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A Digital Computer System for Signal Analysis

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ABSTRACT

Equipment and procedures have been developed for signal processing and the analysis of experimental data in conjunction with a digital computer (Computer Control DDP-24). Digital magnetic tape recordings of time-sampled data obtained at remote field stations during experiments on underwater sound serve as a primary source of data for analysis. The basic computational operations are correlation and spectral analyses.

The system described provides for input to the computer memory from unblocked digital tape, selection of data by means of visual display, and output from computer memory of data or results, as desired. Details of hardware and software for special applications are discussed with particular emphasis on features which enhance the interaction between machine computation speeds and human interpretive power.

PROBLEM STATUS

This is an interim report; work on the problem continues.

AUTHORIZATION

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A DIGITAL COMPUTER SYSTEM FOR SIGNAL ANALYSIS

INTRODUCTION

Field of Application

The Signal Processing Branch has for some time applied digital techniques to the gathering and processing of data for statistical analysis of sound transmission through water (1, 2). In particular, studies have been made pertaining to the detection of known signals over long distances and at low signal-to-noise ratios. The severely destructive influences of the underwater environment on sound propagation dictate the need for a statistical approach to signal detection. Digital methods enable convenient implementation of comprehensive experiments with flexibility in updating throughout progressive stages of the analysis.

Comparison with Earlier System

Speed limitations of the central processor (Bendix G-15D computer) previously used for data processing and computation (3) led to the acquisition of a more modern and faster machine (DDP-24) as the heart of a data handling system. Many techniques from the earlier system have been applied to the new. For example, the new system was planned to maintain compatibility in using magnetic tape recordings of experimental data as used in the earlier system. The equipment for gathering data could thereby remain unchanged. Also, the forms of statistical analyses are, in general, similar. However, different basic features of the two central processors have resulted in different methods of implementation of identical functions.

Possibly a more comprehensive philosophy is incorporated in the design of the newer machine. At any rate, the majority of operations are under program control and are readily modified without changes in hardware. The random-access core memory coupled with parallel word transfers in the new machine, as contrasted with serial drum memory and the consequent emphasis on serial operations throughout the old system, have allowed connecting input-output devices directly to storage registers in the central processor, thereby eliminating the special circuitry for parallel-to-serial conversions and the resultingly more complex timing controls required in the older system.

The special features of the new system, that is, those which would not be found as standard equipment on any general purpose digital computer, developed as a natural consequence of the requirements of a specific problem. These requirements have remained, in general, similar to those handled previously. Prior experience (4, 5) has therefore influenced the current development and has, in some cases, dictated the need of particular functions as, for example, the necessity of reading the magnetic tape recordings of experimental data (hereafter referred to as field tapes) of already established format (6).

Emphasis of Report

The major functions required of the data processing system, over and above those recognized as essential to the operation of any general purpose digital computer, are the principal features of this report. The presentation is in a sequence corresponding to the

natural order of operation. Preliminary mention is made of all the functional requirements before a more detailed discussion of the equipment and computer programs used to implement each is given.

GENERAL FUNCTIONAL REQUIREMENTS

During field experiments, data is recorded on magnetic tapes. The format of recording has been described in earlier reports (3, 6). The present system (Fig. 1) must be able to read these tapes, recognizing specific control signals on the tape and demultiplexing multichannel data.

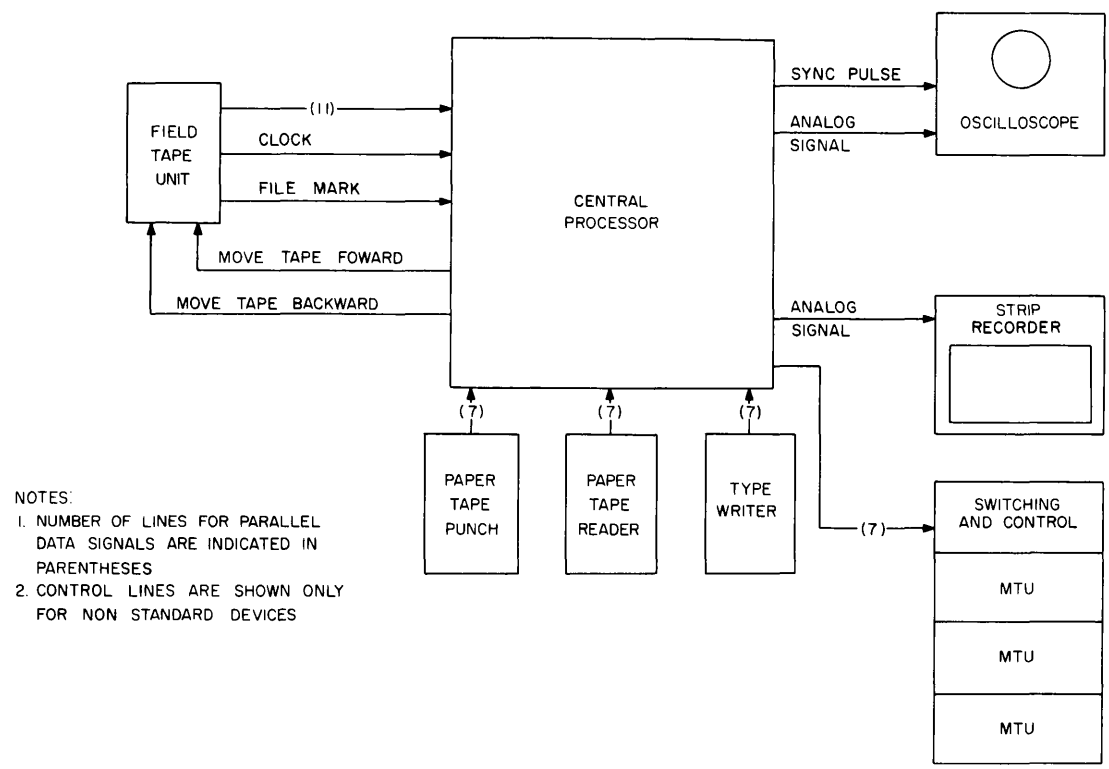


Fig. 1. The signal processing system

A visual inspection of the data at this stage (after reading from field tape to computer memory) is the most effective method of resolving qualitative questions regarding signal adequacy. For example, the usefulness of a signal for detailed analysis depends on both the wave form and amplitude (signal to noise). The simplest form of programmed test for a minimum-amplitude threshold would be insufficient, and more complex programs such as amplitude density determination would be unjustified at this preliminary stage because of the time required. A display of the data held in computer memory on an oscilloscope monitor has proven very effective for a visual editing of the data (5) besides furnishing several other useful functions described in more detail later.

The field tapes serve for permanent storage of data and therefore cannot be used for the recording of computational results from the computer. While they could, of course, be used as prime sources of data during computation, greater flexibility is obtained by

transferring field data to computer tapes prior to computation. After preliminary selection by visual monitor, a selected portion of the signal is transferred from the field tape to IBM-format computer tapes for subsequent use in computation. The time required for this transfer is regained manyfold by the additional flexibility and consequent lessened tape movement achieved with the IBM-compatible tape transports.

The central processing unit is a standard-equipped, stored-program digital computer (7). Besides controlling all special functions, it also performs numerical calculations on the data available from magnetic tape. The principal programs are statistical and include the primary ones of correlation and spectral analyses.

Means for output of the results include the standard computer options of magnetic tape for off-line output, if desired, and on-line typewriter for typeout of answers during computation. A special added option is a strip recorder output which has proven to be particularly effective. For the particular problem, precise values are not needed as much as a knowledge of the overall tendencies in the correlation results (and in some other statistical analyses). The strip recorder output has therefore proven to be a great timesaver (over typeout of results) during machine operation and as a most effective presentation to the person using the computational results. Data can also be output by this means, and the wave form of any signal stored in memory can be presented for examination. The strip recorder and visual monitor, therefore, have complementary functions, since the monitor can be used to display results of computation, if desired. The monitor is normally used for a quick look at the data, the strip recorder for a permanent oscillogram of the results of computation.

The basic requirements of the system consist then of:

- means of reading field tape to computer memory,
- provision for visual inspection of data for preliminary editing,
- means of reading and writing on computer-format magnetic tapes,
- standard digital computer capability of computation by stored program, and
- provision for output in numerical and graphical form.

The methods of implementation of each requirement will be separately discussed.

The input-output programs are concerned with control of equipment to such an extent that they are actually more related to logic design than is the case with strictly computational programs. The hardware (equipment) and software (programs) are thereby so closely interrelated that it is advantageous to describe them together for each transfer or transformation.

DATA-HANDLING FUNCTIONS

Read Field Tape

The field data recording system has been described in a previous report (6). However, a review of the format of recording on field tapes is appropriate, in order to clarify features of the present data handling system. In particular, the fact that data are recorded in essentially continuous records (greatly exceeding the capacity of computer memory) necessitates special control procedures.

The digitized field data consist of ten binary magnitude digits and a sign digit arranged on the magnetic tape, in parallel, by word. A clock signal is recorded in a separate channel with each word (Fig. 2). The clock recording rate is 8 kHz for a tape speed of 30 in./sec, yielding an average bit density of 267 bits per inch.

FUNCTION	TAPE CHANNEL (TRACK)	SAMPLE GROUP (N) MULTIPLEXER CHANNEL NO. 1	2	3	4	5	6	7	8	SAMPLE GROUP (N+1) 1	2	3	4	5	6	7	8
SPARE CHANNEL	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FILE MARK	2									1							
2^0	3	1	1	0	1	0	0	1	0	1	1	0	0	0	1	1	1
2^1	4	0	0	1	1	0	0	0	1	1	1	1	1	0	1	1	0
2^2	5	0	0	0	0	1	1	0	1	0	1	1	0	0	1	0	1
2^3	6	1	1	0	0	1	0	1	1	1	0	0	1	0	1	1	0
2^4	7	1	0	1	1	0	0	0	1	1	0	1	0	1	1	0	0
2^5	8	0	1	0	0	1	0	1	1	1	0	1	1	1	0	0	1
CLOCK	9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2^6	10	1	1	0	1	0	0	1	1	0	1	1	1	0	0	0	1
2^7	11	0	1	0	0	1	1	0	1	0	1	1	0	0	0	1	0
2^8	12	0	0	1	1	0	1	0	0	1	1	0	1	0	1	0	0
2^9	13	0	0	0	1	1	1	0	0	1	0	1	1	0	0	1	0
SIGN	14	1	0	1	1	1	0	0	1	0	0	0	1	1	0	1	1
ODD PARITY	15	0	0	1	0	1	1	1	1	0	1	0	0	0	1	1	0
MARKER	16	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0

Fig. 2 - Field tape format

The words are multiplexed in a serial manner from either four or eight data sources, and a marker signal is recorded in a separate channel with the first word of each cycle of four or eight words.

The long records are subdivided into lengths compatible with computer memory restrictions by recording file marks in an additional channel on the tape. One hundred words for each multiplexed source are recorded between successive file marks. During playback, the file-mark signals occur out of phase with the data clock signal, approximately halfway between two data words. The file marks serve as convenient signals for gating on and off the transfer of data to computer memory and for controlling the start and stop of the tape movement to maintain proper positioning of the tape for successive read operations. The tape must be backed up past one file mark after each read cycle, to avoid skipping any data.

A Potter 906, Mark II tape unit (Fig. 3) is used for reading field tapes into the computer. Control of tape movement, sensing of signals from tape for file selection, and channel demultiplexing are all programmed operations. Delays necessary to allow for start/stop times in tape movements are also programmed.

