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DATA ANALYSIS STUDY AND PERFORMANCE EVALUATION OF THE SCANNING LASER DOPPLER SYSTEM

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RAYTHEON COMPANY

EQUIPMENT DIVISION

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SECTION 1

INTRODUCTION

Data has been analyzed from the Scanning Laser Doppler Velocimeter operating at Marshall Space Flight Center, Hunstville, Alabama, and at Kennedy International Airport in New York. It has been determined that this system is suitable for locating the vortices of landing aircraft in an airport environment. Data was analyzed to evaluate the overall operation of the system, its ability to locate a region of high velocity, and its ability to locate vortices in an airport environment.

In this analysis, use was made of a simulation program which provided information on theoretically expected vortex spectra, evaluations of potential algorithms, and expected location accuracies for given scan patterns. Field tests using an aircraft engine flow field and aircraft vortices during flyby tests were compared to the results of the simulation. From these studies, a vortex location algorithm was developed which provided vortex location for one or two vortices as a function of time. Results of this algorithm used on data from flyby tests were used to study vortex transport, to evaluate system performance, and to provide suggestions for real-time vortex location algorithms. The results of real-time analysis were compared to those which were expected based on theoretical considerations. Results of operations at Kennedy International Airport compared favorably with those predicted by theory and simulation.

Section 2 of this report describes the simulation program and some results obtained from it. The next two sections cover the algorithm used for vortex location and supplementary computer programs used in the analysis. Section 5 presents the results of the data evaluation, including system evaluation and a number of sample results from the algorithm described in Section 3, and from the algorithms used in real-time analysis.

SECTION 2

SCANNING SYSTEMS SIMULATION

2.1 INTRODUCTION

A program has been designed to simulate the operation of a scanning laser doppler velocimeter. The most important portion of the program is a subroutine designed to obtain the spectrum from a laser doppler system focussed at a point in space. This subroutine was originally a separate program designed to simulate velocity measurements on a single vortex, using a laser heterodyne system. Input to the program consisted of the focal range, the distance from the vortex center to the line of sight of the system, and a description of the vortex. The output was either a spectrum or a value of velocity corresponding to some unique point in the spectrum, such as the velocity associated with the highest amplitude.

The new program combines this program as a subroutine with a program capable of scanning in range and angle, introducing threshold values, and performing a weighted centroid to obtain vortex location, as well as a variety of output routines to display spectra and various parameters as functions of range and angle.

2.2 OBJECTIVES

The SLDV simulation program is designed to provide spectra typical of those which would be obtained from a SLDV system focussed at various points relative to a vortex or aircraft engine flow field. From these spectra it selects certain significant parameters and uses them in a vortex location algorithm. A particular flow field and location are input to the program along with scan and processor parameters, and a particular algorithm is specified. The vortex location as obtained from the algorithm is compared to the location given in the input. Specific objectives of the program are to determine significant parameters for vortex location, to evaluate various scan patterns and various algorithms, and to determine spectra which may be compared to experimental results.

2.3 OUTLINE AND DISCUSSION OF MODELS

The program is designed to work with either a "solid core" vortex or the velocity field from an aircraft engine placed at a 45° angle to the scan plane of the system. Thus the two velocity fields are as indicated in Figure 2-1, where the indicated variables are inputs to the program. These variables are:

Flag - 01 for vortex
02 for A/C engine

V_{max} - Maximum speed in flow field

Rad - Radius; for vortex, core radius
for A/C engine, flow field radius

The location of the center of the flow field is given in a polar coordinates as r, ø. Figure 2-1 also identifies the variable "DIST" which is the normal distance from the center of the flow field to the line of sight.

The flow chart for this program is shown in Figure 2-2. The program begins by reading in all the required variables. The scan control routine changes the location (r, ø) of the focus according to the scan parameters read in initially, and stops calculation when the entire scan area has been swept out once. This operation is performed as follows: initially, the routine calculates increments

$$\Delta\phi = 2\ f_\phi\ t\ (\phi_{max} - \phi_{min}) \qquad (2\text{-}1)$$

$$\Delta r = 2\ f_r\ t\ (r_{max} - r_{min}) \qquad (2\text{-}2)$$

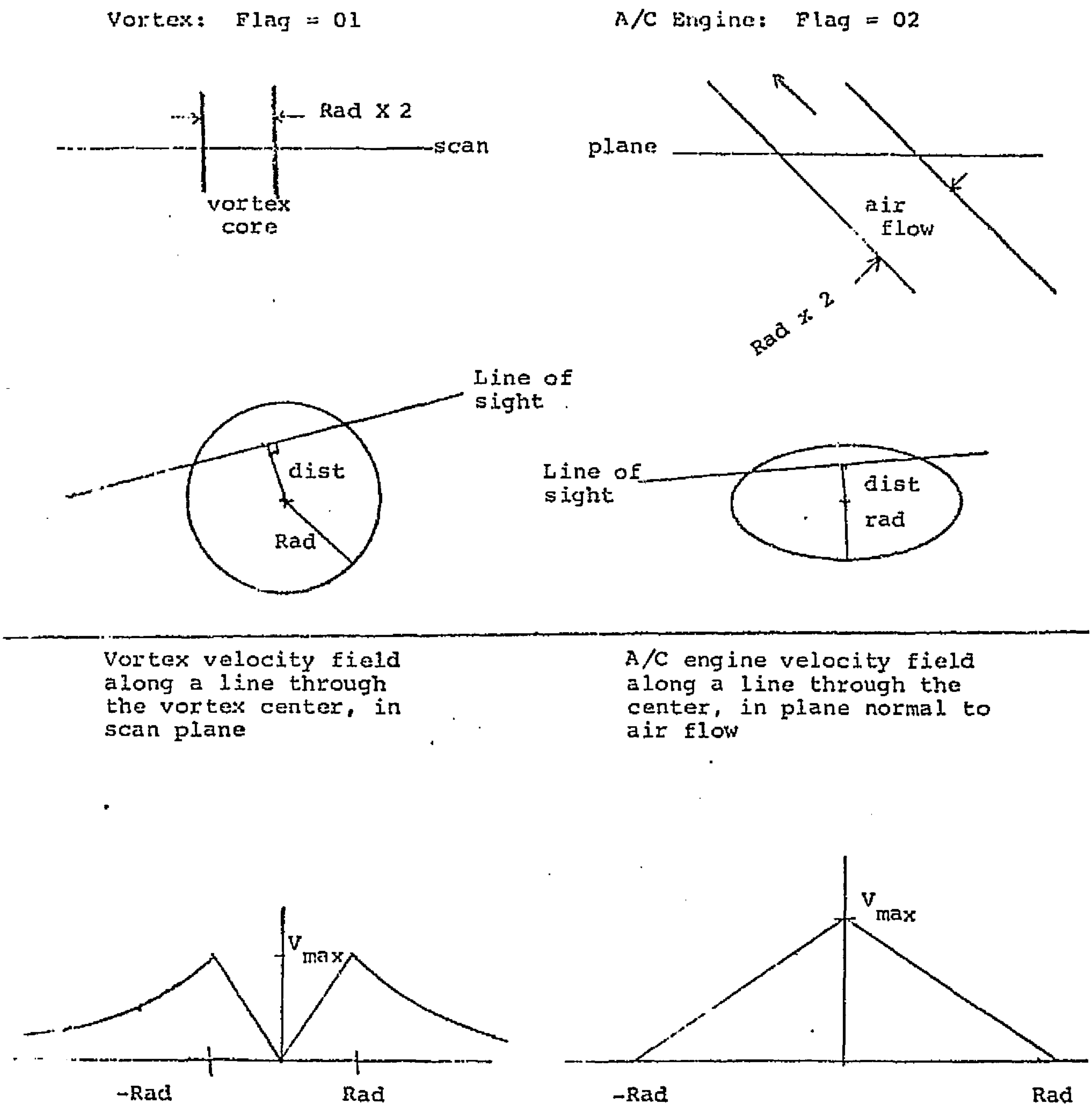


Figure 2-1. Velocity Fields Used in Program VORSIM

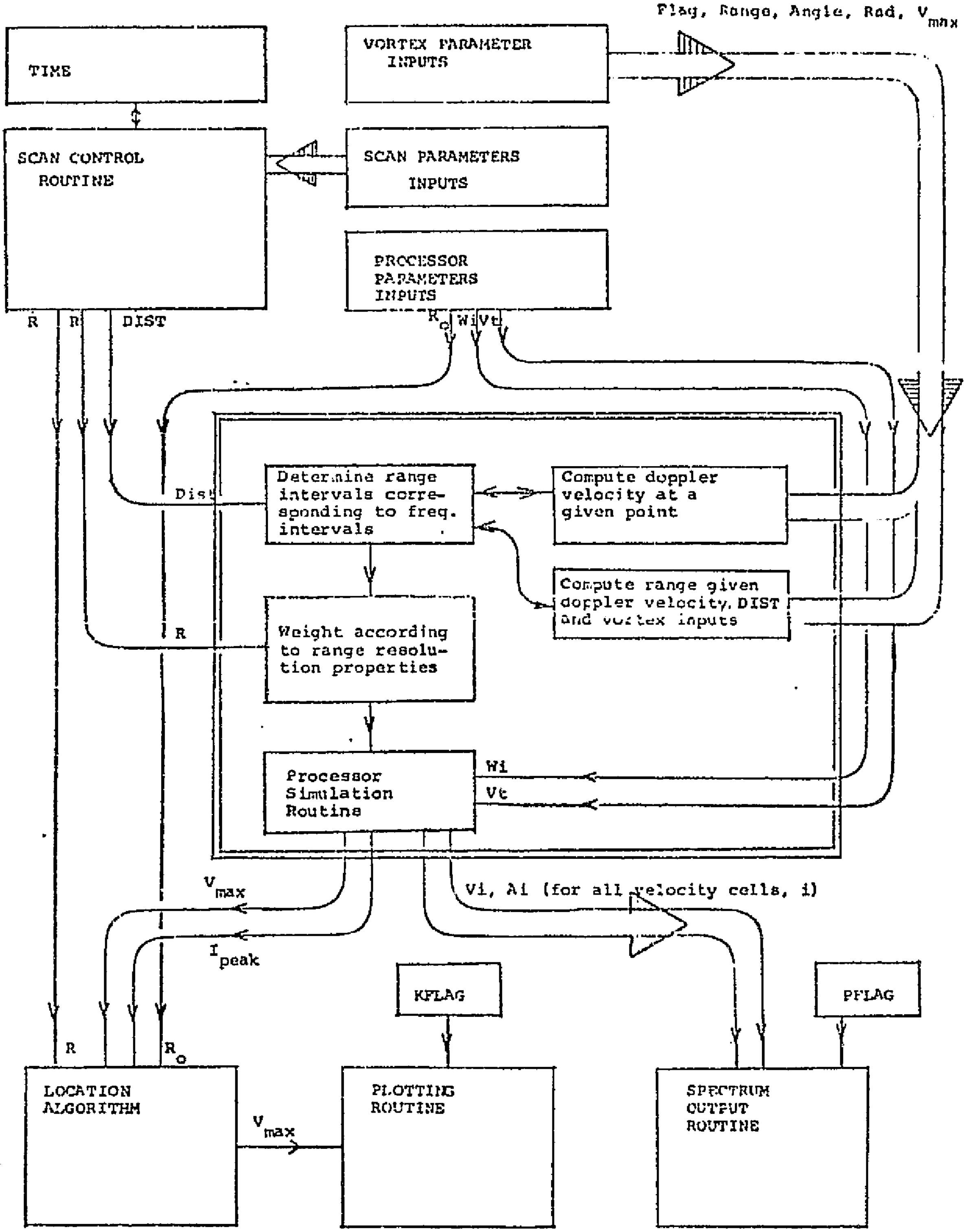


Figure 2-2. Description of Operation of Program VORISM

where

ϕ_{max}, ϕ_{min}, r_{max}, r_{min} are the limits of the scan

f_{ϕ}, f_r are the frequencies of their respective scans, and

t is the time increment between successive data points (i.e., the integration time).

