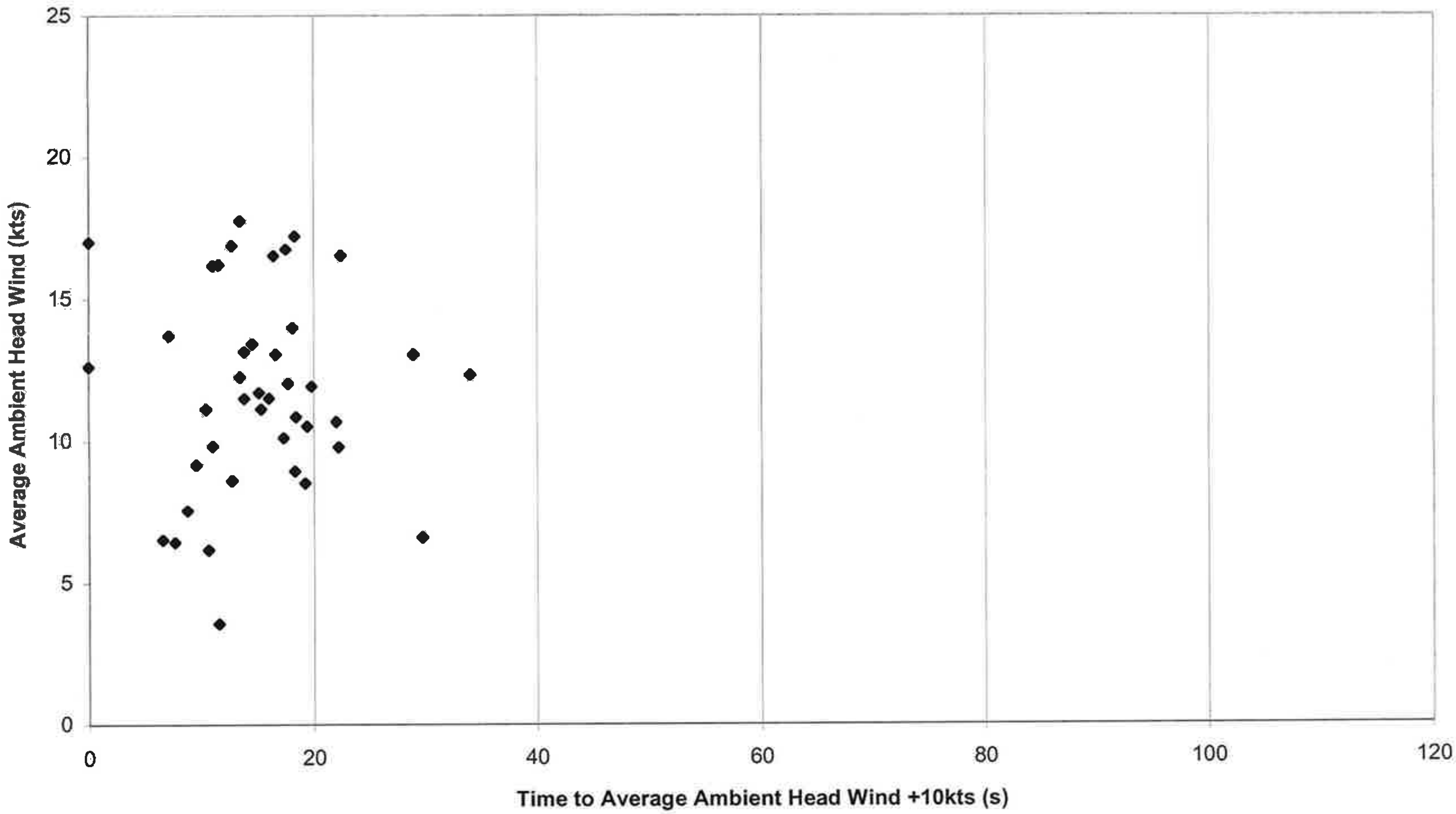


Figure A1.14

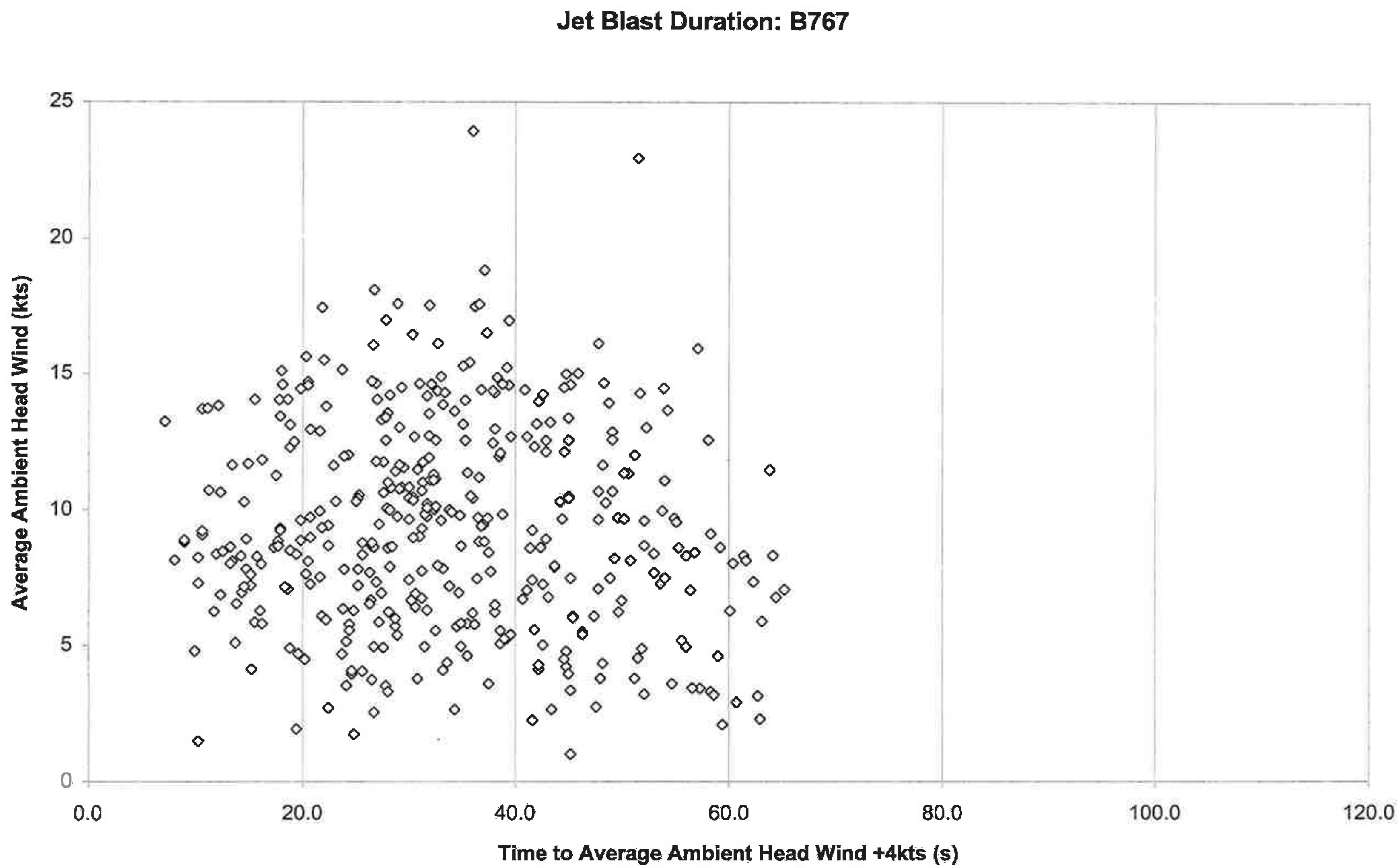

Jet Blast Duration: B767
Average Ambient Head Wind (kts)
25
20
15
10
5
0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time to Average Ambient Head Wind +4kts (s)