Reading magnetic tape is, by nature, an asynchronous operation relative to the internal timing of the computer. A device accepting information from tape cannot force a transfer rate, but must comply with a rate imposed by the conditions of recording on the tape itself and of the tape movement. Also, tape start/stop times are generally much greater than the interval between characters (true even for low-density tapes), and provision must be made to ignore the marginal and otherwise doubtful signals which are generated as the tape is brought up to speed or slowed to a stop. Even with this difficulty, it must still be possible to locate a specific section of data and read it reliably.

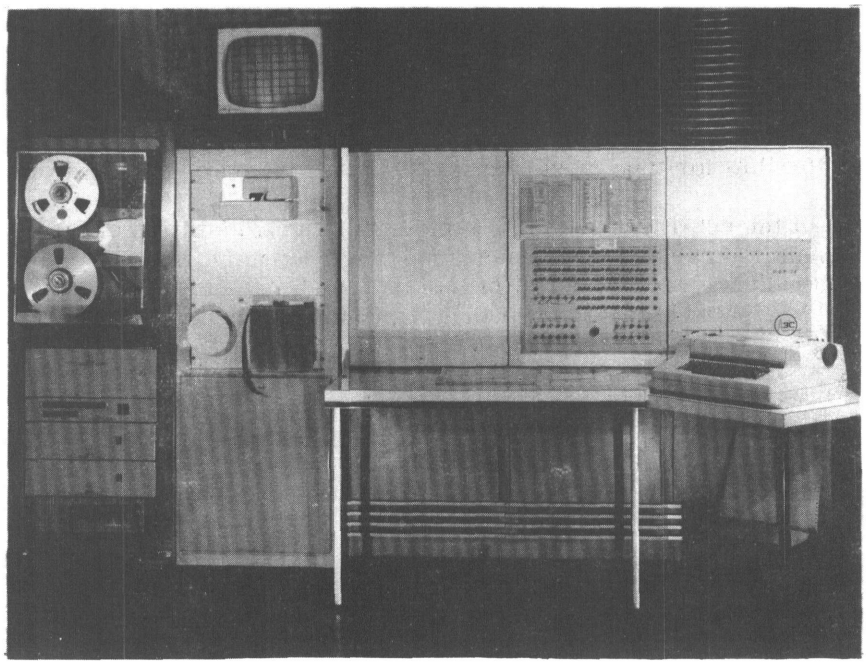


Fig. 3 - Central processor with, left to right, the Potter tape unit, visual monitor, paper tape reader and punch, computer console, and the electric typewriter

The data transfer, therefore, requires close interaction between the peripheral and the central processor, operations within the computer, in general, being allowed upon receipt of controlling signals read from the tape. To close the control loop there must be control signals in both directions between the two devices. The tape-read operation exemplifies a case of cooperation between units rather than one of common control. In the present case the signals used for this two-direction communication are also under direct control of the stored program by means of standard instructions.

Signals sent to the tape transport from the central processor are called output control pulses and are initiated by programmed instructions with an operation mnemonic symbol OCP (8). An additional part of the computer instruction specifies which OCP is generated at any time during a sequence of commands.

An analogous command to receive control signals has the mnemonic SKS referring to a command for sensing a condition. The condition to be sensed is specified also by additional coded digits in the instruction. The SKS command can be used to delay a program until the sensed condition has been satisfied before proceeding to active instructions in the program sequence (8).

In a general sense, the basic functions of the read-field-tape operation are to:

- start the tape movement,
- wait for the normal reading speed to be attained,
- sense the file marks and clock pulses to pinpoint specific data,

- store the desired data in memory,
- stop the tape movement after transferring a specific amount of data, and
- reposition the tape by backing up a sufficient amount ahead of the last file mark passed to allow for tape movement start time in the next reading cycle.

Exclusive of the control essentials, some special consideration of the characteristics of the data signals themselves was necessary. The read amplifiers of the field tape unit, an individual circuit for each of the 11 bits of data (ten magnitude, one sign), have conventional two-level pulse outputs corresponding to the originally recorded binary coded values. The coding is the same as that used in the central processor (absolute magnitude and sign), and no conversion is required before use in computation.

The pulse widths from the tape unit circuits are too short, however, to provide sufficient time for the programmed sensing of control signals requiring discrete increments of time on the order of the data pulse duration for each command repetition and still gate data into the machine with certainty.

The output of each tape data channel is, therefore, gated by the clock signal from tape into a flip-flop storage register (Fig. 4, buffered input channel) where it remains available for transfer by computer program until the next word is read from tape (9). Simple counting of clock pulses allows the computer to demultiplex sequentially by transferring from the buffered input channel into computer memory every nth word, after having determined the first word to be stored by counting clock pulses following a file mark. The file marks are recorded about halfway between two clock pulses, thus allowing for alternate sensing with the assurance that the file mark and clock pulse will not occur simultaneously.

Read Field Tape Subroutine

A generalized flow chart for the Read Field Tape subroutine is shown in Fig. 5. Since the flow chart illustrates the sequence of operations which the program performs, it also serves as a convenient outline for discussion of the functions of the hardware.

The initializing operation, besides the normal "red tape" of clearing or presetting values in memory, used for controlling loops in the program also sets up the commands which determine the data channel selection and demultiplexing interval. The parameters required by the subroutine allow for variation of the first address of the data storage block and the number of files to be read from tape, although in some applications these are constants. This is the case in the program for selection and transcription of data from field tape to IBM-compatible computer tapes.

Before the program start, the operator enters octal-coded numbers into the computer (manually via the A register at the console, Fig. 6), specifying, in order, the number of files to be read, the counting interval of clock pulses for which data are to be stored, and the channel selected. For example, the number 050401 selects channel 1 (first word after a file mark) and calls for storage of every fourth word and a transfer of five files or a total of 500 words for a standard field tape of four-channel multiplex with 100 words in each channel per file.

After initialization, the stored program continues in automatic sequence. First, the buffered input register is selected for input to the computer and a control flip-flop is set to start the tape movement forward. Data transfer must now be synchronized with the known reference point on the tape. A programmed delay first allows sufficient time for

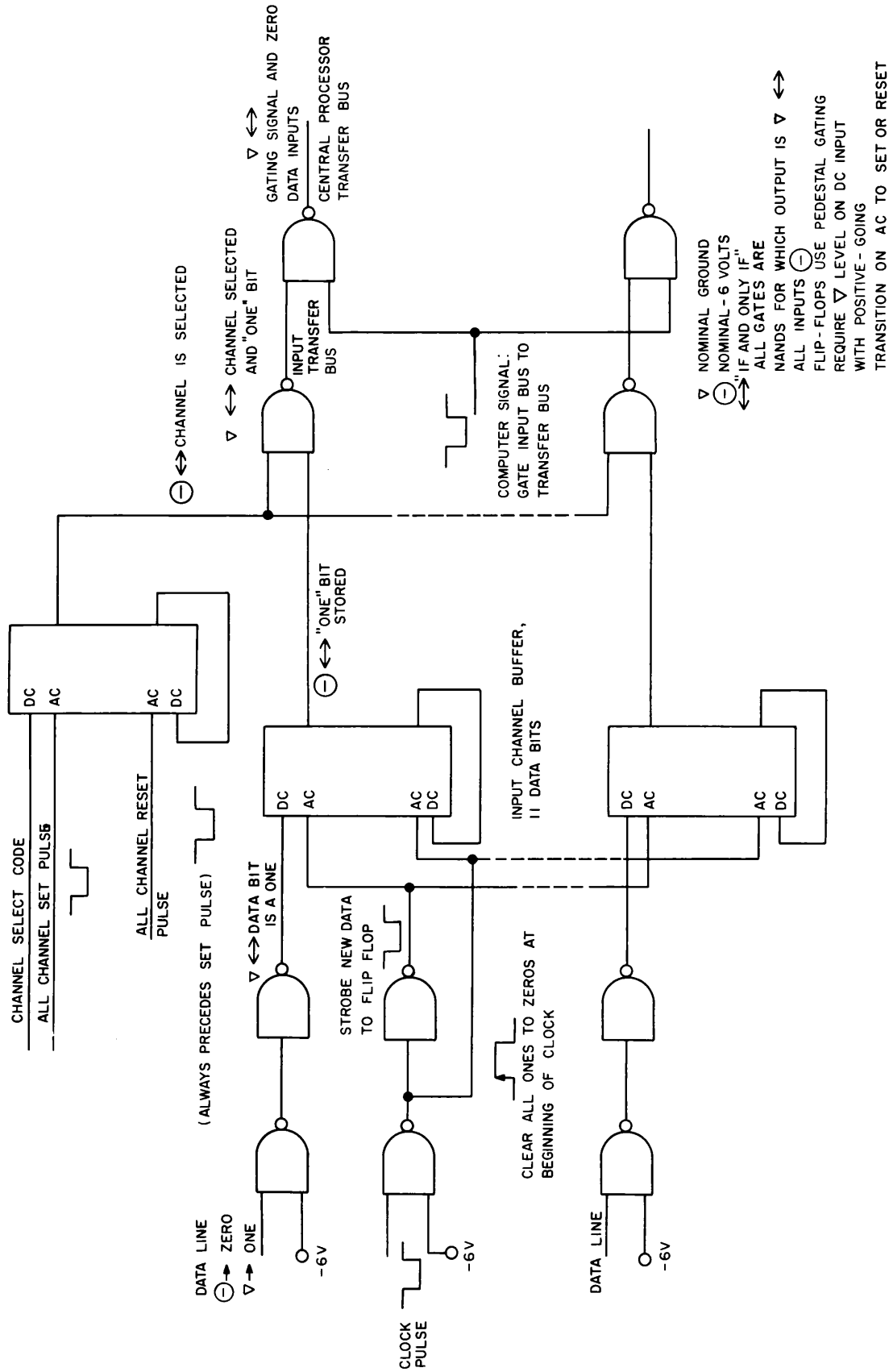


Fig. 4 - Field tape-to-computer interface

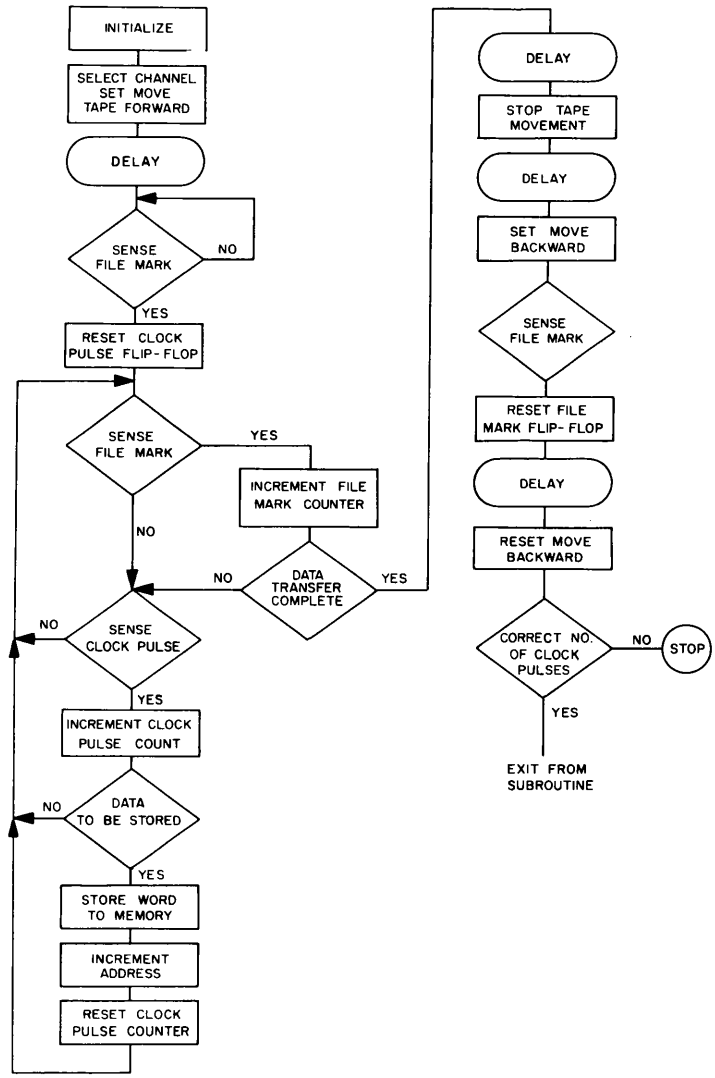


Fig. 5 - Read-field-tape subroutine

tape acceleration to yield a normal velocity for accurate signal sensing. Preparatory positioning of the tape is always such that this speed is readily attained before the next file mark is reached. As a precautionary measure the file-mark sensing flip-flop is reset to allow for possible transients which might occur during the initial movement. The program now waits for the first file mark to be encountered, and, when it is, the desired synchronization will have been accomplished. At this time the clock pulse flip-flop is reset, and the computer program is ready to sense the first clock pulse after the initial file mark and to take appropriate action, depending on the specified channel selection.