Each time a data point is processed, the position is incremented to $(r + \Delta r, \phi + \Delta\phi)$. If one of the scan limits is exceeded, the sign is changed on the appropriate increment. The run is terminated after a calculation, if;

1) both frequencies are zero,

2) one frequency is zero, and

$$Nt \geq 1/(2\ f_s) \qquad (2\text{-}3)$$

where f_s is the other frequency, and
N is the total number of data points processed.

3) both frequencies are non-zero and the slower frequency, f_s satisfies Equation (2-3) above.

Thus, it is possible to run the program for a single point, a single range scan or arc scan, or a complete scan of a given area of the scan plane.

The scan control routine supplies the focal range, and "DIST" shown in Figure 2-1 to the sub-routine which calculates the spectrum. Output from this sub-routine goes to the location algorithm and optionally to two output routines. Most algorithms presently being considered use V_{max} and I_{peak}, but other parameters can be easily obtained.

The optional plotting routine plots V_{max} as a function of r and ϕ for

$$200 \text{ ft} \geq r \geq 1200 \text{ ft in increments of } 20 \text{ ft}$$

$$-2^\circ \geq \phi - \phi(\text{vortex}) \geq +2^\circ \text{ in increments of } .25^\circ$$

V_{max} is plotted as a one digit number corresponding to the velocity cell associated with the given velocity, according to a scale which is printed above the plot. If the cell number is below those shown in the scale, a zero is printed. If the data fails to satisfy threshold conditions, a minus sign is printed. The optional spectrum output gives for every data point;

- Every velocity cell number up to the highest one with non-zero amplitude,
- The velocity associated with that cell,
- The amplitude associated with that velocity, and
- The ranges at which that velocity occurs.

The standard output is the location of the vortex as specified in the input routines, and that determined by the location algorithm.

The program can be used to provide;

- Spectral analysis of returns from a given point,
- Visual location of vortex, and
- Testing of various algorithms for vortex location.

The spectral analysis is obtained by setting both scan frequencies to zero and (r_{min}, ϕ_{min}) to the desired point. With the spectrum output option the amplitude of each velocity filter will be printed.

For visual location of the vortex, the desired scan parameters are set and the V_{max} plot option selected. The output display will show which points in the scan satisfy the location algorithm, and which velocity cell is associated with V_{max}. After this output, the result of the location algorithm is printed.

2.4 RESULTS

2.4.1 SIGNIFICANCE OF I_{PK} FOR VORTEX LOCATION

The Raytheon developed vortex location algorithm considers I_{pk} to be the significant parameter. This is justified on theoretical as well as experimental grounds. Theoretically, it is predicted that the "capture" effect described in Raytheon Report ER72-4053 (Volume II, Chapter 4) will make V_{pk} less sensitive to changes in range than is the actual parallel component of velocity at a point on the line of sight. This is a combined property of the size of the optical system used and the vortex model under consideration and can only be reduced by increased optics diameter. This problem may be analyzed by comparing the range dependence of the component of vortex velocity parallel to the line of sight to the signal versus range curve of the optical system and the bandwidth and spacing of filters in the processor. The geometry of the system is shown in Figure 2-3. The velocity profile is assumed to be that of Figure 2-4. The velocity is:

$$V = \begin{cases} V_o \dfrac{r_o}{r} & (r > r_o) \\ V_o \dfrac{r}{r_o} & (r < r_o) \end{cases}$$

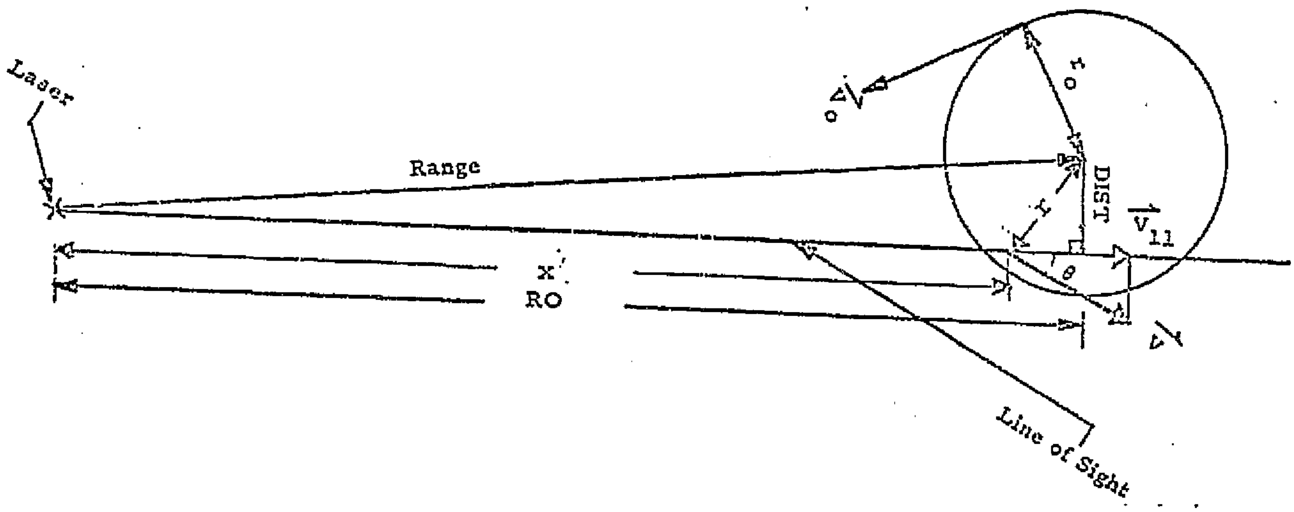


Figure 2-3. System Geometry

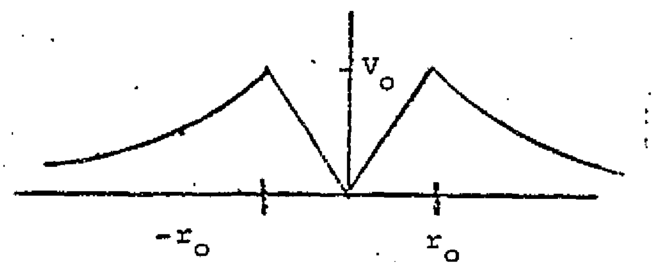


Figure 2-4. Assumed Vortex Tangential Velocity Field

The parallel velocity is calculated by multiplying the cosine of the angle between the velocity and the line of sight. When this is done:

$$V_{11} = V_o \frac{Dist}{r_o} \quad (r < r_o)$$

$$V_{11} = \frac{V_o \; r_o \; (Dist)}{(x-RO)^2 + (Dist)^2} \quad (r > r_o)$$

Given a bandwidth Δf, it is possible to determine the ranges from which a signal will be obtained within that bandwidth as shown in Figure 2-5. Finally, the signal versus range function can be superimposed on this figure and the amount of signal contributed to each frequency band can be determined as the integral of that function over the appropriate region. The signal versus range curve has a Lorentzian shape with a peak near the geometric focus:

$$S = \frac{S_p}{\left[\frac{r-r_p}{\frac{1}{2} Z_c}\right]^2 + 1}$$

Figure 2-6 shows an example of a situation in which a significant amount of signal appears in the highest frequency (velocity) cell, V_{pk}, although the focus of the system is far from the vortex. From this point on through the vortex, the value of V_{pk} remains unchanged, although I_{pk} continues to increase, reaching a maximum at the vortex center.

When an angle scan and range scan are considered simultaneously, it is possible to locate a maximum in V_{pk} which is at the correct angle, but a wrong range to locate the vortex. Computer simulation

