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WHAT CONCERNS THE NEW ENGINEERS

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SCOPE WITH BRAIN POWER PROCESSES AND DISPLAYS

Digital processing interface brings computer power to oscilloscope

Intelligent oscilloscope features simultaneous displays of time-domain waveforms and their frequency spectra, waveform averaging to extract clean signals from noise, and digital filtering of input signals

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☐ For the past two decades, oscilloscopes have been among the engineer's most versatile and widely used tools. And, as bandwidths, sensitivities, triggering circuitry, and storage capability have all improved over the years, the usefulness of this tool has increased.

At the same time, computers have made great strides—advancing to the point where a minicomputer is a common component in many systems today.

Now, for the first time as a product, these two technologies have been brought together in one instrument to create a new field of computer-aided oscillography. The result of this marriage of technologies is called the Digital Processing Oscilloscope.

Like a conventional instrument, the Digital Processing Oscilloscope contains a signal-acquisition unit and a display unit (Fig. 1a). In addition, the new scope contains a third section, called a processor, which has the ability to digitize an acquired waveform, provide an interface with a minicomputer, and to store digital data and convert it to analog form for display (Fig. 1b).

The applications of such an instrument, complete with minicomputer, are limited only by the imagination of the user. A few of the more obvious ones are:

- Signal averaging to extract signals from noise.
- Viewing of a signal after passing it through an arbitrarily constructed digital filter—one that may not even be realizable in conventional circuitry.
- Display of a signal in the frequency domain by calculating its Fourier transform.
- Correction of signal errors caused by such limitations in the measuring equipment as nonlinearity, small impedance mismatches, and the like.
- Automatic scaling of a displayed waveform to any convenient form—a logarithmic frequency scale, for example.

Processor architecture

The Digital Processing Oscilloscope's acquisition and display modules are identical to those of a conventional oscilloscope. Indeed, with the processor section removed, the Digital Processing Oscilloscope becomes a standard Tektronix 7704A oscilloscope.

The processor consists of two major parts: a signal interface, and an asynchronous bus (Fig. 2). The signal interface, which controls the display unit, receives its data from the acquisition unit and from a variety of functional devices plugged into the asynchronous bus.

The data bus allows the devices, all of which are built on 4½-by-11-inch etched-circuit boards, to work independently of each other. Six devices, which require a total of eight device positions, are shown in Fig. 2. The bus has 11 device positions available to allow for new devices being developed. Each device position consists of a single 72-pin edge connector, which provides parallel access to power supplies and address, data, and control lines.

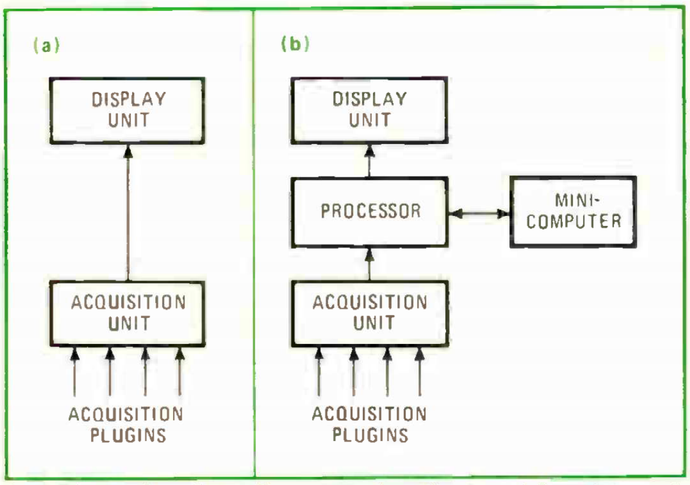
A serially connected line (daisy chain) in the bus establishes device priority in case two devices try to get control of the bus at the same time. Connections are available at each device location for input and output of signals. When wideband and low-noise paths are required, signals are routed directly from device to device via coaxial cables.

The heart of the processor

Probably the most important part of the processor is its three-axis asynchronous sampler and its associated analog to digital converter.

To store an acquired signal, the processor samples the

Closing the loop.
Readers who are interested in discussing this oscilloscope minicomputer combination with the authors may call them on March 22 from 9 a.m. to 2 p.m. PST at (503) 644-0161. Ask for Hiro Moriyasu on Ext. 7047.



