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on

Digital Techniques in Turbulence Research

by

C.H.Gibson

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DIGITAL TECHNIQUES IN TURBULENCE RESEARCH

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Digital Techniques in Turbulence Research

by

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SUMMARY

Rapid advances in electronic information processing capabilities are providing powerful tools for turbulence research. Massive quantities of experimental information are necessary to characterize most turbulent flows, given the primitive nature of theoretical understanding in the field. Analytical treatments are equally dependent on powerful, high speed computers to cope with the most truncated form of the full turbulence problem. Use of digital techniques has great potential for progress in turbulence research but also introduces a new set of difficulties which must be overcome for this potential to be realized.

1. INTRODUCTION

1.1 Progress In Turbulence Research

Despite a dramatic increase in the numbers of scientists engaged in turbulence related work and the growing pressures of modern technology for precise answers about turbulent systems, turbulence remains as one of the principal unsolved problems of classical physics. It is becoming increasingly clear that progress in the field can only come about through a close coupling between "theory" and experiment. "Theories" which work are likely to be no better than rather refined mechanical models, with numerous coefficients which must be determined experimentally. Inspiration for the construction of such models is just as likely to arise from the experiments as from the conservation equations, judging from past experience. We are also finding that extrapolations from one turbulent flow system to another can be very hazardous; e. g., many surprises are emerging from recent measurements of turbulence in the atmosphere and in the ocean which could not have been inferred from the information available from laboratory studies.

Consequently, progress in the field is becoming highly dependent on precise measurement. But turbulence is an intrinsically statistical phenomena, and turbulence at high Reynolds number, the case of most practical importance, is spread over a wide range of length and time scales. It is therefore necessary to make measurements of average quantities characterized by an equivalently large range of space-time separations in order to characterize fully the phenomena: an especially formidable task when more than one component of the turbulent velocity vector is relevant, or when one or more scalar fields such as temperature and humidity must be taken into account.

Instrumentation has only recently permitted measurement of the full range of length scales and the full band of frequencies available in important turbulent flows. The hot-wire anemometer has been under development for several decades, but has become cheap and reliable for the full band of frequencies only since solid-state electronics has made constant temperature operation stable and standard. Insulated hot-film anemometer probes operated in constant temperature bridges have extended turbulence measurements to a wide variety of liquids including blood, water and mercury during the last ten years.

Improved circuitry and improved detecting probes have made possible measurements over the full range of length and time scales for temperature in air, water and liquid metals, concentration of helium and N_20_4 in air or other gas mixtures and promise to extend to salinity in water, humidity in air and possibly turbulent pressure. For a recent review of turbulence measurement techniques see Bradshaw (1971).[1] High quality instrumentation tape recorders have also appeared in the last ten years which make possible analog recording of this wealth of information without loss of either bandwidth or signal to noise ratio.

Since the properties of a multivariate turbulent flow system can now be detected, recorded and played back in their original form, it becomes theoretically possible to generate nearly any statistical parameter of interest in the characterization of their properties. The purpose of the present paper is to review the various options which exist for determining the statistical parameters describing turbulent flow systems, either from the experiment directly or from the experiment stored away on analog tape. Use of digital equipment and techniques is becoming the factor more and more crucial to success in coping with the massive amounts of information generated by a turbulence experiment. Besides providing a powerful new tool for processing analog turbulence data, digital computers now have developed to such speed and sophistication that it is now becoming feasible to carry out turbulence "experiments" entirely within the computer[24] starting with the appropriate conservation equations and boundary conditions and letting the velocity, scalar and pressure fields evolve in space and time. This technique is still restricted to relatively low Reynolds number flows or large scale features but has the impressive advantage that some conditions of the experiment are trivially easy to vary compared to laboratory experiments. Quantities such as the fluctuating pressure field, which have been very difficult to measure are automatically obtained in numerical experiments. At present there is controversy as to the future prospects of these numerical experiments for the solutions of more than highly idealized turbulent flows.

In order to illustrate the amount of information required to describe fully an important turbulent transport system, consider the case of the atmospheric boundary layer over the ocean, where most of the transport processes governing the earth's weather occur. Restricting consideration to only the constant flux thickness of say 10 meters, it would be necessary to have information on length scales up to at least 10 meters, and down to at most the Kolmogoroff length $(\nu^3/\epsilon)^{\frac{1}{4}}$ which is about 1 mm, sampled over a period of at least a second (the time for the wind to move horizontally a distance equal to the boundary layer thickness) at intervals no longer than the Kolmororoff time $(\nu/\epsilon)^{\frac{1}{2}}$ of about 0.07 sec just to define a single realization of the system. ϵ is the rate of viscous dissipation of the turbulence and ν is the kinematic viscosity of the fluid. Since three components of velocity are required, as well as the temperature, humidity and pressure, we see that nearly 10^{14} samples are required for a single realization of the marine boundary layer. Assuming at least 100 samples/average brings us to a total of 10^{16} samples or 10^{17} bits of information at 0.1% accuracy.

For comparison a good quality 7 channel analog tape recorder can store about 10^8 samples on a 10-1/2 inch reel with 8 bit/sample accuracy. Hence a complete description of the system would require over a hundred million reels of analog tape to store the data. Digital tape recording is even less efficient than analog, so probably 5 times as many digital tapes would be required. Thus we find that the magnetic tape necessary to describe the turbulence in the atmospheric surface layer would occupy a substantial fraction of the volume of air for which the turbulence would be homogeneous.

This immense amount of information intrinsic to a full description of turbulent flow systems demonstrates the need for high speed data processing, but also the necessity of developing methods to exclude rationally all but a very small fraction of the data and statistics available for experimental description of turbulent flows, i.e., the data necessary to describe the particular feature of the turbulent flow being studied. In the case of the oceanic boundary layer this might be the fluxes of heat and humidity on the scattering of light nearly parallel to the surface. Experimental investigations of turbulence devoid of theoretical context are likely to produce large quantities of statistical parameters whose physical significance is just as difficult to assess as the original fluctuating signals.

The danger of being overwhelmed by statistical parameters of turbulence has only recently become significant with the rapid advance of digital data processing techniques. Previously, a natural check on the flood of statistical information potentially available from high frequency response instrumentation has been the notoriously tedious nature of turbulence measurements using analog techniques. Now the danger is that one can be overwhelmed by reduced data as increasingly sophisticated digital systems are developed.[25-32]

1.2 Comparison of Digital and Analog Data Processing

Consider the example of turbulence in the atmospheric boundary layer discussed in the previous section. The simplest non-trivial statistic of turbulence is the root-mean-square of the streamwise velocity fluctuation about the mean. However, most analog RMS meters will not respond to frequencies below 1 hz, and a significant fraction of the turbulent kinetic energy in the atmosphere is in these lower frequency bands. It then becomes necessary to either speed up an analog tape recording to shift the spectrum of the recorded signal to higher frequencies, or else design special purpose instruments with very low drift to accommodate the low frequency components.

Power spectra play a central role in turbulence measurements and theory. They may be estimated by analog techniques by measuring the mean-square of the signal passed by a tunable filter with known bandwidth. Again, wave analysers are of little use below about 10 hz, which is a decade above the peak of the energy spectrum in most atmospheric data. Measurements of power spectra with wave analysers at high frequencies involve tuning the filter for every new point, waiting for the average of the squared output signal to converge and then recording and plotting the spectral point in a notebook after suitable slide rule corrections for various filter and amplifier gains. For high precision spectra this is a very tedious, time consuming effort which may need to be repeated to make sure the flow conditions have not drifted during the course of the measurement and then repeated again if it has. Methods for automated spectral analysis with analog instruments have been devised using tape loops, motor driven tuning devices for the wave analyser, strip charted output, and so on, but they are generally expensive, subject to mechanical breakdown, and rather imprecise. Their main disadvantage is inflexibility: only spectra can be calculated, and then only with the bandwidth and averaging periods originally selected.

Contamination of the original signal is generally permanent using analog techniques, since the construction of special purpose compensation circuits which work reliably is a major project. Hot-wire linearizing circuits to convert an anemometer output signal to a voltage proportional to the velocity are in common use, but even these may become unnecessary and undesirable as automated digital calibration techniques are developed. The most flexible analog device is the analog computer which can produce valuable results in the hands of a sophisticated and experienced operator. However, setting up an analog computer to do a reasonably complex operation is a very time consuming, tedious job compared to developing the software for a digital machine to do the same thing (but not impossible - see Reference 33, 34).

The digital computer produces an automatic record of the myraid "dial settings" of the analog machine, and can be altered immediately and reproducibly by any operator simply by resubmitting the program. Digital operations on the data are much more accurate. Few analog computers are better than 0.1%, which would be only 10 bit accuracy, compared to at least 16 bits (0.002%) for digital computers.

The principal advantages of digital data processing techniques in turbulence research are precision, speed and flexibility. In the past, digital methods had the disadvantage of requiring a very large capital investment, but this is no longer true with the advent and wide availability of mini computers. The remaining disadvantage is that digital techniques are still relatively unfamiliar to many experimenters in the turbulence field. This situation should be temporary since students often find digital methods easier to assimilate than analog methods. Indeed, the skill required to produce reliable turbulence results by analog methods is generally quite high and requires an experienced expert to accomplish, whereas any undergraduate can analyze digital turbulence data.

Recent hot-wire anemometer sets are capable of signal to noise ratios of nearly 80 db in terms of the total output noise, and even larger values in parts of the spectrum. The best analog tape recorders have signal to noise ratios of only 50 db, and frequently as low as 35. In fact, few analog instruments are available which would not substantially degrade this signal to noise ratio. Digital instruments with 14 bit precision are common however, corresponding to 84 db. Manipulations with a 16 bit machine are at 96 db precision in integer mode, but can have much more dynamic range using floating point arithmetic and double precision at the cost of speed.

The initial cost to accomplish digital data analysis is nearly as variable as the cost of digital computers, and depends on the volume and type of turbulence data to be processed. A wide variety of strategies can be followed, and will be discussed in later sections of this report. Probably the best solution for most laboratories seriously engaged in turbulence research will be a digital system built around a dedicated computer.

Quite powerful mini computers are now available for the cost of a good hot-wire anemometer set, and solid state memory can be had for less than 5¢ a bit with a few hundred nanoseconds cycle time. Therefore, the price of the laboratory computer is usually determined by the price of peripheral devices, whose price in turn is usually determined by the speed and precision of the data transfer. Few turbulence experiments require more than 10 KHz sampling frequency, but if more than five channels must be sampled at this rate the cost of the multiplexer or the precision of the data must suffer.

Of course it is true that a well designed analog experiment is better than a complex digital operation devoid of any idea. G. I. Taylor's mechanical demonstration of the approach to local isotropy with a variable wind vane (1970)[35] can hardly be improved by digital methods; nor can L. F. Richardson and Henry Stommel's (1948)[36] demonstration of turbulent diffusion laws by observing the dispersion of parsnip peelings with carpenter's tools.

It should be pointed out that the point of view expressed here in favor of digital techniques is not shared by all workers in the field, even those with experience using both methods

2. APPROACHES TO DIGITAL TURBULENCE DATA ANALYSIS

2.1 Planning the Analysis System

As discussed previously, a wide variety of options are available to the turbulence research worker even after he has made the decision to use digital data processing techniques to analyse his turbulence signals. Because of the variety of problems which arise in turbulence measurements, as well as because there is some virtue to learning to walk before learning to run, it is not possible to specify a single digital approach which will be optimum for every case.

The decision will depend on the nature of the problems to be solved, the presently available equipment, software talent, funds and time. When no previous experience exists and no digital equipment is available, the usual approach is to record the turbulence signals on analog tape and then arrange to have the data "digitized"; that is, to have a computer-compatible, digital tape of data samples made from the analog playback using a purchased, borrowed or rented digital system. If the "digitizer" works properly, the digital tape can then be read by a large general purpose computer, and appropriate time series analysis carried out on the data. This approach has the advantage of requiring the minimum amount of initial investment, time and expertise to implement and may be the best approach to an initial experience to digital techniques. A large variety of checked-out programs for time series analysis usually exist for a large, general purpose computer, such as are at most computer centers, and a number of output peripheral devices may be available to display the results in an attractive fashion.

This method has the disadvantage that the hourly rate of the general purpose computer may be quite high for many problems of turbulence data analysis. It may also be found that batch processing is excessively time consuming for the experimenter, since each step in the analysis procedure requires at least the turnaround time of the computer. This may be only a half hour for a well run computer center, but may be a day or more. Most data contains noise, and most programs contain bugs, and these factors can make batch processing an extremely tedious and expensive operation. There are, however, some problems which may require this treatment.

