EVALUATION OF A SEQUENTIAL PHASE COMPARATOR FOR THE REDUCTION OF LASER ANEMOMETRY DATA

By

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1972

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
December, 1974

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ACKNOWLEDGMENTS

I would like to thank Dr. D. K. McLaughlin for his large role as my thesis adviser. I would also like to thank Dr. W. G. Tiederman for all the help and suggestions that contributed to this study.

I am also grateful to the many people that have aided in the completion of this thesis. Dr. M. M. Reischman, Mike Karpuk, and Lloyd Salsman contributed greatly to my knowledge for this thesis. I would like to thank Tim Troutt and Gene Kouba for their aid and friendship.

TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 1

  Description of the Sequential Phase Comparator 4
  Scope of This Study 6

II. EXPERIMENTAL TECHNIQUES 7

  Data Collection Methods 7
  SPC System Apparatus 8
  Interfacing with the SPC 9
    Input Interfacing 9
    Output Interfacing 10

III. EVALUATION OF THE SPC AND DATA REDUCTION SYSTEM 11

  Processor Limitations 11
    Design Requirements 11
    System Imposed Limitations 11
  Parameters Affecting Data 12
  Performance Test 13
    Tolerance Settings 14
    Real Time System Evaluation 15
  Rejection Rates and Measurement Error 17

IV. SUMMARY AND CONCLUSIONS 19

V. DISCUSSION OF DESIGN PARAMETERS AND SYSTEM IMPROVEMENTS . . 21

  SPC Prototype Changes 21
  System Improvement Recommendations 23

SELECTED BIBLIOGRAPHY 26

APPENDIX A - COMPUTER ANALYSIS OF DATA 27

APPENDIX B - OPERATIONAL SETTINGS AND SUGGESTED CHECK PROCEDURES . 33

APPENDIX C - DATA 36

APPENDIX D - FIGURES 41

LIST OF TABLES

Table Page

I. Maintenance Aid Suggestions 22

II. Suggested System Improvements 23

III. Statistical Program Algorithms 29

IV. Computer Program List 30

V. Computer Program Inputs and Outputs 31

VI. System Settings and Procedure Checklist 34

VII. SPC Reduction of Karpuk's Data 37

VIII. Tolerance Data 39

IX. Schmitt Trigger Data 40

LIST OF FIGURES

Figure Page

1. The Basic Dual Scatter Laser Doppler Anemometer 42
2. Photographs of Doppler Bursts and Schmitt Trigger Outputs . . 43
3. Basic Operation of the SPC 44
4. Schematic of Processing of Doppler Signal in the Data Discriminator System with a Missing Pulse at the Beginning of the Burst 45
5. Block Diagram of Reischman's Data Acquisition and Reduction System 46
6. Block Diagram of Karpuk's Data Acquisition and Reduction System 47
7. Schematic of Primary Elements of the SPC Data Acquisition . . 48
8. Schmitt Trigger Variation for Four Trigger Levels 49
9. Local Mean Velocities Determined by the Data Processor Using Different Tolerance Settings 50
10. Local Velocity Fluctuations Determined by the Data Processor Using Different Tolerance Settings 51
11. Mean Velocity Profiles in the Law-of-the-Wall Coordinates . . 52
12. Streamwise Turbulence Intensity Profiles 53
13. Histograms for Four y Locations of Karpuk's Data 54
14. The Rejection Rate of Realization for a Period of Time Versus the Local Mean Velocity 55
15. The Yield Ratio for SPC Reduced Data 56

NOMENCLATURE

A	period count acquired in Counter A
B	period count acquired in Counter B
K	constant for period to velocity conversion (Table V)
N	whole number that determines the tolerance settings
NR	Number of Realizations
P_{2p}	probability of two particles being in the probe volume
R_e	Reynolds Number
t	tolerance value
T_t	particle transit time in the probe volume
T_{br}	time between realizations
U	instantaneous velocity realization
U_B	biased local mean in the streamwise direction
U_c	corrected local mean in the streamwise direction
U_τ	shear velocity
u'	root mean square of the streamwise velocity fluctuations
U^+	nondimensional streamwise velocity
y	distance normal from the wall
y^+	nondimensional normal distance from the wall

CHAPTER I

INTRODUCTION

The Laser Doppler Anemometer (LDA) has become an important and useful tool for the investigation of fluid flow and turbulence. The purpose of the LDA is to measure, without disturbing the flow, the velocity of small particles contained in the flow field and, in most cases, moving at the local fluid velocity. The physical principle of its operation is to measure the Doppler shift frequency of laser radiation scattered off the particles. The scattered light is optically heterodyned to obtain only the Doppler frequency by scattering light from two separate (but spatially and temporally coherent) beams. The dual scatter mode of the LDA, depicted in Figure 1, crosses the two beams to produce an interference pattern that is called the probe volume. As a particle moves through the probe volume the scattered light is modulated at the Doppler frequency. The scattered light is then collected by a photomultiplier tube to produce an electrical signal similar to the drawing in Figure 1. This signal is modified by a Schmitt trigger and then input to a period counter which counts the elapsed time for 10 periods of the Doppler frequency. From this measurement the Doppler frequency can be directly calculated.

The individual realization LDA can be described by the fact that the output signal is not continuous, and a velocity realization occurs randomly as particles travel through the probe volume. Very dilute particle concentrations are required to ensure that the individual realizations are statistically independent. Statistical techniques used to evaluate the mean and standard deviation can be applied to yield an estimate of the mean and root mean square velocities. Donohue, McLaughlin and Tiederman (1) first applied the individual realization LDA to turbulent flow.

Contrasting the individual realization LDA is the continuous wave anemometer which requires a very large number of seed particles. This anemometer was named continuous wave because one or several particles must be in the probe volume at all times producing a continuous output signal. The continuous signal is commonly converted to an analog signal proportional to the instantaneous velocity by a frequency tracker. Trackers are questionable in accuracy at turbulence levels of 15%-20% or above (2). Signal dropout and Doppler ambiguity limit the continuous wave anemometer in application and accuracy.

The individual realization anemometer does not suffer from the difficulties associated with the continuous wave device, and the main criterion involved in the accuracy of the individual realization mode is the verification of signals. Verification of each realization of the individual realization LDA is necessary because of occasional Doppler cycles which are either missing or suppressed. This cycle dropout represents the most serious form of error in the individual realization LDA. The need for verification was demonstrated by other LDA researchers (3, 4).

Figure 2 demonstrates typical LDA signals on an oscilloscope. In each picture the upper trace is a filtered photomultiplier tube signal, which is the input signal to a Schmitt trigger. The lower trace on each photograph is the output from the Schmitt trigger. The top picture represents an acceptable Doppler burst for the individual realization LDA. The bottom photograph shows a missing cycle in the middle of a burst. Since the period counter will then effectively count the time for 11 cycles (rather than 10 cycles), this figure demonstrates vividly the need for the electronic data reduction system to distinguish between these two types of signals.

Prior to this study, the method of reducing data in our laboratory was a lengthy, tedious process referred to as "visual" verification. The visual verification scheme is a process of storing each individual Doppler wave packet on a storage oscilloscope and visually insuring that a sufficient number of pulses enter the period averaging counter to obtain an average period (10 were required). After assuring that the counter has a valid period count, the count was punched on computer cards for later processing by computer. The SPC was designed to replace the human link of this reduction process, and to decrease the time required to reduce LDA data.

The individual realization LDA and radar technology were combined by Salsman (5) to design an instrument for the purpose of verifying LDA signal. The Sequential Phase Comparator (SPC) verifies LDA signal for other instrumentation to accumulate, record, and process. The SPC's operation and performance, as a part of the LDA data reduction system, is evaluated in this study.

Description of the Sequential Phase Comparator

The SPC is a complex instrument that functions in much the same manner as a computer. The 'program' is a diode matrix that controls the functions of arithmetic required to verify LDA signal. For details of the electronic design, see Salsman (5).

The SPC purpose is similar to that of the processors of Asher (3) and Kalb (4); however, the SPC performs a continuous, discrete, and "sliding" phase comparison of each time period between pulses rather than the comparison of the time between 4 or 5 pulses to the time for 8 pulses (divide by 2 or 8/5). The SPC has only one function, but the basic design can be altered to include a variety of operations other than signal verification. The SPC scrutinizes each pulse allowing only valid signals to pass into an external measuring and recording apparatus.

The processor uses two sixteen bit counters to accumulate period counts between each pulse, as shown in Figure 3. The SPC then performs a comparison of consecutive period counts to determine if they are within a set tolerance of each other. After the comparison is made, the most current period count is retained, and a new count is accumulated in the second counter. This process is continuous and repeated each time a pulse arrives.

The comparison is made during each pulse, by an algorithm based on the normalized error formula:

$$\frac{A - B}{A} = t$$

where A is greater than B. By rearranging the above algorithm, the equation becomes:

$$2^N * (A - B) - A = 0 \; ; \; 1/t = 2^N$$

The reason for making the tolerance a function of two is due to the method of implementing the multiplication operation. Since the value of N can be any positive integer, t can be set at any value proportional to powers of two (i.e. 50%, 25%, 12.5%,. . .).

The counting method has several variations including the SPC designed by Salsman (5). The systems of Asher (3) and Kalb (4) are period counting processes that require 8 pulses to complete a comparison. The counting system does not require the continuous signal required by the frequency tracker. Asher shows varying error caused by false readings for the 4 to 8 comparison (divide by 2) or the 5 to 8 comparison (divide by 8/5) processors. His work demonstrates the possibility of error in the 8 pulse comparison scheme because of false readings. The SPC was designed on a one period to one period comparison eliminating the false reading error.

Figure 4 demonstrates the process that the SPC performs during signal verification. This figure shows the SPC action for signals with early dropout, with the SPC accepting the ten remaining good pulses. The comparison signal demonstrates the location of each comparison the SPC performs. It performs a comparison as each pulse arrives. The SPC control signal depicts the acceptance or rejection of each pulse with a high output indicating acceptable pulses. The period counter requires 10 pulses to complete an average count. After 10 pulses enter the counter and are verified by the SPC, then a print pulse is generated and the data is punched on paper tape.

Scope of This Study

The SPC prototype has been proven to verify instrument generated test signals, but the important test of performance is LDA signal verification. This study places the SPC in a LDA data reduction system to evaluate the SPC performance in actual data analysis.

A description of instrumentation used to process the LDA data as well as a brief description of signal collection are included in the second chapter. Part of the second chapter is devoted to the apparatus required to produce compatible signals between the SPC and the other instrumentation of the system.

Processor and system limitations are presented in chapter three along with performance tests on the SPC. The major portion of the tests of performance are comparisons with data verified earlier (2, 6).

The fifth chapter discusses changes or improvements that have been discussed to improve the complete SPC reduction scheme. These changes range from maintenance to complete system changes.

Appendix A summarizes the computer program operation used to reduce data accumulated by the SPC system. Appendix B gives the system settings and a procedure checklist. Appendix C contains the data collected for this study. Appendix D is figures for this text.

CHAPTER II

EXPERIMENTAL TECHNIQUES

In prior LDA studies at Oklahoma State University, Reischman (2) and Karpuk (6) recorded output signals on analog magnetic tape. This data is used to base a comparison of results performance test for data reduced by the SPC. A description of collection methods are presented first in this chapter.

Data Collection Methods

The methods used in recording the analog tapes were different for each researcher. Reischman used only one photomultiplier tube as a signal receiver, and a bandpass filter to reduce electronic noise and eliminate pedestal frequencies. A block diagram of Reischman's data collection apparatus is shown in Figure 5. Karpuk used an optical scheme to cancel noise and pedestal frequencies producing a signal with less noise. Figure 6 shows Karpuk's collection system.

The two data reduction schemes of Karpuk and Reischman differ only by the bandpass filter. This requires the use of two SPC reduction schemes as shown in Figure 7. The filter was used for Reischman's data only.

SPC System Apparatus

The block diagram of the SPC system (Figure 7) begins with the analog tape. The taped signal is reproduced by a Sanborn-Ampex model 2000 magnetic tape recorder at either 7 1/2 (visual verification speed) or 60 (real time) inches per second. Since the data was recorded at 60 inches per second, the reduction in speed by 8 allowed the visual observer more time to verify the signal and reduced the required SPC frequency response.

The Multimetrics model AF-120 bandpass filter was placed in the circuit for the reduction of Reischman's data. The next link was a Schmitt trigger constructed from a Digital Equipment Corporation W-501 module. The Schmitt trigger has adjustments for both the upper and lower trigger voltage levels (see Figure 4). The input signal must pass both trigger levels before the output level will change. This produces a series of equal level pulses when the Schmitt trigger encounters a Doppler burst.