Figure A1.15

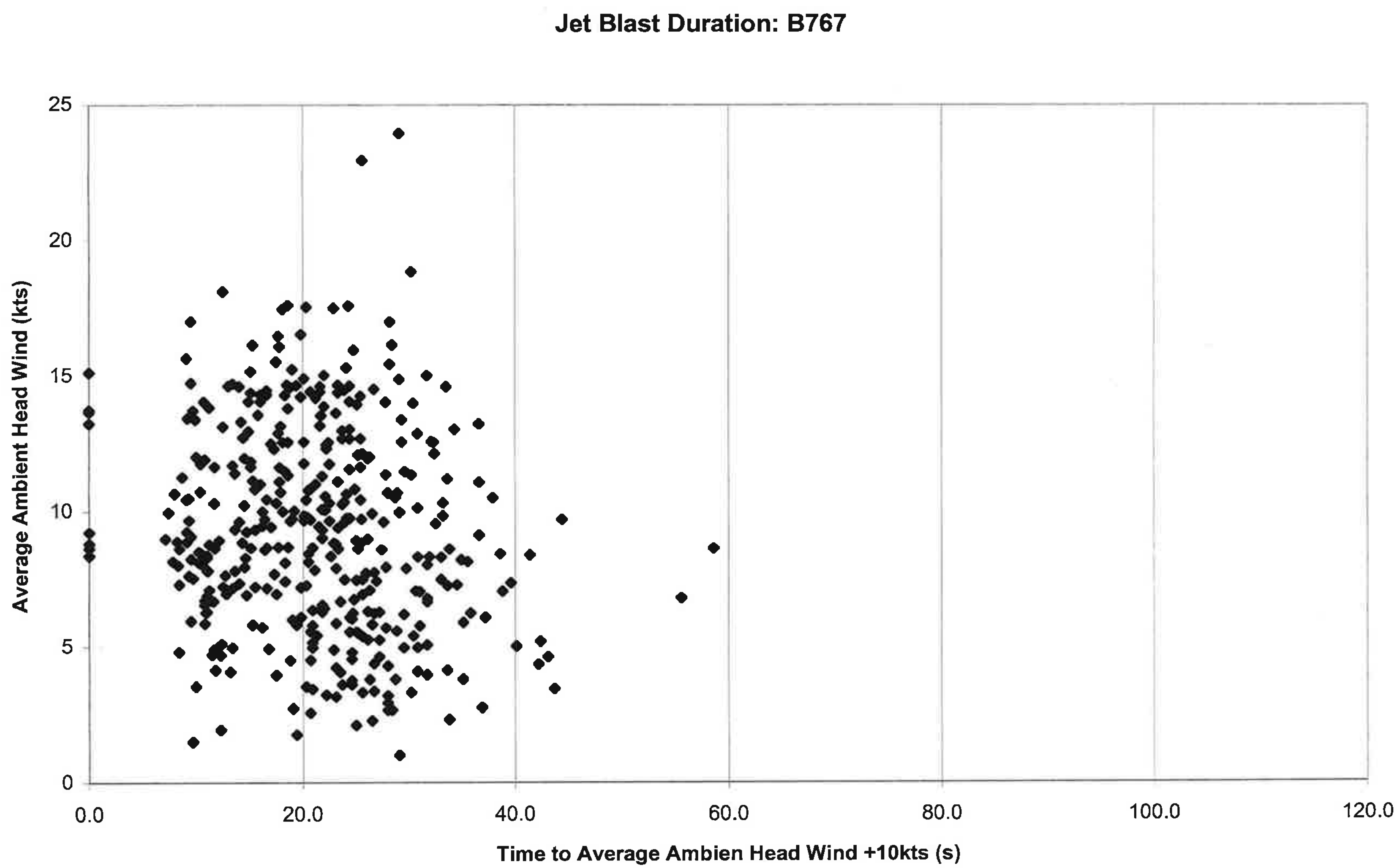

Jet Blast Duration: B767
Average Ambient Head Wind (kts)
25
20
15
10
5
0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time to Average Ambien Head Wind +10kts (s)

Figure A1.16

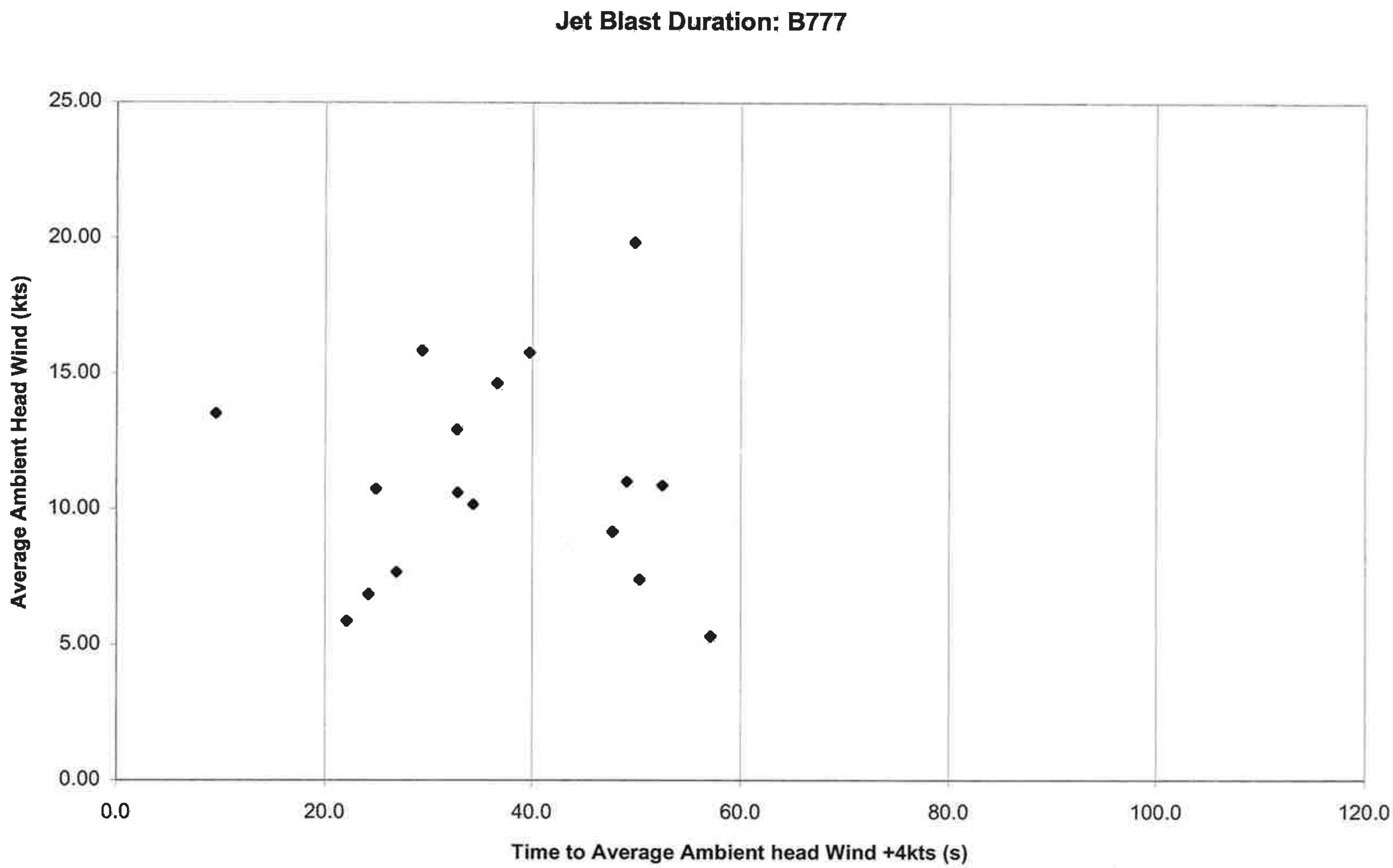

Jet Blast Duration: B777
25.00
20.00
15.00
10.00
5.00
0.00
Average Ambient Head Wind (kts)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time to Average Ambient head Wind +4kts (s)