The next level of sophistication is to purchase or lease a dedicated computer and peripheral devices which will do all the data acquisition, analysis and display necessary for the particular set of turbulence problems anticipated. This approach is generally avoided as long as possible for a number of reasons. The initial investment is substantial, probably at least as large as the total investment in other electronic equipment for the experiment. Purchases of computers are generally subjected to an unusually large amount of administrative and fiscal considerations, i.e., to red tape. Computer centers may view them as competition and a threat to their own income (rightly), funding agencies may be required by law to list them in a central computer pool with periodic time utilization reports required, and most accountants and administrators are unable or unwilling to listen to or believe arguments that another computer is needed. A bewildering variety of options are available, and the number and complexity is accelerating rapidly. Whatever system is chosen, it is almost certain to be obsolete by the time it is working.

A factor which is sometimes overlooked or underestimated in planning a digital data processing scheme is the cost in time and money required to develop the programs (software) necessary to produce the desired results. It is of little use to the experimenter if a machine has a very fast memory cycle time if an adequate and reliable compiler has not been written for a computer language which is suitable for the data analysis he wants to do. High speed peripheral devices run under the control of the computer, but only if the monitor systems have been written, and written in such a way that the efficiency of the information exchange between the computer and the peripheral device is adequate to take advantage of the speed of the device. Hundreds, and sometimes thousands of man-hours of programming effort can be required to get a green computer into efficient service. The fastest, cheapest, latest hardware is likely to have the weakest software. It is sometimes better to use a slower computer with a well established and debugged software system than to attempt to unscramble the idiosyncrasies of the latest generation devices.

Another very real danger in digital turbulence research is the tendency to lose sight of the fluid mechanics in the interesting but sometimes overwhelming problems of digital processing. The temptation to optimize every program must be balanced by questioning whether the time spent working on the programs will save investigator time, or simply save computer time to obtain the same amount of information about the flow. When the investigator finds he is spending more of his time thinking about computers than about turbulence, it is time for him to decide which field he wants to be in, since it is likely that progress in the respective areas is commensurate with the time spent.

2.2 Digital Data Acquisition Systems

A device which converts analog signals to a computer compatible digital record is called a digital data acquisition system, or "digitizer". The digital record might be in the form of punched cards or punched paper tape, but because of the very large volumes of data samples characteristic of turbulence experiments, the discussion will be limited to digitizers which produce digital tapes. Magnetic tape is at present the most compact storage medium for digital information.

The "digitizer" can be reasonably simple, or extremely complex, depending on the speed of sampling, the precision of the sample, the number of channels to be sampled and so on. One of the easiest "digitizers" to implement is a mini computer used as controller for the other components (see Fig. 2.2.2.) This has the advantage that the "controller" can be developed into the analyser at a latter stage.

Digital tape generally consists of seven or nine channels of binary information recorded in parallel on 1/2 inch wide magnetic tape. One of the channels is usually devoted to a parity bit, determined by evenness or oddness of the sum of bits in the sample to increase the reliability, so the sample has either six or eight bits of peecision per each character. When the computer reads the recorded sample it compares the parity with the parity bit. If it does not agree a "parity error" has occurred, which implies a faulty recording. More than one character can be used per sample to increase the precision, but this complicates the design of the data acquisition system and the computer program necessary to unscramble the data on the digital tape.

The digital information recorded as a sample is produced by an analog to digital converter, or ADC. The ADC may cost anything from a few dollars to several thousand depending on the frequency and precision of the conversion. The basic function of the ADC is to produce a set of binary voltages corresponding to the sign and magnitude of the input analog voltage. The binary voltages have a level corresponding to "true" and "not true", which must be matched with the "logic levels" of the tape recorder. Unfortunately a variety of logic levels are used in various digital instruments.

A schematic diagram of a simple digital data acquisition system is shown in Figure 2.2.1. Incremental digital tape recorders are available at reasonable cost which use stepping motors to advance the tape asynchronously when the machine senses a write pulse on a control line. Write rates of up to about 1 KC are possible with such machines. This may require that the analog tape be played back at lower speed than it was recorded in order to cover the full bandwidth of some turbulence signals. Push-button manual controls exist on most such machines to cause then to write end of file marks and insert file gaps. Record gaps, longitudinal check character gap and a longitudinal parity character are written when a control line receives a particular magnitude and duration pulse.

Figure 2.2.1

SINGLE CHANNEL DIGITIZER

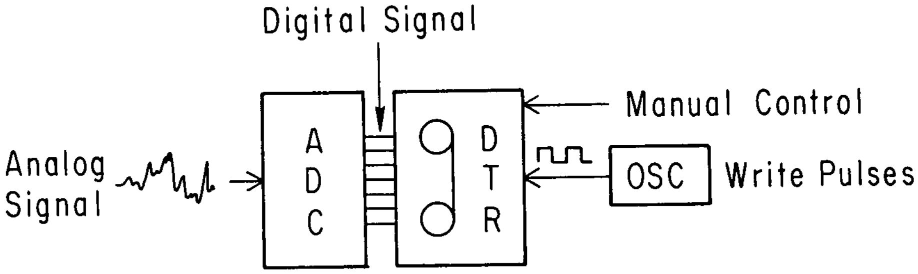
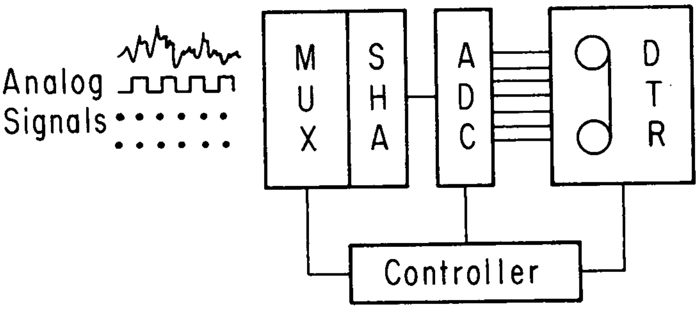


Figure 2.2.2

MULTIPLE CHANNEL DIGITIZER



Standard laboratory square wave generators can supply the write pulses at the desired amplitude and sampling frequency. Some programmable square wave generators can even supply a particular number of pulses so a standard record length can be generated. Otherwise it will be necessary to supply the computer with data files of various lengths, and to write a non-trivial computer program which will produce a new digital tape with the record gaps inserted.

The data must be broken into records of a few hundred or thousand samples because of the finite number of core memory locations in the computer. It is generally inefficient to work with record lengths which are longer than the core size of the computer.

The simple system in Figure 2.2.1 will generate a digital tape which can be read by a standard batch computer. It can be assembled from components which will be readily available in most campuses or modern research laboratories. The entire system can be purchased for less than $3,000. However, it will soon be evident to the user after he has generated a few hundred data files by this manual system that his time could be better spent. If a batch computer is used to insert record gaps in very large data files, he may also find that the computer time is costing him substantial sums of money, which could be saved using a more automated and flexible system.

When more than one channel of turbulence data is to be sampled, it is necessary to construct a more sophisticated data acquisition system such as that shown in Figure 2.2.2. The figure shows analog signals connected to a multiplexer ("MUX" or "scanner"). Under the control of step pulses from the controller MUX switches sequentially through a specified number of inputs connecting each in turn to the ADC. If simultaneous samples are desired, a sample pulse from the controller causes the value of each input to be simultaneously sampled and retained by the sample-and-hold amplifiers (SHA) until the next sample pulse is received.

The controller is a system which produces the necessary control pulses to the various devices in the right sequence and at the right times so the analog data will be sampled at the desired frequency, precision and sequence, so that a suitable digital data tape is produced. Since several high speed channels may be of interest it will generally not be possible to use an incremental tape recorder for a multichannel data acquisition system. Instead, a continouous tape speed is maintained by the digital tape transport, and it is up to the controller to write the data on the tape in the correct format at the right time.

Much higher data rates can be achieved in this way than with incremental recorders, which are usually limited to about 500 Hz. For example, a continous tape speed of 30 inches per second with a packing density of 556 "bits" (6-8 bit characters) per inch corresponds to a sampling rate of 16,680 6-8 bit samples per second. Since the Kolmogoroff frequency in the atmosphere is seldom above 2 KC, as many as 8 channels of high speed turbulence data could be digitized in real time at this rate.

Controllers can be constructed by assembling a set of digital logic modules and a clock which will produce the required sequence of pulse commands. The cost of the hardware required is one or two thousand dollars, but the design and construction of such devices may require many man-hours unless sophisticated manpower or a standard design is available. It is probable that most controllers in the future will be implemented by using a dedicated mini computer, since the price of the controller rapidly becomes dominated by "software" costs as the price of the hardware decreases. Also, it is much easier and more flexible to program a mini computer to control the sampling and data recording procedures than it is to construct one from digital logic modules.

As will be pointed out later on, the extreme flexibility of the mini computer in the place of the controller in Figure 2.2.2 makes it a factor of great power and potential in the acquisition of turbulence data, since by programming various decision making procedures and pre-processing routines, the mini computer can intelligently edit and manipulate the information coming into the multiplexer, and only record the information which is of interest. Such a procedure is called "conditioned sampling" or "pre-processing". It is also possible to have the computer control the experiment, move probes to new positions, change operating conditions, check the data for errors, overranging or noise and take corrective and operator warning actions, as well as reduce and display the results. Complex calibration schemes can be implemented for multifunction sensitivities using digital techniques which would be out of the question using analog equipment.[37]

2.3 Batch Computation

Assuming a digital data tape has been produced containing a time series of turbulence data samples which can be read by a FORTRAN "read" statement (or equivalent) when mounted on a computer's tape recorder, the usual procedure is to analyse the data using a large batch processor such as used by most computer centers. Hopefully, the data will be properly recorded by the data acquisition system, as described in the previous section, and can be read into the machine record by record. Before designing the data acquisition system or digitizing any data it is wise to seek the advice of the computer center at which the data is to be reduced regarding the precise format of data tapes which they require. A wide variety of constraints and options exist which can make it difficult, unnecessarily expensive, or impossible for the computer to read some digital tapes.

As indicated previously, the main advantage of using a large high speed computer to reduce turbulence data is that it is likely to have available extensive software for time series analysis which can be implemented in a short time. A big machine will also be fast, and will have a number of peripheral devices which may be too expensive for a small laboratory computer system. There may be some advantage to having a large core size, such as being able to Fourier transform a longer record length, and the larger word size may be needed to permit integer manipulation of the data without overflow.

3. STATISTICAL DESCRIPTION OF TURBULENT FIELDS

3.1 Probability and Stochastic Processes

Turbulent fields are intrinsically stochastic and therefore require statistical description[38]. Detailed discussion of the application of probability theory and the theory of stochastic processes to the turbulence problem is beyond the scope of the present paper and may be found in books by Lumley[2], Monin and Yaglom[3] and Batchelor[4]. Useful treatments of random processes are given by Thomas[5] and Papoulis[6]. One factor inhibiting progress in the understanding of turbulence has been the extreme complexity of description which may be used. Three dimensional velocity, pressure, scalar and sometimes body force fields interact and evolve in nonlinear random ways. Constructing a formal mathematical apparatus to cope with the general problem is a major task in itself. Extracting the tools which are most useful in practical application, and which illustrate physical mechanisms most clearly is sometimes even more challenging. The purpose of the present section is to outline briefly some of the more useful tools and ideas. Section 4 will describe the application of digital data processing methods to the estimation of these statistical parameters.

3.2 Distribution Functions

The most basic tool for describing random variables is the probability distribution function, which is the probability that the function is less than a given value. If more than one function is important then a joint probability distribution function is needed, which is the probability that the random variables are each less than specified values. If n variables are important, an n-joint distribution function of the n variables is required. Thus a joint distribution function of order three is required to describe the values of the three velocity components at a point in space and time for a particular turbulent flow. If the flow is stationary, the distribution function is the same for all times. If the flow is homogeneous, the distribution function is the same for all space. If the flow is isotropic the distribution function is independent of the orientation of the coordinate system. See (4) for a description of the great simplifications which result in the distribution functions and their moments when these assumptions of homogeneous, stationary, isotropic turbulence apply.

The simplifying assumptions of homogeneous, isotropic, stationary, turbulent fields are most appropriate "locally"; that is, for differences between field values at points separated by small distances. This hypothesis was first formulated by Kolmogoroff in 1941[7]. In Kolmogoroff's theory, similarity hypotheses were proposed for the joint probability density function for velocity differences between n separation vectors. Therefore he considers a $3n$ joint distribution function.

Distribution functions may be differentiated to give probability density functions. The probability density functions may be Fourier transformed to give characteristic functions.

3.3 Moments

The expected value of an integer power of a random variable is called a moment. For example the mean square is the second moment of a random variable. Subtracting the first moment from the random variable gives a new random variable with mean zero. The second moment of this variable is called the variance. The third moment normalized with the variance is called the skewness. The fourth moment normalized with the variance is called the kurtosis. The fifth normalized moment is the superskewness and seventh is the hyperskewness[8]. These two latter quantities were early harbingers of the advent of digital data processing in turbulence, and were invented by Frenkiel and Klebanoff in this first substantial paper to appear where digital techniques played an important role.