The interface blocks indicated on each side of the SPC are described later on in this chapter. The interfacing apparatus was placed inside the SPC prototype. Changes in the signal entering and exiting different parts of the system were required to allow electronic compatibility between instruments.

The period averaging counter is a General Radio model 1192B. The mode of operation for data collection is a period times ten requiring ten pulses to measure an average period. The counter can also be controlled to a small degree by external signals, but a display cycle follows every time the counter is stopped. The counter has a BCD coded output of the period as it is displayed on Nixie tubes. This output is connected to a Non-Linear Systems model 2607 serial converter in combination with a Tally model P-120 paper tape punch to record the period for later processing.

The model 9820 Hewlett Packard computing calculator was the final instrument used to reduce LDA data by the SPC system. A model 9863A tape reader and a model 9862A plotter were used by the computer to input and output data. Statistical processing and histogram plotting are performed by the 9820. Appendix A includes a description of the program used to reduce data.

Interfacing with the SPC

The SPC was designed to fit into the visual verification scheme as a replacement for the human link. Its only purpose was to verify the LDA signal and in some manner indicate the good burst. The interface added another function of controlling the recording of good period counts. The input interface also altered the Schmitt trigger signal to make it compatible with the SPC.

Input Interface

The Schmitt trigger described earlier in this chapter was part of the pulse-shaping electronics, but the signal it produced could not be used to operate the electronics of the SPC. The output signal from this Schmitt trigger alternates from 0 volts to -3 volts as the Doppler input goes above and below the trigger levels. The input requirements for the TTL circuits of the SPC are 0 to 2 volts. To produce a compatible signal, a conversion of voltage levels was required. For this purpose another Schmitt trigger process was used consisting of an operational amplifier and a TTL Schmitt trigger. The amplifier adjusts the signal amplitude and DC bias voltage. The input to the operational amplifier comes in the form of pulses from the external Schmitt trigger. The pulses are amplified and biased to voltage levels that will trigger the TTL Schmitt trigger. In this manner, the pulse train is converted to a signal that the SPC can verify.

Output Interfacing

The output interface produces the following control signals: 1) print, 2) stop counting, and 3) BCD to ten level conversion. The SPC also controls the signal input to the counter. The SPC only allows the verified signal to pass through into the counting system. The print control indicates to the recording system when a valid period is obtained. The stop control stops any period count that fails to meet verification requirements before ten pulses have entered the counter. The stop control allows the counter to start a new count and increases the data rate by prematurely stopping any rejected period count before it is completely accumulated. The BCD to ten level code conversion was required between the counter and the paper punch system.

The interfacings are mainly controls for other equipment, but control signals enter through the output interface. The counter produces a pulse when it has obtained ten pulses which is used by the SPC to generate a print pulse for the punch system (see Figure 4).

CHAPTER III

EVALUATION OF THE SPC AND DATA REDUCTION SYSTEM

The evaluation of the SPC data reduction system includes a short description of the SPC's performance alone. The main concern of LDA researchers is the performance of the entire system; therefore, a large portion of this evaluation was on system response.

Processor Limitations

Design Requirements

The main objective placed on the design was the verification of the LDA signal. The Schmitt trigger output of the LDA signal reproduced from analog tape at a speed reduction of 8 from the recorded speed was defined as the signal requiring verification. The verification of an externally accumulated period count and the rejection of bad signals were the prime purposes for the SPC design.

System Imposed Limitations

The most restrictive part of the SPC system is the period recording process. The maximum transfer of data to the paper punch is 20 periods per second (as advertised by the manufacturer), but due to the amount of electronic delay in the interface and mechanical wear in the punching mechanism, this number has decreased to 10 periods per second. This rate indicates that if two or more acceptable bursts are less than 0.1 seconds apart the system will only respond to the first signal.

The counter also presents a limitation on data rate by not allowing an instantaneous reset control. Due to this lack of control, the counter is delayed by a punch cycle even if the SPC stops the count before ten pulses arrive. This counter reset time decreases the data rate more than any other instrument in the system, and when noise is present on the signal, the counter reset time decreases the rate more because the counter is started more often on bad counts.

Another limitation that the system contains appears in the ability of the Schmitt trigger to produce a pulse train that has been triggered by a constant phase of the input signal. The zero crossing Schmitt trigger described earlier decreases this problem.

The SPC frequency response limits the Doppler frequency, thereby limiting the LDA operation. The SPC prototype has a frequency range of 80 to 90,000 Hz and fulfills all of the initial design requirements. All the limitations apply to the processing techniques and not to system errors.

Parameters Affecting Data

Many parameters were discovered as being crucial to the performance of the SPC reduction system. The parameters recorded in Karpuk's and Reischman's data collection were considered as the most important variables. Schmitt trigger settings and bandpass filter settings were first duplicated exactly for Reischman's data. Karpuk did not consider these variables as being major parameters because of the noise canceling optical arrangement. A check was applied to the Schmitt trigger to determine the effect of varying trigger levels on the output data. Figure 8 is the plot of $\overline{U}$ versus trigger level. Trigger levels above the noise level do not change the output significantly. Appendix C contains the data obtained from this check and indicates the change in the number of acceptable realizations for varying trigger settings.

Several subtle parameters appeared because of difficulties experienced in duplicating exactly the electronic system used by Karpuk and Reischman. The signal entering the counter originated from completely different electronics, and ring from the SPC output made the counter triggering level a major source of bad data collection. The tape recorder amplifiers were also found to change the data output because alignment was not correct and reproduced a signal with a high degree of noise imposed on the output. In general, noise appeared to be a major problem encountered by the SPC electronics.

It has become obvious from this investigation that some means should be devised to check the entire system at one time instead of each individual instrument. This investigation has also shown that the complexity of the system will require a large amount of preparation for future researchers using this prototype model of the SPC.

Performance Test

It is obvious from the previous discussion that many system parameters do affect the data collection process, but the only variable contained within the SPC is the tolerance value. Referring to Figure 3, it is easy to see that using the 25% tolerance setting the SPC will always reject Doppler pulse trains from which one or more cycles of the signal is missing.

Tolerance Settings

Four tolerance values were used on four different mean velocities in a turbulent channel flow to determine the effect, if any, that varying the tolerance would have for different flow conditions. The tape reproduction speed for this data is 7 1/2 inches per second. Visually verified and SPC verified data are compared in Figure 9 for the results of typical calculations of the local mean velocities (before correcting for the natural statistical bias analyzed in Ref. 9). The 95% confidence limits placed on the visually verified data were calculated in the same manner as in Reference 1. The error limits include most of the SPC verified data within their boundaries. The 50% tolerance falls below the limits for some of the data. At this tolerance it has been observed that data with missing pulses can pass the verification requirements. Data with missing pulses will record period times 10% or more longer than the correct Doppler period. Thus, these measurements contain data which is in error on the low side. This is the direction of the discrepancy in the mean velocity at the 50% tolerance setting. Both the 12.5% and the 25% agree almost exactly with the visually verified data.

The 6.25% tolerance data again indicates a slight difference from the visual case. There are two possible reasons why the values at the 6.25% tolerance vary from the visual case. The first reason which has been a major contributer to error throughout this study is signal noise.

The number of verified points accepted at 6.25% tolerance is decreased greatly from the 25% tolerance case causing a second reason for the variation in data. This lack of points would be indicated by a decrease in turbulence, as shown in Figure 10 at a mean velocity of 1.2 (see Appendix C).

Figure 10 is a plot of the calculated rms velocity fluctuations again compared to the visually verified data. As in the mean velocity case, the turbulent intensities agree very closely for the 12.5% and 25% tolerance settings to the visually verified data. The 50% tolerance case indicates that the observation of dropped pulses does alter the statistical values obtained from the data. The figure shows to a much larger extent that the 6.25% tolerance does not agree as well as the 12.5% setting. The data indicates that this occurred with some of the measurements. The lack of points was due to the amount of time the signal was recorded on the analog tape. The number of data realizations obtained for each point are recorded in Appendix B.

Real Time System Evaluation

A major reason for the design of the SPC was to reduce the time required to analyze LDA data. A method of shortening the time taken for the SPC reduction process is to use the actual recording speed (60 ips) to replay the data. This decreases the time required to reduce the data by 8, and gives more insight into problems that can be encountered during on-line operation.

The data used in this part of the study was recorded by Karpuk at a Re = 12,790. The SPC tolerance was set at 25%. Figure 11 shows the mean velocity profile in the law-of-the-wall coordinates. This figure indicates that the SPC and visually verified data are in some agreement. At larger Y^+ values, the velocity data are below the values obtained by Karpuk. This condition lead to the conclusion that the signal reproduction amplifiers were not matched exactly for the two different transport speeds (7 1/2 and 60). This was verified by using a well aligned set of reproduction amplifiers. Tests on the amplifiers have shown that careful alignment is important and poor alignment can change the mean velocity. The data for Figure 11 has indicated a variable that was not recorded by Karpuk in his experimentation and could not be repeated exactly. After aligning both 7 1/2 and 60 inches per second tape amplifiers as described in the tape recorder manual, a value of V^+ lower than Karpuk's data was obtained at both speeds and closely agreed with each other (see Appendix C). We believe the systematic error of lower mean velocities stems from the electronic alignment of the tape recorder reproduction amplifiers.

Figure 12 compares the streamwise turbulent intensity profile obtained from the SPC and Karpuk's visually verified data. The agreement again is very close and also agrees with other investigators' hot-wire measurements in similar turbulent flows (7, 8).

The four histograms shown in Figure 13 are obtained from this data. Figure 13a is at a Y^+ of 1.57 and comes from the data taken at the nearest approach to the wall. Figure 13b is from a Y^+ of 12.65, or the location of highest turbulent intensity. Both graphs c and d were from the middle of the flow field. These four graphs demonstrate the range of velocities the instrument must be capable of responding to.

The time required to reduce data was decreased greatly from Karpuk's reduction time. The number of points obtained is shown to increase from Karpuk's data, but there is also a large increase in accepted realizations when the SPC reduces data at the slower tape speed (see Appendix C, TABLE VII).

Rejection Rates and Measurement Error

The low seed density associated with the individual realization LDA requires that the rejection rate of data be small, or long processing times are required from the data. Figure 14 indicates the number of realizations per unit time and compares this rate to the number of verified realizations per unit time for different mean velocities. This data shows the relationship between the number of realizations and the local mean velocity. The proportionality shown in this figure verifies a major assumption made by McLaughlin and Tiederman (9) in a correct biasing scheme. Figure 15 shows a constant rejection rate of 70% for varying flow conditions and burst rates. This figure tends to indicate that the amount of data lost by system response time is small or at the higher burst rates the rejection rate would be larger than in the slow mean velocity flow or lower burst rate. The data for both of these figures was reduced with a tolerance setting of 25%.

The rejection rate increases as the tolerance value is increased as shown by the tolerance data in Appendix C. Calculation of duty cycle indicates a low probability of two or more particles being present in the probe volume at any one measurement itme. The 12.5% and 25%

tolerance data also indicates this for some data by collecting very nearly the same amount of realizations. The average duty cycle for Karpuk's data is given as:

$$100 * [T_t / T_{br}] = 1.6\%$$

or the probability of two particles in the probe volume of

$$P_{2p} = 0.016$$

A secondary assumption to the biasing analysis of McLaughlin and Tiederman (9) is that this probability is much less than one and is verified by the present data.

CHAPTER IV

SUMMARY AND CONCLUSIONS

The Sequential Phase Comparator does perform the task of reducing laser Doppler anemometry data with a high degree of accuracy. Many unforeseen difficulties were encountered during this evaluation, and due to the complexity of the instrumentation involved, more problems are possible. The reliability of the SPC system depends on the operator's reliability in adjusting the system variables. To ensure the correct output, a test should be devised to check the entire system before each data run.

The data of this study shows that the SPC and visually verified reduction systems do give comparable statistical values of velocity and fluctuation measurements. The SPC does allow the researchers more realizations to obtain a higher degree of accuracy and less time required to reduce the results.

The conclusions of this study are:

1) The SPC prototype meets the design objectives of replacing the visual verification scheme.
2) The SPC gives the same results as obtained by Reischman and Karpuk using the visual verification scheme.
3) Limitations of the SPC restrict data collection rates and frequency response.

4) Tolerance effects on the data are clear, with 25% tolerance performing the best signal analysis.
5) The SPC decreases the time required to reduce data and increases the number of realization available for the statistical data.

CHAPTER V

DISCUSSION OF DESIGN PARAMETERS AND SYSTEM IMPROVEMENTS

During the course of this study, many suggested changes were discussed and some changes were made. These suggestions varied from simple additions to the SPC to complete reconstruction of the prototype unit. The changes that were not put into the prototype model for this study are presented here in order to record suggested improvements based upon the experience gained in this study.