Figure A1.17

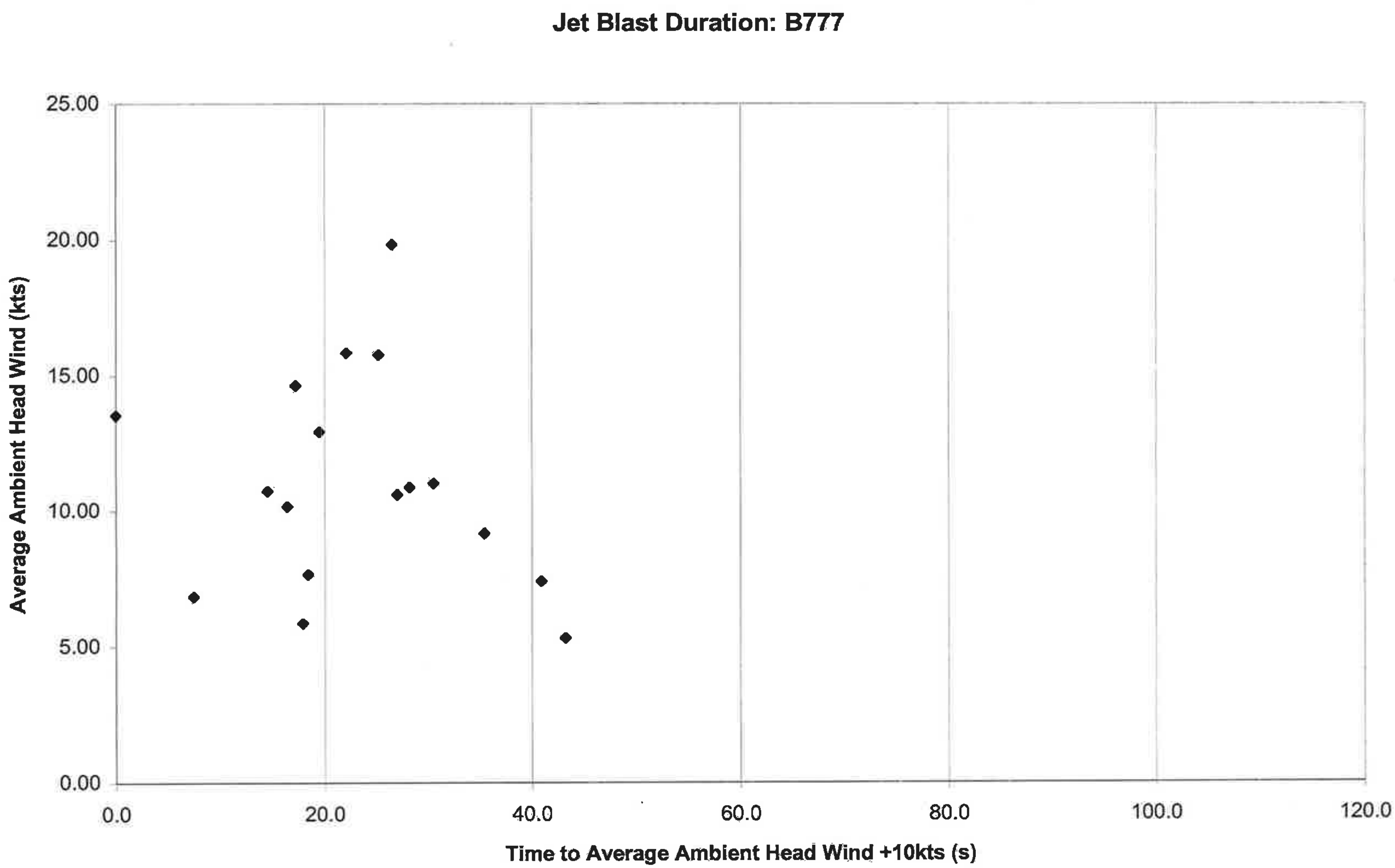

Jet Blast Duration: B777
25.00
20.00
15.00
10.00
5.00
0.00
Average Ambient Head Wind (kts)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time to Average Ambient Head Wind +10kts (s)