When the random variable is a velocity or temperature difference between two separated points in space, the moments are called structure functions. When the random variables are velocity components at two points the moments are called velocity product moments, clearly tensor quantities of order equal to the order of the moment.

3.4 Fourier Transform Representation

The contraction of the moment tensor corresponding to the two point velocity product as the point separation vanishes is proportional to the kinetic energy per unit mass of the turbulent fluid at that point. The Fourier transform of the contracted tensor may therefore be considered the distribution of turbulent kinetic energy over wavenumber space, since the contracted tensor with zero separation is simply from its definition the integral of the Fourier transform over all wavenumbers.

The power spectrum is particularly useful because it represents variability of turbulent fields at different length scales. As mentioned previously, turbulence theory predicts an approach to local isotropy at small scales, and therefore at high wavenumbers. The second order structure function at small separations is closely related to the power spectrum at high wavenumbers. Symmetry of difference distribution functions at small separation may be tested by measurements of the symmetry of high wavenumber spectra or small separation structure functions.

Relations between velocity components and scalar fields at various points can be tested by computing moments involving different components, scalars or multipoint differences. Second order moments are called covariances with a variety of Fourier transform parameters such as cospectra, quadspectra, crosspectra, coherence functions and so on, which express different aspects of the joint variability of the two random variables. An important case is the Reynolds stress tensor $\langle u_i' u_j' \rangle$, which is a second order velocity product moment for zero separation of the points of sampling the fluctuating velocity components u_i' and u_j'.

3.5 Conditional Statistics

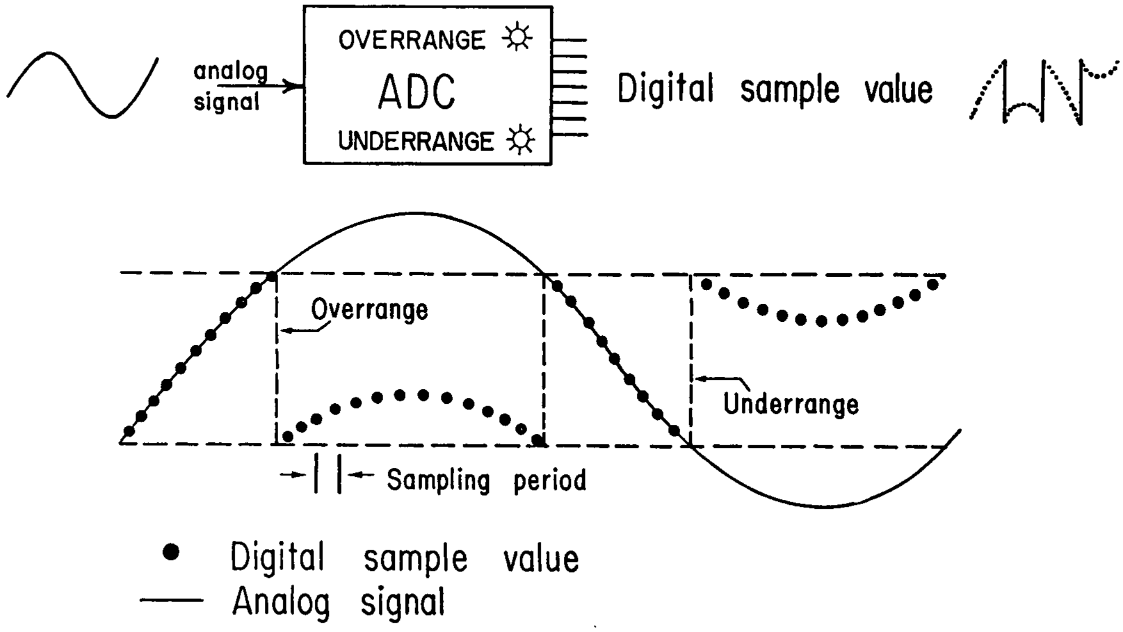
Special statistical parameters may be useful to test various features of turbulent flows, such as the turbulent - nonturbulent interface, which are sufficiently distinct to be identifiable by a computer program. Considerable interest presently exists in characterizing "spots" or "bursts" of turbulence which appear in laminar boundary layers in transition to turbulence. The statistical description of a "burst" might be obtained by referring the sampling of velocity, dissipation or temperature to the distance from the upstream edge of the "burst" (for example, where a variety of conditions might be required before the sample begins. Conditions for the statistic may be some phenomenon external to the turbulent region but possibly related, such as the phase of vibrating ribbon which may trigger a turbulence response or the phase or amplitude of internal or surface waves below the marine boundary layer. Evaluation of such conditional statistics is particularly suited to digital data processing methods.

4. DIGITAL ESTIMATES OF TURBULENCE STATISTICAL PARAMETERS

4.1 Sources of Error in Digital Analysis

In order to take full advantage of digital data processing techniques it is important that careful attention be paid to possible sources of error in the process of sampling, recording and manipulating digital data in order to avoid degrading the information in the turbulence signals. A digital device used to represent a voltage has a specific dynamic range, just as its analog counterpart. If the analog voltages presented to an analog to digital converter gradually exceed the maximum or minimum range of the converter the next recorded number will be close to the opposite range as shown in Figure 4.1.1. This will obviously have a dramatic effect on any statistic which depends on the derivative of the signal calculated from the digital record. For this reason it is wise to have a suitable overrange/underrange detector on the digital conversion device. It is possible to use this extreme jump in indicated derivative in the computer program to correct for such overranges if the sampling rate is rapid enough to detect the large jump in sample value.

Figure 4.1.1



If the analog signal fluctuations are attenuated to avoid overranging or if the fluctuations are superimposed on a large d.c. offset, only a few bits may be available to represent the fluctuations and the signal may be lost in the "digital noise".

If the analog signal contains significant energy at frequencies high compared to the sampling frequency the energy will be "aliased" into the low frequencies. Low frequency energy can also leak into high frequencies for very steep spectra, so it is necessary to pay attention to both low and high pass filtering after the sampling frequency has been chosen.

Most mini computers presently available are 16 bit machines, corresponding to integer numbers in the range ± 32767 and floating point numbers of 5 place accuracy in the range $\pm 10^{\pm 38}$. Calculations must be arranged to stay within the bounds to avoid "overflow" or "underflow". Floating point calculations are subject to accumulation of roundoff errors.

A frustrating (but common) example of integer overflow is the calculation of the number of samples being analysed. An integer multiplication of the number of records times the number of scans-per-record works successfully on a small number of records (used to test a new program) but can fail for the large numbers of records used for actual analysis because of integer overflow.

It is possible to do all calculations with integer arithmetic by programming checks on overflows and taking corrective action. A common technique is to use "block floating point" calculations where each integer array contains a factor to scale it to its correct value. Calculations are done using integers. When the result overflows or underflows the array factor is scaled down or up and the calculation continues. Calculations done with integer arithmetic run 10 to 50 times faster than floating point calculations and require half as much memory for data storages. The necessary overflow/underflow controls can be implemented at the machine language level, making the program more efficient but the programming much more difficult. Such programs are prone to unexpected failures because it is difficult to anticipate "worst case" data values. Nonetheless, individual programs which consume a significant fraction of available computer time are tempting targets for this kind of improvement. The future solution seems to lie in the coming inexpensive floating point hardware and bigger memories in laboratory computers. Floating point calculations can suffer from truncation errors in long summations. Summing 10^6 numbers with 5-place calculations truncates additional terms after the first 10^5 terms have been added. This effect can be reduced by summing deviations about an approximate average, so that the sum does not grow so quickly. Subdividing the summation is a great improvement, e.g., subtotal each record individually and accumulate the subtotals. Truncation errors are reduced by reducing the difference in magnitudes between two quantities being added.

Cancellation of significance can occur when the difference of two nearly equal numbers is taken. This often occurs in the calculation of average moments. Calculation of moments about zero and then correcting these quantities to moments about the mean is a bad procedure because of the cancellation that will occur. It is best to calculate the average first, sum moments about an approximate average, and then correct this sum to moments about the true average.

The effect of round-off error (both truncation and cancellation) should be minimized by careful program organization. This allows successful calculation of statistical quantities from large data samples with small computers.

4.2 Histograms

The numerical estimate of the probability density function of a random variable is the histogram of a large number of representative samples. The histogram is obtained by dividing the range of possible values of the signal into equal parts or "bins" and counting the number of samples which fall into each bin. This number divided by the total number of samples is the value of the histogram for a particular "bin". In the limit of an infinite number of samples and narrowing bin width the histogram should converge to the probability density function of the random variable.

Limitations on estimating the probability density function using the histogram occur due to the finite number of samples available and the finite width of the bins. The effect of undersampling is illustrated in Figure 4.2.1, which shows a number of histograms calculated from conductivity probe measurements of salt concentration in a sphere wake[10]. Each histogram was calculated from 5 records of 2048 samples of the concentration signals, or 1024 samples/histogram. The shapes of the individual histograms are quite different, as indicated by the variability of the moments. Kurtosis values vary by a factor of 2; skewness values by a factor of 10.

Figure 4.2.2 shows the same sort of data[11] averaged over 80 records or 163,840 samples. In this case the points are smoother, but the probability density function is not very well defined because the bin width is too wide (1/3 standard deviation).

Figure 4.2.3 shows a histogram calculated from 64,000 samples of a random variable (by Paul Masiello) where the bin width is narrow enough to permit good definition of the probability density function near the mean. The distribution is quite skewed, however, and it is unlikely that the indicated skewness of -1.253 has more than one or two significant figures.