The program now alternately tests for clock-pulse and file-mark signals. The time between clock pulses is a nominal 125 μsec, and the separation of file mark and nearest clock pulse is about 60 μsec. This gives sufficient timing offset to allow for sensing the pulses sequentially rather than simultaneously. An additional timing margin is provided in that each signal sets a flip-flop which is reset when sensed by the SKS command in the

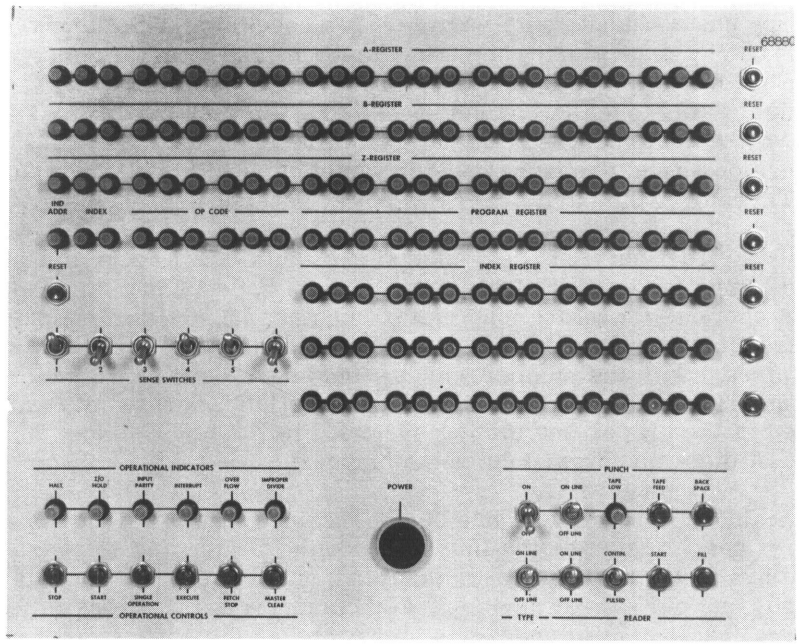


Fig. 6 - Central processor control and the indicator panel

program. There is assurance, therefore, that no signals will be missed through timing variations.

A data word is transferred from the buffer register to memory storage whenever the clock pulse associated with the specified channel is sensed. Getting in step after the initial file mark requires having received and counted the nth clock pulse, which at this time will also correspond to the nth channel of the tape format previously described. After a word is stored in memory, the storage address counter is incremented and the clock pulse counter is reset. Counting clock pulses up to the desired multiplexing interval conditions the data transfer to memory, once the desired channel has been located.

Whenever a file mark is encountered, the program will sense this fact and make a tally. The tallied value is compared with the stored value specifying the number of files to be read, and the conditional program transfer is made to continue or to stop read, depending on the result of the comparison.

When the file mark has been read to terminate data transfer, tape movement is stopped. A programmed delay is generated to allow for deceleration time, and the move-backward control flip-flop is then set. The program senses for the file mark indication in order to position the tape a proper distance ahead of the one which terminated the reading operation. A specific programmed delay is generated as soon as the file mark is sensed, and tape movement is then stopped. The delay was determined such that, upon the next start of the read operation, this same file mark will serve as the synchronizing reference mark for data transfer, as just described. The procedure accomplishes a block transfer from a continuous data source. For example, when the transfer is made from field tape to computer tapes with IBM-compatible format, the alternate read field tape-write computer tape preserves the continuity of the sampled data from record to record on the gapped computer tape.

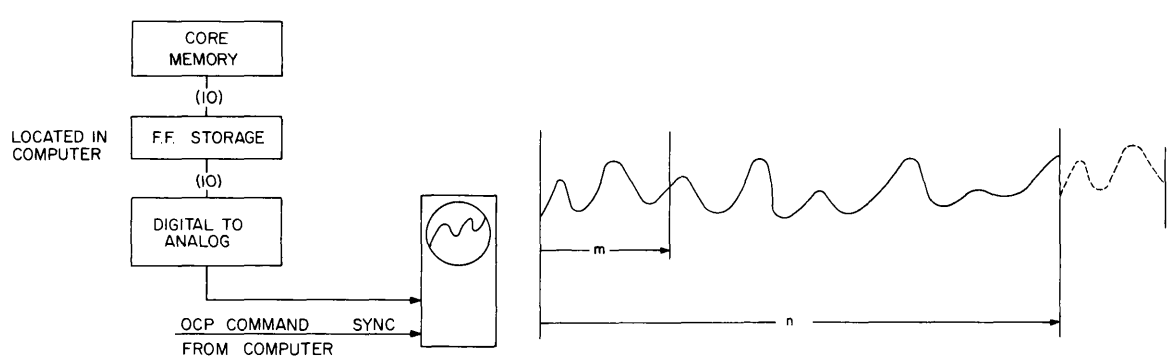
The field tape has a channel with parity bit for checking the validity of individual words. A check can be made during the transfer by means of an "exclusive-or" gating arrangement of hardware for detection of improper combinations, or by a programmed equivalent check of data stored in computer memory. However, because of the normally high reliability of the equipment and the nature of the analysis, only gross errors (e.g., continuous failure of a read amplifier), which would be readily caught, would be of serious consequence. Therefore, the parity check is not at present implemented.

However, it is clear that a serious confusion of data could occur if a single clock pulse is missed, since the demultiplexing, as described, depends on a proper count of clock pulses. A check is therefore made after each read cycle is terminated to compare the total number of clock pulses received during the data transfer (between the specified number of file marks) with the number which should have been on the tape. A complementary check is also made to determine whether the last address into which a data sample is stored is the proper one for the specified initial address and the expected amount of data. A discrepancy will cause an error stop.

The Read Field Tape subroutine has been described in more detail than those which follow, because it best illustrates the interaction of hardware and software and shows the flexibility made available through programmable control and sense signals between the central processor and peripheral devices. For computer applications in which a wide variety of external equipment is used, this approach has the advantage of ready adaptation to varying requirements, to a large extent by simple stored program implementation. The data interface is of course required, but the computer can generate the sequential commands and timing, using its standard complement of instructions as a basis.

Visual Monitor

For the simplest form of visual display, it is necessary only to transfer data in sequence from a part of core memory to a flip-flop storage register, Fig. 7a. The output of the register is connected to a ladder-network type of digital-to-analog converter which sums individual current weights proportional to the significance of each binary one present to generate an analog voltage output corresponding to the digital value (10). A sync pulse for starting the oscilloscope sweep is generated by a programmed OCP command just prior to loading the register with the initial value in the data block. The transfer is continually recycled from the beginning of the data block until the monitor program is stopped by the operator.



(a) Computer to monitor (b) Display by the moving data window

Fig. 7 - Visual monitor

The D/A converter handles digital magnitudes only; therefore, a preliminary data transformation is applied to each value before entry to the flip-flop register. The effect is to change the bipolar values in computer storage (i.e., sign and magnitude) to appropriately scaled positive values; the apparent shift in axis is compensated by positioning of the oscilloscope zero level.

The duration of one sweep is usually adjusted to coincide with the time required for transfer of the entire block of data, although other settings can be used without objectionable flicker.

A long block of data can be examined in more detail by an option in the monitor program which effectively moves the equivalent of a data display window of m values (corresponding to a duration of one scope sweep) progressively through a data block of n values, Fig. 7b. A wraparound is implemented when the nth value has been accessed, and, as with the fixed display version, the monitor continues until the program is stopped by the operator.

A flow chart of this operation is given in Fig. 8. At the end of each sweep, corresponding to the display of m values, the initial address is incremented so that the start of the next sweep will display a value advanced by one address in the data block. Tests are required in the program for the completion of one sweep, wraparound when the nth value is accessed during a sweep, and reinitialization after the nth value has become the first value displayed. These tests are T1, T2, and T3, respectively, of Fig. 8.

An additional program feature has been used with the monitor so that, on alternate sweeps, the data are accessed from entirely different data blocks in the computer memory. The D/A converter is input to a dual sweep oscilloscope, and the result is a display of two different signals arranged for visual comparison. The precessing option applied during the sweep for one data block and not for the other provides a means for determining the amount of shifting required to bring two time samples in phase if they are clearly alike, except for lead or lag in time of the sample. The precessing option is under direct manual control by means of a toggle switch on the console, and a tally is maintained of the number of addresses through which the display window moves while the option is active. When the switch is turned off, the display remains fixed at the new position. If the signals are visibly alike, the lag or lead can be readily determined to the nearest sample. It has been determined through use of this visual comparison that signals which have been degraded by doppler may be obviously alike otherwise (general shape of envelope is identical) even though the results of the correlation computation give results below the threshold for likelihood of a common signal.

Computer Tape Preparation

As previously mentioned, transfer of data from the field tape to the computer tape before computation has advantages over the use of field tape as a direct source of input for analysis. The principal reasons are the more ready access to specific data provided by the multiple tape units, Fig. 9, and the pre-editing that can be accomplished by visual selection of data during the reformatting process.

A basic program for the data processing system, therefore, provides means for data selection and transfer. A block diagram, Fig. 10, is helpful to the computer operator for determining what options are available. This can also serve as a guide in a description of a typical procedure. Conditional transfers controlling the program sequence are indicated by triangular blocks. Manual toggle switches on the computer console (Fig. 6) provide optional paths to be set by the operator as desired at any particular time. Conditions of the so-called "sense switches" are interpreted by commands at strategic points in the program.