Figure A1.18

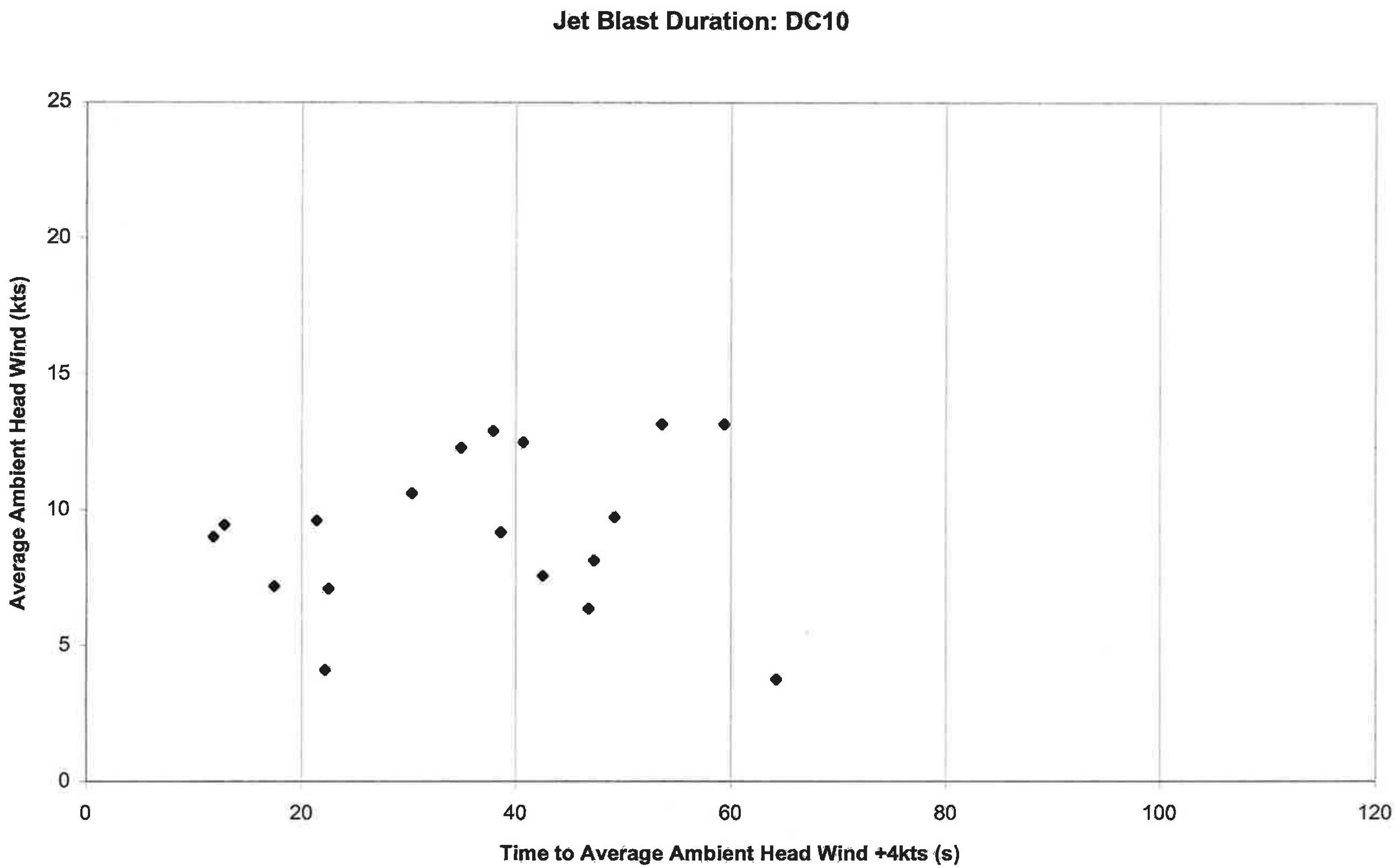

Jet Blast Duration: DC10
Average Ambient Head Wind (kts)
25
20
15
10
5
0
0
20
40
60
80
100
120
Time to Average Ambient Head Wind +4kts (s)