SPC Prototype Changes

The SPC prototype has already demonstrated the tedious task of electronic maintenance and error diagnostics. Table I lists changes in the prototype that would aid in the maintenance of the SPC.

From this table, the first two items are not physical changes in the SPC but additions to testing procedures. Item 3 completes the construction of a switching network that was originally intended to aid in locating any design errors in the program matrix. The switch matrix would allow the operator to input statements or delete any program step. This item also allows a quick means of checking the diode matrix, if the LED's (Light Emitting Diodes) are installed.

TABLE I

MAINTENANCE AID SUGGESTIONS

1. Manuals indicating maintenance and diagnostic procedures, including wiring and layout diagrams.
2. Construct a test tape of signals covering the full operation range of the SPC and signals that are like the Doppler burst.
3. Complete the installation of the switch panel and LED display to check the diode matrix and add manual entry into the diode program.
4. Install a TTL comparator for the purpose of checking the program route.

Item 4 in the table was suggested after many hours had been spent in trying to locate an error in construction. The comparator can be used to indicate when the program begins on any step by comparing that step number to a set of switches. The output from this system would be a pulse that could be used on an oscilloscope to compare with any unusual occurance in the SPC performance. This feature could also be used to determine some experimental data consideration such as the number of times the periods are equal in each counter, or the number of bursts that have a positive phase shift due to the Schmitt trigger. The main purpose for this addition to the SPC is to locate any program step that may cause a malfunction.

System Improvement Recommendations

The complete SPC system has several points that can be improved. Many changes in the SPC itself would increase the capability and performance of the instrument. Listed in Table II are changes that were suggested during this study.

TABLE II

SUGGESTED SYSTEM IMPROVEMENTS

A. Increased Frequency Range

1. Add a choice of inputs to signal entering the processor by a divide by n circuit (n is any positive integer).
2. Install Read Only Memory (ROM) circuit in place of the diode matrix.
3. Repackage the electronics into a smaller unit to reduce the long connection length between components.

B. Increased Data Rate

4. Construct an inboard counting system to allow the SPC more control over the data collection procedure.
5. Include a high speed recording system or memory recording unit to permit higher data collection rates.
6. Redesign the entire system using higher speed logic and a simpler design approach.

Item 1 is another method of increasing the frequency range of the SPC system by allowing the processor to work on a lower frequency signal than the input or counting system contains. By this method, a divide by two would double the high frequency range. Items 2 and 3 in Table II are improvements to increase the high frequency response of the SPC. Conservative estimates have placed the change in response from 90 KHz to 4 MHz for the improved package. Item 3 would not be as important as installation of the ROM (Item 2), but the increased frequency range would require short connection lengths.

The inboard counter (Item 4) was suggested after much deliberation over the existing counter. This item was a consideration of the basic design, but accuracy and cost were the main reasons for using the General Radio Counter. Later it became apparent that the lack of control over its operation would offset any advantage the counter contained.

The high speed recording system of Item 5 would allow the data collection rate to increase which would become necessary in higher velocity flow fields.

The last item was a way of collecting all of the suggestions into one instrument and performing the processing operation with higher speed logic to extend the instrument range farther. If the complete processing unit were placed in one package, with the exception of the computer, the number of system variables would be much less.

Many of these suggestions were conceived when errors appeared in the data reduction process, but all have merit when a new processor design is considered. The complete package design would be the instrument that could perform data processing for most if not all LDA applications.

The SPC prototype as it is today is very limited to certain flow fields or flow conditions and has many repeated parameters in different instruments.

SELECTED BIBLIOGRAPHY

(1) Donohue, G. L., D. K. McLaughlin, and W. G. Tiederman, "Turbulence Measurements with a Laser Anemometer Measuring Individual Realizations." Physics of Fluids, Vol. 15 (1972) p. 1920.

(2) Reischman, M. M., "Laser Anemometer Measurements in Drag-Reducing Channel Flows." (Ph. D. Dissertation, Oklahoma State University, 1973)

(3) Asher, J. A., "Laser Doppler Velocimeter System Development and Testing." General Electric Technical Information Report No. 72CRD295, October, 1972.

(4) Kalb, H. T., "Performance of the Model 6 Doppler-Data-Processor Measuring Instrumentation." Arnold Research Organization Report, June, 1972.

(5) Salsman, L. N., "A Digital Signal Processor for Laser Doppler Anemometer Systems." (M.S. Thesis, Oklahoma State University, December, 1973)

(6) Karpuk, M. E., "A Laser Doppler Anemometer for Viscous Sublayer Measurements." (M.S. Thesis, Oklahoma State University, May, 1974)

(7) Eckelmann, H. and H. Reichardt, "Hot-Film Measurements in Oil." Proceedings of Symposium on Turbulence in Liquids, Rolla, Missouri, 1971.

(8) Hussain, A. K. M. F. and W. C. Reynolds, "The Mechanics of a Perturbation Wave in Turbulent Shear Flow." Report FM-6, Department of Mechanical Engineering, Stanford University, 1970.

(9) McLaughlin, D. K. and W. G. Tiederman, "Biasing Correction for Individual Realization Laser Anemometer Measurements in Turbulent Flow." Physics of Fluids, Vol. 16, N 12, 1973.

APPENDIX A

COMPUTER ANALYSIS OF DATA

COMPUTER ANALYSIS OF DATA

Statistical analysis of LDA data is computed by a Hewlett Packard 9820 computing calculator. The program used in this study was basicly a histogram plotting program obtained from Hewlett Packard. Revisions were made on the program to the input and output. These changes consist of allowing the computer to read paper tape and to output more required data results. Table IV lists the program used for most of this study. Table V lists the program inputs and outputs with the exception of the histogram.

Many variations can be made in the program, but the limited storage space of the 9820 restricts the program to its present program storage space. Any change in the program listed in Table IV would require a cut in another part of the program. To go beyond this program length, two programs would have to be computed using two data passes. The limited storage space of the 9820 does not permit the storage of data; therefore, an iteration process is required to get the mean and standard deviation. The algorithms for this program are listed in Table III.

TABLE III

STATISTICAL PROGRAM ALGORITHMS

EQUATION	STATEMENT NO.	STATEMENT FUNCTION
$\frac{\Sigma u}{NR} = U$	61,9,23	$\frac{K}{T} = u$, Σu , $\frac{\Sigma u}{NR}$
$\frac{\left(\frac{K}{\Sigma T}\right)}{NR} = Uc$	61,46	ΣT , $\frac{K}{\Sigma T} / NR$
$\sqrt{\frac{\Sigma u^2 - (\Sigma u) U}{(NR - 1)}} = u'$	9,24,52	Σu^2 , $\frac{\Sigma u^2 - (\Sigma u) U}{NR}$, $\sqrt{\frac{\Sigma u^2 - (\Sigma u) U}{(NR - 1)}}$
$\sqrt{U(Uc) - (Uc)^2} = u'_c$	53	$\sqrt{U(Uc) - (Uc)^2}$

TABLE IV

COMPUTER PROGRAM LIST

```
0:
SPC 8;FXD 4⊢
1:
0→X→Y;CFG 0;GSB
"A"⊢
2:
GSB "F ⊢
3:
FXD 6;IF FLG 13;
GTO 10⊢
4:
PRT X;1+Y→Y→R16;
IF B>X;1+R6→R6;
GTO 7⊢
5:
IF X>B+AR8;1+R9→
R9;GTO 7⊢
6:
R((X-B+A/2)/A+20
)+1→R((X-B+A/2)/
A+20)⊢
7:
IF X>R4;X→R4→R11
⊢
8:
IF R5>X;X→R5→R13
⊢
9:
R0+X→R0→R18;R1+X
X→R1→R19;GTO 2⊢
10:
R8-1+R17→C;R11-R
4;R13-R5;R18→R0;
R19→R1;R16→Y;AR1
7+B→B;GSB "B"⊢
11:
IF R12=1;SPC 5⊢
12:
IF R(X+19)=0;
JMP (X+1→X)>C⊢
13:
PRT X,R(X+19),10
0R(X+19)/Y,((R4-
R5)*.5(X/R8-1))↑
2*R(X+19)/Y⊢
14:
PRT (R0/Y-(X-6)(
R4-R5)/R8)YR10/R
0-R10;SPC 1;IF (
X+1→X)≤C;GTO 12⊢
15:
X-1→C;IF X>R17;R
((R(X+12)/R7)(X+
12)+7)→R7;JMP 0⊢
16:
SCL B-A/2,R8A+B,
-.15(R7+3),R7+3;
AXE B,0,5A,10;
GSB "C"⊢
17:
B-A/2→X;LTR X,0,
111⊢
18:
PLT X,0;PLT X,RR
6;PLT X+A→X,RR6;
PLT X,0;JMP (1+R
6→R6)>C+20⊢
19:
C/20+1.49-1E11+1
E11-1→R4;0→X→R5⊢
20:
FXD 4;IF AC+B>10
0;FXD 3;IF AC+B>
1000;FXD 1⊢
21:
LTR B+XA,-.15(R7
+3),222;PLT B+XA
;JMP (R4+X→X)>R8
-1⊢
22:
FXD 0;LTR B+.01(
C+1.5)A,R5,221;
PLT R5;JMP (R5+1
0→R5)>R7+1⊢
23:
R0/Y→X;FXD 4⊢
24:
(R1-R0X)/Y→R6⊢
25:
GSB "D"⊢
26:
.0064(C+1.5)A→R0
;.0064*1.15(R7+3
)→R1⊢
27:
B+(C+1)A-40R0→R2
;R7+3-2R1→R3⊢
28:
LTR X-R0,0,221;
PLT "X";LTR X-R0
,1.7R1,221;PLT "
-"⊢
29:
LTR R2,R3,211;
PLT "X";LTR R2,R
3+1.7R1,221⊢
30:
PLT "-";GSB "E"⊢
31:
LTR R2+7R0,R3,22
1;PLT X;R3-4R1→R
3⊢
32:
LTR R2,R3,221;
PLT "S";LTR R2+2
.5R0,R3+1.5R1,11
1⊢
33:
PLT "2";GSB "E"⊢
34:
LTR R2+7R0,R3,22
1;PLT R6*Y/(Y-1)
;LTR R2+7R0,R3-4
R1,221;PLT R15⊢
35:
CFG 13;ENT "NORM
AL CURVE?",A;IF
FLG 13=0;GTO 39⊢
36:
YA/2.5066√R6→R0;
(C+1)A/50→R1⊢
37:
LTR B,R0*EXP (-(
B-X)↑2/2R6);B→Y⊢
38:
PLT B,R0*EXP (-(
B-X)↑2/2R6);JMP
(R1+B→B)>CA+Y⊢
39:
CFG 13;PEN ;PRT
"DATA RUN NO.",R
15;ENT "NEW X0 C
ELL NO.",R17;IF
FLG 13;GTO 0⊢
40:
ENT "NO. OF CELL
S",R8;1→R12;Y→B;
GTO 10⊢
41:
"A";0→RX;JMP (X+
1→X)=120⊢
42:
ENT "K=",R14;
ENT "NO.",R15;
ENT "CELL WIDTH=
?",A;ENT "X0=?",
B;PRT R15,R14⊢
43:
PRT "CELL WIDTH"
,A,"X0",B;SPC 1;
ENT "NO. OF CELL
S",R8;-1E99→R4;-
R4→R5;RET ⊢
44:
"B";PRT "CELL NO
.","NO. OBS. IN
CELL"⊢
45:
PRT "% RELATIVE
FREQ.","ENER DEN
 FUNC.","VEL. FLU
C.";1→X;IF R12=1
;R17→X⊢
46:
SY (R10+R14)→R10
;RET ⊢
47:
"C";PRT "XMAX","
XMIN","RANGE",R4
,R5,R4-R5,"MEDIA
N",(R4-R5)/2+R5⊢
48:
PRT "LOW HIGH FR
EQ",R5*R14*1E8,R
4*R14*1E8;IF R6>
0;PRT "NO. LESS
X0",R6⊢
49:
IF R9>0;SPC 1;
PRT "NO. TO LARG
E",R9⊢
50:
20→R6;IF R12=1;R
17+20→R6⊢
51:
RET ⊢
52:
"D";PRT "U",X,"U
C",R10,"VAR",R6*
Y/(Y-1)→R9,"U'",
√R9,"VAR C"⊢
53:
PRT XR10-R10↑2→Z
,"U'C",√Z→Z,"U'C
/UC",Z/R10,"ERR
+/-"⊢
54:
PRT 1.96√(R9/Y),
"U'/UC",√R9/R10,
"NO. OF POINTS",
Y;SPC 1;RET ⊢
55:
"E";LTR R2+5R0,R
3+.1R1,111;PLT "
-"⊢
56:
LTR R2+5R0,R3+.8
R1,111;PLT "-";
RET ⊢
57:
"F";IF FLG 0=0;
CFG 13;ENT "X=?"
,X;IF FLG 13=0;
GTO +3⊢
58:
IF FLG 0=0;IF Y≠
0;GTO +2⊢
59:
SFG 0;CFG 13;
FXD 0;RED 7,X;
IF X≤0;GTO +0⊢
60:
IF FLG 13;RET ⊢
61:
X+R10→R10;8 (X+R
14)→X;RET ⊢
62:
END ⊢
R128
```