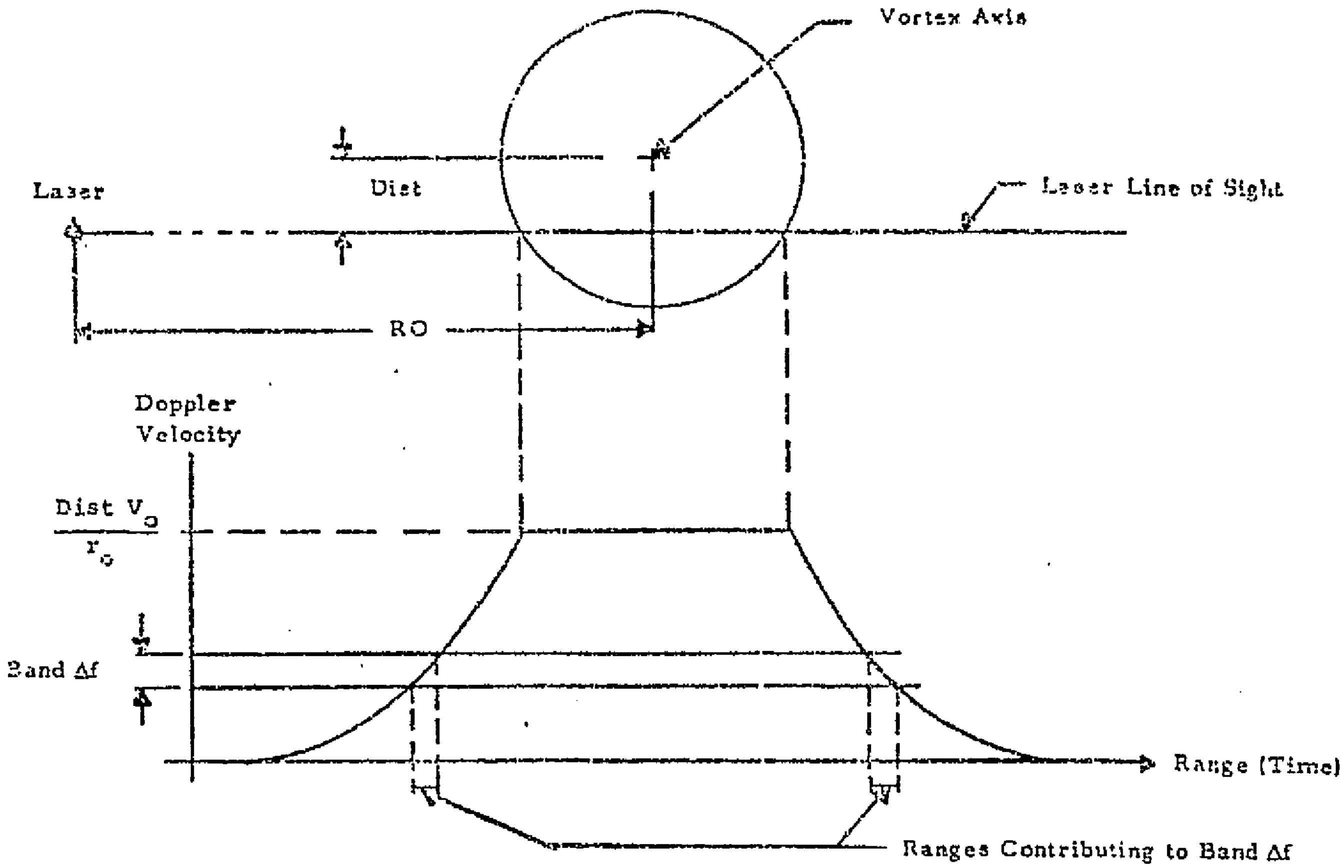


Figure 2-5. Doppler Velocity Profile in Range Scanning System

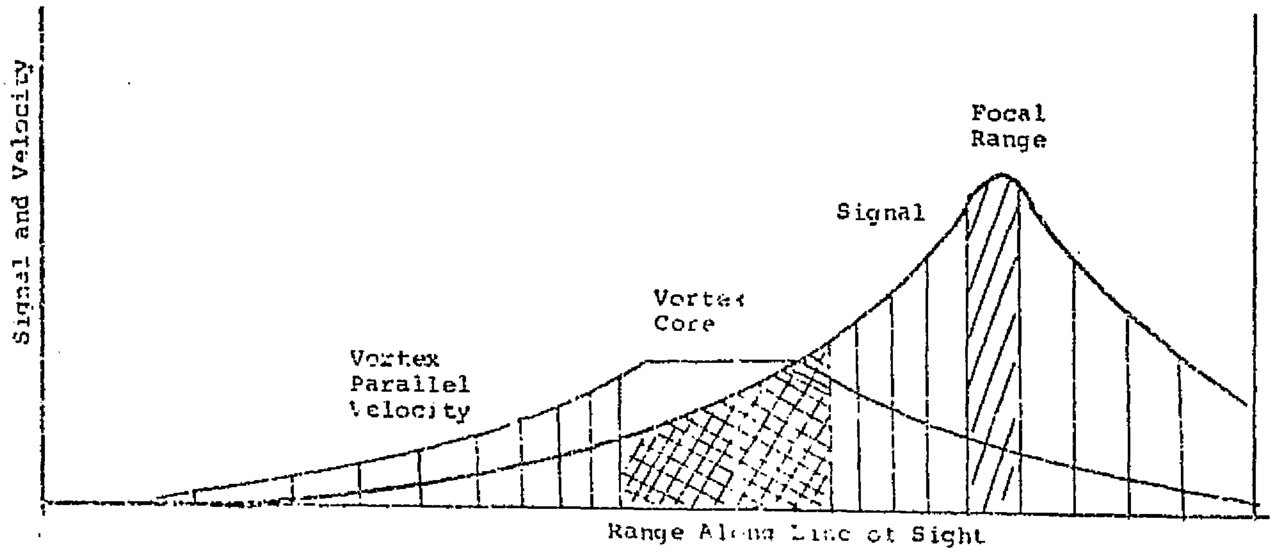


Figure 2-6. The usefulness of V_{pk} is based on the assumption that significant signal will be obtained only from the focal region (light-shaded region) while in fact considerable signal may be obtained from a solidly-rotating vortex core far away from the focus (dark-shaded region). However, I_{pk} will still have a maximum when the system is focussed on the vortex.

results showing I_{pk} and V_{pk} at different angles and ranges are shown in Figure 2-7.

In summary, the optical system by its nature is more sensitive in angle than in range, and it is desirable to use a parameter which depends strongly on range for vortex location, thus enhancing the range resolution, rather than one which is sensitive mostly to angle. The parameter most sensitive to range is I_{pk}. A change in the postulated velocity profile will reduce this effect somewhat, but for reasonable profiles, it is expected to be present to some degree.

Experimental evidence supporting this conclusion may be found by comparing the scatter plots of V_{pk} with those of I_{pk}. Often, there are long regions of data at a nearly constant high velocity while regions of high intensity are considerable smaller. This has been observed repeatedly in the data from Kennedy International Airport, and verifies the general conclusions arrived at theoretically.

A possible problem in the use of I_{pk} is that the particle density may change in regions near the vortex. However, the errors in vortex location caused by this situation should be considerably less than those which would be obtained by locating the vortex with V_{pk}.

2.4.2 LOCATION ACCURACY

An aircraft engine flow field was simulated with the following parameters;

Radius	-	10 feet
V_{max}	-	100 feet/second
Location	-	500 feet at 9°

This test was similar to tests performed at MSFC in Huntsville, Alabama on 22 May 1974. Several runs were made using a simple

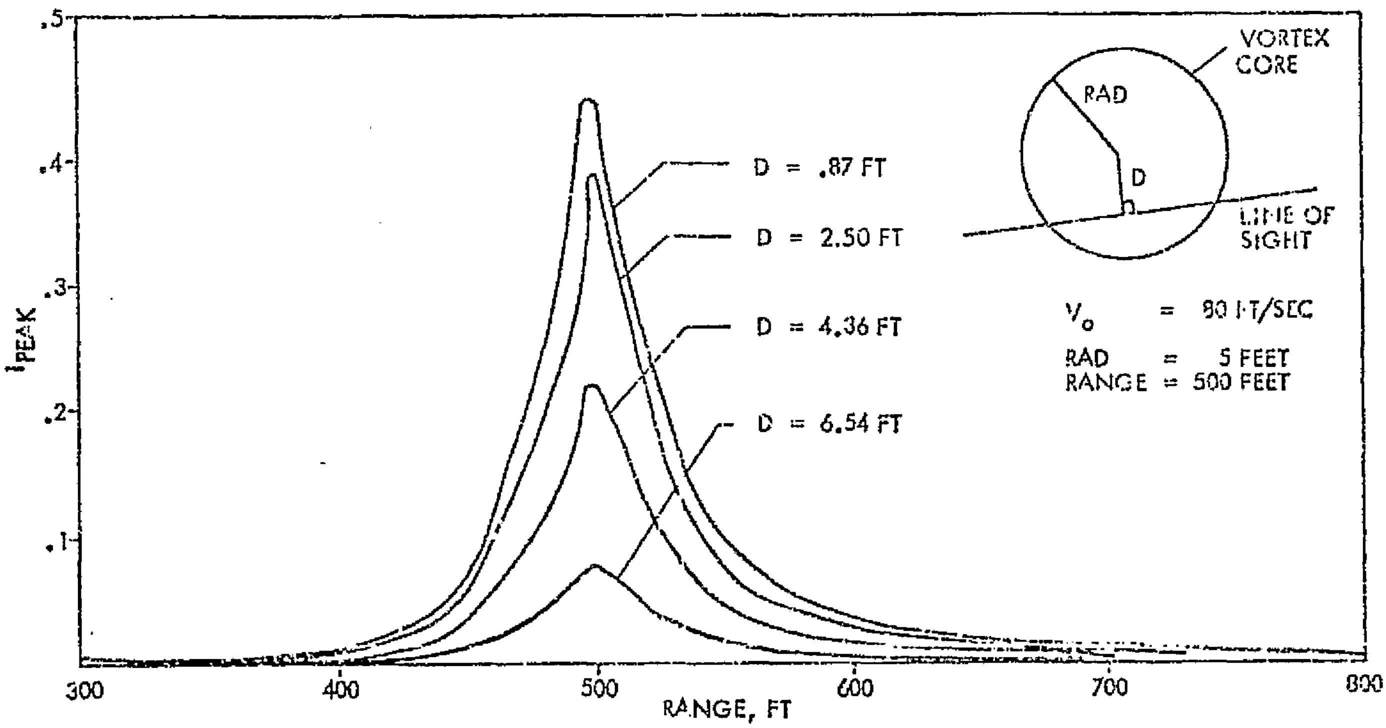


Figure 2-7. Computer Simulation Results Showing Sensitivity of I_{pk} to Range and Angle. V_{pk} Values are as Follows:

D	.87 FT	2.50 FT	4.36 FT	6.54 FT
V_{PEAK}	15 FT/SEC	41 FT/SEC	71 FT/SEC	62 FT/SEC

algorithm with scan parameters typical of those used in the MSFC tests. Scan parameters were varied slightly from run to run to ensure that different locations in the scan area would be used in each run. The algorithm consisted of velocity thresholding at cell 9 (that is, accepting cell 10 or above) and amplitude thresholding with;

$$A_t = R_o/(\text{Range in feet})$$

where R_o is to be determined.

The following results were obtained:

Angle Scan			Range Scan			R_o	# of Points Exceeding Threshold	Location	
Max	Max	Freq	Max	Min	Freq			Range	
25°	4°	.1sec^{-1}	1200	200	6sec^{-1}	40	3	488.00 ft.	8.764°
25	4	.1	1200	200	6	30	5	508.093	8.858
16	4	.11	1200	200	5.4	30	3	497.600	8.836
14	.4	.09	1000	250	6	30	4	502.400	9.008
15	4	.12	1200	200	6.5	30	7	505.323	9.079
30	3	.1	1200	200	6.2	30	5	512.000	9.083
19	3	.1	900	200	5.5	30	7	503.838	9.092
			Averages				4.86	502.465 ft.	9.076°
			Standard Deviations				1.68	7.805 ft.	0.385°

The standard deviations are nearly in agreement with those reported in analysis of the experimental data; typically .5° and about 3 meters.

A vortex was simulated with the following parameters:

Radius - 10 feet

V_{max} - 75 feet/second

Location - 500 feet at 9°

The velocity threshold was set at 19, allowing points with velocities in cell 20 or greater to be accepted. The amplitude threshold was;

$$A_t = R_o/(\text{Range in feet})$$

where $R_o = 20$ was chosen for all runs. The following results were obtained.

Angle Scan			Range Scan			R_o	# of Points Exceeding Threshold	Location	
Min	Max	Freq	Max	Min	Freq			Range	Angle
29°	4°	.12 sec^{-1}	1200 ft	200ft	6.2sec^{-1}	20	17	516.174 ft.	9.139°
30	3	.09	1200	200	5.3	20	22	527.033	9.079
33	3	.13	1200	200	5.3	20	7	514.467	9.212
25	3	.10	1200	200	6.0	20	24	512.851	9.024
			Averages				17.5	517.631 ft.	9.114°
			Standard Deviations				7.6	6.413 ft.	.081°

SECTION 3

VORTEX LOCATION ALGORITHM

3.1 INTRODUCTION

Data from the system may be analyzed in one of three ways. Real-time analysis may be performed by using data from the processor in a real-time graphics display consisting of a PDP-11 minicomputer with CRT displays. Alternatively, the data may be stored on magnetic tape for later analysis. In both cases, some data reduction (thresholding and width integration) has already taken place in the processor, so that the reduced amount of data is suitable for real-time analysis. However, some of the data is lost in this way. The final method of data analysis is the use of the high speed tapes which include the position coordinates, time, and the amplitudes of all filters in the spectrum analyzer for each integration period.

In this section, an algorithm is presented which provides the locations of one or two vortices from either the low speed or high speed tape data. The algorithm is used to study vortex transport, to provide suggestions for possible real-time algorithms, and to evaluate threshold settings and system performance.