Figure A1.19

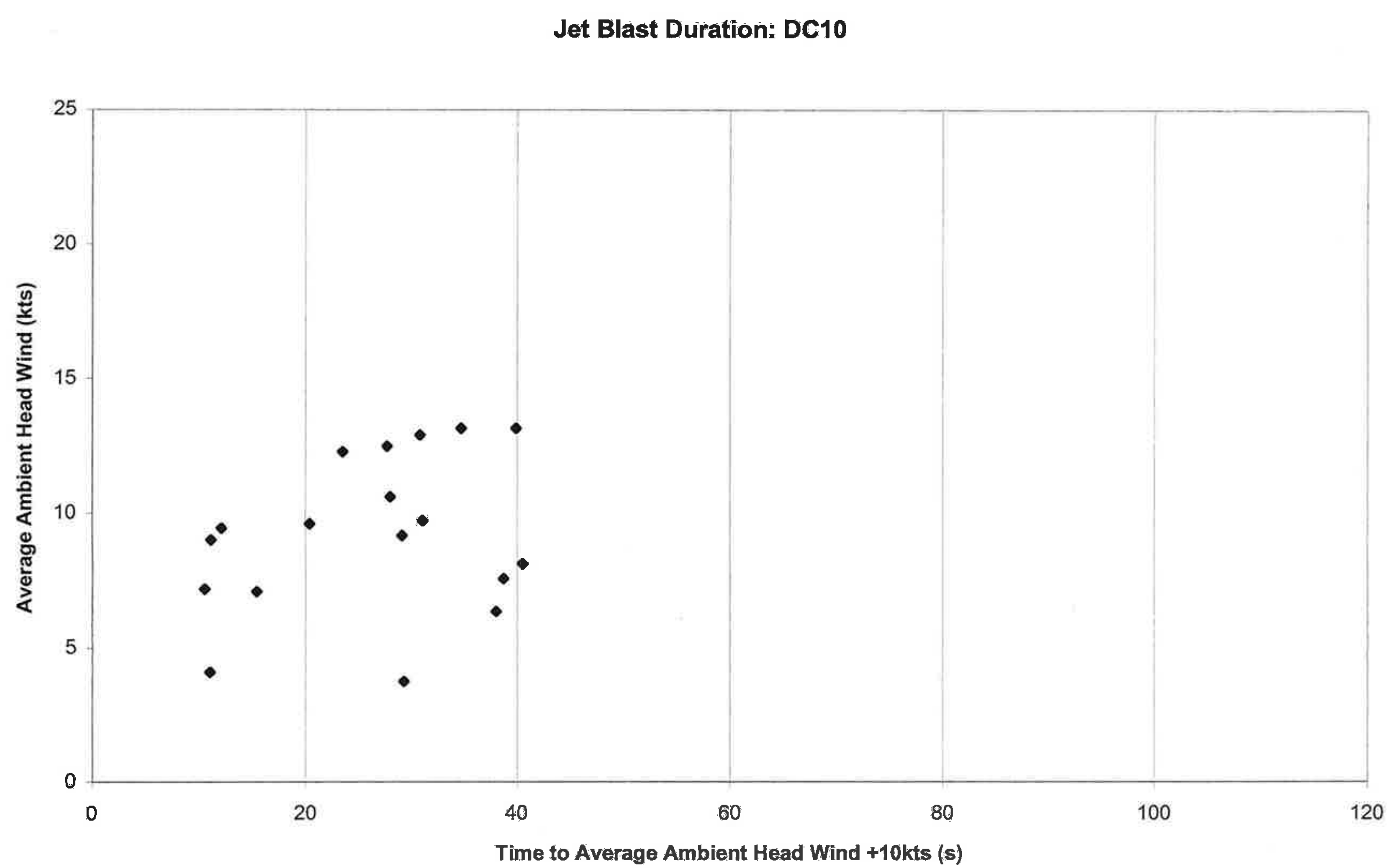

Jet Blast Duration: DC10
Average Ambient Head Wind (kts)
0
5
10
15
20
25
0
20
40
60
80
100
120
Time to Average Ambient Head Wind +10kts (s)