TABLE V

COMPUTER PROGRAM INPUTS AND OUTPUTS

Computer Response	Manual Reply
⊢	END RUN PROGRAM
K	Doppler frequency constant including counter time period and tape speed. RUN PROGRAM
NO.	Data run code number. RUN PROGRAM
CELL WIDTH	The width of each cell you would like in the histogram. RUN PROGRAM
XO=?	The least value expected in the data, or 0 for this study. RUN PROGRAM
NO. OF CELLS	The number of divisions the abscissa is divided into. RUN PROGRAM
X=?	RUN PROGRAM if data is to be read from paper tape, or the first data point and RUN PROGRAM if data is entered through the keyboard.
NORMAL CURVE	RUN PROGRAM if you wish the normal distribution curve or 1 RUN PROGRAM if you do not.
NEW XO CELL NO.	RUN PROGRAM if you do not wish to replot part of the histogram, or the cell number you wish to start a replot at. RUN PROGRAM
NO. OF CELLS or K again	The new number of cells. RUN PROGRAM

TABLE V (Continued)

```
         20041.1100
                        CELL NO.
              .0025
                        NO. OBS. IN CELL      XMAX
 CELL WIDTH
                        % RELATIVE FREQ.      XMIN
              .0300
                        ENER DEN FUNC         RANGE
                        VEL. FLUC.                          .474147
              0.0000          3.000000                      .046370
                              4.000000                      .427777
             .181850          2.721088        MEDIAN
             .154038           .001171                      .260259
             .046370           .011045        LOW/HIGH FREQ
             .124941                           1.164076596E 04
             .142667          4.000000         1.190299063E 05
             .153867          6.000000        U
             .161012          4.081633                        .1877
             .187776           .001721        UC
             .137871           .007363                        .1616
             .192587                          VAR
             .168736          5.000000                        .0056
             .246176         27.000000        U'
             .185913         18.367347                        .0748
             .140602           .007583        VAR C
             .155216           .003682                        .0042
             .191006                          U'C
             .243059          6.000000                        .0650
             .147767         28.000000        U'C/UC
             .172583         19.047619                        .4024
             .113403           .007709        ERR +/-
             .116487          -.000000                        .0121
             .140658                          U'/UC
             .126866          7.000000                        .4632
             .140565         26.000000        NO. OF POINTS
             .133275         17.687075                  147.0000
             .151540           .006998
             .130776          -.093682        DATA RUN NO.
             .219715                                  20041.1100
```

APPENDIX B

OPERATIONAL SETTINGS AND SUGGESTED CHECK PROCEDURES

TABLE VI

SYSTEM SETTINGS AND PROCEDURE CHECK LIST

Instrument	Settings	Adjustment or Check Procedures
Tape Recorder (Sandborn 2000)	7 1/2 or 60 inches per second	Follow manual procedure to adjust amplifiers. This adjustment should be checked often.
Bandpass Filter (Multimetrics)	Settings were taken from Reischman's experimental notebook	Check frequency cutoffs to insure proper operation.
Schmitt Trigger	Settings determined by noise level. Upper level - 0 volts Lower level - below noise	The noise level can be determined by adjusting the lower trigger level until noise begins to trigger pulses. Observe both input and output signals on an oscilloscope to determine noise level and adjust the trigger to operate outside this level.
SPC	Tolerance settings of 50, 25, 12.5, and 6.25% were used in this study. 25% was used for the real time data.	Tolerance is set before each data run by switches on the SPC. To check the operation of the SPC tolerance requires a "word" generator as an input.
Paper Tape Punch (Tally)	Automatic punching	Punch all numbers for all digits on the counter by putting a signal generator output through the entire system and varying the frequency to obtain the numbers on the display.

TABLE VI (Continued)

Counter (General Radio)	10 period average mode 1.0 or 0.1 microsecond time base 100 millisecond display time AC Input trigger 100:1 Input attentuation 2.5 volt trigger level peak to peak Storage - off (on back of counter)	The counter is checked by inputing a 10 KHz signal into the system and obtaining the correct period count on the counter. The trigger level is found by inputing a signal directly into the counter then adjusting the input magnitude until the counter begins to register a correct count. (Begin with a zero magnitude input). This will be the input trigger level set on the counter.

APPENDIX C

DATA

TABLE VII

SPC REDUCTION OF KARPUK'S DATA

Tape Speed 60 ips

U_τ = .0996

Re = 12,790

y	y+	NR	U	U_c	u+	% Error of U	u'	u'/U_c
.00214	1.569	185	.1805	.1555	1.6067	5.87	.0733	.4715
.00410	3.005	571	.3459	.2987	3.0864	3.27	.1379	.4617
.00605	4.518	776	.5150	.4434	4.5815	2.64	.1936	.4365
.00996	7.578	1108	.6835	.6013	6.2131	1.99	.2315	.3850
.01386	10.545	570	.8311	.7498	7.7459	3.27	.2467	.3290
.01777	12.649	686	.9820	.8933	9.2302	2.08	.2728	.3054
.02167	16.645	644	1.0253	.9359	9.6684	2.13	.2576	.2753
.03144	24.381	261	1.1857	1.1084	11.4528	2.75	.2684	.2422
.04706	36.494	311	1.2964	1.2436	12.8498	2.01	.2351	.1890
.07050	55.202	370	1.4074	1.3821	14.2808	1.31	.1809	.1309

TABLE VII (Continued)

y	y+	NR	U	U_c	u+	% Error of U	u'	u'/U_c
.12130	95.910	596	1.5195	1.4679	15.1674	1.06	.2003	.1351
.24920	197.038	310	1.7109	1.6941	17.5046	.98	.1510	.0891
.49920	394.711	150	1.8726	1.8588	19.2064	1.11	.1297	.0698
TAPE SPEED 7 1/2		Alignment Check						
.24920	197.038	1239	1.7085	1.6746	16.81	.99	.1787	.1067

TABLE VIII

TOLERANCE DATA

Tape speed 7 1/2 ips

Investigator	Tolerance(%)	NR	U	U_c	+/- Error	u'	u'/U_c
Karpuk (403)	50	295	.5367	.4752	.0207	.1812	.3813
NR = 260	25	288	.5413	.4858	.0211	.1830	.3767
U = .4979	12.5	153	.5356	.4713	.0304	.1921	.4076
+/- error = 4.4%	6.25	92	.5112	.4500	.0376	.1842	.4049
*10 min. SPC data run							
Reischman (Sol-12) y+ = 13.6	50	601	.8882	.8127	.0192	.2405	.2959
NR = 300	25	597	.9193	.8540	.0184	.2292	.2684
4 passes through Data by Reischman	12.5	419	.9110	.8487	.0217	.2267	.2671
U = .924	6.25	109	.8976	.8290	.0442	.2355	.2841
y+ = 37.1	50	246	1.1465	1.0916	.0254	.2029	.1859
NR = 169	25	216	1.1881	1.1588	.0243	.1819	.1570
4 passes by Reischman	12.5	97	1.1909	1.1627	.0365	.1834	.1577
U = 1.194	6.25	19	1.2080	1.1943	.0562	.1250	.1047
y+ = 377.0	50	204	1.6203	1.6129	.0140	.1021	.0633
NR = 90	25	239	1.6371	1.6337	.0093	.0730	.0447
2 passes by Reischman	12.5	227	1.6158	1.6128	.0090	.0691	.0429
U = 1.665	6.25	125	1.6117	1.6092	.0110	.0629	.0391

TABLE IX

SCHMITT TRIGGER DATA

U_B	U_c	u'	u'/U_c	NR	Schmitt Trigger Settings High/Low
.3223	.2856	.1095	.383	1582	-0.5/-1.0
.2968	.2587	.1088	.421	1737	-0.5/-1.5
.2903	.2510	.1094	.436	1541	-0.5/-3.0
.2923	.2555	.1064	.417	1026	-0.0/4.0
.2821	.2504	.0965	.378	260	

Data collected from Karpuk's No. 304 run with visual verified results given by the bottom line above.