Figure 4.2.1

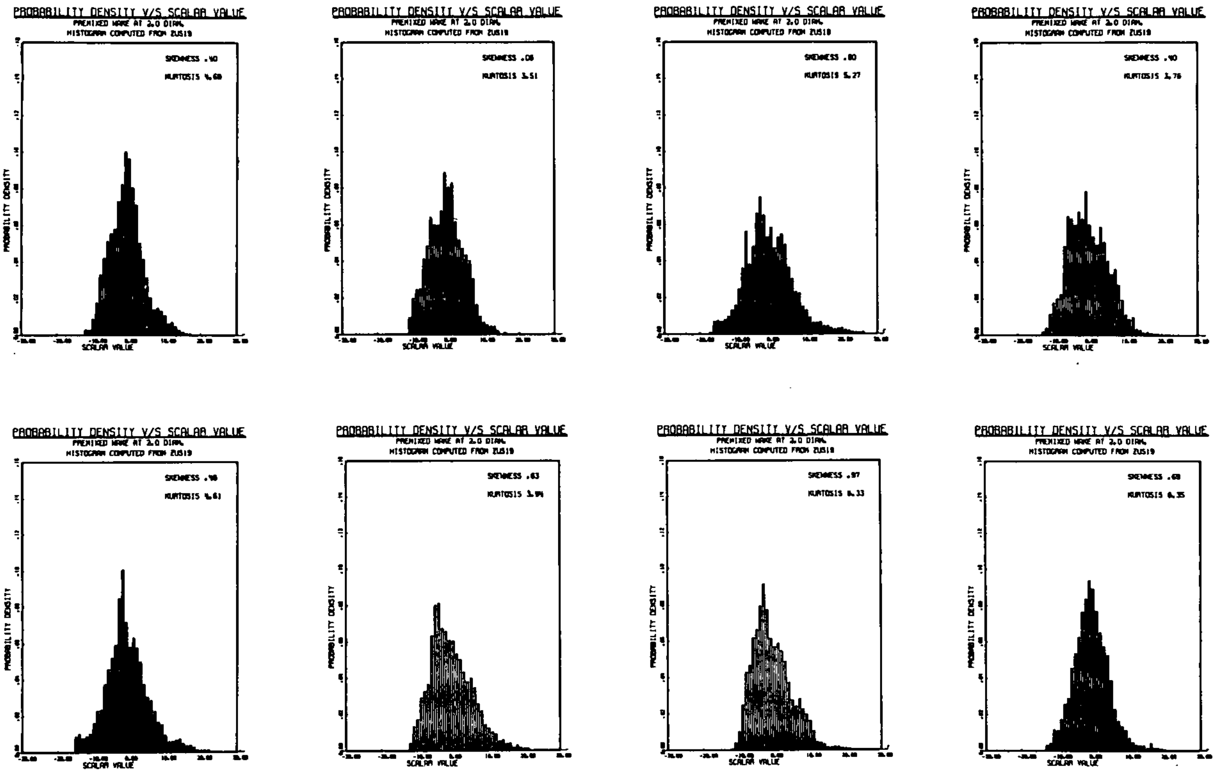


Figure 4.2.2

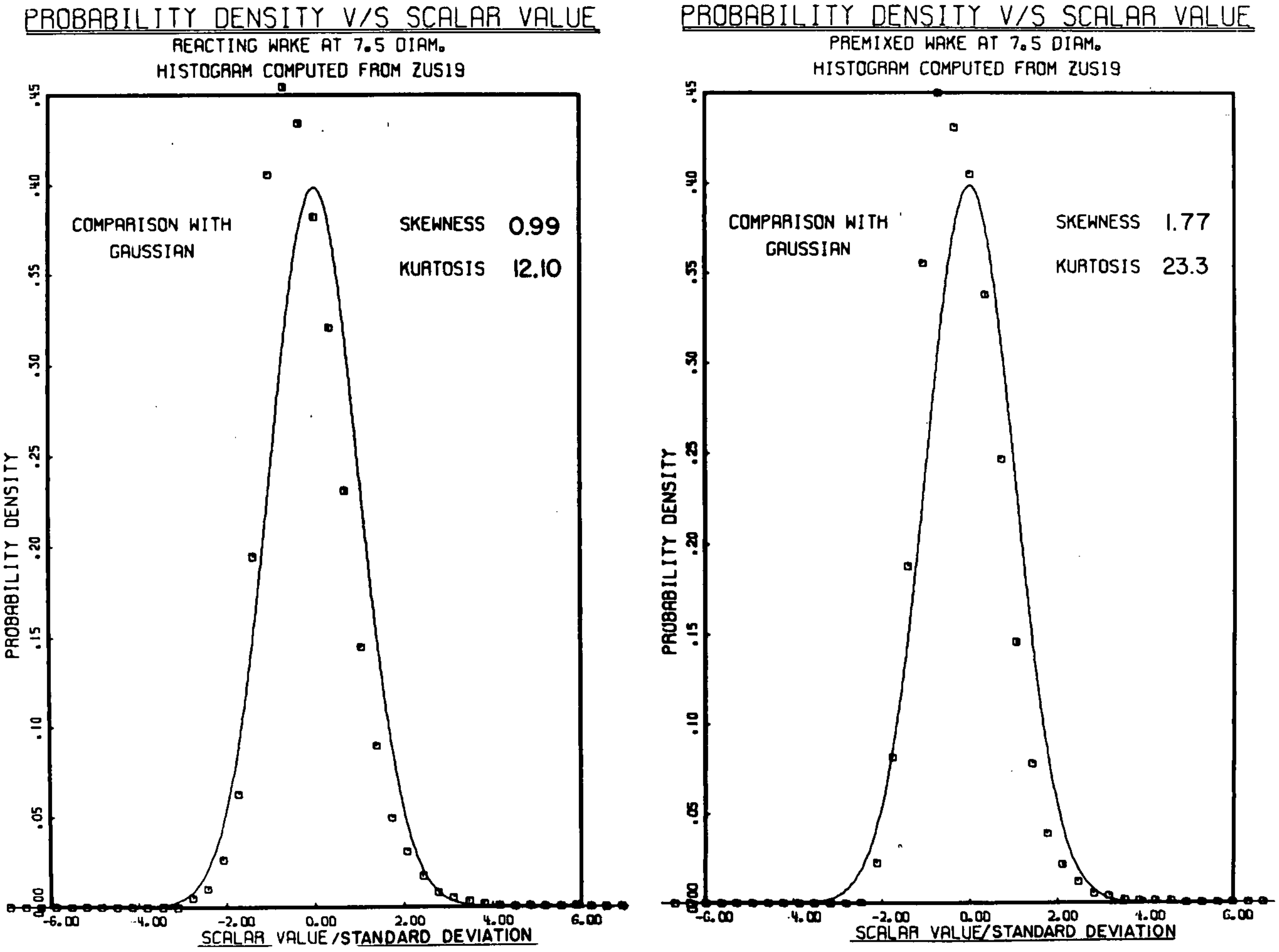


Figure 4.2.3

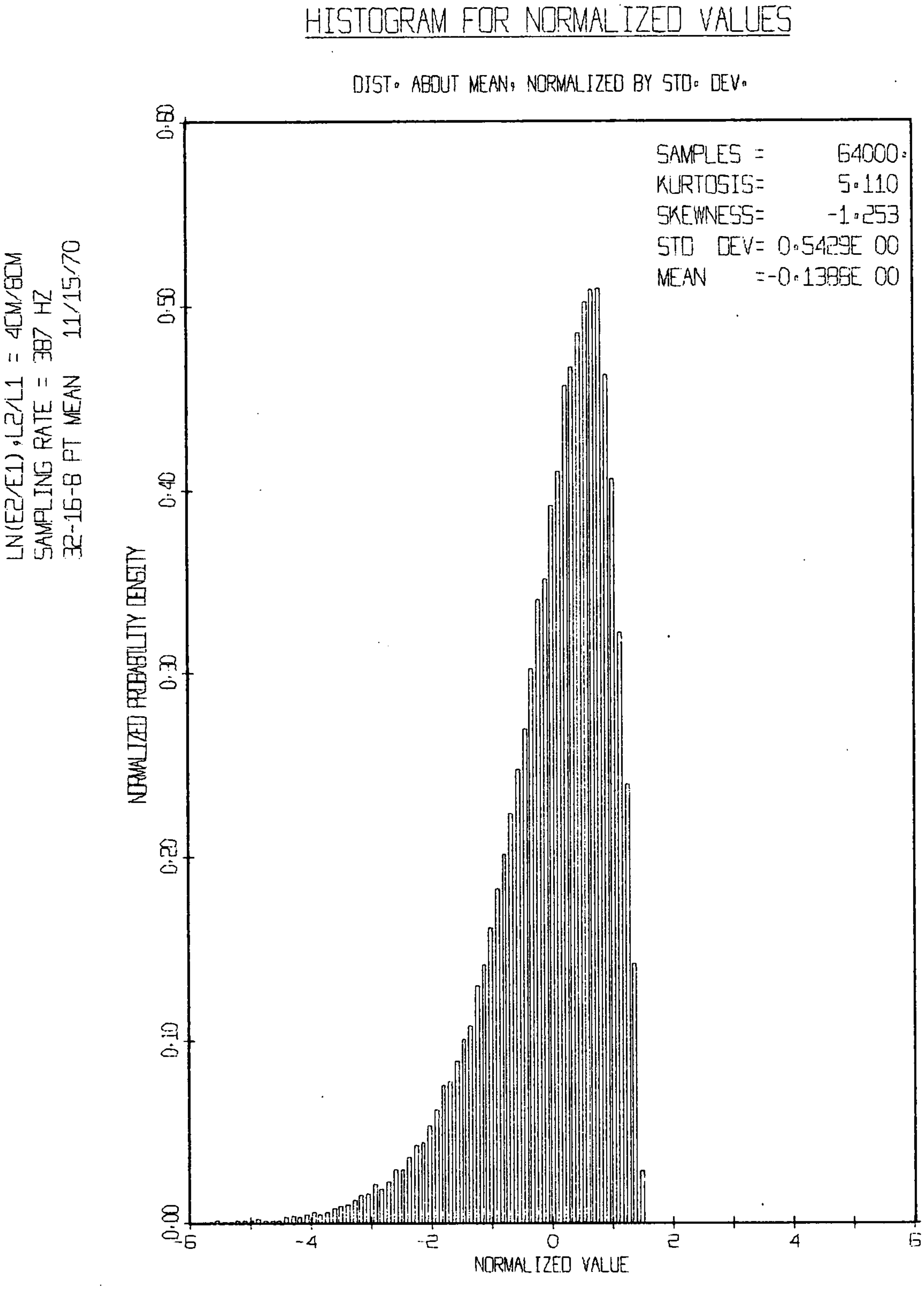


Figure 4.23 also illustrates another powerful capability of digital data processing; namely, the capacity of the computer to preprocess incoming data before entering the sample for subsequent analysis, thus reducing the volume of samples to be recorded and manipulated in the calculations. The random variable $\ln\,[E_2/E_1]$ was generated by the laboratory computer by preprocessing several hundred velocity derivative samples for each sample stored in the data file used to calculate the histogram shown in Figure 4.2.3. E_1 is the mean squared derivative averaged over eight cm of air and E_2 is the mean square from samples in the center four cm of the data used for E_1. Consequently Figure 4.2.3 represents a statistic calculated from several million velocity derivative samples, which would be more than could be accommodated in the disc file of the computer.

The quantity $\ell n\ [E_1/E_2]$ is similar to the ratio of mean dissipation rates for concentric averaging volumes which arises in connection with Kolmogoroff's third universal similarity hypothesis[12] and was used[13] to test the assumption that the distribution is independent of the size of the sampling volume. Kolmogoroff's third hypothesis also includes the assumption that the averaged dissipation should be a lognormal random variable, which is tested by digital techniques as shown in Figure 4.2.4, which is a so-called Gaussian plot with coordinate system stretched so that the distribution function of a Gaussian random variable falls on a straight line. This is demonstrated in Figure 4.2.5 by a plot of the distribution function estimated from 256,000 samples of the signal from a random noise generator. The kurtosis was 3.011 compared to 3.0 for a Gaussian distribution, and the skewness was -0.0007 compared to 0.0. Both Figures 4.2.4 and 4.2.5 are from automatic computer plots for Gaussian comparison.

Figure 4.2.4

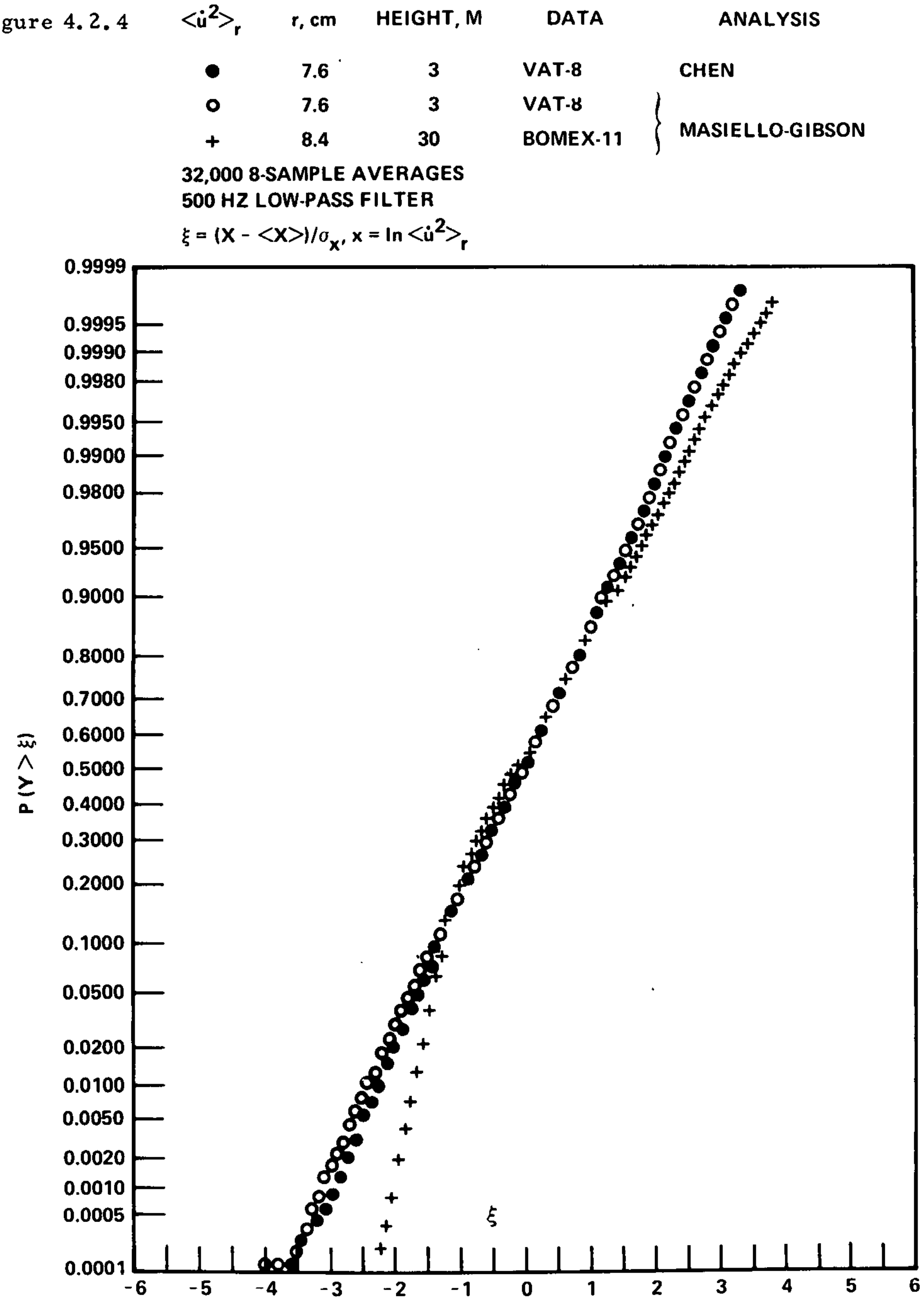
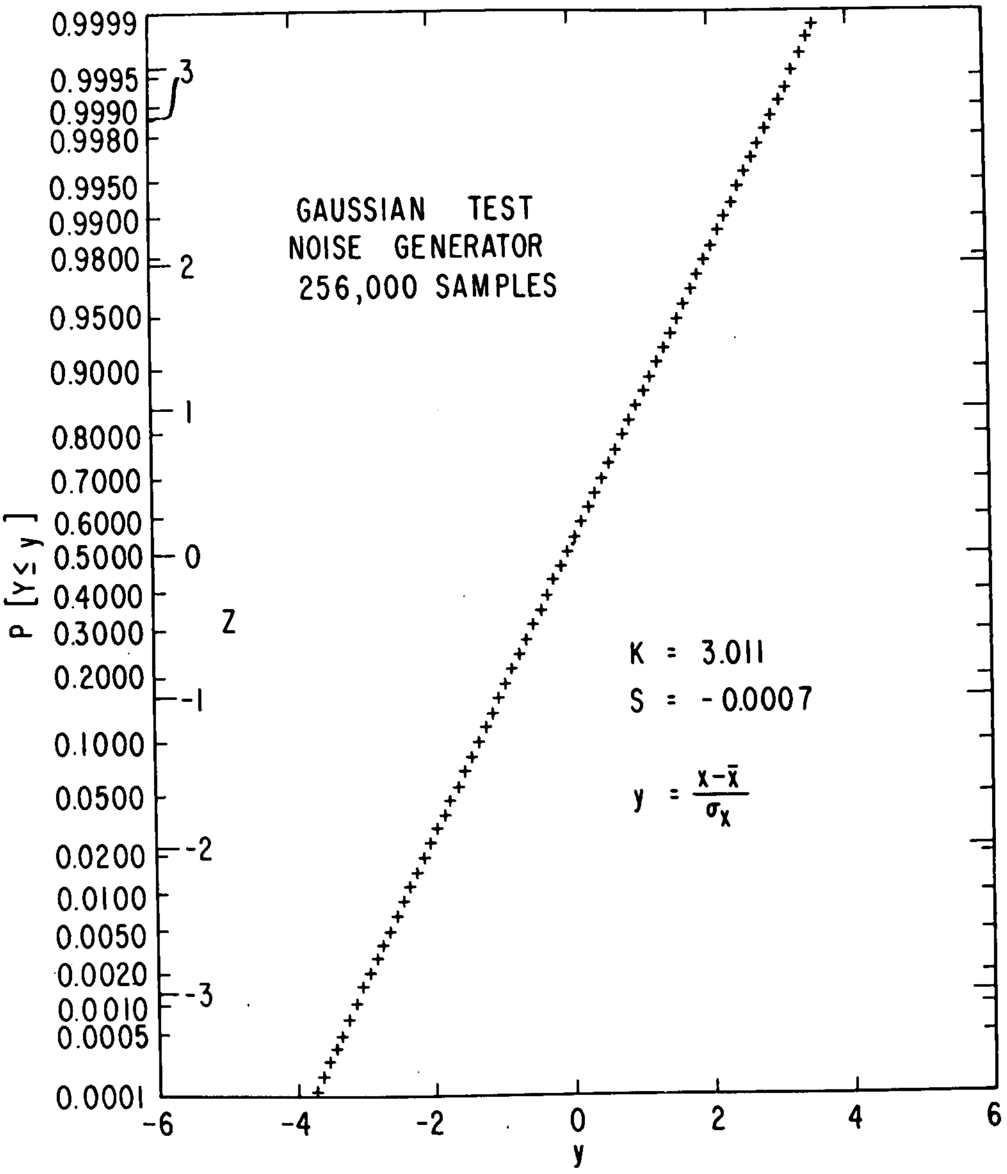