3.2 OBJECTIVES

The data available to the real-time Graphics Display component of the system includes position coordinates (x and y) and N, I_{pk}, V_{max}, and V_{pk}, as shown in Figure 3-1, for each data point which satisfied the threshold conditions. This generally results in about two to four hundred data points per scan frame. A similar situation exists in the high speed tape data after thresholding has been performed by the computer. The next problem is to determine the location of one or two vortices from the data associated with

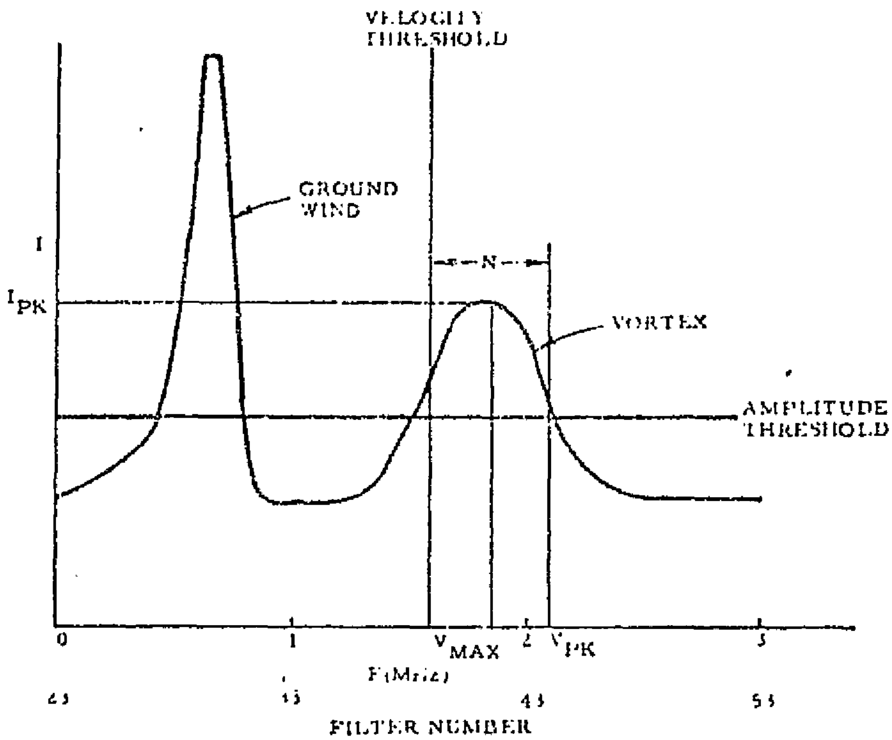


Figure 3-1. Definitions of V_{pk} and I_{pk} from Vortex Signal Spectrum

these points. Several algorithms have been proposed to provide these locations. All algorithms considered have a common pattern. A point is selected to be the center of a correlation circle and a weighted average of x and y for all points inside the circle is used to determine the location of the first vortex. Then a decision is made as to whether a second vortex exists. If it does, the process is repeated. Significant variations between algorithms include the method of searching for correlation circle centers and the decision criteria used to determine how many vortices are present. It is not believed that the weighting function chosen for the average causes a significant change in vortex location. Several situations have been examined where a change in weighting function on a given set of data changed vortex locations by less than one meter. Parameters presently considered especially significant in these algorithms are V_{pk} and I_{pk}.

The initial algorithm developed by NASA used V_{max} for the search and weighting functions. Since V_{max} was generally the first velocity cell above threshold (due in part to a low choice of velocity threshold combined with high wind velocities) this was changed to V_{pk}. Later, the weighting function was changed to the product of V_{pk} and I_{pk}. As a result of successful location of vortices using the algorithm to be described in Section 3.3, and of theoretical considerations outlined in Section 2, a second algorithm was programmed which used I_{pk} for the search and the $V_{pk} \cdot I_{pk}$ product for the weighting function.

3.3 OUTLINE OF ALGORITHM

3.3.1 INTRODUCTION

The vortex location algorithm was designed to work on data from the high speed tapes. Several problems are encountered in processing high speed tapes which are not of concern when low speed tapes are processed. These are discussed in Section 3.3.2. The amount of data to be handled is considerable reduced by use of the "triplet" algorithm described in Section 3.3.3. After the triplet algorithm is performed, a small number of points remain, from which vortex locations may be obtained. This step is discussed in Section 3.3.4.

3.3.2 PROCESSING HIGH SPEED TAPES

In data from the low speed tapes, there is a number identifying the scan frame. However, in the high speed tape data, this does not occur, so it is necessary to determine the end of the scan frame by noting when the angle scan reverses direction. Since there is quantization noise associated with the angle, this process is not straightforward. Accurate location of the end of scan frame is important whenever a vortex is near the edge of the scan. Failure to locate the end of the scan correctly may lead to errors in vortex location on frames which end too early or start too late. The most successful means of locating the end of the scan frame is the split-gate method.

This method averages out the fluctuations in angle and provides the ability to terminate a scan at any angle turnaround, even if the angle limits are changed during a scan. The method may be explained with the aid of Figure 3-2. Initially, the program looks at the first four hundred frames of data, and multiplies each value of θ by the gate value. The gate value is -1 for frames 1 to 200 and +1 for frames 201 to 400. The results are added together and the sign of the sum is determined. The gate is maintained at a width of 400 frames and advanced in time by one frame. If the sign of the sum does not change, the process is repeated. If it does change, the scan ends with the last frame number before the middle of the gate.

In the low speed tape data, amplitude and velocity thresholds and width integration have been set, and the values of I_{pk}, V_{pk},

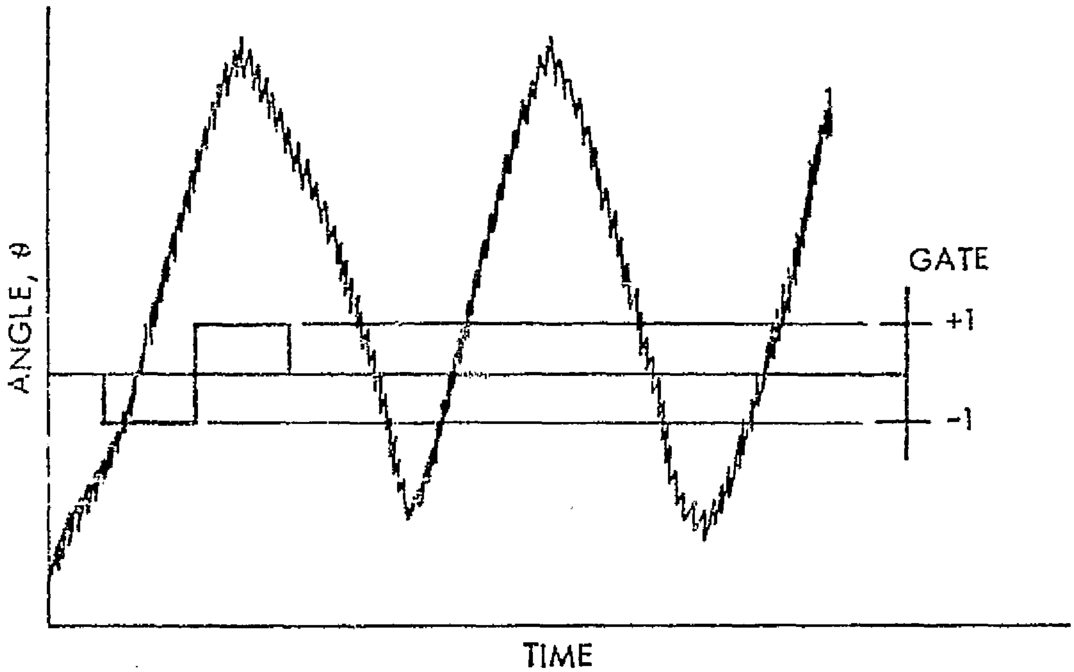


Figure 3-2. Split-Gate Method of Determining Angle Turnaround

V_{max}, N, x, and y are obtained whenever the threshold conditions are satisfied. With the high speed tapes amplitudes of all filters are given, allowing the algorithm to employ any combination of thresholds and width integration. In the algorithm, I_{pk} is located first by finding the highest amplitude above the velocity threshold. If width integration is to be performed, this amplitude is averaged with the appropriate number of adjacent amplitudes. If the resulting amplitude exceeds the amplitude threshold, it becomes I_{pk}; otherwise $I_{pk} = 0$. The width integration process is not identical to that performed by the processor, but should almost always give the same result and may be performed in considerably less time.

A range dependent amplitude threshold was considered, but has been rejected since it is believed that it could lead to vortex locations at greater range than they should be. Furthermore, the algorithm is very insensitive to the ratio of peak signal to threshold and over the range of interest, the $1/R^2$ variation in signal will not affect the vortex locations.

3.3.3 TRIPLET ALGORITHM

To reduce the number of data points, only those which are relative maxima in range and angle are accepted. The triplet algorithm takes the points three at a time and determines whether or not to accept the middle point based on its I_{pk} relative to that of the other two.

As the data is read in, the algorithm looks at the points immediately before and after the one under consideration. If neither satisfies the threshold conditions, the point is discarded. If <u>one</u> of these points does also satisfy the threshold conditions, the point under consideration is accepted if its I_{pk} is greater than or equal to I_{pk} of the adjacent point. If <u>both</u> adjacent points satisfy the thresholds, then the given point is accepted only if its I_{pk} is greater than or equal to that of <u>both</u> adjacent points. The following table illustrates the process. The table shows whether or not point two will be accepted as a data point if points 1, 2, and 3 have the I_{pk} values shown.

Frame #	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
I_{pk}	–	17	–	–	17	18	–	17	17	–	17	16	16	17	18
Accept 2?		NO			NO			YES			YES			NO	

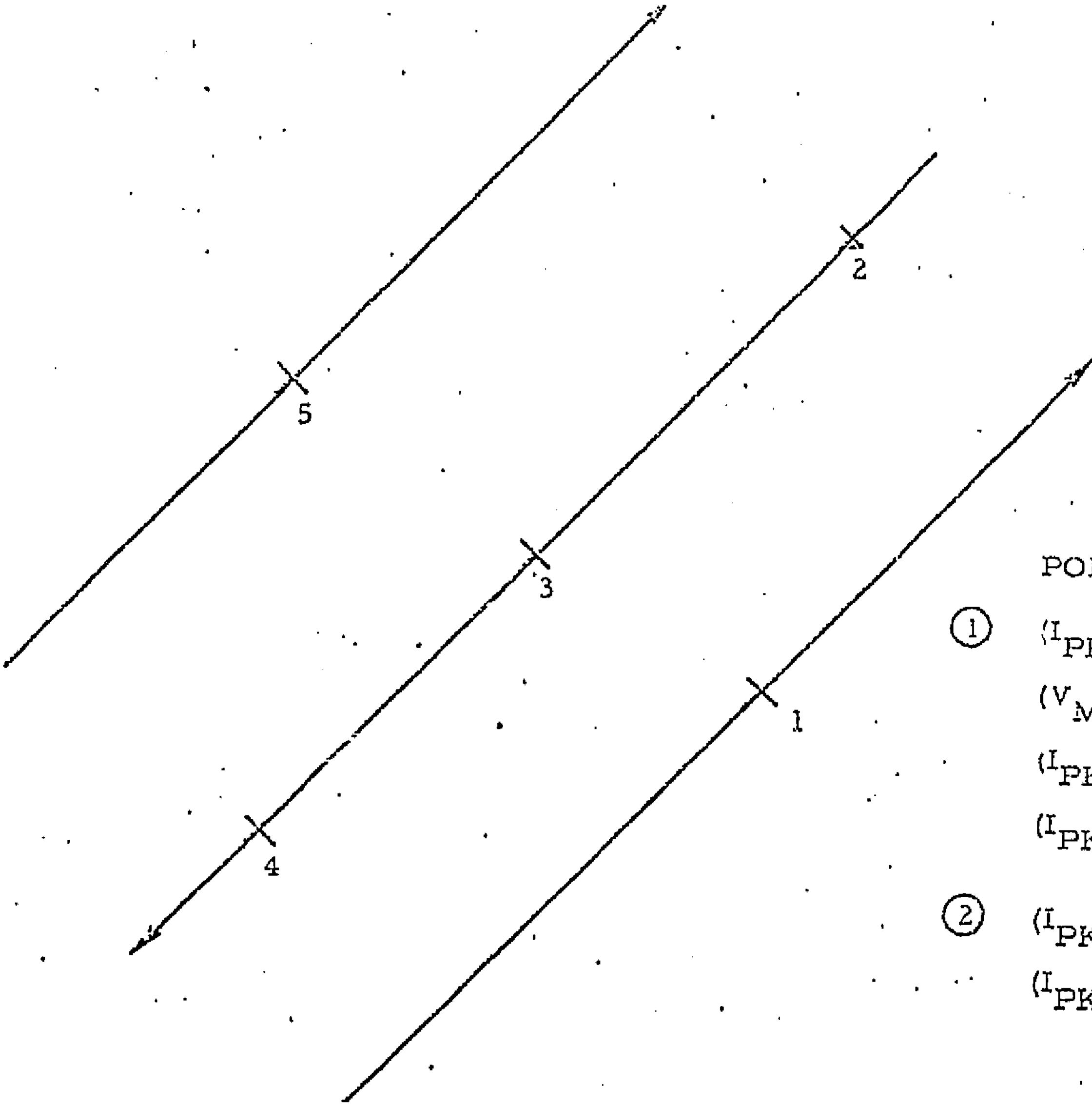
Frame #	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
I_{pk}	17	17	17	17	17	18	16	17	16	17	17	16	18	17	18
Accept 2?		YES			NO			YES			YES			NO	