APPENDIX D

FIGURES

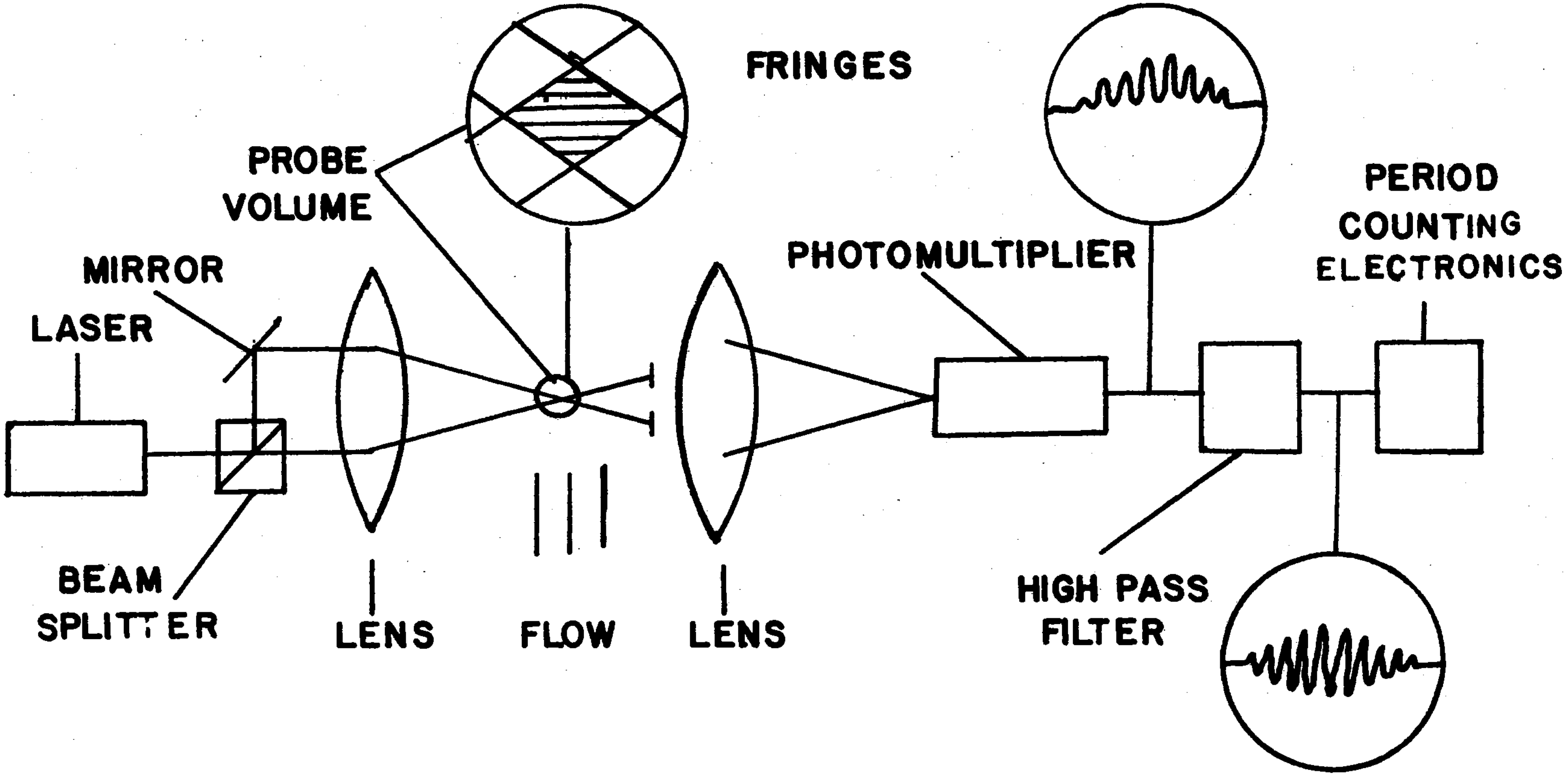


Figure 1. The Basic Dual Scatter Laser Doppler Anemometer

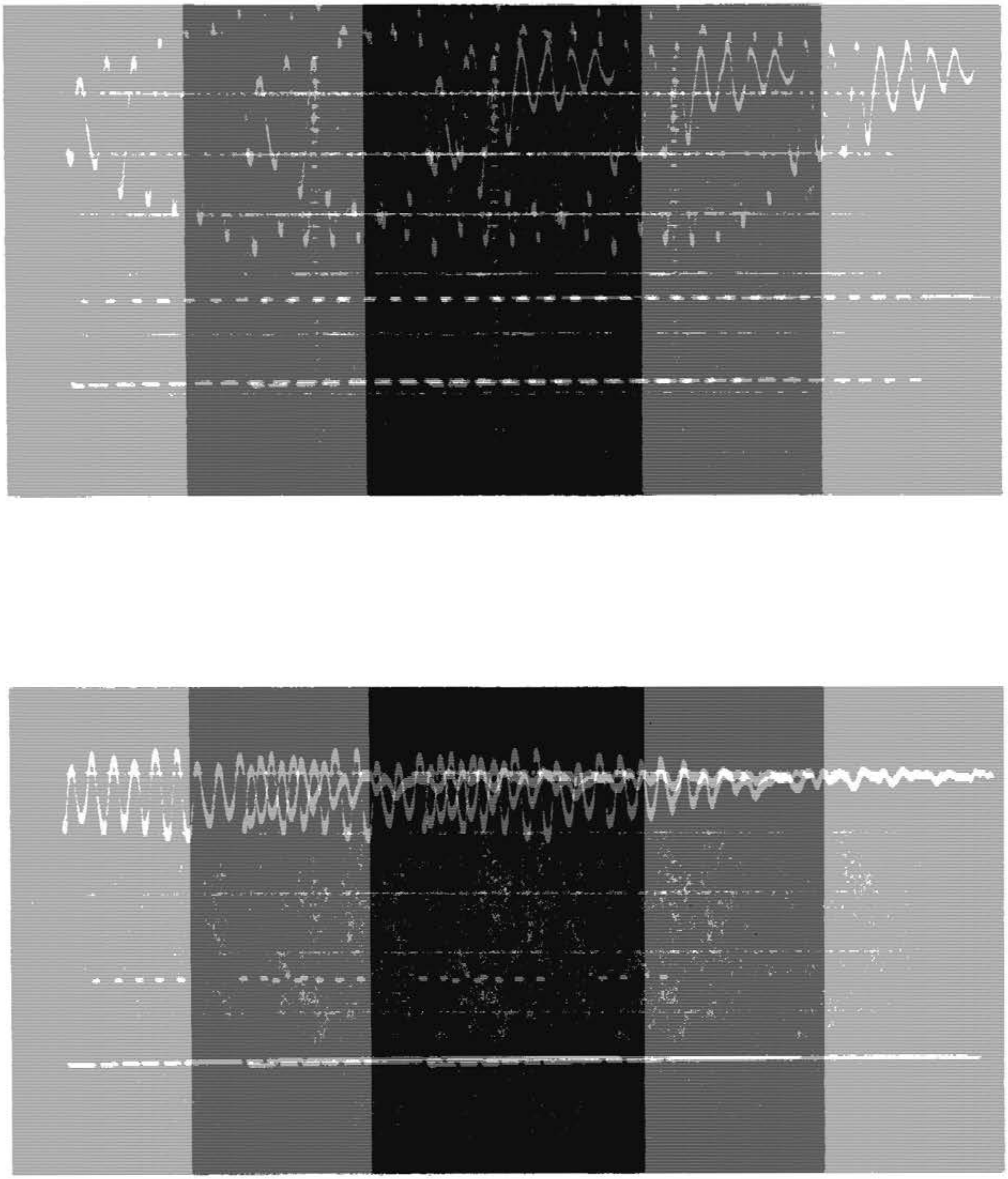
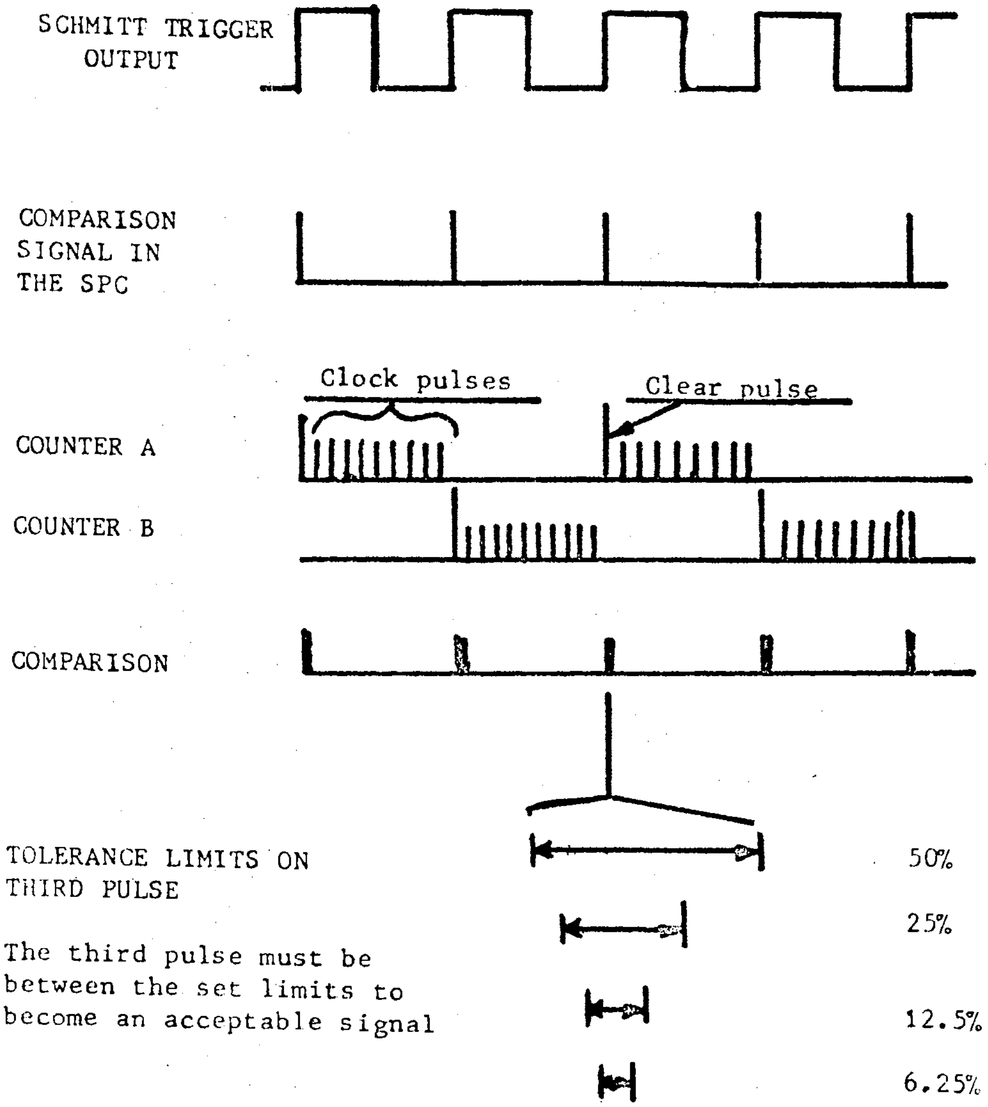


Figure 2. Photographs of Doppler Bursts and Schmitt Trigger Outputs



The third pulse must be between the set limits to become an acceptable signal

Figure 3. Basic Operation of SPC

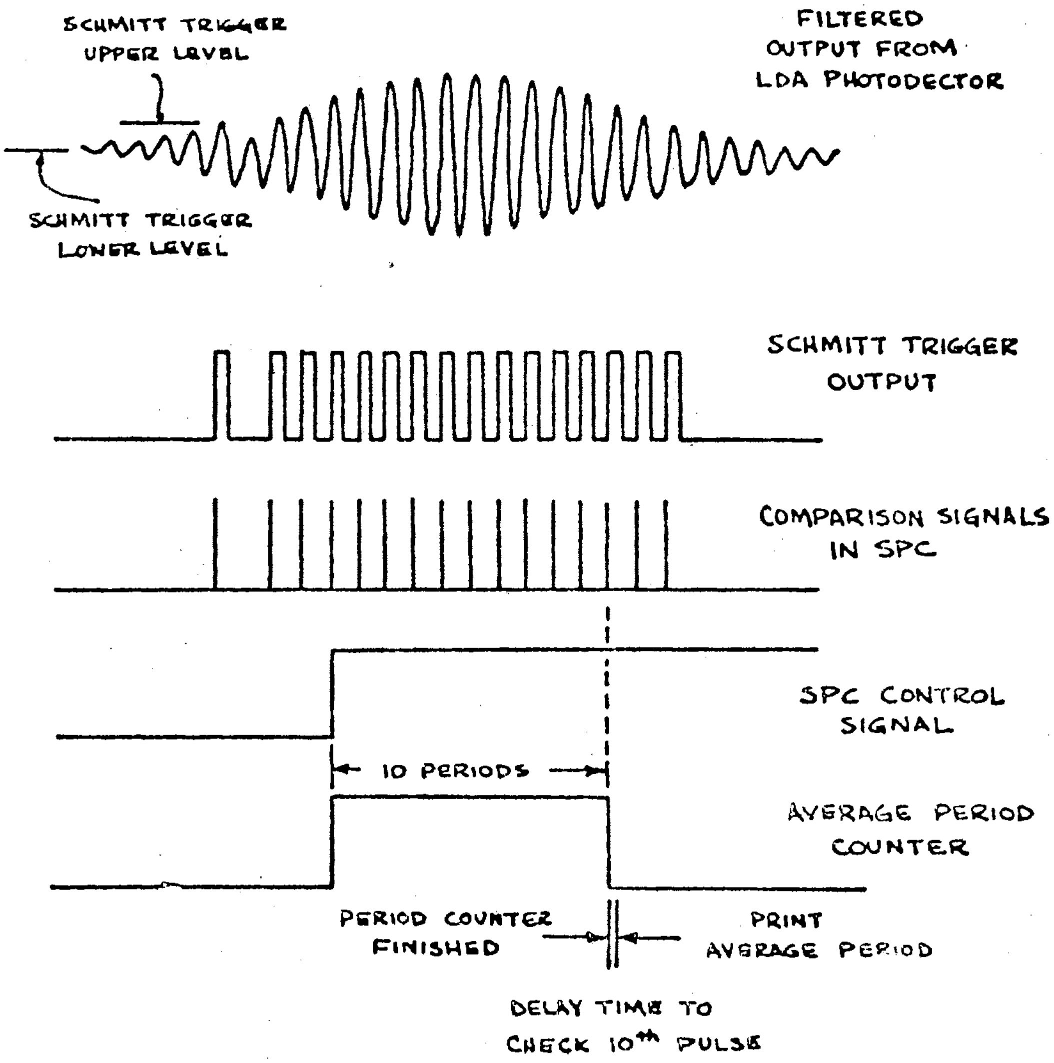


Figure 4. Schematic of Processing Doppler Signal in the Data Discriminator System with a missing pulse at the Beginning of the Burst