Figure A1.20

Jet Blast Duration: L1011

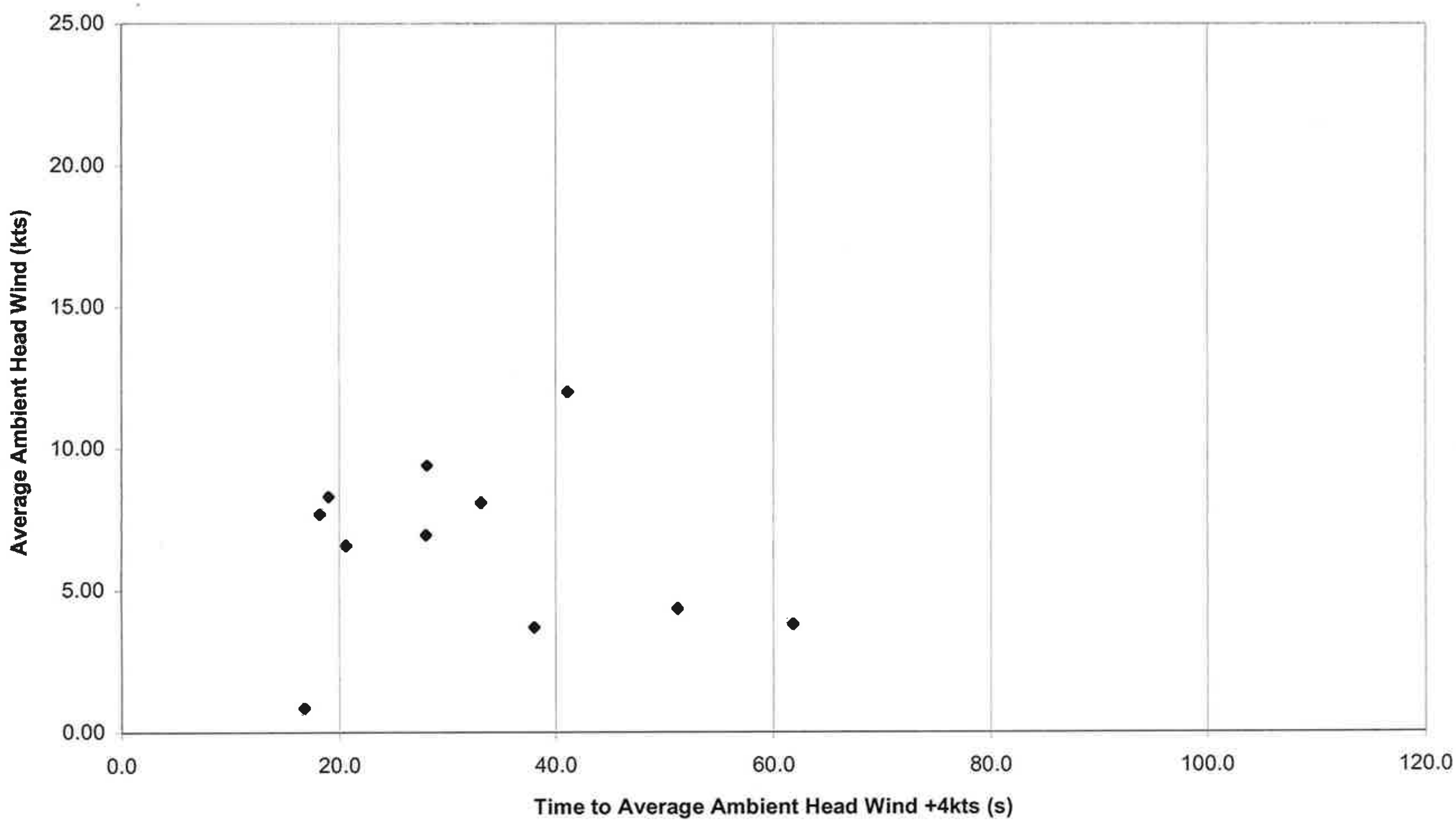


Figure A1.21

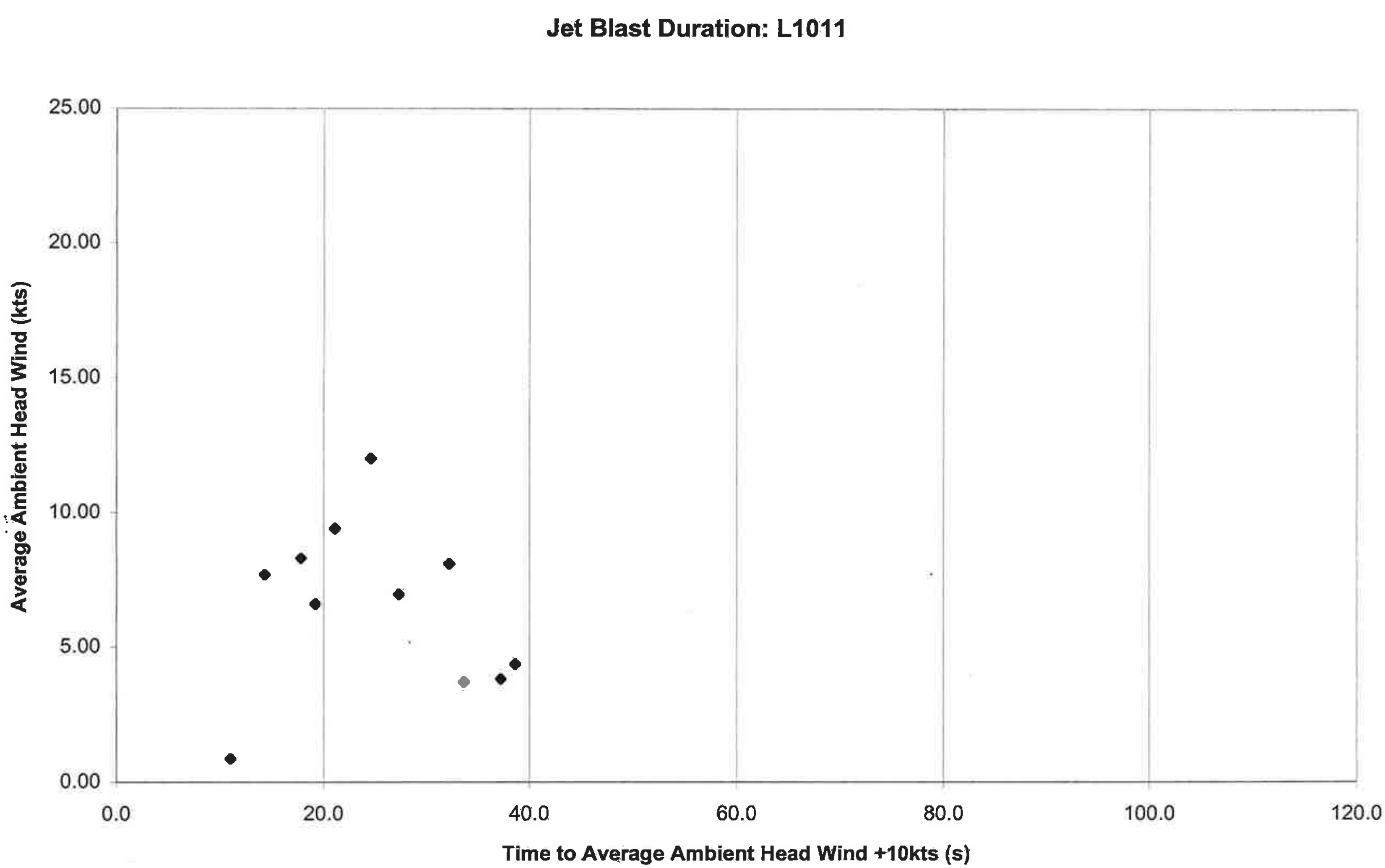

Jet Blast Duration: L1011
Average Ambient Head Wind (kts)
25.00
20.00
15.00
10.00
5.00
0.00
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time to Average Ambient Head Wind +10kts (s)