If R_{min} is the range of the lowest point in the table and R_{max}, the highest, R_l and R_u are defined as; $R_l = R_{min}$ and $R_u = R_l + 10$. A flag is set to 1 for all points with $R_l \leq R \leq R_u$. Taking these points, the triplet algorithm is performed. Any time it succeeds, the given point is accepted. If $R_u < R_{max}$, R_l and R_u are increased by 10 and the process is repeated. After this has been done until $R_u \geq R_{max}$, all relative maxima of I_{pk} versus range and angle have been obtained. An illustration of this is given in Figure 3-3.

All points having I_{pk} less than γ times the highest I_{pk} are eliminated with γ being an input variable between zero and one. Several options available including the following:

1. Points which are accepted by the triplet algorithm but are within one degree of the edge of the scan are rejected.

2. Points in a ten meter range bin are neglected if the edge of that bin comes within 5 meters of the maximum or minimum range scan.



POINT 3

① $(I_{PK})_3 > I_T$

$(V_{MAX})_3 > V_T$

$(I_{PK})_3 > (I_{PK})_2$

$(I_{PK})_3 > (I_{PK})_4$

② $(I_{PK})_3 > (I_{PK})_1$

$(I_{PK})_3 > (I_{PK})_5$

Figure 3-3. The Triplet Algorithm Selects Relative Maxima in Range and Angle. The Lines Show the Scan Pattern.

3. A point which would be rejected on the basis of the triplet algorithm in angle, but which is more than two degrees from the nearest point in its range bin is accepted.

4. A comparison is made between the highest I_{pk} in a scan and that of the previous scan, rejecting the scan if it is less than half of the previous one.

3.3.4 VORTEX LOCATION

From these points, the point with the highest I_{pk} is selected and an average of x and y, weighted with I_{pk} on all points within a circle of radius R of the first point is performed. This new point is made the center of a new circle and the calculation is repeated. This continues until a fixed location is reached or a given number of iterations is exceeded. The second vortex is located in the same way with the criterion that the first point at the center of the circle must be outside the first circle. It is important to note that points in the region where the circles overlap will be included in each vortex. The data points are identified with a flag which may assume the following values,

Flag	Meaning
0	point not associated with a vortex
1	point associated with Vortex 1
2	point associated with Vortex 2, or
3	point associated with both vortices.

If after a given number of iterations, the number of points in the overlap region exceeds the number of points exclusively in either vortex, then the point which initiated iteration for vortex 2 is deleted and the process is repeated. If vortex 2 is not successfully located after three tries, the algorithm locates only vortex 1 and proceeds to the next scan frame. If $x_2 < x_1$, the identification of the vortices is reversed so that vortex 2 is always the one furthest from the van. A file is created by the algorithm which contains the position, time, and number of points associated with each vortex in each scan frame. This file may be used with a plotting or curve fitting routine for further analysis.

The time is taken to be the time associated with the point which initially defined the correlation circle for the vortex. In a modified program which will use low speed tapes, this time will not be available. Then it is necessary to determine time from the angular location of the vortex:

$$\theta_n = \arctan(y_n/x_n)$$

and

$$time_n = \frac{\Delta t}{\Delta \theta} (\theta_n - \theta_{start}) + time_{start}$$

where

$$\frac{\Delta t}{\Delta \theta} = \frac{t_{stop} - t_{start}}{\theta_{stop} - \theta_{start}}$$

SECTION 4

SUPPLEMENTARY PROGRAMS

In addition to the vortex location program, several supplementary programs were used in the data analysis. A tape translation program reads the tape produced by the 1108 computer and writes a tape which is capable of being read by the CDC-6700. The information contained in a single record on the 1108 data tape consists of the data collected at the end of one integration period contains header information and a list of the amplitudes associated with the 104 cells. This data is in 36-bit words, which are arranged in 6-bit lengths of tape 7-bits wide (with the seventh bit being a partiy bit). The CDC-6700 reads these as 60-bit words, 10-bits in length and 7-bits in width. The program then shifts the appropriate bits for each 36-bit word to the correct location for the right-most bits of a 60-bit word, and masks the remaining 24-bits, thus producing a 60-bit word with the same value as the original 36-bit word. The new 60-bit words are then written onto a new tape to be used by the vortex location algorithm.

After the vortex location algorithm has been used, two other programs are also available. The results of the vortex location algorithm may be used in a plotting program which has the capability of providing fast plots of x versus time, y versus time, and y versus x at a teletype or line printer location as well as high quality plots on one of several plotting devices.

Also, a least square fit may be performed on the data to determine vortex transport, wind velocity in the horizontal direction in the scan plane, and the deviation from a straight line in x versus time, y versus time, and y versus x.

SECTION 5

DATA ANALYSIS

5.1 SYSTEM PERFORMANCE

Overall system performance, as determined from the results of vortex location algorithms has been very good. Standard deviations of vortex location from least square fits have repeatedly been less than five meters and often as low as two meters. During the program, several system problems were noted. Only one of these, however, had any significant effect on the data.

In the B-720 flyby of April 11 and 12, the range scan was improperly set so that the scan covered a range of about 15 meters instead of 150 meters as it should have. This problem was located because vortices were always located at maximum range, and had lower signal strength than would be expected at that range, based on the signal strength of the ground wind return. After this problem was corrected, several range and angle calibration errors were noted at various times, with range errors being 5 to 30 meters, and angle errors less than 2 degrees.

An error was located in the timing of the end-of-frame interrupt, which caused overlap in data at the edge of the scan. This was corrected by causing a delay in the interrupt signal. In the dumps of data from Kennedy International Airport, the parameter N, which measures the width of the spectrum, was observed to be zero sometimes, and also was observed to have values inconsistant with the values of V_{max} and V_{pk}. This was caused by problems in the interface which were easily corrected.

On test runs with data from the Gulfstream flyby of June 17 and the B-737 flyby on July 2, initial data analysis was very unreliable. This was found to be due to a low velocity threshold which required a high amplitude threshold. The high amplitude threshold then eliminated the vortex peak of the spectrum shown in Figure 3-1. This problem was located by examining spectra from printouts of the high speed tape data for the B-737 flyby. The principal symptom which can be used to indicate the existence of this problem is a consistant value of V_{max} at or very near the velocity threshold.

Excessive fluctuations were noticed in the amplitudes of the various cells, indicating a need for width integration of the spectrum. When width integration was used in tests at Kennedy International Airport, an improvement in vortex location accuracy was observed.

Two significant software problems were noted in the tests at Kennedy International Airport. When two point clusters were obtained in the raw data, on some occasions, the algorithm located two vortices in one cluster and neglected the other cluster. This problem was eliminated by the use of the I_{pk} algorithm. Also, if only one point cluster was present in the raw data, the algorithm usually located two vortices in that cluster. This indicated a need for stronger criteria for determining when only one vortex is present in the scan frame. It has been suggested that the use of the coefficients A, B, and C in the algorithm be modified so that B% of the points in a correlation circle must have V_{pk} (or I_{pk}) greater than A% of the highest V_{pk} (or I_{pk}) in vortex 1 rather than in the given correlation circle, and that furthermore the number of points in the second circle must exceed C% of the number of points in the first circle.

At the present time, all of the above problems have been corrected with the exception of revision of the use of the A and B parameters. The data quality is very good with one or two "fingers" of data satisfying threshold conditions in each scan frame. A minor change in hardware was also required to operate the I_{pk} algorithm in real-time. This involved interchanging the locations of N and I_{pk} in the interface to make I_{pk} the most significant part of the word which contains I_{pk} and N, to allow a faster search to be performed on I_{pk} by eliminating the need to unpack this word.

5.2 DATA EVALUATION AND RESULTS

5.2.1 MSFC TESTS

A number of preliminary tests were conducted at MSFC for system evaluation. These included soft target tests using the flow field behind an aircraft engine to determine range calibration and evaluate the overall performance of the system, and a number of aircraft flyby tests to evaluate the system under actual operating conditions.

The flow field of an aircraft engine was used as a soft target. The blades of the propeller were 7 feet in length. Examination of the data from this flow field indicated that the peak intensity exhibited a well-defined maximum in the region of the aircraft engine. It was determined that the flow field was approximately the same as shown in Figure 2-1 with a peak velocity in excess of 60 mph and a radius of approximately 10 feet. Figure 5-1a shows the location of points in a single scan frame which exceeded a velocity threshold of 28 feet/second and an amplitude threshold of 59.

Processing of this data was accomplished using the Raytheon vortex location algorithm. At the time this analysis was performed, the triplet algorithm was used in range only. The data points are shown in Figure 5-1b. Location results from several scans are summarized in Table 5-1. The average location is in error by two meters and the data shows a very small standard deviation. A similar analysis was conducted with the final version of the Raytheon algorithm with essentially the same results.