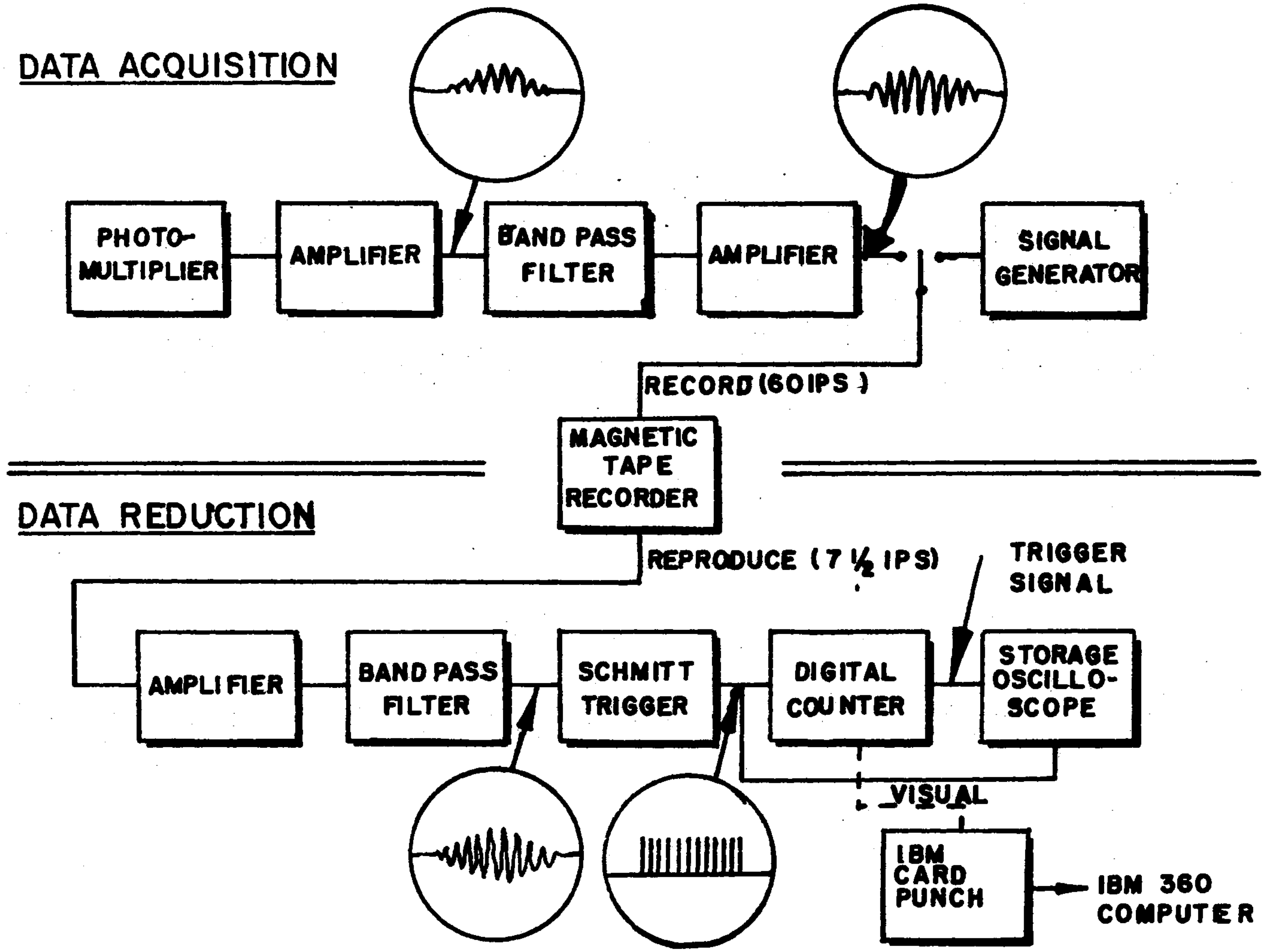


Figure 5. Block Diagram of Reischman's Data Acquisition and Reduction System

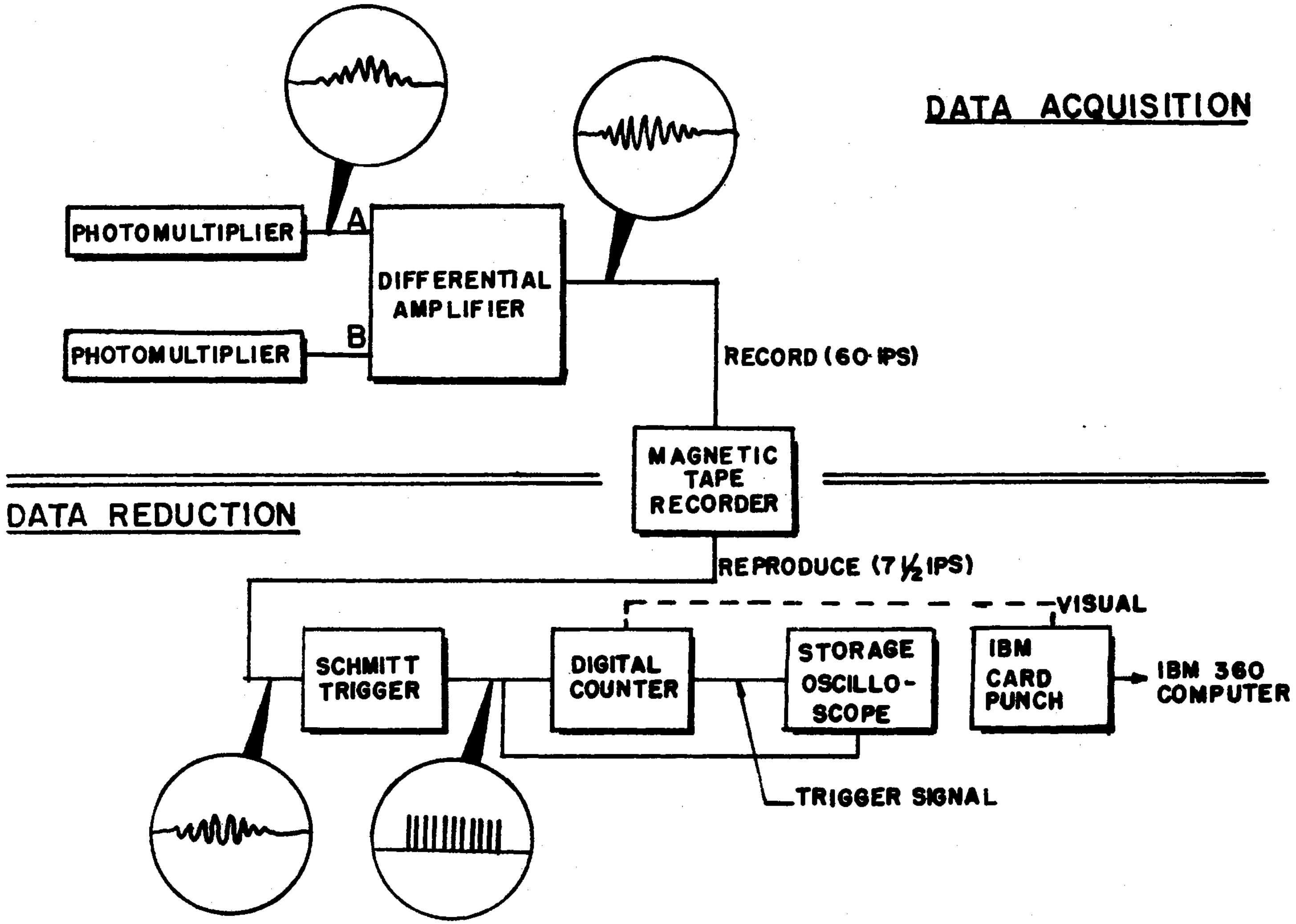


Figure 6. Block Diagram of Karpuk's Data Acquisition and Reduction System

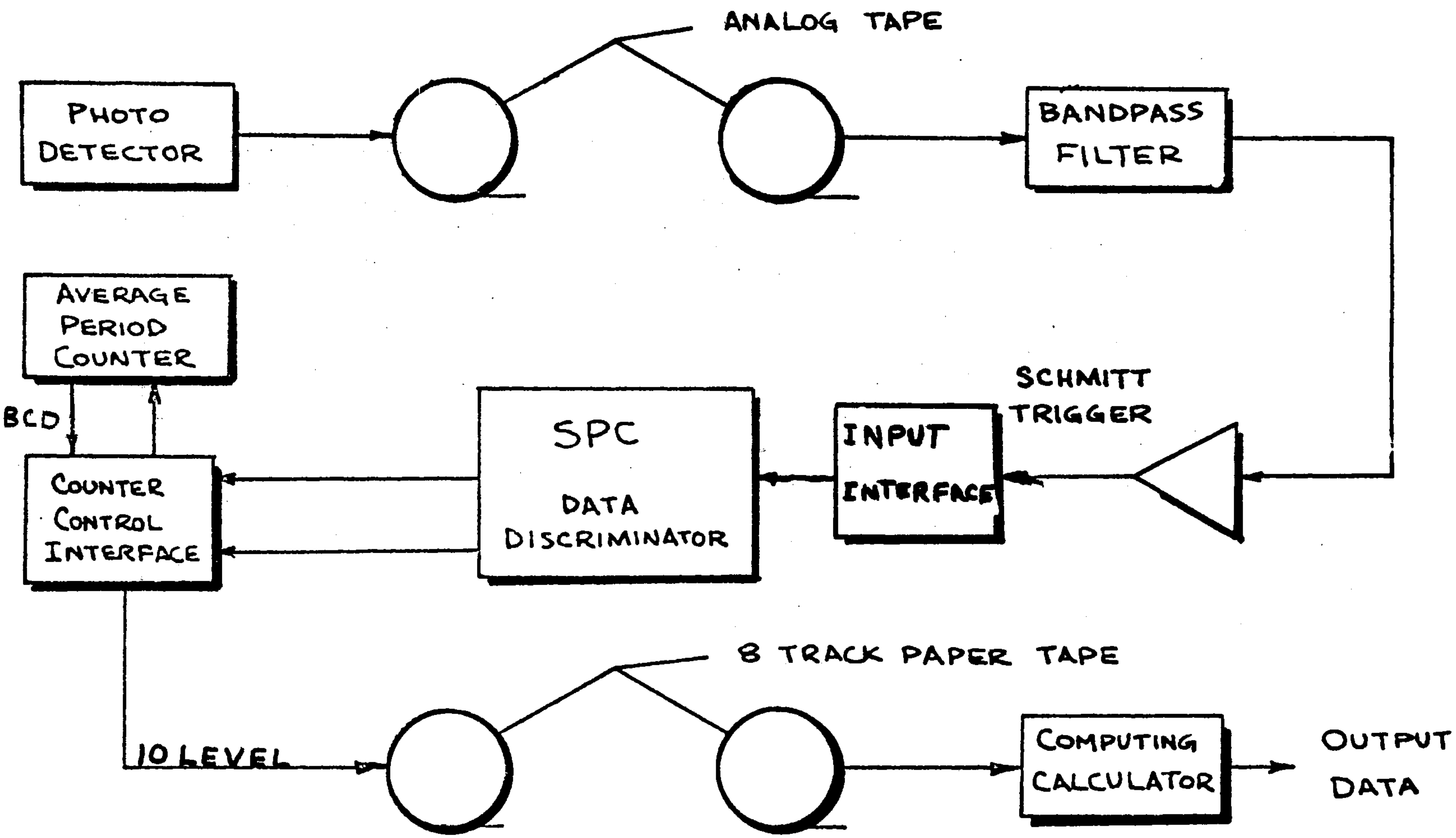


Figure 7. Schematic of Primary Elements of the SPC Data Acquisition System

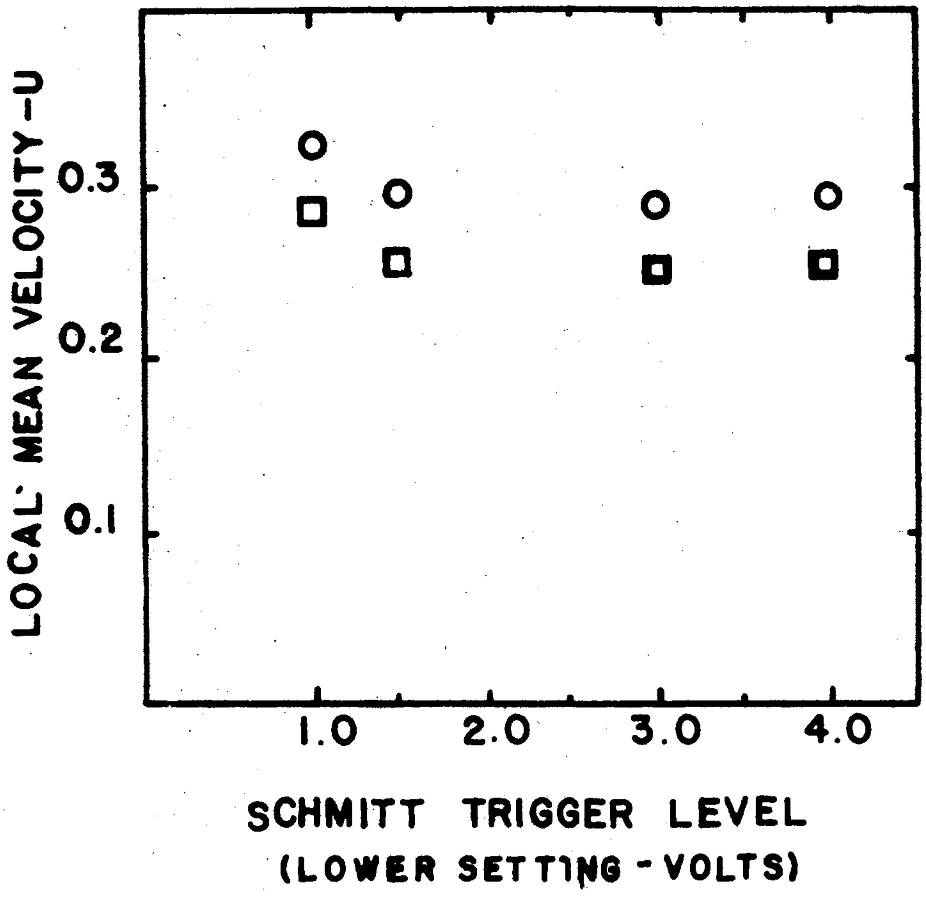