Figure 4.2.6 shows a test of the independence of ratios of dissipation rates for different averaging volumes by comparing the joint histogram with the product of the individual histograms. In this case the data was preprocessed into two data files representing the ratio of mean dissipation rates for three concentric sample volumes. See reference 13 for details.

The histogram is useful in estimating moments of random variables by integrating the appropriate power of the random variable multiplied times the histogram. It is generally more efficient to calculate moments from the histogram than directly because the histogram is derived by sorting into bins and collecting rather than multiple exponentiations and summations required in the direct moment determination. The histogram is also very useful to determine whether or not higher order moments have converged, as illustrated in Figure 4.2.7, which shows a plot of $x^3\ f(x)$, where $x = (T, x)/\sigma_{T,x}$. The integral under the curve in Figure 4.2.7 should be the skewness of $T,x \equiv dT/dx$. It was necessary

Figure 4.2.5



to accumulate 25 million samples of dT/dx before the scatter in the large values of the histogram was small enough to permit the integration. Extreme values to 50 times the standard deviation of dT/dx were needed to complete the skewness, which demonstrates the very large dynamic range necessary in high Reynolds number turbulence measurement, as well as the extreme intermittency which develops in the dissipation rate.

Figure 4.2.6

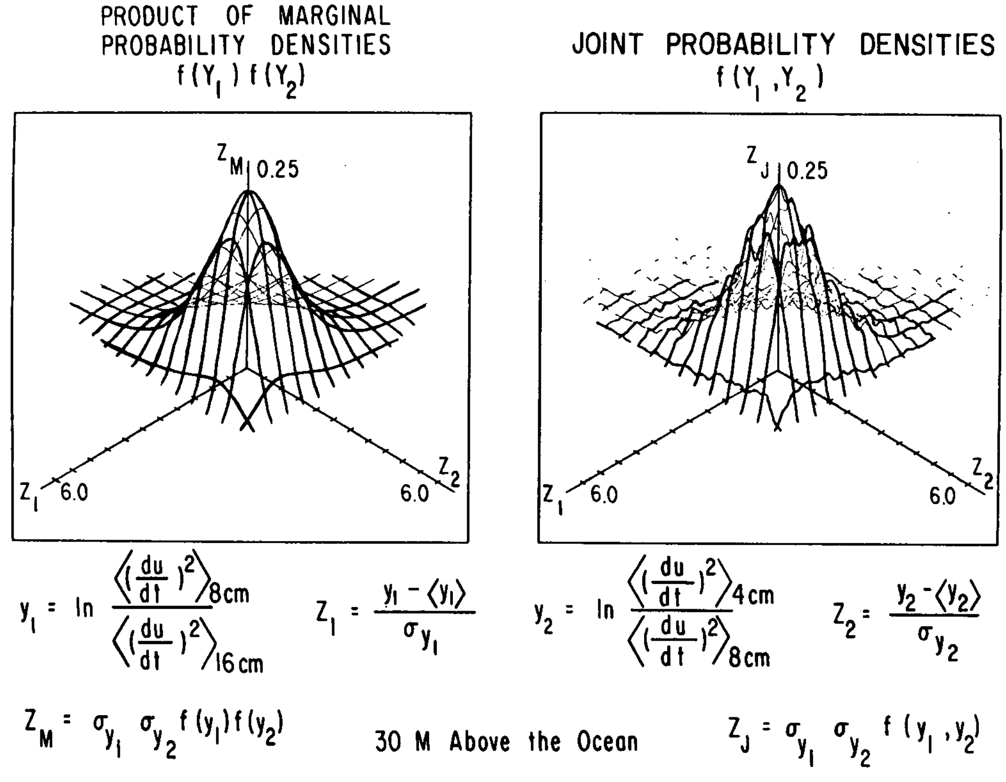
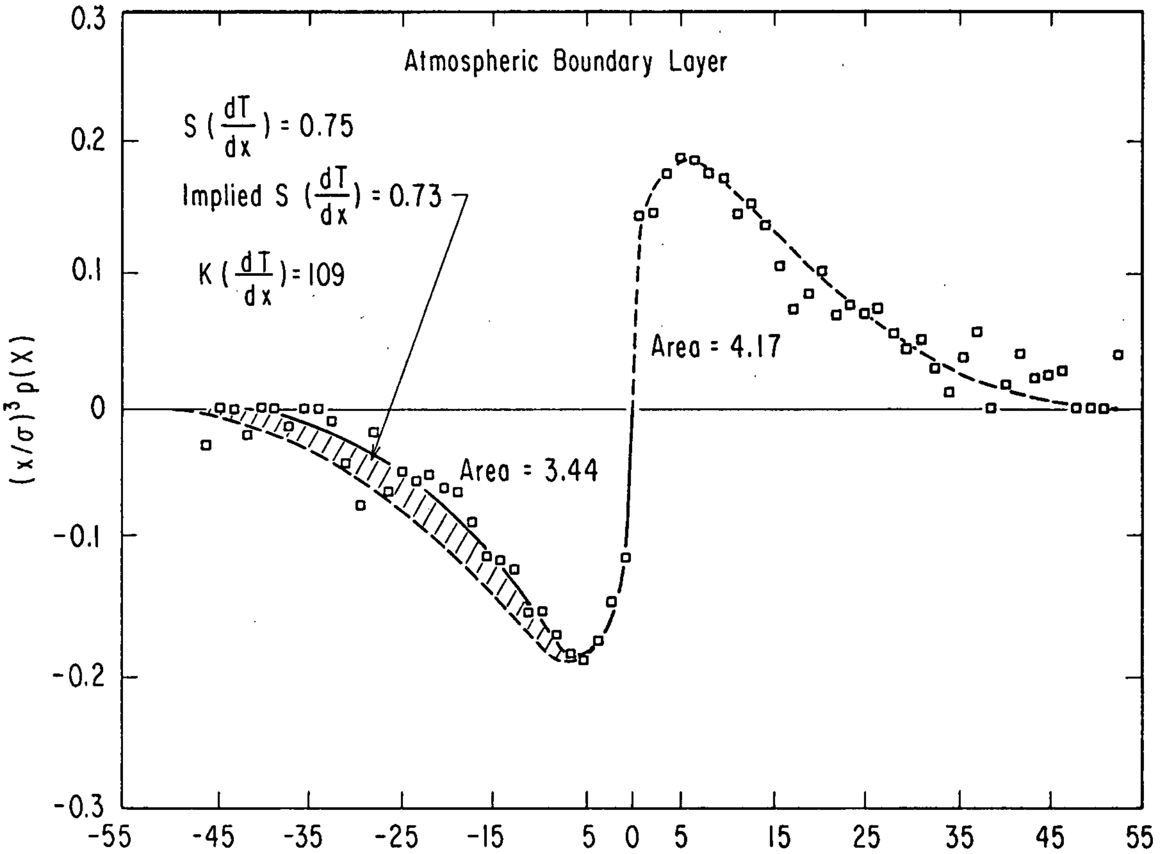


Figure 4.2.7



4.3 Fast Fourier Transform

As previously discussed, present statistical descriptions of turbulent flow involving Fourier transformed data or correlation functions play a central role. It is therefore vital that computer programs for efficient Fourier transformations exist. Considerable symmetry exists in the descrete Fourier representation of a time series of N data points, and it is possible to considerably reduce the N^2 operations required in calculating Fourier coefficients in the most straightforward manner indicated by their definition. This was apparently recognized as early as 1903 by Runge[14] whose method was applied by Danielson and Lanczos in 1942[15] and later by Rudnick of Scripps Institution of Oceanography in 1966[16], according to a survey of the history of such algorithms by Cooley, Lewis and Welch[17], although the power and implications of the fact were not widely recognized till the publication by Cooley and Tukey in 1965[18]. Cooley and Tukey described their method as a "Fast Fourier Transform" and pointed out that only approximately $N \log_2 N$ operations were needed rather than N^2 to make the transformation. This amounts to a factor of 15 when only 100 points are transformed but for a thousand points the improvement is a hundred fold and for a million $N/\log_2 N$ is 50,171. Such an improvement in efficiency makes use of the straightforward programs prohibitively slow for very large data samples.

Other techniques can be used to further improve the efficiency of Fast Fourier Transforms. For example, using a routine for complex time series on real data wastes half the time[19]. A tenfold increase in speed can be achieved by a machine-language, integer arithmetic FFT. A threefold improvement can be achieved by ordering all computations with the same phase factor to be done sequentially[20]. Thus, two orders of magnitude in speed can exist between a tightly coded, machine language, integer arithmetic routine which is algorithmically efficient and a straightforward FORTRAN routine even though both routines employ the "Fast" Fourier Transform algorithm.

4.4 Computation of Power Spectra

A number of pitfalls exist in digital estimation of the power spectrum of an analog time series[39,40]. Power at frequencies above half the sampling frequency must be filtered before the data is sampled or it will be "folded back" (see Bracewell[21] , Jenkens and Watts[22] or Enochson and Otnes[23]) and appear at lower frequencies through a process called "aliasing". For signals with very steep power spectra, that is with high power at low frequencies, the possibility of "leakage" to higher frequencies must be considered. Atmospheric and oceanic data are subject to this so-called "infrared catastrophy", and must be "prewhitened" to obtain a more uniform distribution of power over the frequency band of interest.