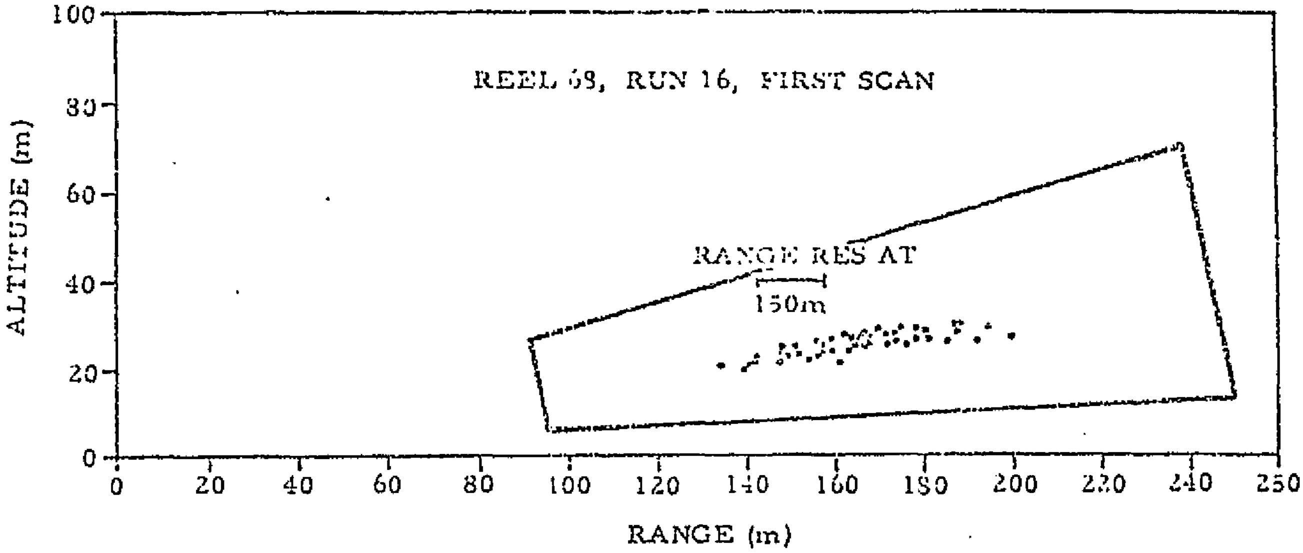


Figure 5-1a. Results of Thresholding for Aircraft Engine Data

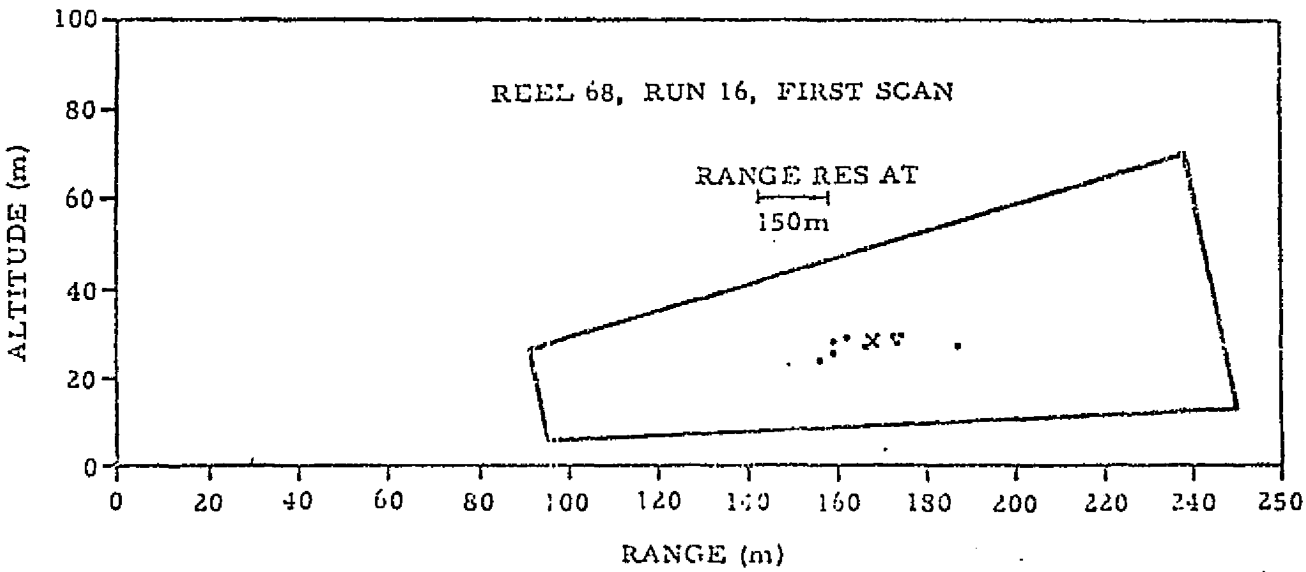


Figure 5-1b. Results of Triplet Algorithm for Data in Figure 5-1a.

Table 5-1

Aircraft Engine Test Results

Reel 68, Run 16

	X	Y
13 Points	169.25 m	27.32 m
12 Points	165.95	26.90
2 Points	172.66	27.92
Average	169 m	27.40 m
Standard Deviation	3 m	0.5 m
Actual Location	167 m	--

Several aircraft flyby tests were performed at MSFC including the flyby of a B-720 aircraft on April 11 and 12, 1974, a Gulfstream on June 17, a B-737 on July 2, and a B-720 on August 8. These tests were performed to evaluate the system performance and determine optimum adjustment of parameters and necessary modifications.

The vortex location algorithm was used to obtain horizontal range (x) and altitude (y) versus time displays of vortex transport, for the B-737 flyby of July 2 and the B-720 flyby of August 8. Figures 5-2, 5-3 and 5-4 show some sample results. Least square fits were performed on these and other runs to obtain average transport velocities and standard deviations. The results are shown in Tables 5-2 and 5-3. For the B-720, the vertical velocity was measured and the results are shown in Table 5-4. These velocities are somewhat less than was expected.

Data quality in the B-737 flyby was much better than in the B-720 flyby. It is believed that the B-720 does not have as well defined a vortex as the B-737. Furthermore the B-737 test was conducted with more favorable wind conditions. Because of wind shear and gusting, it is difficult to determine which of the fluctuations in vortex location in the B-720 flyby are due to atmospheric conditions and which ones arise from fluctuations caused by the algorithm.

The B-737 vortices were located initially with about 20 meters separation between centers, while those of the B-720 were separated by about 30 meters. These numbers compare favorably with 3/4 of a wingspan; the wingspans are 28.35 meters for the B-737 and 39.87 meters for the B-720. It was observed that during the early stages, the vortices often tend to move somewhat closer together. This is not expected on theoretical grounds, but is certainly possible if the vortices are at different altitudes and wind shear exists.