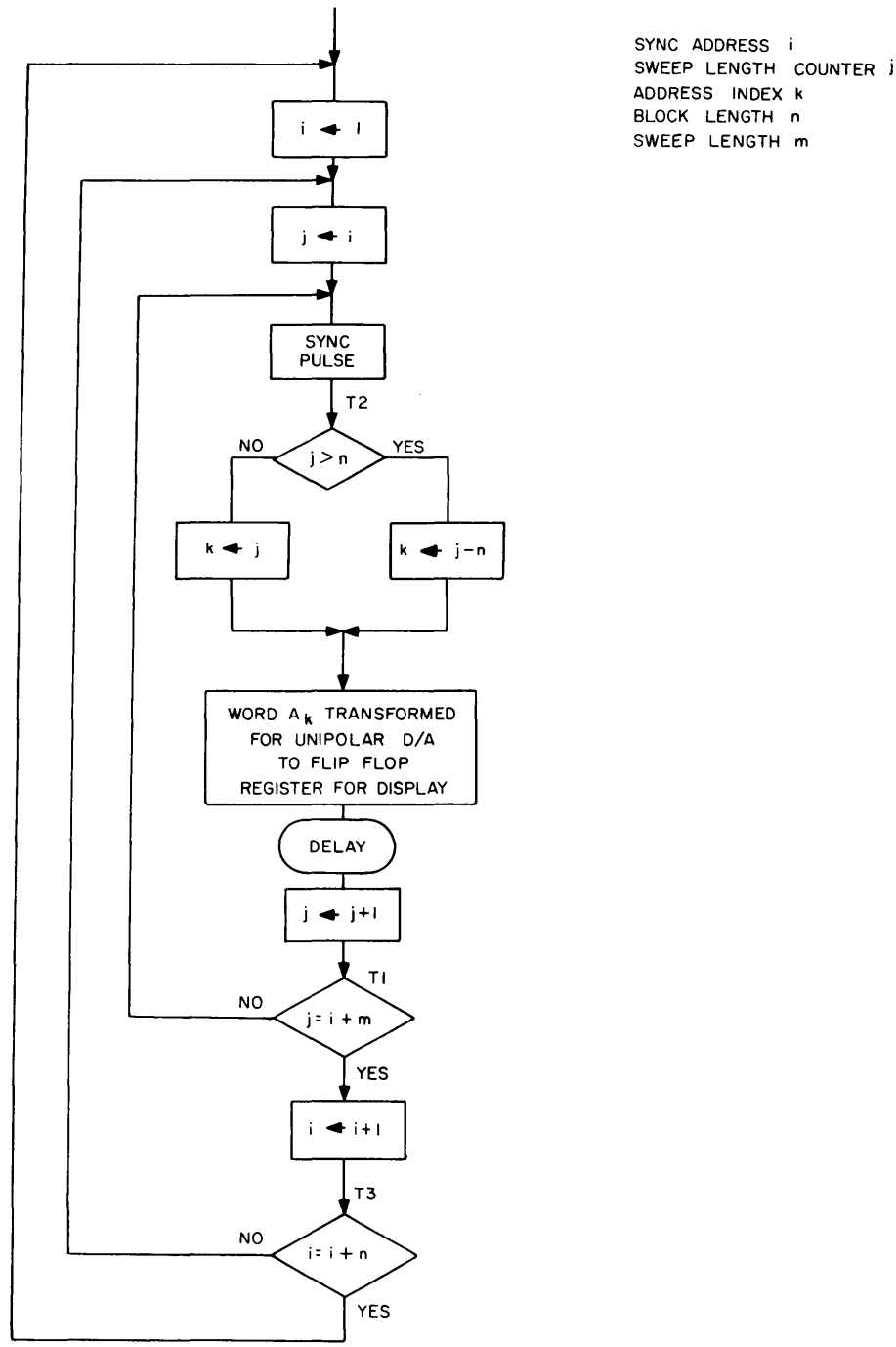


Fig. 8 - Visual monitor subroutine

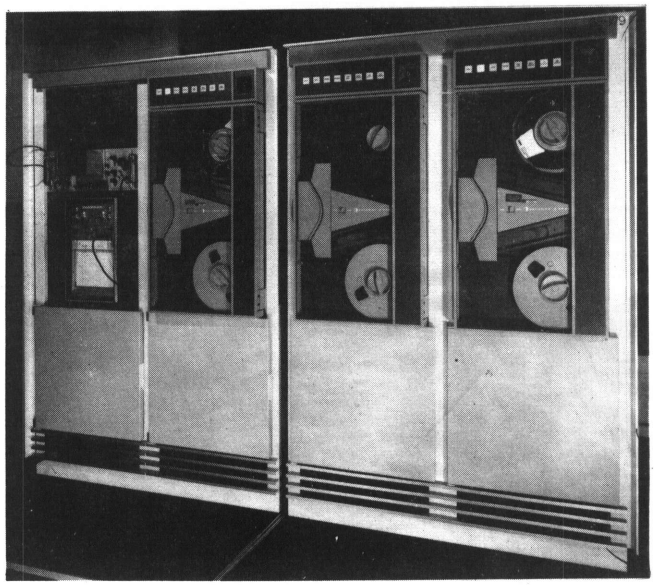


Fig. 9 - Memoscope, strip chart recorder, and the IBM-compatible magnetic tape units

Data for formatting is located by use of the visual monitor. The operator may desire to take some exploratory looks at the data before deciding what to copy onto computer tape for computation later.

Reference to Fig. 10 shows that data will be read and then displayed on the oscilloscope if no switches are set. Before starting the program, the operator positions all the toggle switches off and enters the demultiplexing control word into the register by pushbuttons on the computer console. The details of encoding this control word have been already described as part of the Read Field Tape subroutine.

Five files of data or 500 computer words supplies a reasonable length block for display purposes. After the read cycle the program immediately goes to the display loop and continues showing the signal on the oscilloscope until the operator intervenes. Through controls on the console and short control routines, he can move the tape backward or forward a specified number of files or simply read in the next sequential data for display. The tape must be stopped during the display because of programming necessity. However, a continuous read and display of data is not feasible anyway, because the transfer rate is too high for anything but the most cursory viewing.

Exploratory viewing of different channels may be desirable, and changing the selected channel requires only that the initializing constant be changed before the start of the read cycle. If the register is left blank, the previously used selection is repeated.

A flow chart of the Visual Monitor subroutine is shown in Fig. 8. A sync pulse for the oscilloscope is generated at the start of each pass through the data by means of a standard OCP command. Each word in the data block is effectively transferred in sequence from memory to a flip-flop register feeding a D/A converter. During transfer, a conversion is made from absolute value and sign of the computer internal storage into a single polarity representation for the resistance-ladder type converter. Six bits of precision are sufficient for this view of the data.

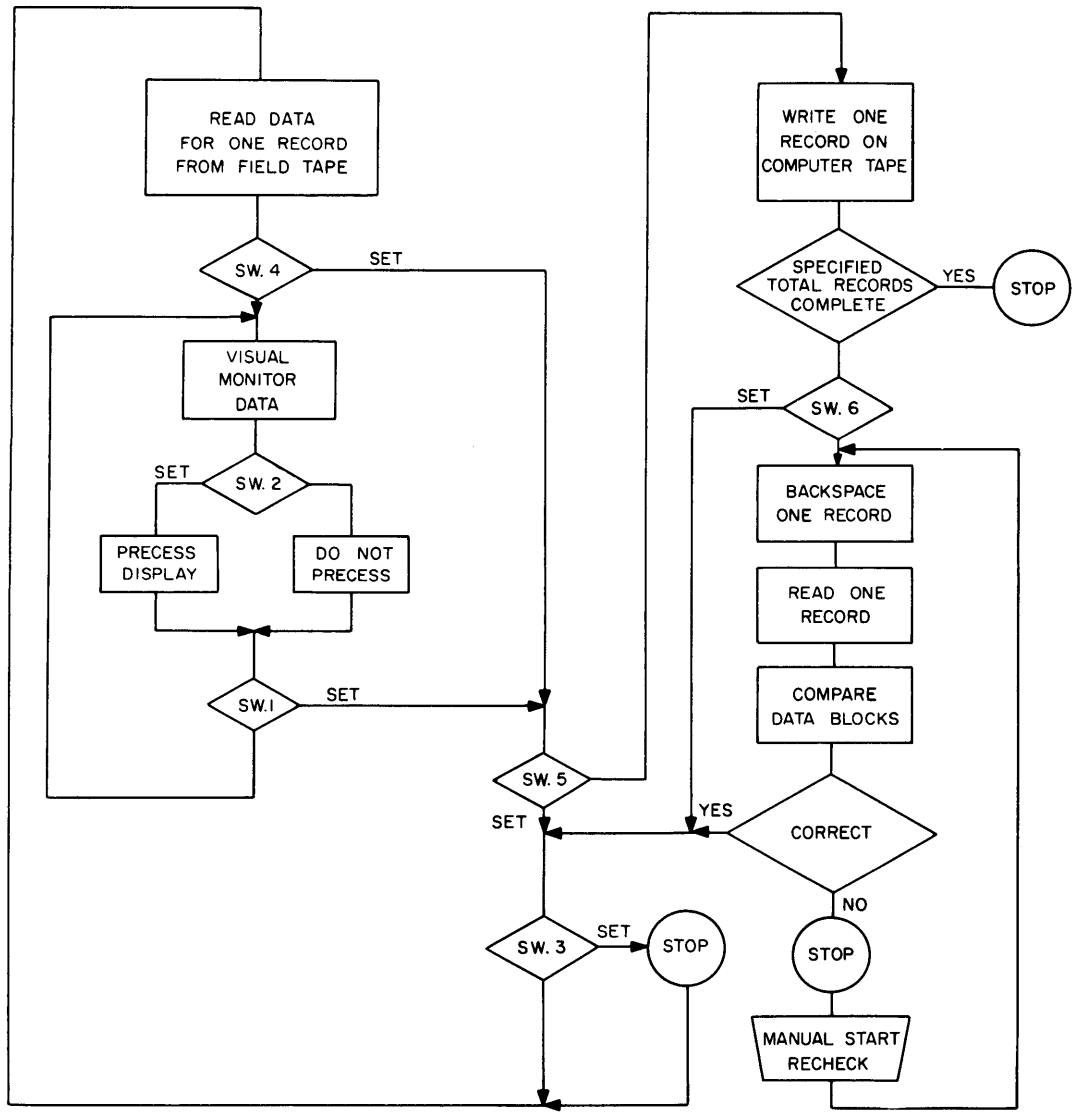


Fig. 10 - Computer tape preparation program

The generation of a sync pulse for the oscilloscope allows freedom in the adjustment of the sweep length to show a part or all of the data. With a fixed time relative to readout from addresses in the data block, a short-duration sweep would give the enlarged view of only the initial part of the data. An option is therefore available, controlled at will by a toggle switch setting, to change the sync timing while the data are being displayed. This has the effect of slowly precessing the viewed portion through the data block, thereby presenting a magnified view of any part desired. Transfers and settling times are fast enough that there is no objectionable flicker, even though, in this mode of operation, there is an interval between sweeps dependent on the ratio of the total data block length to the length of that displayed, since only one sync pulse occurs for the total length.

After preliminary examination of the data the operator is ready to transfer selected portions to the computer tape. A running tally is always available of the number of file

marks passed from the start of the tape, so that data coincident in sampling time on each channel can always be located if desired. The basic procedure is to locate a portion of tape of interest for all channels and transcribe a definite number of samples for each channel in turn, relocating the reference point on tape by means of the file mark counting. As a double check, a signal of one data channel is preserved on the memoscope (Fig. 9) for a visual verification of the relocation, whenever desired. A reference block could be stored in memory also and verified by computer after the reread cycle, but this has not been a necessary expedient. Automation to this extent has not been stressed in this program because of the emphasis on the necessity of judgment by the operator. Too much prearranged sequencing would be more detrimental to smooth and accurate operation. The visual characteristics of the data may frequently suggest to the operator such a variety of consequent choices of action that the less sophisticated programmed sequencing, in the broad sense, turns out to be the most effective in practice.

When data suitable for analysis have been located, through use of the visual monitor, transcription from field tape to computer tape can begin. The operator stops the program in the display loop and manually enters at the console, into a particular address in memory, the number of records to be written. This control number is compared at the end of each write cycle with a tally of the records completed, for automatic termination of the data transfer.

The toggle switches are now set in accordance with the block diagram (Fig. 10) to select an alternate Read Field Tape-Write Computer Tape sequence, and the program is started at the address beginning the Write One Record subroutine. The sequence will repeat without interruption until the specified number of records has been written.