Power spectra of turbulent temperature, velocity and humidity fall off at about 6 db/octave (slope of -2 on a log-log plot of power spectrum versus frequency) which is steep enough to give substantially larger errors than the data scatter for power spectral estimates averaged over a few hundred records. The situation is worse if a steep low frequency subrange exists such as occurs due to buoyancy in stratified turbulence, or due to diffusion for strongly diffusive scalar properties. An easy way to flatten the spectrum of a signal with slope -2 is to differentiate. For slopes of -5/3 this results in a slope of + 1/3 on a log-log plot.

Figure 4.4.1 shows the effect of low frequency leakage on atmospheric velocity data sampled at two frequencies using a "boxcar window"; that is, transforming the time series directly. Several hundred 1024 data point records sampled at 50 and 500 Hz were transformed and averaged. The spectra were multipled by the frequency f raised to the 5/3 power and plotted by the computer. The power spectral estimates in Figure 4.4.1 are the convolution of the signal power spectrum with spectra of boxcar functions with length equal the time of one record[21]. Since the low sampling frequency boxcar is wider in time it is narrower in frequency, so less low frequency energy leaks into the overlap region of the two spectra.

Figure 4.4.2 shows comparable spectra calculated from the derivative of the same data, sampled with boxcar windows and the same frequency and high frequency filter settings. Because the derivative spectrum has low energy at low frequency, there is less energy to leak out to high frequency and consequently the spectra agree well in the overlap region, except for the effect of the filter effect. Note the filter effect is more substantial for the derivative spectrum of Figure 4.4.2 than for the velocity spectrum of Figure 4.4.1.

Digital prewhitening may be accomplished by transforming the first difference of the signal, and the "postdarkening" by correcting the resulting spectrum for the transfer function of the differencing operation. The result of this operation is illustrated by Figure 4.4.3 using the same filtering sampling averaging and plotting procedures on the same data as before. Note that the filter effect is less than in Figure 4.4.2 because the filtering occurs before the differencing rather than before differentiation.

Figure 4.4.4 shows the effect of using a triangular data window on the low frequency leakage, shown in Figure 4.4.1. A triangular window means that the data is multiplied by factors which increase linearly from zero to one from both ends of the record to the middle. Because the side-lobes of the triangular window fall off at 12 db/octave rather than 6 db/octave, much less energy is transferred from low to high frequency in the convolution operation between the triangle and signal spectra.

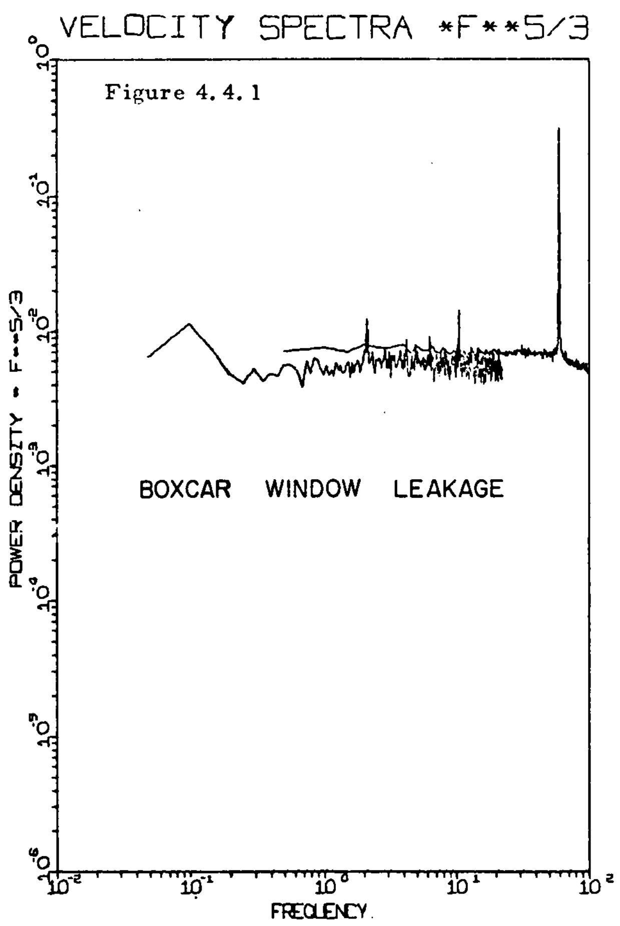


Figure 4.4.1

POWER SPECTRA OF VELOCITY SAMPLED AT DIFFERENT FREQUENCIES WITH BOXCAR DATA WINDOW

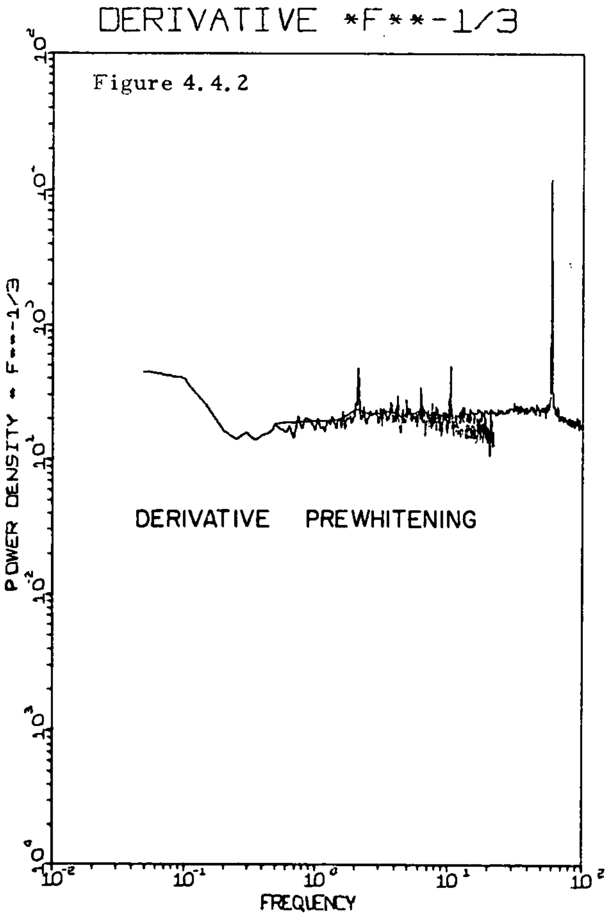


Figure 4.4.2

POWER SPECTRUM OF VELOCITY DERIVATIVE SAMPLED AT 50 AND 500 HZ WITH BOXCAR DATA WINDOW

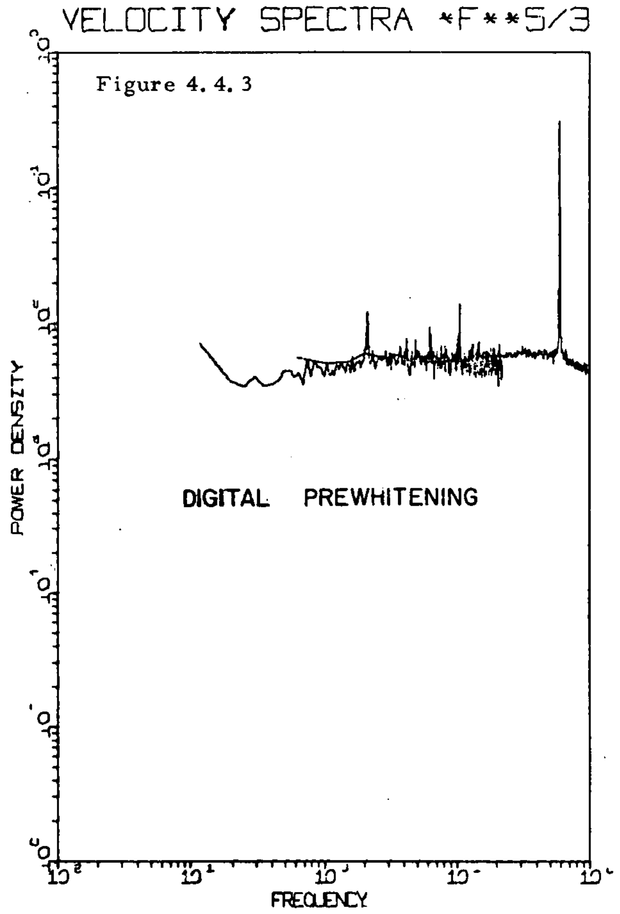


Figure 4.4.3

POWER SPECTRA OF VELOCITY SAMPLED AT 50 HZ AND 500 HZ WITH A DIGITAL PREWHITENING

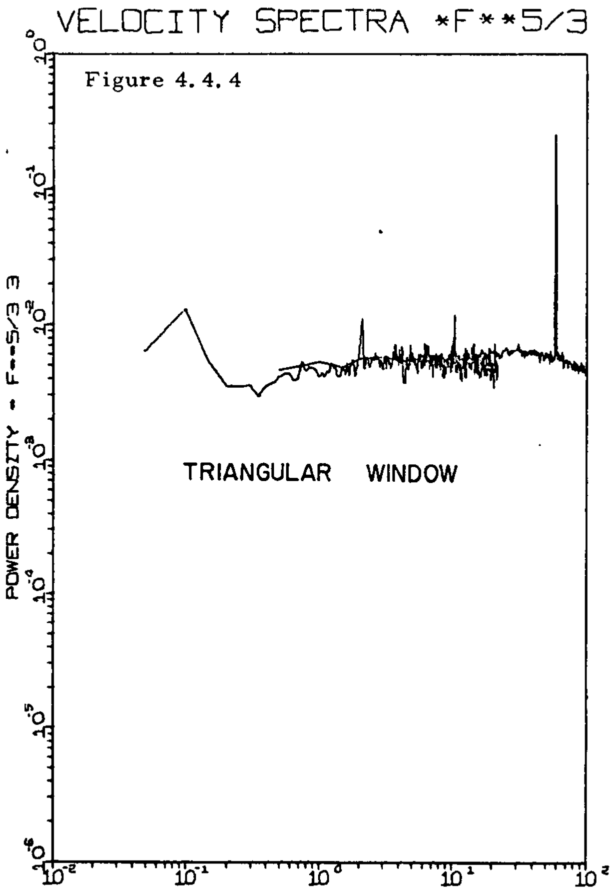


Figure 4.4.4

POWER SPECTRUM OF VELOCITY SAMPLED AT 25 HZ AND 250 HZ WITH TRIANGULAR DATA WINDOW

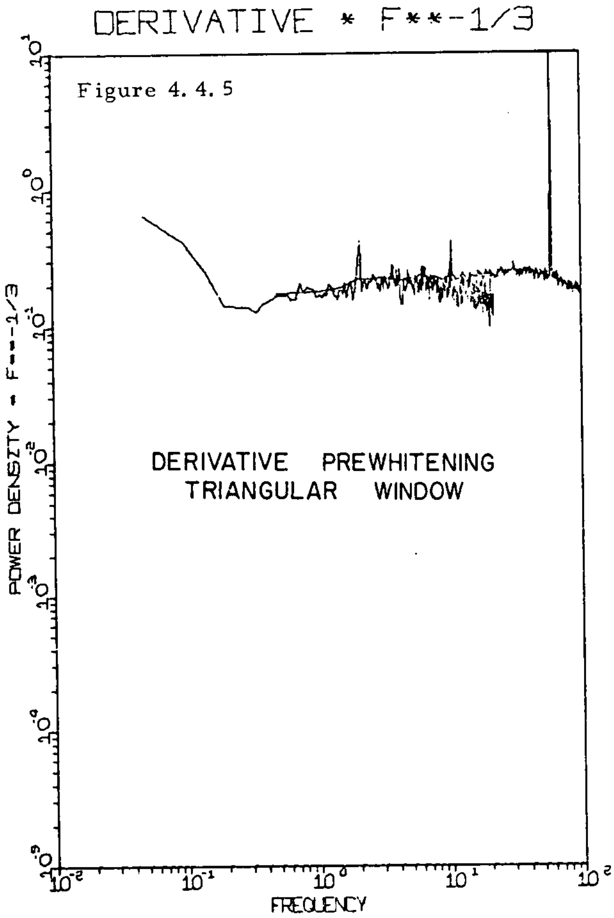


Figure 4. 4. 5

POWER SPECTRA OF VELOCITY DERIVATIVE SAMPLED AT 50 AND 500 HZ WITH TRIANGULAR DATA WINDOW

Figure 4. 4. 5 shows the result of both derivative prewhitening and the use of a triangular data window. It can be seen that the spectra agree very well in the overlap region. Derivative and undifferentiated signal spectra in the preceeding spectra differ by factors of $1/4\pi^2 \cong 0.025$.

A variety of other techniques have been devised to assist in accurate digital estimation of power spectra; and are described in the previously sited references. It is advisable to use and compare the results from more than one method and sampling frequency wherever possible.