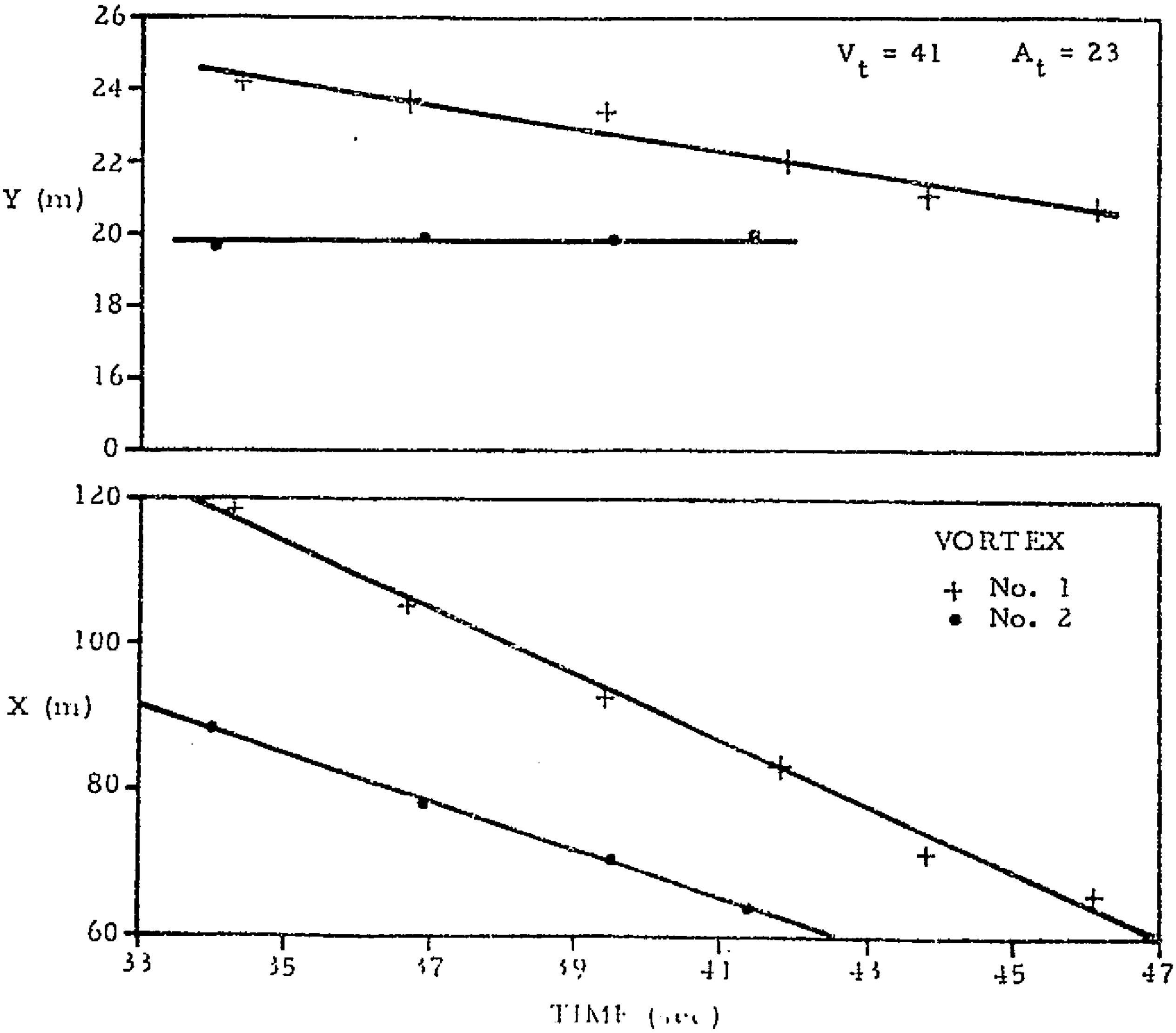


Figure 5-2. Vortex Time History for a B-737

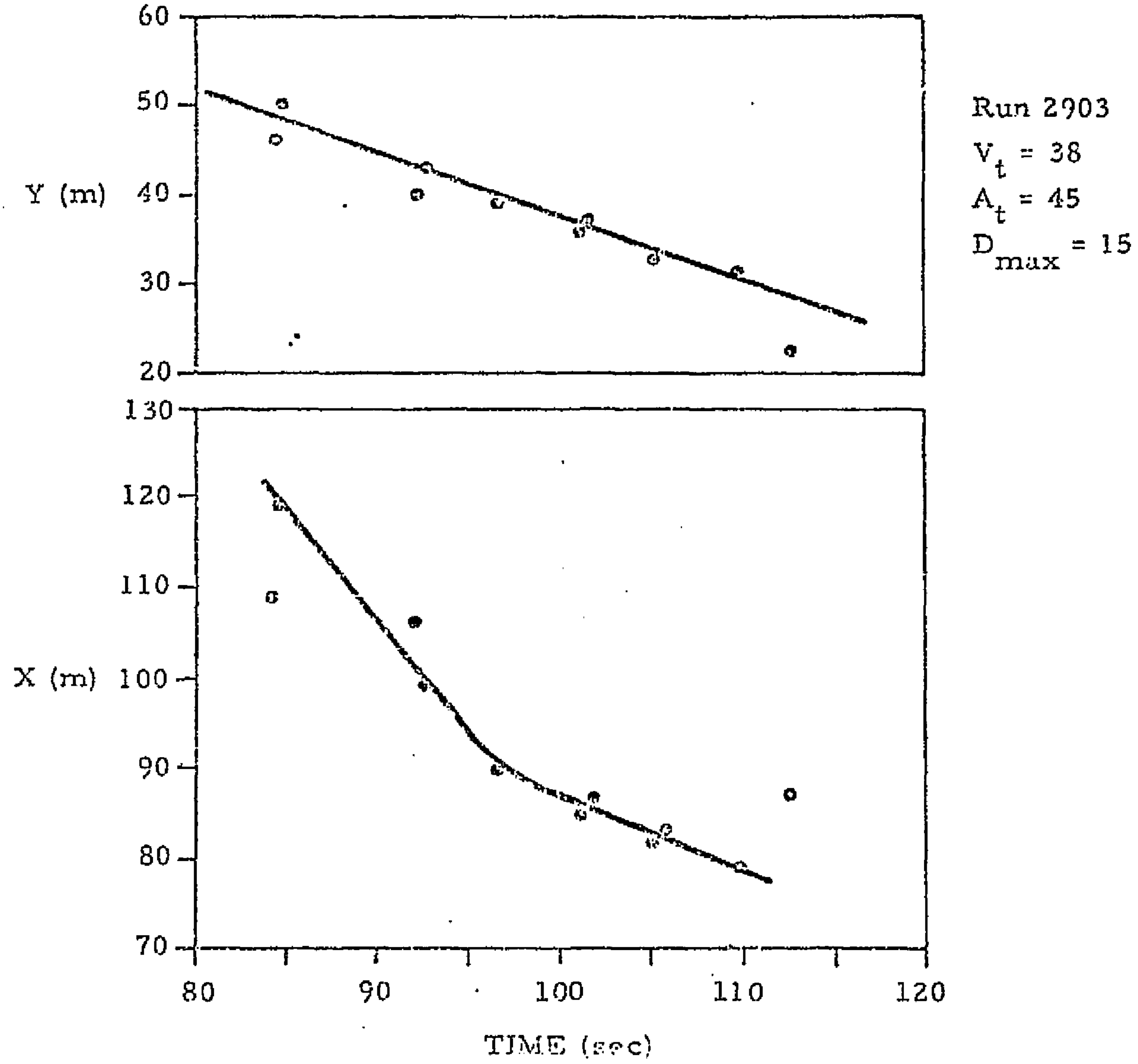


Figure 5-3. Vortex Time History for a B-720 Flyby

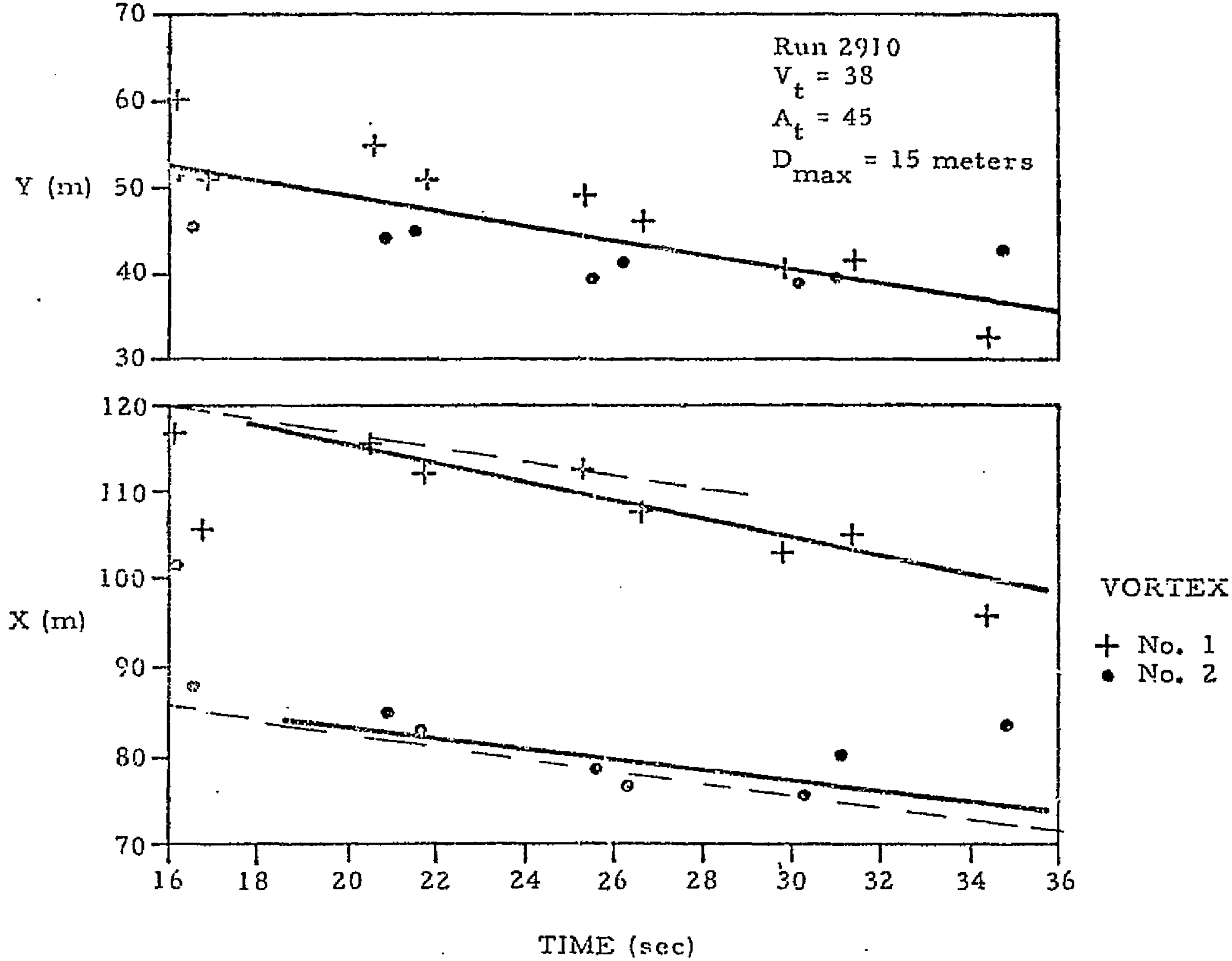


Figure 5-4. Vortex Time History for a B-720 Flyby. Points Show Results from Van 2. Solid Lines are Least Square Fit to Points. Dotted Lines are Least Square Fit for Van 1.

Table 5-2

Vortex Transport for B-737

VAN 1

VELOCITY THRESHOLD	AMPLITUDE THRESHOLD	$\left(\frac{\Delta x}{\Delta t}\right)_F$ (m/sec)		$\left(\frac{\Delta x}{\Delta t}\right)_C$ (m/sec)		σ_F(m)		σ_C(m)	
41	55	3.94		3.57		6.57		2.08	
44	55	4.44		4.10		5.82		7.94	
42	60	4.66		2.01		5.16		1.42	
		AV	SD	AV	SD	AV	SD	AV	SD
		4.35	.37	3.23	1.09	5.85	.71	3.79	3.60

VAN 2

VELOCITY THRESHOLD	AMPLITUDE THRESHOLD	$\left(\frac{\Delta x}{\Delta t}\right)_F$ (m/sec)		$\left(\frac{\Delta x}{\Delta t}\right)_C$ (m/sec)		σ_F(m)		σ_C(m)	
41	25	-4.62		-4.07		2.2		1.7	
40	25	-4.61		-4.18		1.6		1.4	
41	23	-4.43		-3.24		1.1		0.6	
40	27	-4.26		-4.03		3.9		1.8	
		AV	SD	AV	SD	AV	SD	AV	SD
		-4.48	0.17	-3.88	0.43	2.2	1.2	1.4	0.5

Table 5-3

Vortex Transport for B-720

Run	$\left(\frac{\Delta x}{\Delta t}\right)_1$ (m/sec)	$\left(\frac{\Delta x}{\Delta t}\right)_2$ (m/sec)	σ_1 (m)	σ_2 (m)	Approximate Altitude Range (m)
1909	1.7	1.1	7.6	3.5	35 to 20
1910	1.1	.7	3.2	5.8	40 to 30
1913	2.1	2.0	4.8	11.2	50 to 35
2910	-1.1	-.7	1.8	2.2	50 to 35
2903	(only one vortex)	-1.7 to -.9	-	-	50 to 30

Table 5-4

Vertical Velocity Comparison

Run	Vertical Velocity
1909	-1 m/sec
1913	-.7 m/sec
1910	-.7 m/sec
2910	-.8 m/sec
2903	-.7 m/sec

5.2.2 KIA TESTS

Data from operations at Kennedy International Airport on nine days has been evaluated and analyzed. A variety of conditions occurred on these days, allowing comparison of vortex tracks under high, moderate, and low crosswind conditions. The data was evaluated for the purpose of determining system performance and designing system modifications, especially in software, to make the system more suitable for real-time operation in an airport environment. In general the data received from the system by the real-time Graphics Display was of very good quality, with one or two vortices clearly separable, but the original algorithm was not always sufficient to locate the vortices correctly from this data.

This problem was primarily due to the size of the range resolution element of the system, which is dependent on amplitude threshold. On a number of occasions, excellent results were obtained because the amplitude threshold was set correctly for the particular situation. However, this is difficult to accomplish in real-time. Therefore, a second software package was designed as described in Section 5.2, which decreased the dependence of the results on the amplitude threshold setting. Preliminary results indicated that the number of location errors was significantly reduced as was the standard deviation from a least square fit to x versus time with the improved software.

Significant improvements in results were obtained with the second software package. Figure 5-5 shows typical improvement in vortex transport plots in going from the V_{pk} algorithm to the I_{pk} algorithm. Note that scatter is substantially reduced, but the problem of locating two vortices where only one is present has not been solved. Figure 5-6 shows the effect of using the N_r R restriction with $N_r = 2$. Both runs were performed with the V_{pk} algorithm. The N_r R restriction eliminated the location problem for single vortices. At this point in the analysis, the change in the A, B,

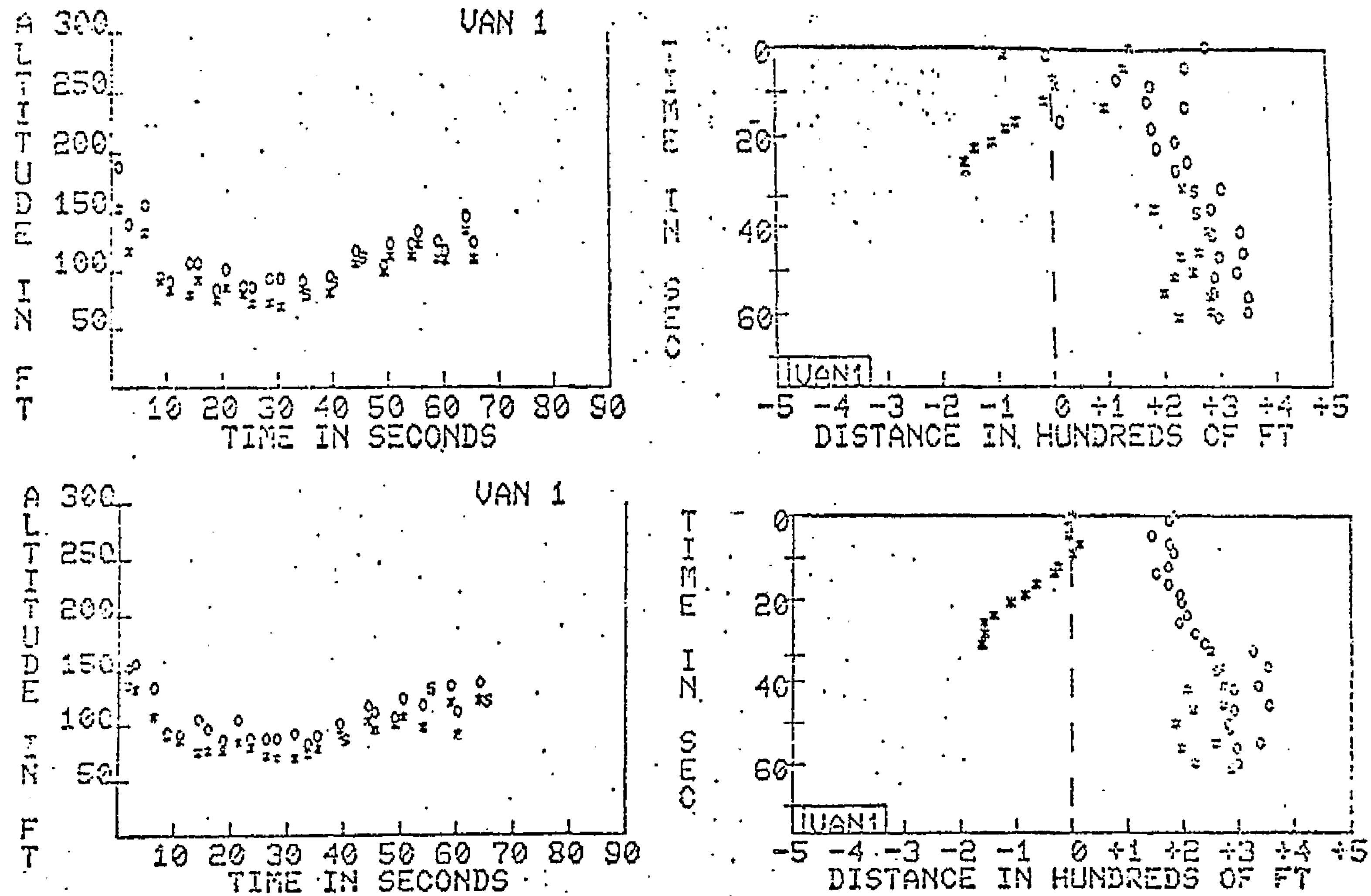


Figure 5-5. Improvement in Vortex Location using I_{pk}

Top: Results of V_{pk} Algorithm

Bottom: Results of I_{pk} Algorithm

Correlation Radius was 90 Feet for both Algorithms.
The Aircraft was a B-747.