Field data have been read in multiples of hundred-word groups and are, therefore, most conveniently transcribed in a similar manner. A fixed record length is suitable for purposes of the computations to follow. The record length of 500 words gives a good match to the efficiency of data transfers and other requirements of programs, for example, block lengths chosen for correlation analysis. For certain particular cases requiring different record lengths compatible with the period of signals, data are more readily recopied from the computer tapes to computer tapes of different record lengths than handled directly from field tapes in other than multiples of 100 words.

Figure 10 shows an optional loop for verifying that tapes are an exact copy of the data in the computer memory. The Backspace One Record and Read operations store data from the record just completed into a separate part of memory, and a word-by-word comparison with the original memory block is performed. Any discrepancy causes a program halt. A manual restart at this point will cause a repeat of the check, since a read error may occasionally be caused by a temporary condition. Here again, automatic repetition for a certain number of trials of the check, if an error is detected, is not included, because of the large number of possible alternative corrective actions which may be used. Generally, unless errors occur on the check of a few records, this test is bypassed by setting switch 6, the option indicated on the block diagram. The write operation includes a parity check of the correctness of the longitudinal parity.

After the specified records are completed, the operator manually executes a command which writes a file mark on the computer tape. Separating groups of records by file marks expedites the future location of a specific data block, since standard computer commands include skip a File or Backspace a File. Use of these commands enables positioning the tape at any file, which in our case corresponds to some specific channel of field tape. The file marks written on computer tapes are standard IBM codes consistent with common terminology. The term file mark for one of the signal tracks of our field tape was chosen before joint use with IBM-compatible tapes was foreseen. The previously detailed description of the function of the field tape file mark should prevent any serious confusion of meaning.

Formatting computer tapes in the manner just described produces sequential records from one sampled data channel of the field tape. Although there are record gaps on the tape, taken together the records constitute a discrete representation of a continuous signal over the period of time consistent with the number of records and the sampling rate used in the field equipment. The total records between successive file marks on computer tape is usually referred to as a file, and in our case each file is the digitized sample of a continuous signal.

Generally, we are interested in statistical analyses concerned with more than one signal recorded in the field concurrently. Therefore, adjacent files on the computer tape will usually be of closely related data, for example, recordings made at different locations of a common dominant signal source. The multiplexed channels of data on the field tape have this type of relationship, frequently consisting, for example, of a signal received simultaneously on widely spaced transducers.

Transfer to successive files of the computer tape of signals which were originally received at the same time is very readily implemented by returning to the same reference file mark and demultiplexing a different channel for copying to the computer tape format. The Read Field Tape subroutine maintains a running tally of file marks passed during the copying cycle. A short program loop is available for backing up (or moving forward) a specified number of file marks. Using the running tally the operator can therefore reposition the tape at any time and select channels of data from the field tape for observation or for transfer, as desired.

A normal procedure is to copy a specified number of records of data to computer tape from the same part of the field tape for each of the multiplexed channels, thereby producing successive files of data corresponding to the same time sample for each channel. Identification of files on tape is at present entirely manual, only data being recorded on the tape. The normal operating procedures for computation have not required encoded identification on the computer tape, although if a need arises such information can be included. The type of analysis programs being run require a maximum use of storage for data, and programmed steps are therefore kept to bare essentials.

COMPUTATIONAL PROGRAMS

Correlation

The following descriptions of computational programs are presented as typical examples of the primary applications of the system to the analysis of experimental data. Emphasis will be on the operational procedures and input-output options rather than details of the mathematical computations.

The most frequently used program is that for the correlation of two data samples (11). The digital computations are performed on time-sampled data and are therefore represented by the discrete form of the correlation equation:

$$r_{xy} = \frac{\left[\frac{1}{N}\sum_{i=1}^{N} x_i y_{i+\tau}\right] - \overline{X}\,\overline{Y}}{\sqrt{\left[\overline{X}^2 - (\overline{X})^2\right]\left[\overline{Y}^2 - (\overline{Y})^2\right]}} .$$

The symbols are defined as follows:

r_{xy} = correlation coefficient between variates x and y,

N = total number of samples,

x_i = the ith sample,

τ = lag between samples,

$\overline{X}, \overline{Y}$ = average of the N samples, and

$\overline{X}^2, \overline{Y}^2$ = mean square of N samples.

The crosscorrelation coefficient r_{xy} is normalized to a maximum range of ±1. For the case in which the x and y are the same data samples, the computation generates the autocorrelation function as the value of τ varies. For the case of data with zero mean values, the equation simplifies to

$$r_{xy} = \frac{\frac{1}{N} \sum_{i=1}^{N} x_i y_{i+\tau}}{\sqrt{\overline{X}^2 \, \overline{Y}^2}}$$

Even though the assumption of zero mean is essentially true for most of our data, the program as written provides for the nonzero mean case. Figure 11 shows the order of the various operations in the routine. The partial results at intermediate stages are stored in computer memory at locations represented by the symbolic addresses.

The application of this program to the detection of a known signal in different time samples and at unknown relative time lags requires that the time lags introduced into the computation be relatively large compared to the sample length. In fact, lags frequently exceed the sample length possibly held in computer memory. Usage of the program is different in this respect from the standard case in which lags are kept to a small fraction of the sample (11). However, the signal to be detected is, in general, periodic, and in certain cases the reference data sample represents exactly one period.

The arrangement of the program with regard to input-output options is outlined in Fig. 12. For this illustration, the magnetic tape record lengths are assumed to be 500 words (data samples), although the record lengths can be varied to better match the x and y bloc lengths to periodicities of certain signals. The limitation is, of course, total memory capacity, but for some special cases within that restriction the reference bloc length can be made to be one period of the sample signal.

The magnetic tape input is formatted, as previously described, on one tape reel (with the possible exception of the reference signal) with some number of records of each data sample, each set of tape records representing a continuous signal and terminated by an end-of-file mark. Sense switch options in the program provide intermediate stopping points to allow for initial selection of signals, particuarly with regard to the data placed in the x bloc or reference signal. It frequently happens that one reference signal, which could, for example, be an essentially noise-free signal generated in the laboratory, will be correlated against recorded data from different sources arranged in successive files on a data tape. The procedure for this situation will be outlined briefly.

The initial manual inputs, as indicated in Fig. 12, specify the number of records from each file to be correlated with the reference signal and the number of values to be typed out in the vicinity of the maximum coefficient for each record. After this initialization the reference signal is read into the x bloc of core memory storage with switch 6 set to stop on completion of this step. At this time a different tape mechanism can be selected, if desired, or as for the early system with only one tape transport, the tape reel could be changed.