Figure 8. Schmitt Trigger Variation for Four Lower Trigger Levels

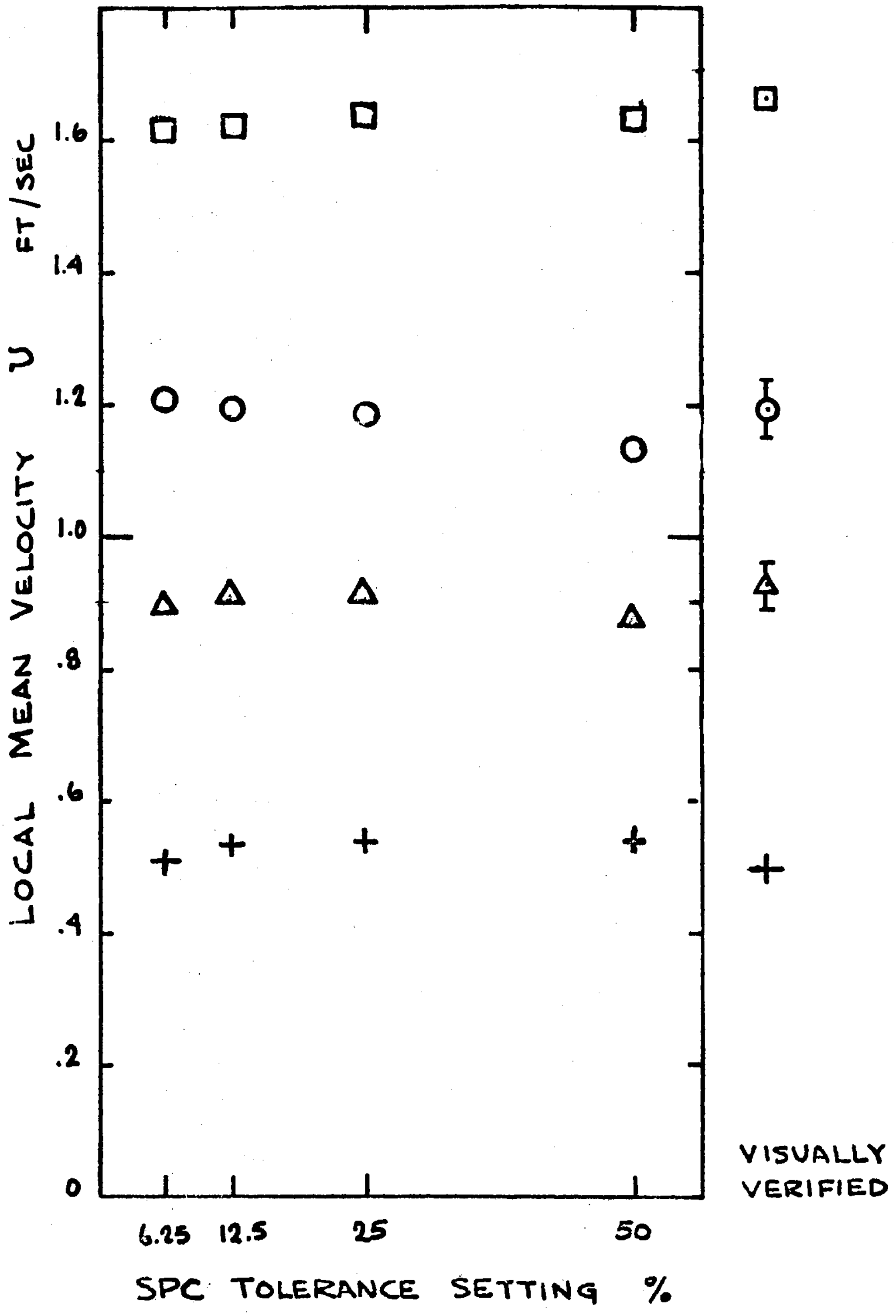


Figure 9. Local Mean Velocities Determined by the Data Processor Using Different Tolerance Settings

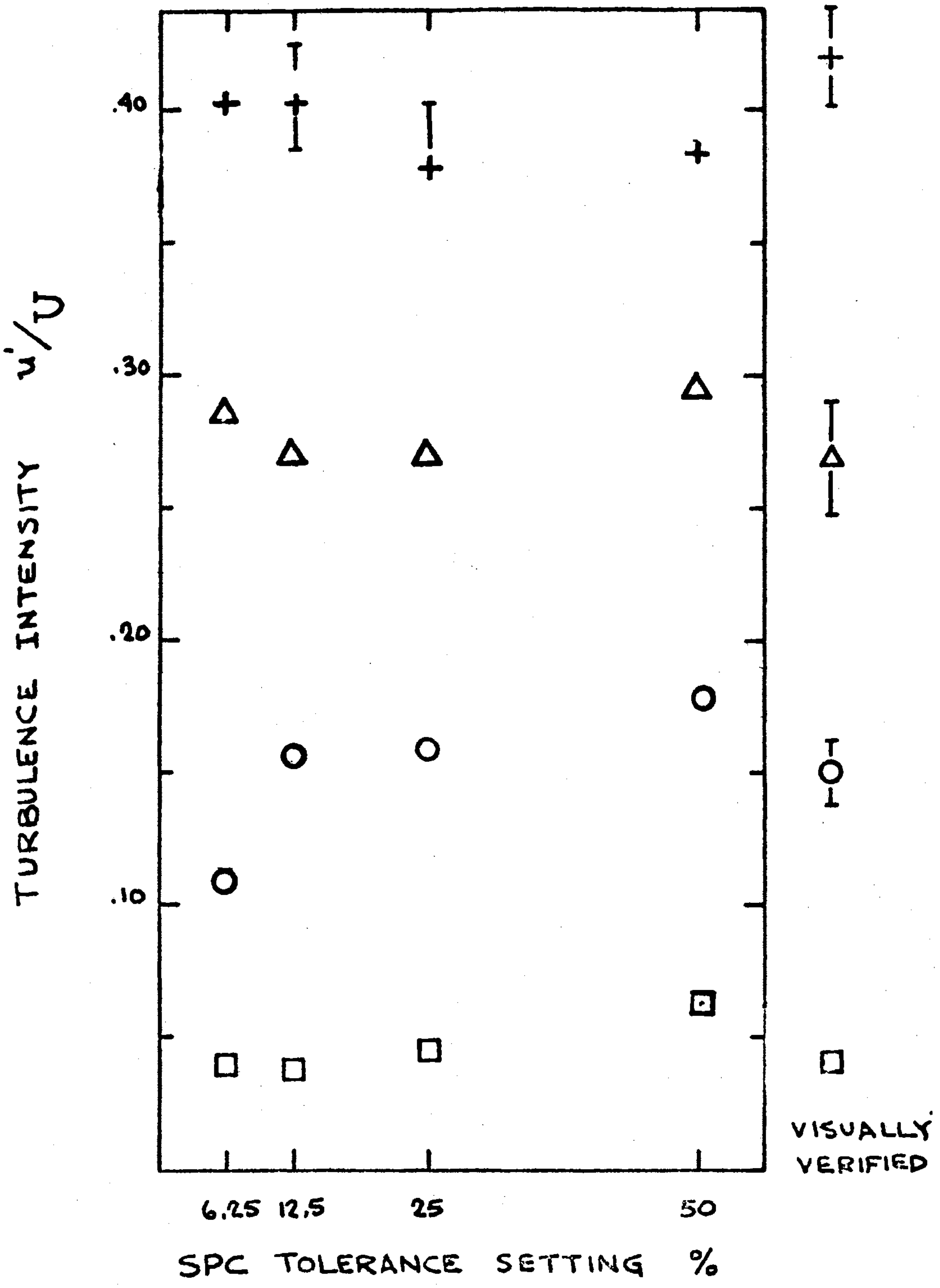


Figure 10. Local Velocity Fluctuations Determined by the Data Processor Using Different Tolerance Settings