4. 5 Conditional Sampling-Preprocessing

A very powerful aspect of digital time series analysis in turbulence research is the capacity of the computer to reject uninteresting data based on some programmable criterion, or to modify the acceptable samples in a programmable way before they are recorded. The conditioned sampling may be from the real time experiment or from high capacity low frequency to low capacity high frequency storage, such as from tape to disc or from disc to core. In any case the purpose is data reduction.

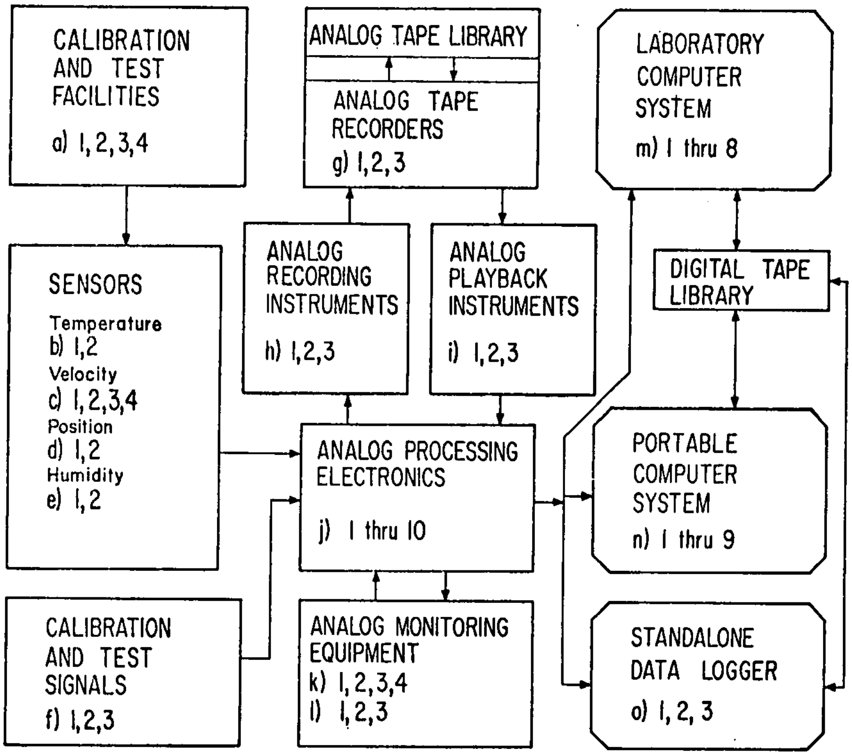
Preprocessing can also accomplish data reduction by accumulating a large number of samples into a preanalysed sample, or it may accomplish a calibration or nonlinear operation to reduce the subsequent processing time. For multichannel operations many retreaval and restorage operations can be saved by preprocessing operations. High speed microprogrammable "firmware" offers the possibility of preprocessing turbulence data at nearly any degree of sophistication desired, including multichannel on-line Fast Fourier Transformation.

5. DIGITAL TURBULENCE ANALYSIS SYSTEM

5.1 Schematic Diagram

Figure 5.1.1 is a schematic diagram of the turbulence data analysis system developed in the Applied Mechanics and Engineering Sciences Department of the University of California at San Diego. As previously discussed, a very wide range of options exist for digital turbulence data analysis systems and the system in 5.1.1 is intended as an example of functional characteristics rather than a recommendation of specific equipment.

Figure 5.1.1



LEGEND

a) 1. Wind tunnel
   2. Water tunnel
   3. Controlled temperature air jet
   4. Portable calibration wind tunnel

b) 1. H-P Quartz thermometer
   2. Cold wires & A.C. bridges, thermistors

c) 1. Cup anemometers and vane
   2. 3-D sonic anemometer
   3. Hot wire and film anemometers
   4. Ducted current meter

d) 1. Cambridge dew pointer
   2. Lyman-Alpha humidiometers

e) 1. Litton inertial guidance platform
   2. Wave gauges

f) 1. Voltage reference
   2. Signal generator
   3. Noise generator

g) 1. Honeywell 7600
   2. Sangamo 3500
   3. H-P 3950

h) 1. Pre-emphasis circuits
   2. Multiplexer
   3. Calibration and input selection patch panel

i) 1. De-emphasis circuits
   2. Demultiplexer
   3. Flutter compensation

j) 1. Buck and gain amplifiers
   2. Multiplier
   3. Sum and difference amplifiers
   4. Overload indicators
   5. Low and high pass filters
   6. Differentiators
   7. Frequency to voltage converters
   8. Square law detector
   9. Integrators
   10. Voltage to frequency converters

k) 1. Chart recorders
   2. Integrating digital voltmeters
   3. Frequency counters
   4. RMS meters

l) 1. Ubiquitous spectrum analyzer → 2. Oscilloscope → 3. x-y plotter

m) Refer to Figure 5.2.2

n) Refer to Figure 5.3.2

o) 1. A/D Converter → 2. Data buffer → 3. Digital tape drive

Calibration and test facilities (a) include wind, water and mercury tunnels as well as various jet and calibration facilities, some in different parts of the building connected to the computer by signal leads. On-line operation is often desirable in order to avoid signal contamination by tape recorder noise. Extensive storage on digital tape is an option in case complete on-line processing is not possible, either in the Laboratory Computer System (m) or the Portable Computer System (n) used for field experiments. Sensors (b), (c), (d) and (e) with associated electronics produce analog voltages which are adjusted to appropriate amplitude ranges and bandwidths before processing (m) or (n), analog recording (g) or digital logging (o). Calibration and test signals (f) are processed and recorded in the same way in order to permit subsequent or on-line conversion of the data to absolute units. Analog record and playback instruments (h) and (i) are used to extend the dynamic range and channel capacity of the analog tapes through pre-emphasis-deemphasis (prewhitening-postdarkening) and multiplexing the test or data signals.

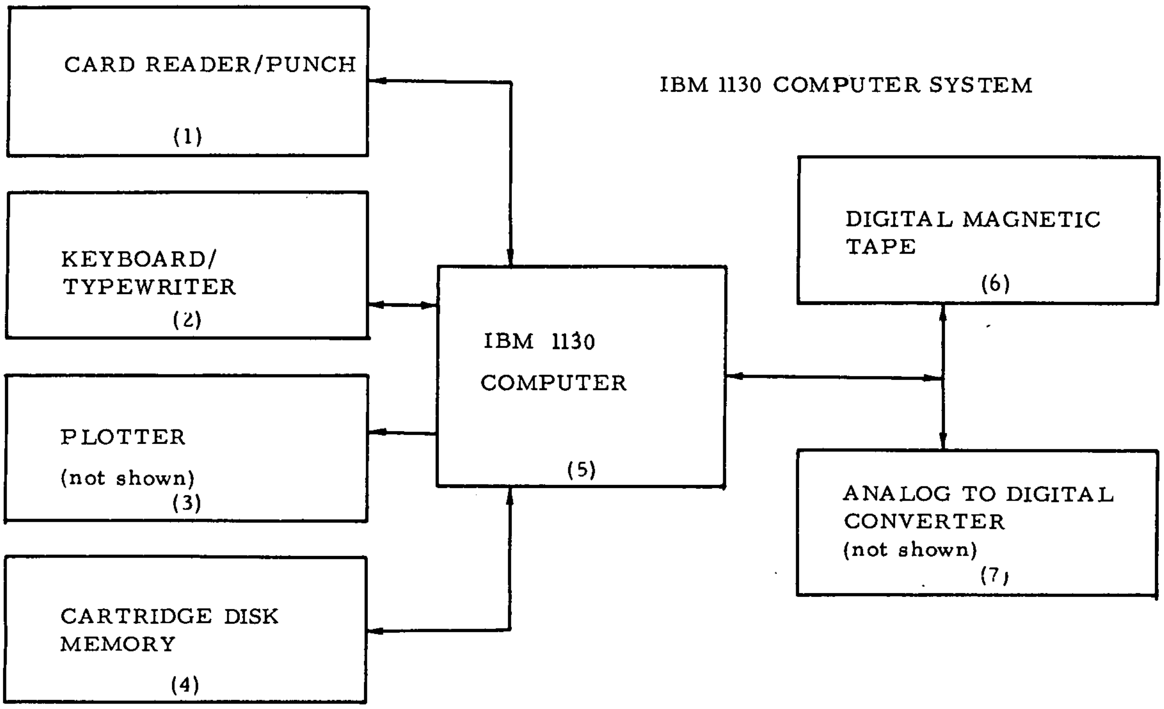
Analog monitoring (k), (l) is accomplished by plotting the various raw signals or by spectrum analysis and plotting with a hardwired digital spectrum analyser. Farther analog monitoring (not shown) is accomplished by a variety of overrange lights at the analog recording and A/D conversion points.

5.2 IBM 1130 Computer and Time Series Analysis Section

Figure 5.2.1 is a photograph of the IBM 1130 Laboratory Computer System and Figure 5.2.2 is the corresponding schematic diagram. Communication to the computer is possible through the card reader/punch (1), the keyboard/typewriter (2), the digital tape (6) and the A/D converter (7) and the cartridge disk memory (4). Output from the computer can go to all of the above devices except the A/D converter (since no D/A has been implemented) as well as the Calcomp incremental plotter (3).

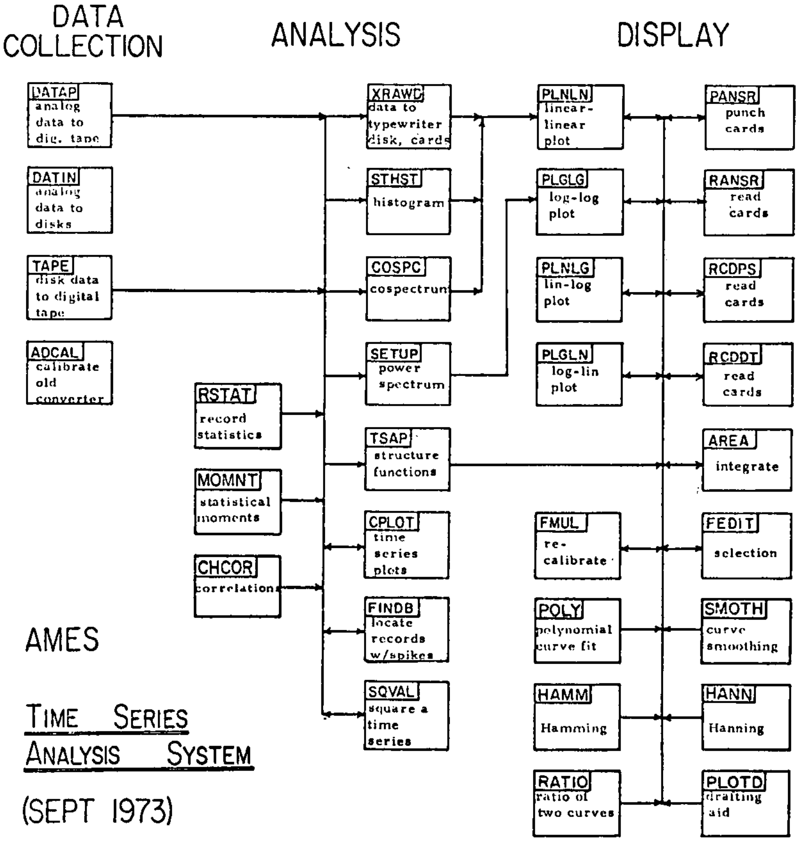
Figure 5.2.1

Figure 5.2.2



Data processing with the IBM 1130 is accomplished by means of an integrated group of computer programs for the study of stochastic signals which are stored in memory, disc and tape. These programs are grouped according to their function: data collection, analysis and display as shown in Figure 5.2.3. Data collection programs digitize analog signals. Analysis programs use statistical and spectral techniques to reduce data. Display programs organize and output reduced data. Standardized formats are used for communication from data collection programs to analysis programs and from analysis programs to display programs. This standardization allows raw data to be processed by any analysis program and reduced data to be output by any display program. An operation which is required by more than one program is performed by a subroutine; a change in that operation is incorporated into its subroutine and is thus effected throughout the system. These features make the system synergistic. A program introduced into any group can be used in conjunction with programs in other groups. An improvement in an operation for any one program simultaneously improves that operation in all other programs.

Figure 5.2.3



Currently available data collection programs provide for transfer of blocks of data from the A/D converter directly to digital tape (DATAP) or for double buffered ("gapless") transfer from A/D to disk (DATIN). An auxilliary program transfers data between disk and tape (TAPE). Future additions to the data collection programs will include a conditional sampling program. Digital tapes are formatted with an alphanumeric description at the beginning, many records of data in the middle, and an end-of-file mark at the end. Each block of data consists of the binary integers received from the A/D. The user specifies the number of channels of data read from the A/D and the number of scans of these channels in one record. Record length is limited by available memory size. All analysis programs accept this format of digital tape from the data collection programs.