Figure A1.22

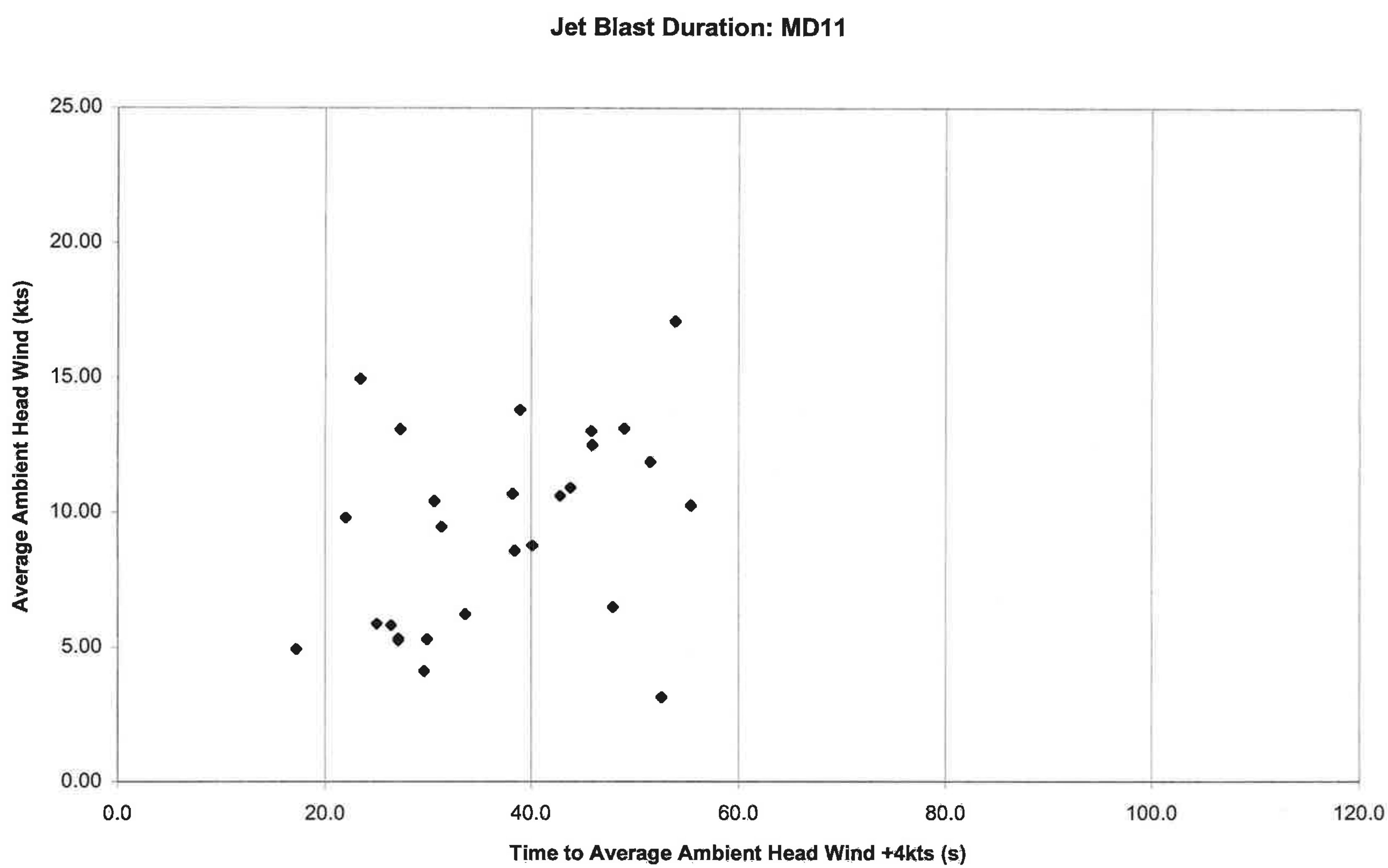
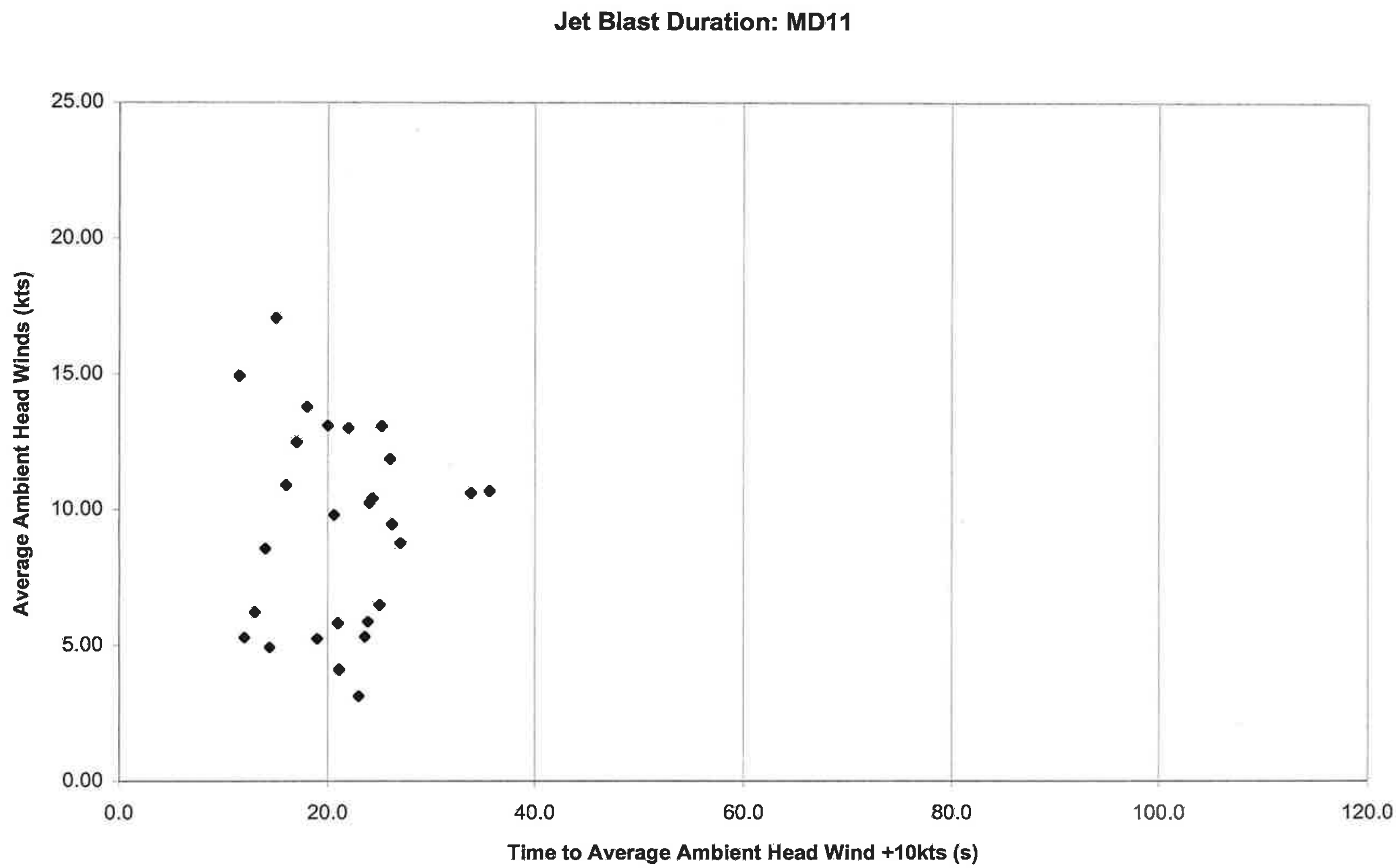

Jet Blast Duration: MD11
25.00
20.00
15.00
10.00
5.00
0.00
Average Ambient Head Wind (kts)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time to Average Ambient Head Wind +4kts (s)

Figure A1.23



Jet Blast Duration: MD11
Average Ambient Head Winds (kts)
25.00
20.00
15.00
10.00
5.00
0.00
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time to Average Ambient Head Wind +10kts (s)

Figure A1.24