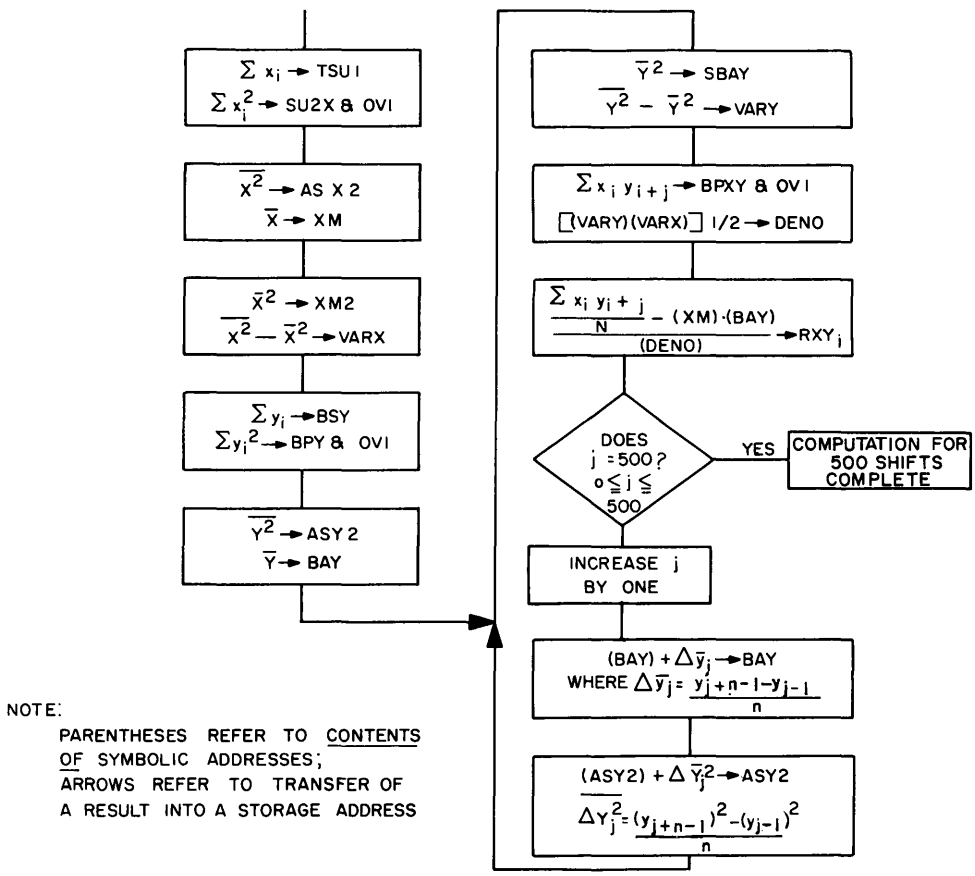


Fig. 11 - General sequence of the correlation computation

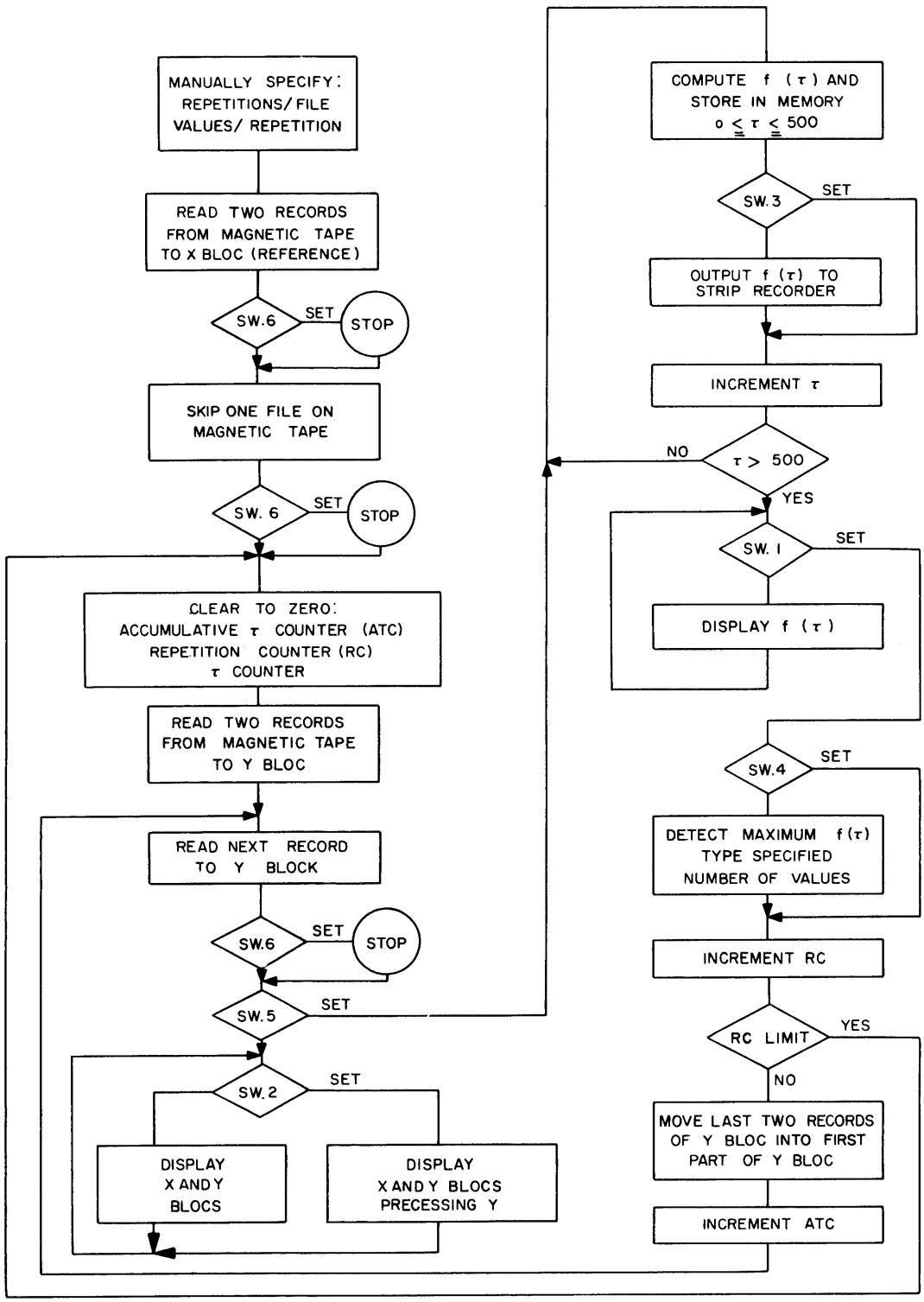


Fig. 12 - Correlation program

The program which reads three records into the y bloc is then started. Several options are available at this stage, and these are selected by the sense-switch toggle controls on the console. If a visual check of the data is desired, the two blocks of data can be observed with the visual monitor (previously described), with the additional option of moving the longer data bloc relative to the reference through the precessing option. Generally, the visual monitor is used only in the preliminary stages of an analysis.

The correlation program computes and stores the correlation coefficients in the memory addresses made available in the y bloc as the time lags are introduced. The total x bloc is crosscorrelated with an equal-length sample of the y bloc, and the equivalent of a time shift is obtained by using a more advanced portion of the y bloc for each τ step. During computation the result for each lag can also be transferred into the buffer register supplying the strip recorder, thereby furnishing a direct graphical output. For this use, the recorder is started manually and allowed to run continuously. Possible variations in computing time for each lagged product are less than 0.1%. After 500 lags have been completed the results can be displayed on the oscilloscope, if desired. This option, like that for displaying data blocs, is generally used only in preliminary stages as a quick-look option.

Whenever quantitative comparisons are important, the typeout option becomes useful. The program first detects the maximum correlation coefficient and then types as many values as originally specified along with the associated value of τ for each. The typeout is arranged to be symmetrical about the maximum; i.e., results are chosen an equal number of shifts below and above that for the maximum coefficient to achieve the total specified. If the maximum happens to be near either end of the 501 values stored in memory for a given set of three tape records in the y bloc, the number of values typed out is appropriately reduced.

Upon completion of typeout, a test is made to determine if the repetitions, as specified initially, have been completed. The repetition counter is seen (Fig. 12) to count the number of multiples of 500 shifts which will be accomplished for a particular file of y bloc data.

The x bloc is correlated with a continuation of the sampled y data by repeated accesses to the magnetic tape. The block diagram indicates the method of moving data forward in memory, discarding the earliest record in preparation for bringing in a new record from tape. The "increment ATC" refers to the increase by 500 of the "constant" used for generating the τ values during typeout. The first value of the correlation coefficient computed for a file of data is for τ equals zero, and this is the reference for succeeding values within the file. Movement of another file of data is preceded by reinitialization of this "accumulative τ counter."

After completion of the final typeout cycle for any one signal (tape file), the program automatically reinitializes control words in memory, as necessary, such as the counters indicated on the diagram. The reference data in the x bloc remain intact throughout the computation until deliberately changed by the operator, and, with the data arranged on the tape in files as previously described, it is necessary only to move forward on the tape past the end-of-file mark to restart the entire procedure for the next signal in sequence. Note that the manual entries need be made only once, unless they are to be changed.

In continuous or unattended operations, a sequence is used which bypasses the monitor options. In practically all cases the strip recorder is the primary output medium, with complementary typeout also being used in some cases.

The diagram does not show a final stop (unless by operator intervention), and this is the actual case in the program. However, the standard procedure in formatting the input

tapes is to put two end-of-file marks in succession after the last file of data. If the machine happens to be unattended at the time the last file is completed, reading the second file mark instead of the expected data record causes a stall, because of an incomplete read-tape operation (an input-output hold) the equivalent of a programmed halt.

The following brief discussions of programs are included to illustrate typical applications of the system to the standard methods of signal analysis (12). Although various combinations of related routines have been made, memory limitations have prevented the compilation of a comprehensive single program. However, any particular segment can be read into computer memory readily, when needed. The separation of routines, therefore, does not cause excessive difficulties in the relatively small organization where the experimenter may also be the operator of the equipment, although efficiency is reduced.

Amplitude Density

First-order probability distributions of digitized data are determined by the relative frequency of occurrence of each discrete value. The algorithm for establishing the function used in this program is that of counting the number of times a value occurs by incrementing the contents of the memory cell selected by the value itself (plus a constant to position the results in a desired portion of the computer memory) (13, 14). Each time a tally is made, the incremented word is compared with a limiting constant, chosen in this case to be full scale on the strip recorder output. When the limit is reached, the contents of the memory block included in the total range of digital values represent the amplitude distribution and are ready for output on the strip recorder.

Data of ten bits and sign are supplied from magnetic tape. This word length, corresponding to a range of ±1023, requires a block of 2047 addresses in memory for the counting process.

Although, generally, a large data sample is available from tape, provision is made for manual adjustments at the start of the program, if desirable, to compensate for short records and still obtain at least a gross indication of the amplitude distribution. A constant (BIAS) can be initially added to the contents of all tally addresses; the increment (TINC), added for each occurrence of a value, can be varied, or fewer significant digits may be used by specifying the number of places for right-shifting each data word before use. The latter option, of course, reduces the extent of the count in memory and results in larger steps or intervals between values on the distribution curve. Provision is made for observing the results on the oscilloscope monitor, and this option can be selected by a switch setting before the tally is completed.

Power Spectrum

The power spectrum program is separate from the correlation routine, chiefly because of memory capacity limitations, since maintaining a large data sample is important in both of these computations. The conventional method of analysis (11) employing a cosine transform of the autocorrelation function is used, but the correlation routine is stripped to the bare essentials and arranged somewhat differently than the previously described version.

The standard rule for the number of lags for the autocorrelation equal to 1/10 of the total data sample has been applied. The number of cross products is also reduced for each shift. The entire 2500 data samples allow 250 summations of lagged products. Because the autocorrelation is an even function, only cosine terms are required in the transform to obtain the power spectrum. Smoothing is accomplished after the transformation by the Hamming method of replacing the computed amplitude for a specific

frequency with 0.54 times this amplitude plus 0.23 times the computed amplitudes at the frequencies lying $\pm\Delta f$ from the given frequency. Results are normalized to a maximum value of one and are typed out.

A provision is made for averaging the independent results of any specified number of cases (multiples of 2500 samples). Data are supplied from magnetic tape, and a large number of cases could be averaged in this way. Use of the program has shown that about eight runs give smooth results. A discussion of the various subtleties of the confidence to be placed in the results cannot be adequately considered in this report. The best that can be said is that the averaging of several cases as described has given good results based on empirical tests with known data.

A program has also been written using the so-called Fast Fourier Transform algorithm for computation of power spectra. Although memory limitations restrict the sample length to 1024 words, results have been very promising. The computation time speedup is about 60 to 1 for comparable data samples.

Miscellaneous

Besides the application of the system to the computational programs already described, it has utility in transformations of information between different codes or storage mediums. This type of usage is so varied and dependent on changing needs that the following are chosen as only examples from many possible cases.

If a graphical display of a data sample is desired, the digital information can be readily transferred from magnetic tape to a static representation, using the strip recorder. This obvious procedure actually has considerable utility, since it enables a close examination of long strings of data and can reveal peculiarities which have a relationship to the computational results.

The system has frequently served as a go-between in the preparation of experimental data for input to larger digital computers. Our field tapes are not in a form suitable for direct input to the average computer. However, the IBM-format magnetic tapes are an essentially standardized medium of input to most makes of computer. Regardless of the word lengths or other coding features of the internal data words, tapes suitable as a direct input to machines using IBM-compatible tape systems can be readily prepared.

An interesting subroutine which was developed for experimenting with pseudorandom sequences uses the recursive function which has had long standing application to the generation of pseudorandom noise signals (15, 16). The general hardware implementation determines the next input to an extreme position of a shift register when the entire contents of the register are shifted away from that position, based on the "exclusive-or" combination of the present conditions at selected positions of the shift register. The program directly simulates the procedure of the well-known technique.

Initial manual inputs to the programs specify the shift register length and the "taps" selected for determining the next input state. The typeout is the series of zeros and ones which comprise the pseudorandom sequence. The typeout terminates after one period of the sequence has been completed.

Not all taps produce a maximum-length sequence. The maximum length possible for any given number of bit positions in the shift register consists of all possible combinations of zeros and ones in the register minus the case excluded for this particular gating arrangement, that of all zeros. The program can test a specified tap selection by generating a sequence as described while simultaneously counting the number of states and, with the known maximum available $(2^n - 1)$ as a reference, checking for one of the three

possible cases: "not maximum length," "maximum length," or "repeating without terminating." The last case, of course, means that a repetitive cycle is being generated which does not include the all-one condition used for terminating the programmed loop.*

Pseudorandom sequences of ones and zeros generated in this way have been used to prepare tapes for use in checking out specific computational programs. In these cases a positive or negative word of some specific magnitude replaces each one or zero in the sequence, respectively.

A subroutine which has been used effectively with the correlation program for an output option determines the approximate envelope of the correlation coefficients taken as an effective time series. The raw results are known to oscillate very much like an amplitude-modulated sine wave of frequency equal to the center frequency of the filter used in collecting our particular data. The smoothing is based on the assumption that each adjacent pair of computed values is separated by an essentially constant interval of time commensurate with the known center frequency and sampling rate. For each correlation coefficient a value is determined for strip recorder output corresponding to the maximum value of a sine waveform consistent with the condition that the currently computed coefficient and that for the previous lag be on a continuous sine wave with the prescribed angular separation. The results of this procedure produce a quite adequate envelope of the raw results for the qualitative observation desired, even though the assumptions can obviously give only an approximation.

RESULTS

The DDP-24 computer was put into operation for the development of programs about the middle of December 1964. Furnished with the machine was a comprehensive set of programming aids including diagnostic routines, tracers, standard subroutines and compilers. The principal programming systems are a Fortran II compiler and a symbolic language assembly program (DAP). The DAP package includes a library of standard subroutines covering the most frequently used functions. Because of our specialized programming requirements, in particular, the need of only a limited number of routines plus the critical premium placed on storage space in memory for data, the DAP has been used for all the major programs used with the system (17).

Most of the hardware and software currently in use were developed during the first half of 1965. Programs are, however, continually being modified, particularly in the area of input-output, to improve the efficiency or the readiness of access to computational results. Modifications to hardware are also made as particular needs are encountered. The stored program capabilities with regard to input-output enable great flexibility in adapting to the new requirements as they arise during progressive stages of data analyses. However, the basic elements of the data transferring routines remain fixed, once established. Different combinations of a subroutine or special code transformations may, of course, be compiled for specific applications.