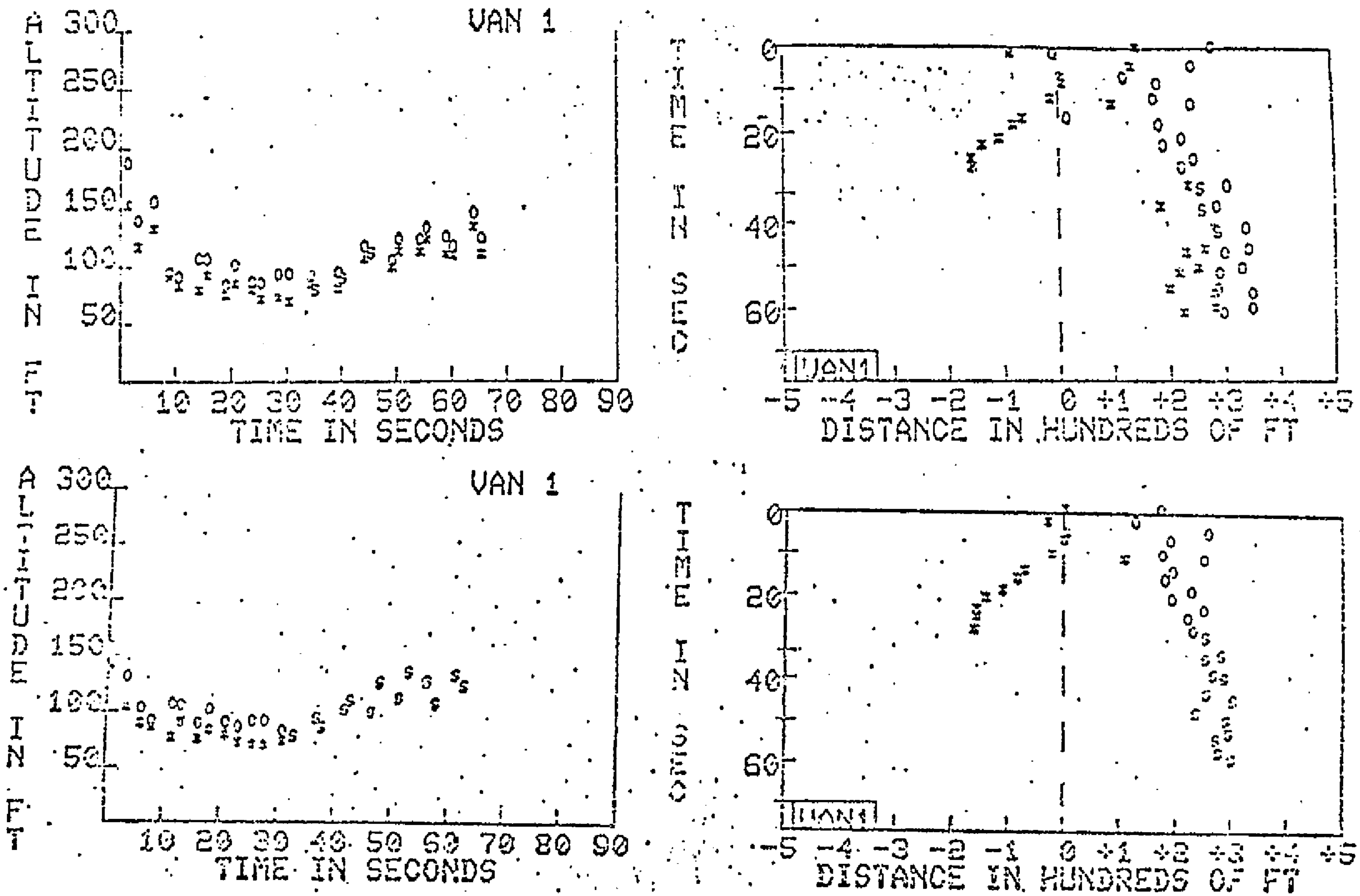


Figure 5-6. Improvement in Vortex Location using N_r R Restriction

Top: V_{pk} Algorithm using $N_r = 1$

Bottom: V_{pk} Algorithm using $N_r = 2$

R = 90 Feet for both. The Aircraft was a B-747.

and C parameters had not been made.

A sample of the results obtained using the complete new software package is shown in Figure 5-7. Data was taken during the evening with very calm wind conditions. The I_{pk} algorithm was used with a correlation radius of 90 feet. The C parameter was set to 25, and the N_r parameter to 1. This indicates that in the new software package, the C parameter reduces the need for the N_r parameter. It is anticipated that this will reduce the need for changing the correlation radius with aircraft type.

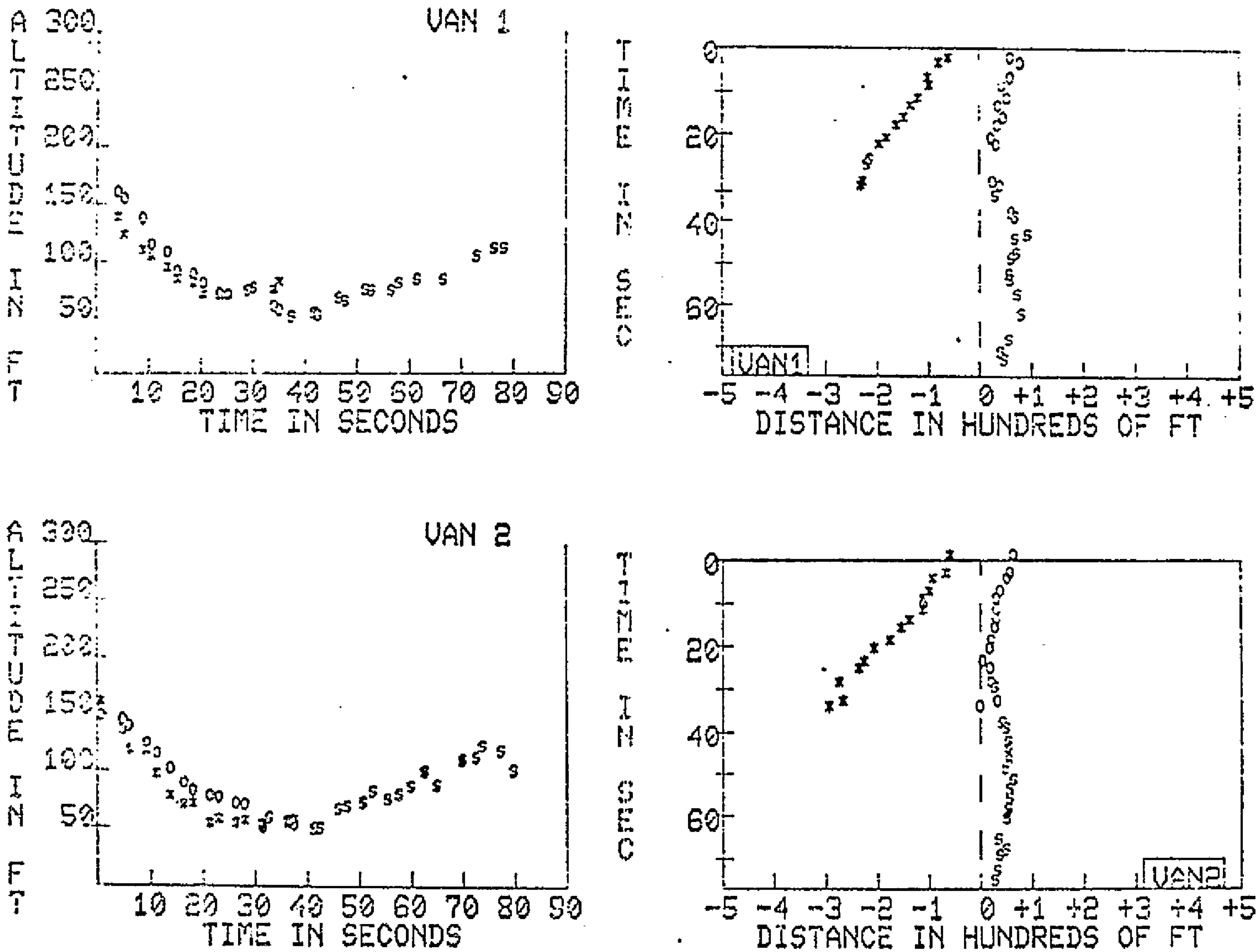


Figure 5-7. Vortex Time History for Flyby Number 16 on Day 310. Aircraft was a B-747 and the I_{pk} Algorithm is used.

SECTION 6

SUMMARY AND CONCLUSIONS

It has been established that the scanning laser doppler velocimeter is capable of locating regions of high velocity in field tests involving both an aircraft engine flow field and actual vortices in flyby tests. Furthermore it has been confirmed that the system is capable of locating vortices in real-time in an airport environment. The original algorithm was dependent on carefully adjusted threshold settings and was somewhat limited by the optical system range resolution.

Evaluation of data from operations at KIA indicates that operator performance in setting these controls has improved considerably since the early MSFC tests, and that very few runs are lost due to improper threshold settings. Simultaneously, algorithm modifications have reduced the requirements for correct threshold settings, with this combination of events resulting in very significant improvements in the vortex location capability of the system.

Furthermore, the algorithm modifications have minimized the effect of optical range resolution with the result that the "scattter" in the results has been reduced.

The results of field tests on aircraft engine flow fields are in good agreement with the predictions of the simulation work, and standard deviations from least square fits to actual vortex data are in agreement with location accuracies predicted by the simulation. Standard deviations of a few meters are obtained in most cases.

Further improvements in the system may be made with the purpose of reducing the number of operator-variable parameters. For example, methods of adaptive thresholding might be developed to allow the system to select optimum thresholds for a scan based on results of the previous scan. Also it may be possible to determine a correlation radius and values of A, B, C, D, and N_r which are suitable for all aircraft in all conditions.