Available analysis programs allow examination of raw data, statistical analysis and spectral analysis. Raw data records can be output directly (XRAWD), searched for extreme values (FINDB) or displayed as time series plots (CPLOT). Statistical programs include histogram (STHST), correlation coefficient (CHCOR), structure functions (TSAP), moments (MOMNT) and record-by-record statistics (RSTAT). Spectral analysis includes the power spectrum with windowing and prewhitening/post darkening options (SETUP) and cospectrum (COSPC). A program for calculation of cross spectra with associated coherence and transfer functions is under development.

Lists of (x, y) data calculated by analysis programs are saved in a special disk file. Analysis programs transfer execution to an appropriate plotting program. For example, histograms are transferred for linear plotting while power spectra are transferred for logarithmic plotting. However, the data remains in the disk file where it may be modified or replotted by selection of other data organizing and plotting programs. The user may save reduced data on cards for transfer to another computer or for reentering the reduced-data file onto disk at a later date.

Available plotting programs use log-log (PLGLG), semilog (PLGLN, PLNLG), and linear-linear (PLNLN) coordinates. All programs determine axis scales suitable for the data at hand. The log-log plot is on a fixed 3 decade (in x) by 5 decade (in y) format to facilitate comparison of spectra. To the extent possible, the plotting programs derive their annotation from the tape label, program being executed, and selected data and analysis options. The user may provide additional annotation. A drafting aid is being developed which will allow greater freedom with respect to selection of axis size, scales, use of multiple sets of data and coordinates, and plot annotation.

Data organizing programs allow integration (AREA), polynomial fitting (POLY), and recalibration (FMUL), editing of (x, y) data (FEDIT), Hamming and Hanning of spectra (HAMM and HANN) and curve smoothing (SMOTH). The integration program might be used to check that the integral under a power spectrum equals the variance calculated by a statistics program or to calculate a cumulative distribution function from a histogram. Polynomial fitting is useful to smooth a curve. Recalibration allows user specification of variables A, B, C and D in the formulae

$$\mathrm{NEW}\ x = A * \mathrm{OLDX}^{B}$$

$$\mathrm{NEW}\ Y = C * \mathrm{OLDY} * \mathrm{NEWX}^{D}$$

The new x and y values replace the old values in the reduced-data file on disk. This simple routine is useful for multiplication by calibration coefficients, frequency to wavenumber conversion, multiplication of a spectrum by frequency squared (to obtain the dissipation spectra) and so forth. The data editing eliminates specified ranges of x data from the list, for example to remove a power spike at 60 Hz from the plot or integration of a dissipation spectrum. Hamming and Hanning are useful techniques to reduce distortion of highly colored spectra[39]. Other programs are added to the display group as needed.

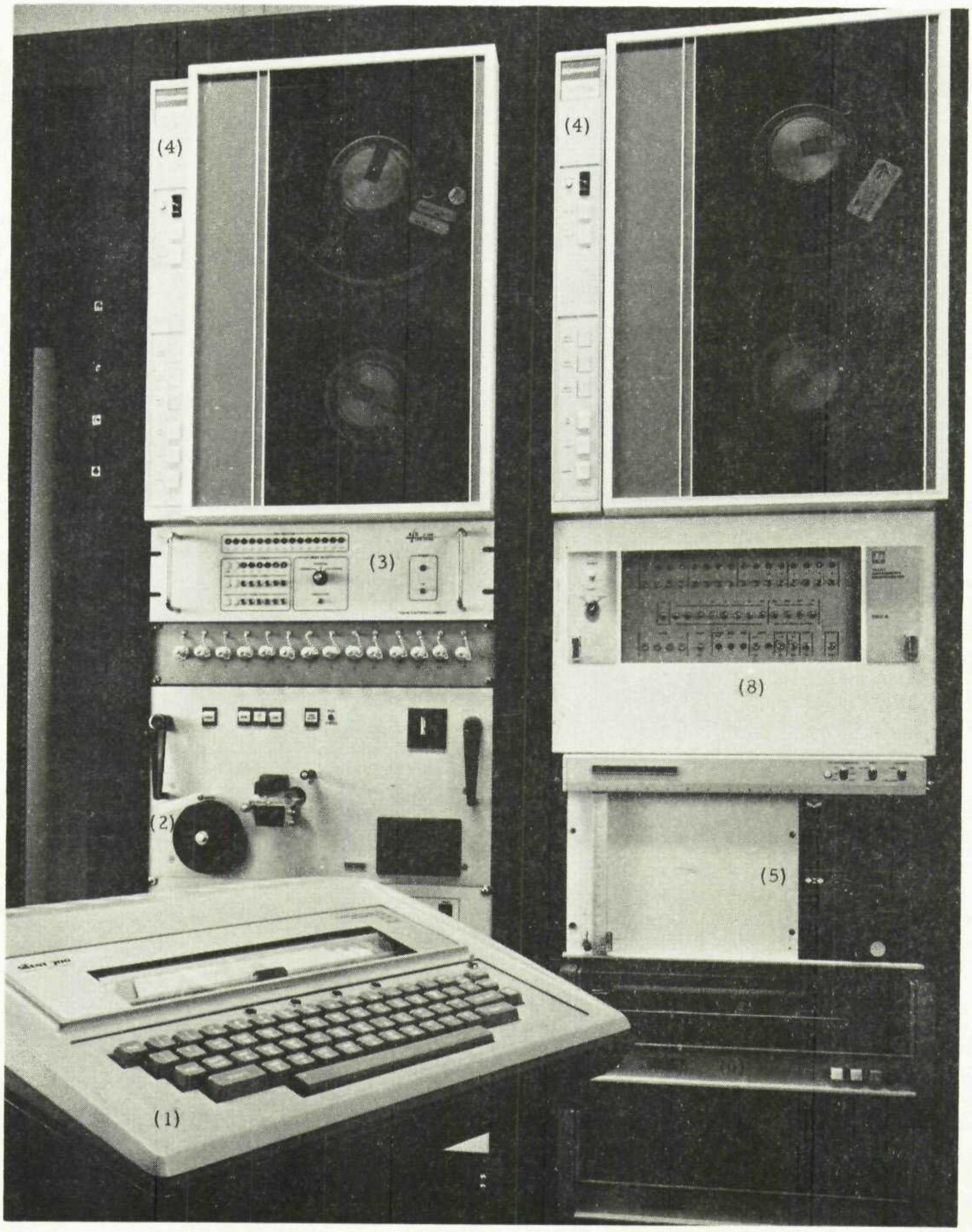
The available groups of programs, data collection, analysis, and display, are not exclusive. A new group of on-line processing programs is anticipated to allow the computer to be used as a piece of laboratory test equipment. Possibilities here include on-line calculation and display of voltages, rms values, vector voltages, spectra, correlations, and distributions.

5.3 Portable Computer for Field Experiments

Figure 5.3.1 is a photograph of a mini computer system designed for use in field studies of atmospheric and oceanic turbulence, as well as on-line data collection and processing with a laboratory experiment. Figure 5.3.2 is the corresponding schematic diagram.

Despite the smaller physical dimensions of the system, the mini computer is potentially much faster and more versatile than the previously described IBM 1130 system. Its memory is at least four times larger, faster and cheaper than the 1130, it has more storage capacity and speed in both tape and disk, and it can be conveniently interfaced to microprogrammable preprocessing units. The primary limitation at this time, as is usually the case for new mini computers, is the rate of development of system software.

Figure 5.3.1



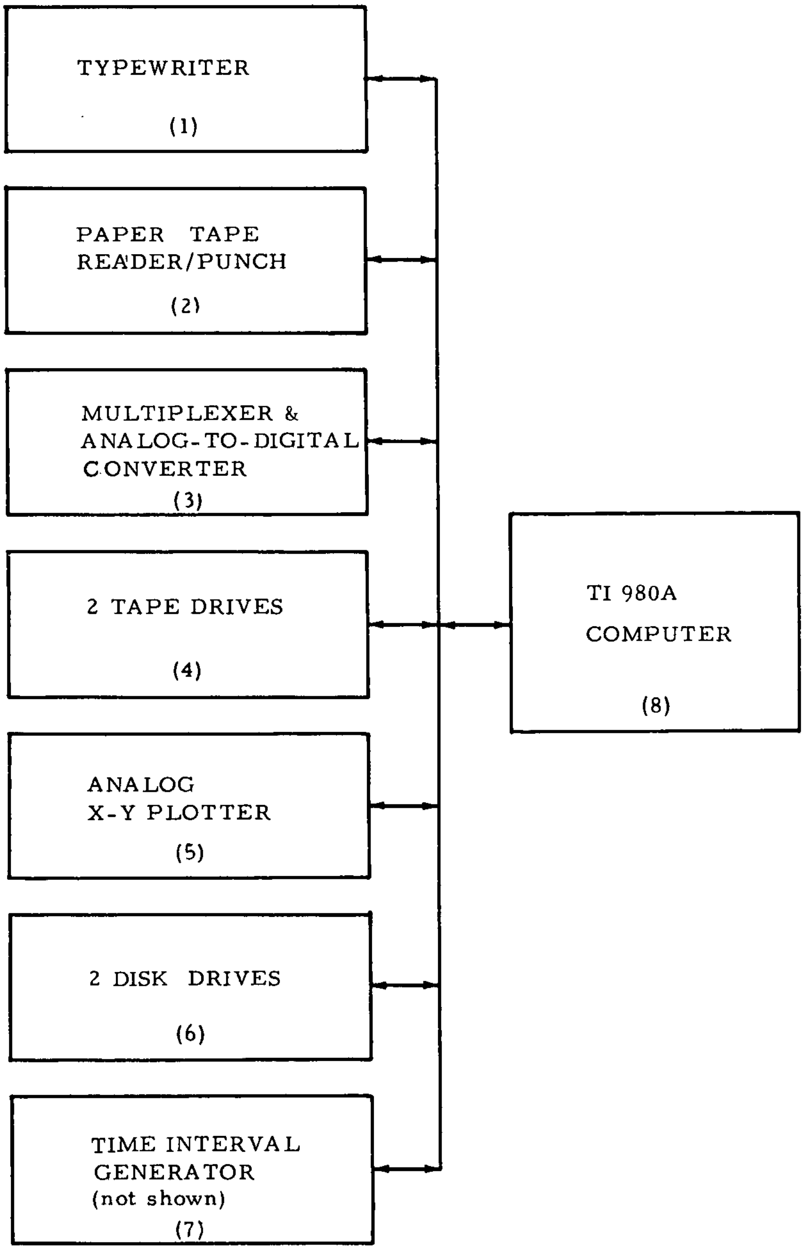
6. FUTURE DEVELOPMENT

6.1 Computers

The rapid pace of computer development is phenomenal, complex and difficult to assess with respect to its implications regarding progress in turbulence research. Instruction rates of the ILLIAC IV using parallel processing with an array of 64 independent processors can now be as high as 200 million/second at an I/0 transfer rate of a billion bits/second[24]. We saw in an earlier section that this corresponds to the amount of turbulent information produced per liter of turbulent air in the atmospheric boundary layer. Nevertheless, by clever programming it may be possible to take advantage of this enormous amount of computing power to perform meaningful numerical turbulence experiments.

Developments of faster, cheaper, better organized hardware promise to improve greatly the convenience and cost of mini computers so that they can be more easily implimented to assist the

Figure 5.3.2



turbulence experimenter. Microprogrammable control memory which stores special purpose instruction routines in read-only-memory can dramatically increase the usefulness and power of mini computers dedicated to turbulence data acquisition and analysis. The latest innovation is the use of so-called nanoprogramming, which permits two levels of microprogramming to produce a virtual computer (as distinct from virtual memory) and may give mini computers better access to higher level languages, and therefore a broader range of software in a shorter period of time. Software development time is presently a major factor in the way of implementing digital techniques for turbulence research. Development of increasingly compact, cheap "micorcomputers" will affect both instrumentation and data processing capabilities.

6.2 Computer Graphics

A variety of devices and control programs are available to display and preserve reduced or new turbulence data. The incremental plotter is very useful, since it provides a precisely drawn permanent copy of the reduced data with whatever labels the user wishes to program the computer to have the plotter draw. x-y plotters can also be used to draw curves and display computer stored data, but they are not satisfactory for detailed labelling. Storage oscilloscope displays are very useful, although somewhat expensive. Hard-copy from scope displays are getting cheaper, but are not yet of high quality and low price. The trend is in the right direction.

6.3 Computer Controlled Turbulence Experiments

A very exciting possibility is the prospect of incorporating feedback from the computer to the experiment itself, so that when a preestablished criterion has been met the computer can initiate a change in the experimental conditions, probe position or data acquisition procedure. Development and effective use of this option will depend very much on the imagination and initiative of the experimentor as he hopefully gains better understanding of the complex processes involved in the turbulence phenomenon. Unfortunately, no computer is available which can do the thinking.

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