The initial checkout of the equipment and programs (particularly input-output) was by trial runs on controlled data. For example, tapes were prepared on the field equipment which contained a sequential binary count rather than sampled data for use in testing the routine to read data with the field tape unit. Since extensive planning had gone into that particular subroutine, it was gratifying to have it operate correctly on the first trial after minor adjustments. This initial success with what was considered to be one

*All ones is the initial condition, and the first test for terminating is made after the second state has been set.

of the more difficult operations increased our confidence in the predictability of results with the direct control of external devices by stored program.

The first checkout of the correlation routine was made using computer generated data representing, first, a sampled square wave and, second, a sine wave. A more extensive followup included preliminary formatting from field tape to computer tape, the field equipment being used to prepare sampled data tapes. To empirically determine the effects of extraneous noise and phase shifts on the relative value of correlation coefficients, data were prepared with known amounts of noise added to the signal and, independently, with regulated amounts of simulated doppler. In certain cases the computer memory could hold a full period of the signals being correlated. Other signals, like some of those used in field experiments, exceeded the memory capabilties but were also tested by using a part of the signal correlated against the full period read into memory in sequence from magnetic tape. Correlations were also run in which the number of significant digits of sampled data was reduced.

The program operation using this test data was successful and repeatable in all cases. Qualitatively, the results were predictable on the basis of known information and theory. The accuracy of the numerical procedures had been already verified with the results, using the internally generated data previously mentioned.

Some of the results of computation on the data prepared in the laboratory under controlled conditions furnished useful information in addition to serving as a test of the programs and equipment. In particular, better defined guidelines were established for a choice of preferred signals for detection in the presence of destructive effects of ambient noise, and in establishing a threshold for meaningful correlation coefficients, especially for the case of the reference signal being less than a complete sample of one period of a pseudorandom signal.

A few examples will be given to illustrate how this experiment with data prepared under accurately controlled conditions was applied as a sort of empirical calibration of the program and systems.

1. For a pure sampled signal for which the reference consisted of a full period of the pseudorandom sequence, only a slight change occurred in the discrimination capability of the correlation routine as the data precision was reduced from ten bits and sign to four bits and sign.

2. The effects of doppler cause a rather abrupt deterioration of correlation results as the frequency shift increases (or decreases), and this occurs for less change in frequency as the length of the reference signal is increased.

3. The correlation of a partial sample (about 1/80) of the full period of a signal versus the complete signal from magnetic tape gave an excellent correspondence of maximum correlation at the correct signal period. However, intermediate values always reached a value of at least 0.2 for each 500 shifts and exceeded 0.4 from 15 to 25 of the 164 tape records required for the full signal, depending on which portion was used as the reference.

4. For correlation of a short period signal (total in reference) correlation coefficients exceeded 0.5 at a S/N ratio of -6 dB.

Controlled experiments of the type just mentioned serve as guidelines for evaluation of computations on raw data. The knowledge gained of what to expect from the equipment and computational procedures under specific conditions aids in the interpretation of results when the variables affecting signals are introduced by conditions in the test environment.

The performance of the system, including the DDP 24, has been very reliable. Percentage efficiency based on availability is consistently in the high 90's. Operations of the central processor is checked with a diagnostic routine on a regular basis to assure accuracy of computation. Major malfunctions would generally cause obvious errors, and the diagnostic is a safeguard against more subtle failures of intermittent nature.

The increased speed of the new system over its predecessor has provided a significant reduction of time between collection of experimental data and the availability of computational results. Relative speeds are indicated by the time of 45 sec for computation of correlation coefficients for 500 time lags using a reference signal of 1000 words with the present system, as contrasted with 16.5 hours for 800 lags using an 800-word reference on the earlier machine. The greatly increased speed has also furnished tangible benefits in the improved confidence in interpretation of results, since, for example, lag times up to a full period of a 41-sec-period signal have become feasible.

Outputs from several programs are shown as representative of the capabilities of the system (Appendix A). The strip recorder output has proven to be particularly advantageous for the type of analysis in which qualitative results and trends are of more use than precise numerical values. The strip recorder provides a speed advantage over typeout, for example, since it does not steal any appreciable time from computation, whereas the typewriter holds up normal operation until typing is completed.

This system has greatly enhanced the signal analysis capabilities of the Signal Processing Branch and continued high usage is anticipated. Several additional features have been planned, including, for example, direct input from A/D converter. An enlargement of the memory capacity is desirable to improve resolution in analysis of pseudonoise signals of sequence length such that a full period cannot be stored in the present memory. Experiments are planned for further improvement of input-output options, as, for example, a facility for isometric display on an oscilloscope or plotter.

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Appendix A

EXAMPLES OF OUTPUT

The following illustrations are introduced to show the various forms of output available during editing of data or for presentation of results of computation.

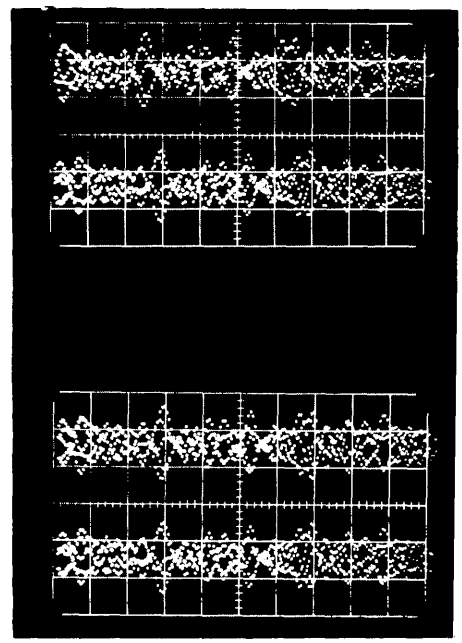

Fig. A1 - Concurrent display of two data blocks on a dual-beam oscilloscope showing the option for a relative time-shift of signals. The lower trace in each block is the same reference signal. The upper block shows different time samples (unaligned) of the same signal, and the lower block shows the upper trace now shifted in time for alignment with the reference.

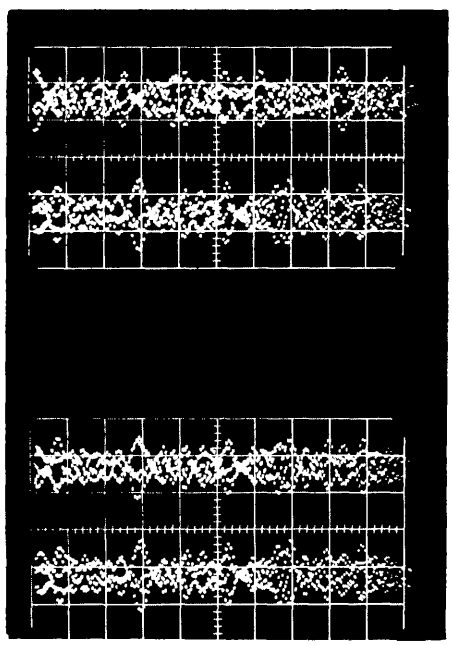

Fig. A2 - Concurrent display showing, in the upper block, the reference signal (lower trace) compared with the same signal (unaligned) with 32 knots of simulated doppler shift and, in the lower block, the dopplered signal shifted for alignment with the reference signal at the center of the screen

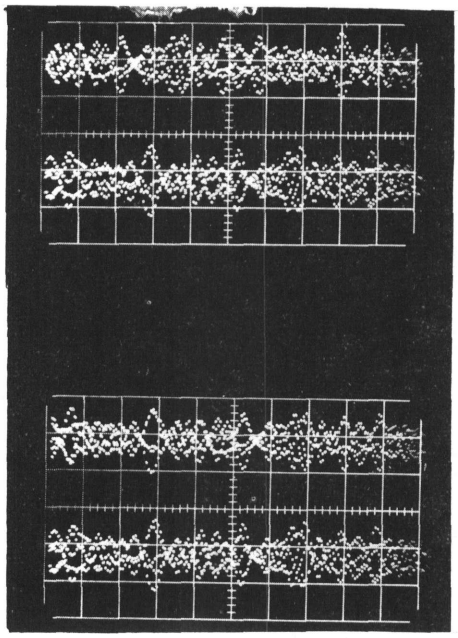

Fig. A3 - Concurrent display showing a similar comparison as in Fig. A2 but with 64 knots of simulated doppler shift

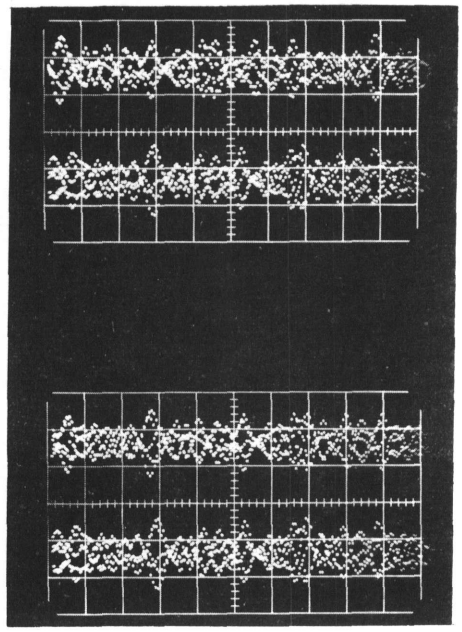

Fig. A4 - Concurrent display showing a similar comparison as in Fig. A2 but with 128 knots of simulated doppler shift

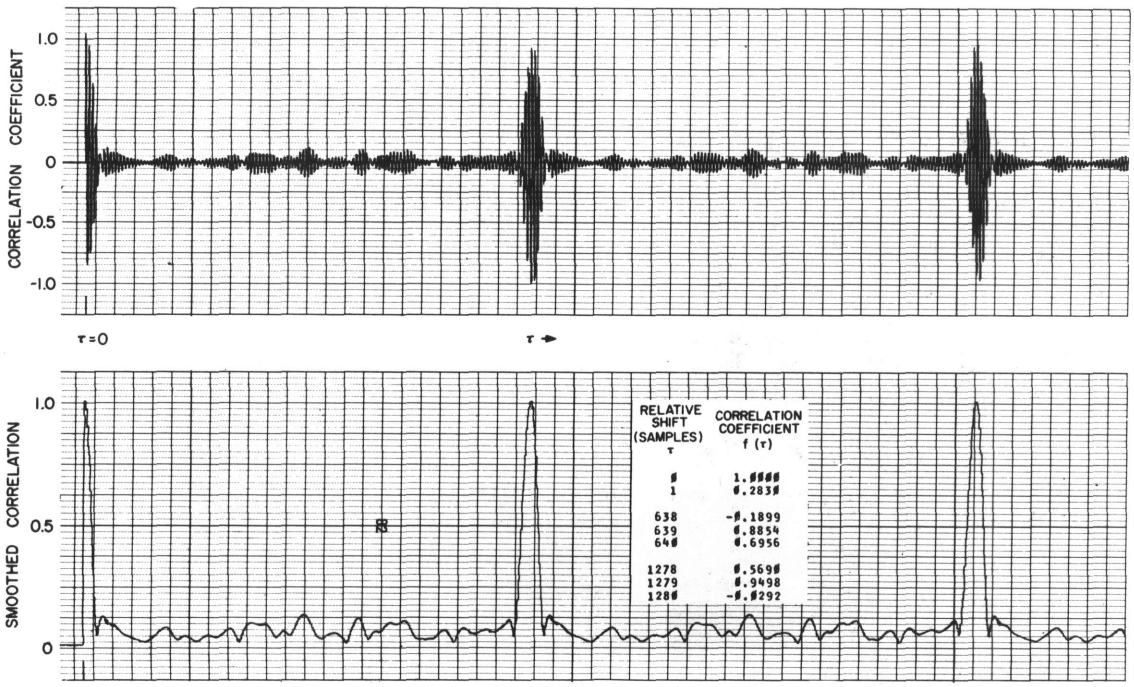

Fig. A5 - Autocorrelation of a sampled pseudorandom noise signal periodic at approximately 640 samples. The lower trace is the smoothed envelope (scaled 2:1) of the raw results.