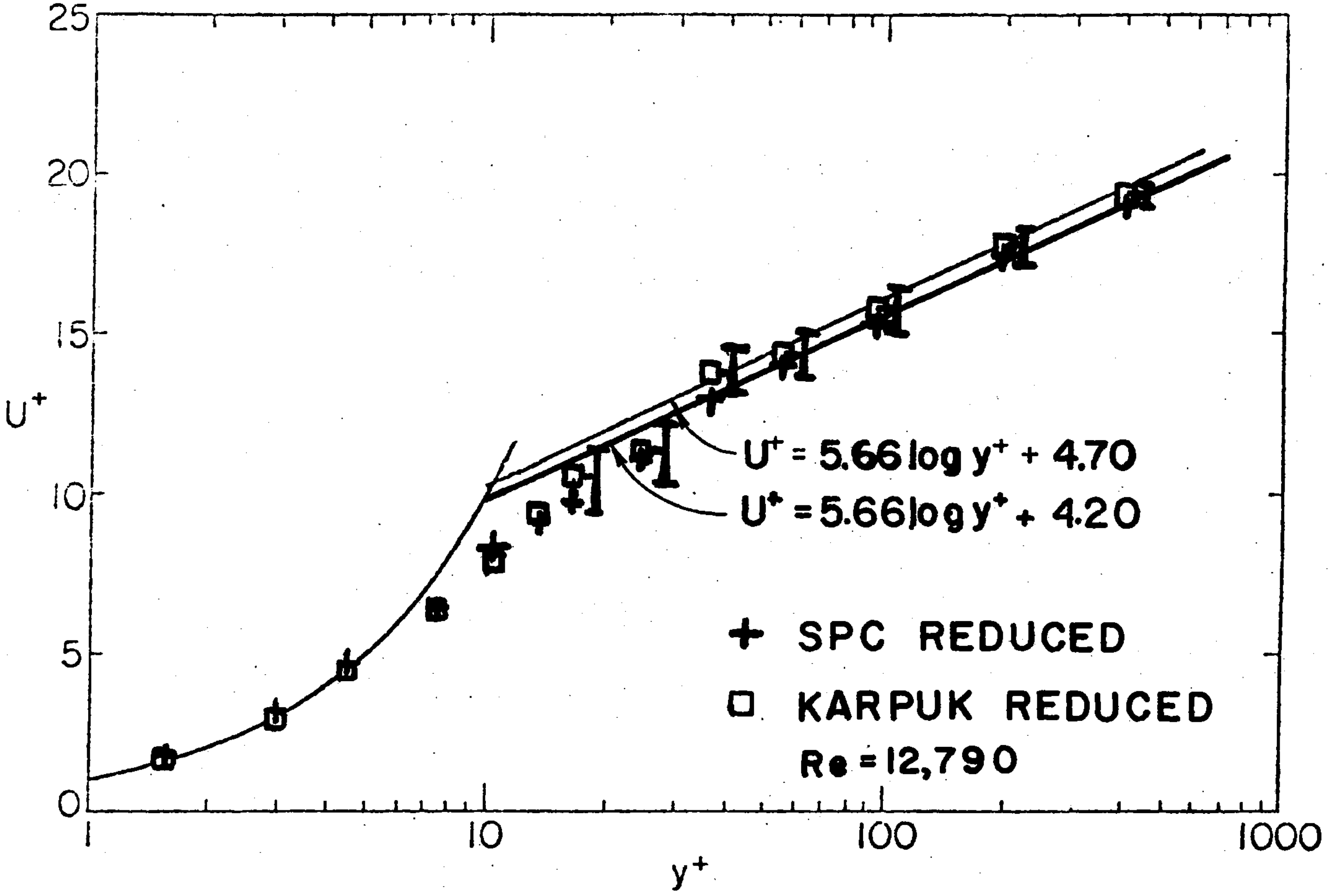


Figure 11. Mean Velocity Profiles in the Law-of-the-Wall Coordinates

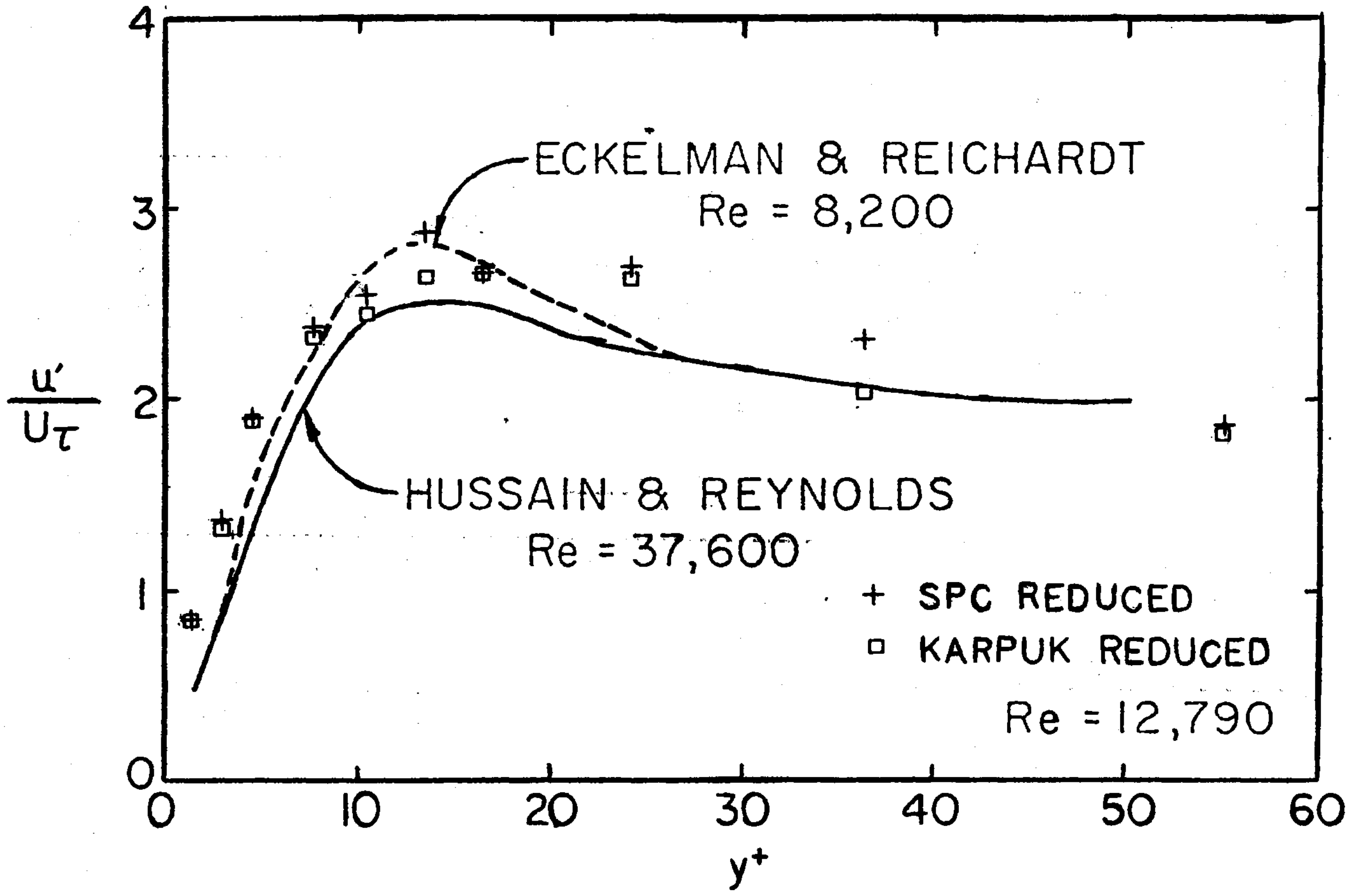


Figure 12. Streamwise Turbulence Intensity Profiles

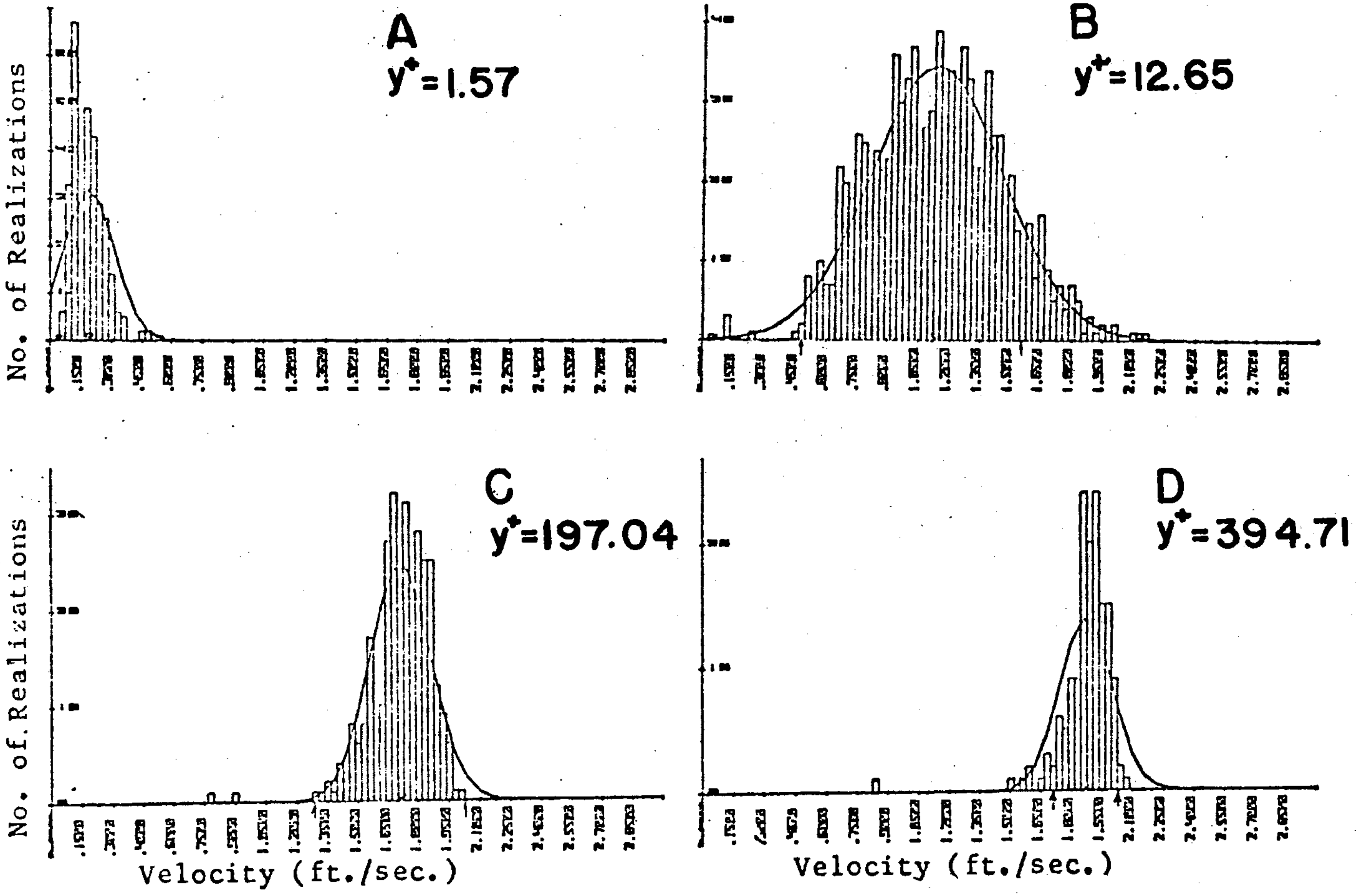


Figure 13. Histograms for Four y Locations of Karpuk's Data

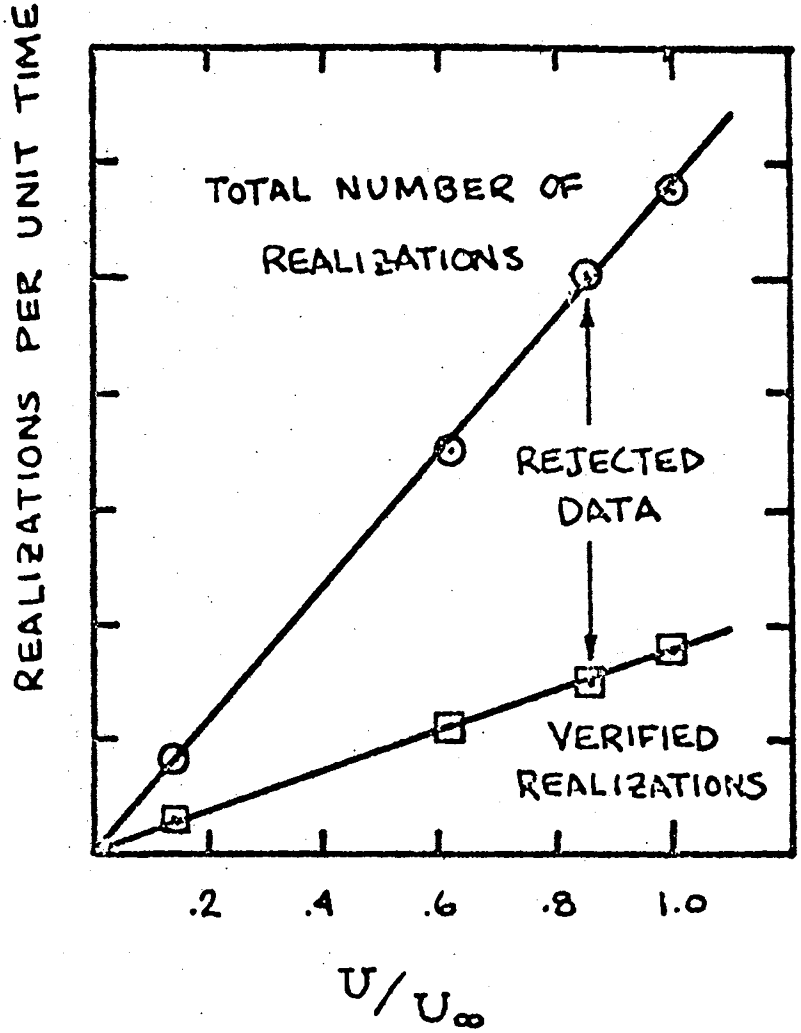


Figure 14. The Rejection Rate of Realizations for a Period of Time Versus the Local Mean Velocity

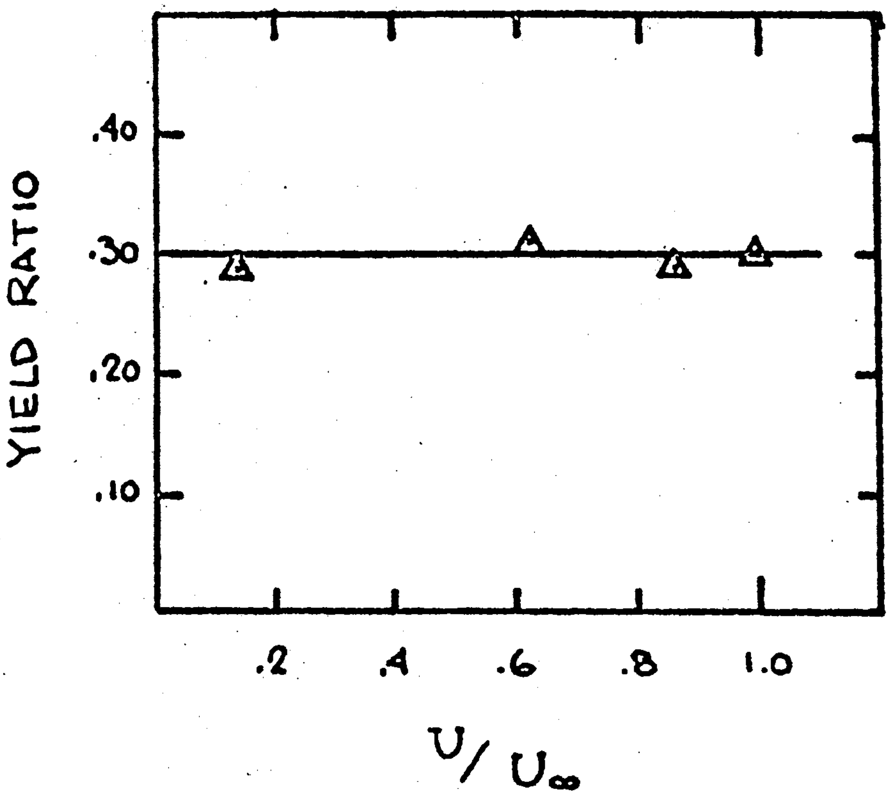


Figure 15. The Yield Ratio for SPC Reduced Data

VITA

William Roland Adcox

Candidate for the Degree of

Master of Science

Thesis: EVALUATION OF A SEQUENTIAL PHASE COMPARATOR FOR THE REDUCTION OF LASER ANEMOMETRY DATA

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