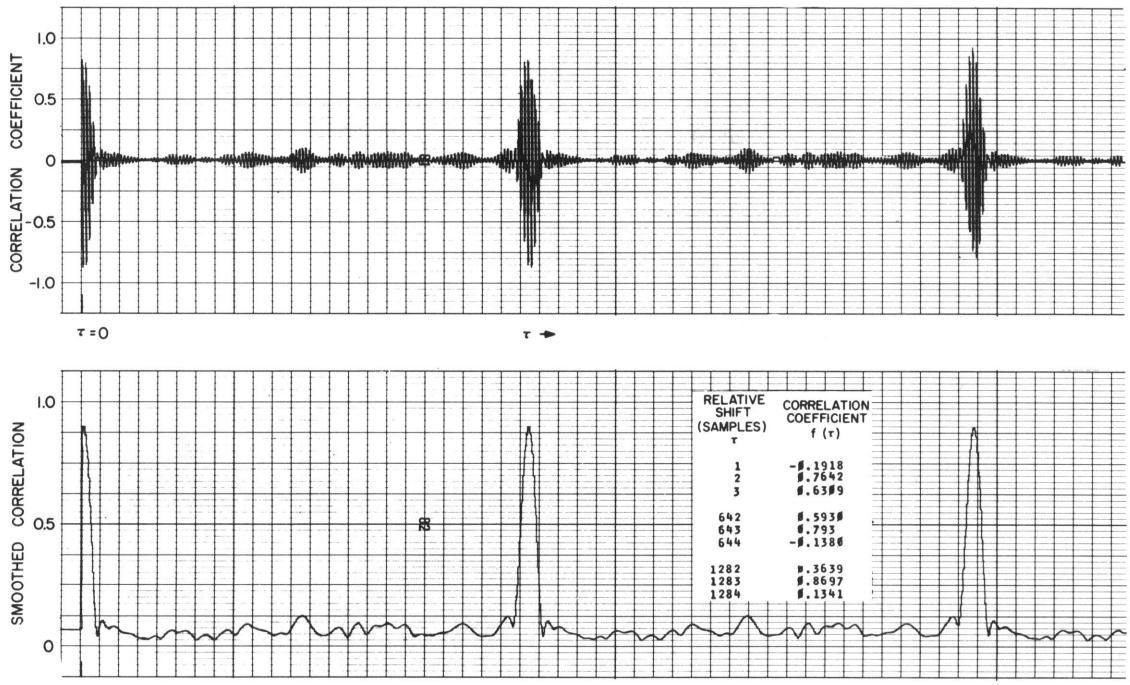

Fig. A6 - The reference signal of Fig. A5 crosscorrelated with a similar signal sampled at a slightly different rate to simulate the effect of 4 knots of doppler shift

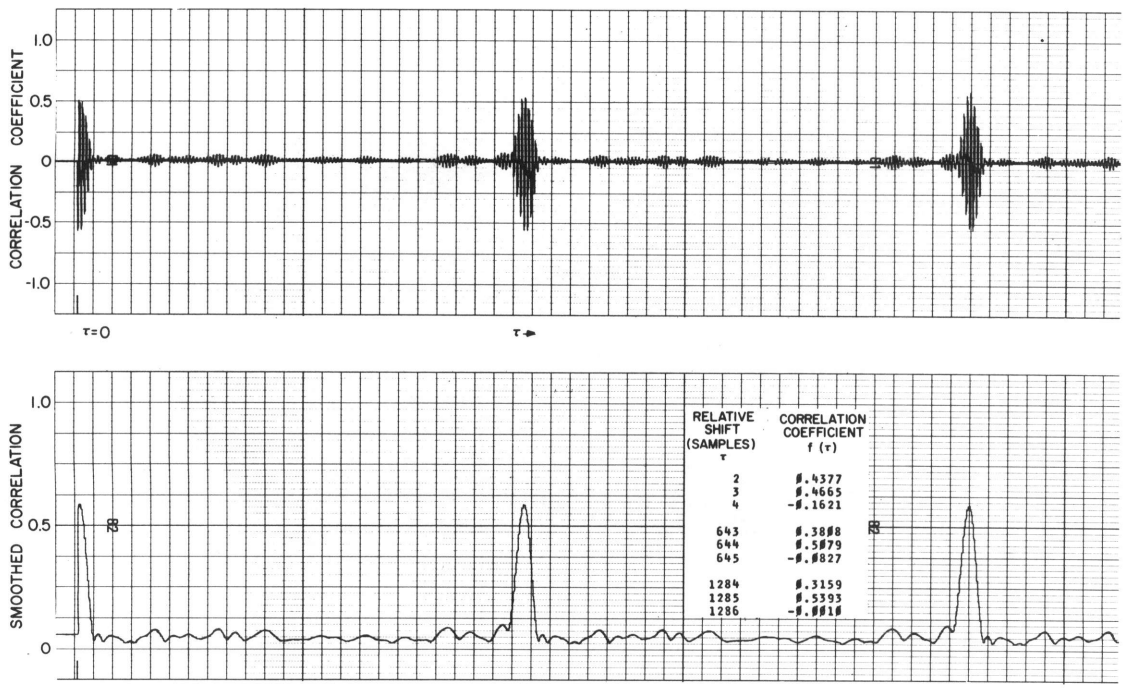

Fig. A7 - A similar crosscorrelation as in Fig. A6 but with 8 knots of simulated doppler shift

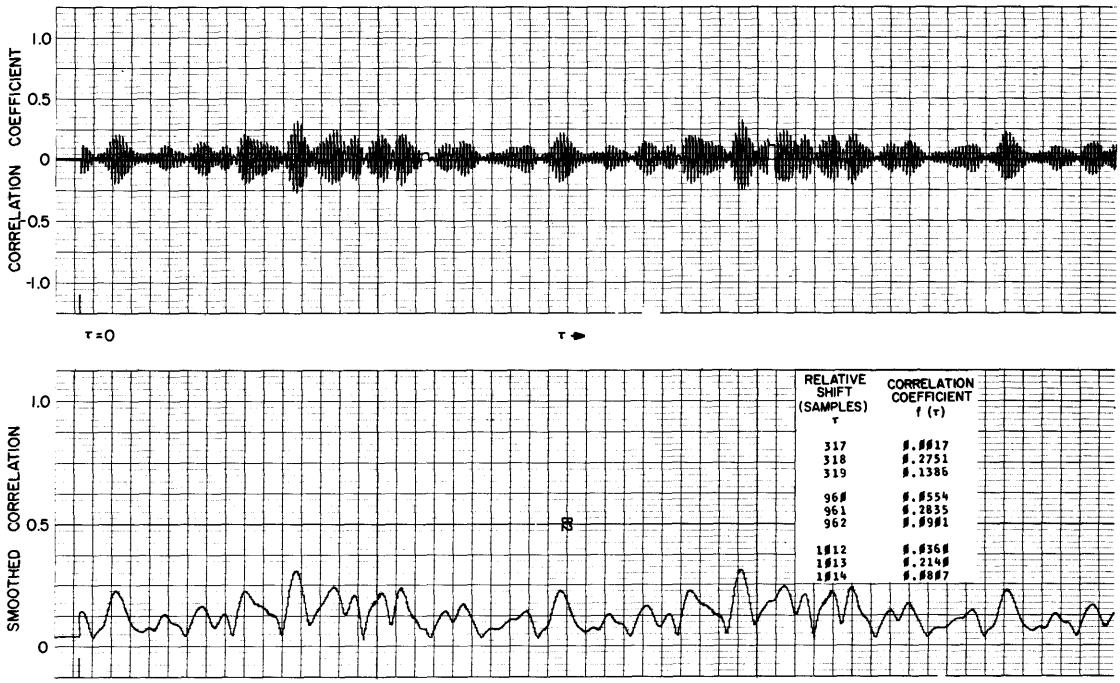

Fig. A8 - A similar crosscorrelation as in Fig. A6 but with 16 knots of simulated doppler shift

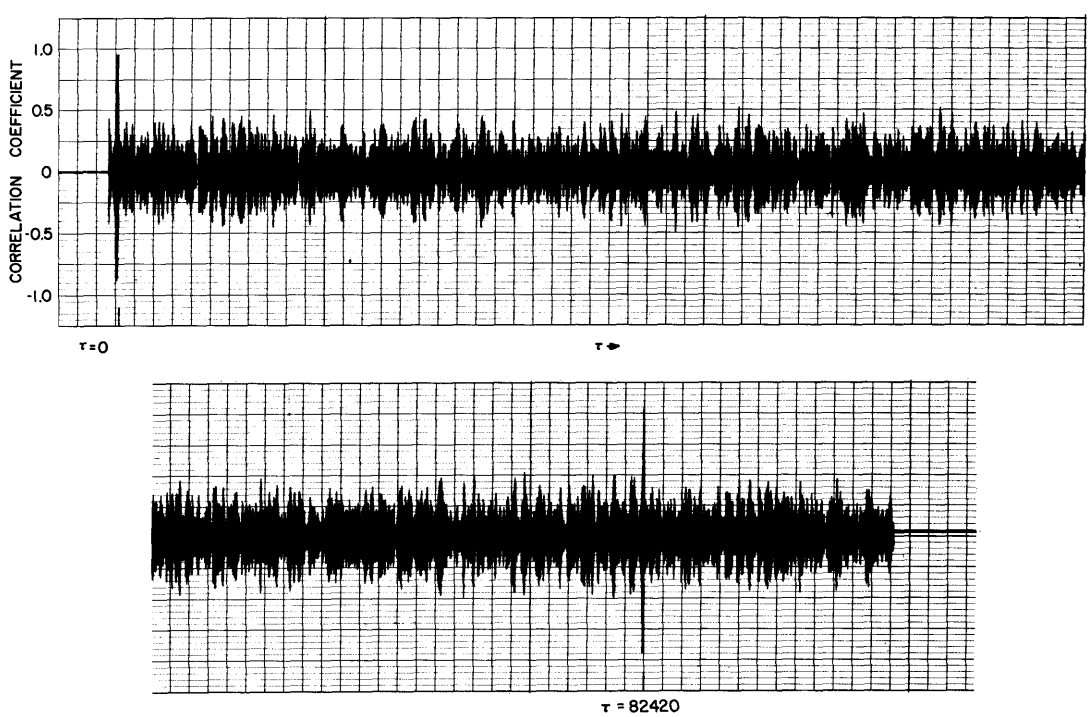

Fig. A9 - Autocorrelation of a sampled pseudorandom noise signal periodic at approximately 82,420 samples (1000 sample reference)

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13. ABSTRACT

Equipment and procedures have been developed for signal processing and the analysis of experimental data in conjunction with a digital computer (Computer Control DDP-24). Digital magnetic tape recordings of time-sampled data obtained at remote field stations during experiments on underwater sound serve as a primary source of data for analysis. The basic computational operations are correlation and spectral analyses.

The system described provides for input to the computer memory from unblocked digital tape, selection of data by means of visual display, and output from computer memory of data or results, as desired. Details of hardware and software for special applications are discussed with particular emphasis on features which enhance the interaction between machine computation speeds and human interpretive power.

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