1. Adding an interface. Conventional oscilloscope (a) contains only acquisition and display units. Digital Processing Oscilloscope (b) also contains a processor for linking scope to a minicomputer.

scope's vertical axis every 6.5 microseconds. It samples the two other major axes (horizontal and blanking) 95 nanoseconds later. This allows time for the sweep-circuit start-up lag, which would otherwise prevent the storage of the leading edges of rapidly rising signals. A delay line in the display unit displaces the real-time vertical by the same amount, and thus coincidence of real time and stored signals is maintained when they are simultaneously displayed.

Significantly, the sampling rate imposes no limitation on the processor's frequency response because there is no need for all of the samples of a given waveform to be obtained on a single sweep. Of course, the faster the sweep speed needed to display a signal, the smaller the number of samples obtained per sweep, and the longer it will take to digitize the waveform. The sampler is nonsynchronous with the sweep to prevent the sampler from looking at the same points over and over again.

The vertical sample of the acquired waveform is converted by a 10-bit successive-approximation a-d converter to one of 1,024 possible levels, which correspond to 10 CRT divisions, eight of which are displayed.

The a-d converter then converts the horizontal sample to one of 512 horizontal memory positions that line up with the 10 horizontal divisions on the CRT faceplate. However, if the blanking sample indicates that the CRT was blanked—for retrace or channel switching, for example—when the vertical or horizontal sample was taken, the converted data is discarded. Conversely, if the CRT was unblanked, a memory address is generated and the vertical binary word is stored at that address in the processor memory.

An additional data acquisition mode is available. The computer may, at any time, obtain directly from the a-d converter the value of the last vertical sample, allowing inputs of unchanging data in a single operation or construction of arrays consisting of more than 512 elements of slowly varying data.

Perhaps the second most important device in the processor is its memory. This is a nonvolatile 4,000-byte-by 10-bit magnetic-core unit, which serves both to store data and act as a buffer for computer input/output functions. The memory stores acquired waveforms and scale factors for display and computer input, and stores computer output for display on the CRT. Data acquisition independent of I/O speed and flicker-free displays are results of this local memory.

The I/O device provides a bilateral processor/computer link: the computer has full access to the processor through the I/O device, and the processor in turn may interrupt the minicomputer at any time.

Controlling the display

Two devices in the processor are responsible for generating the data seen on the oscilloscope's screen: the display generator and the character-display control. The display generator creates waveforms from data stored in the processor memory or directly from computer output, while the character-display control generates characters from data stored for that purpose. The character-display control is also used in the opposite mode—to convert acquisition-unit readout information into ASCII format for storage in the processor memory.

The display generator can operate in two modes: Y versus time (y,t) and X versus Y (x,y). In the (y,t) mode, all specified memory locations (A,B,C,D) are examined sequentially and all non-zero points in the array are plotted. In the (x,y) mode, each point is plotted when directed by the computer, thus enabling the computer to generate a refreshed display of multivalued functions—spirals, for instance.

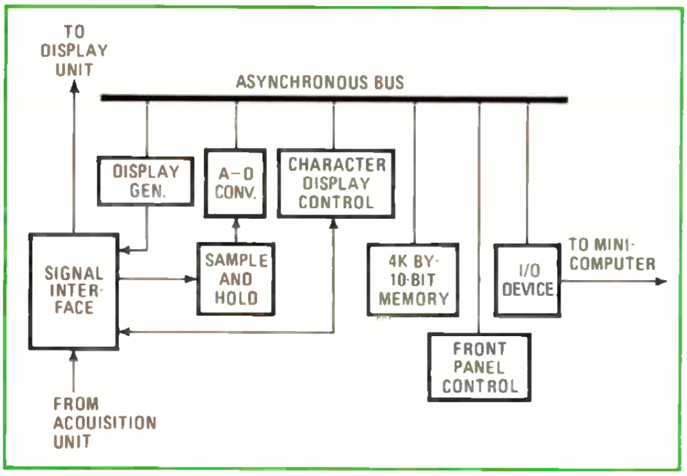
The fact that the (y,t) mode plots only non-zero points becomes significant in certain difficult measurement situations, such as measuring single-shot phenomena, where only a small number of points can be stored. The reason is that, in its normal mode of operation, the processor makes a linear interpolation between the plotted coordinates. Thus, if some points are missing, the display will ignore them, not return to zero, and then go back up to the next plotted point. If a point plot is desired, a strap option can be installed at pins provided on the display generator board.

The character display control device allows use of the full character set of the 7704A for both computer input and display on the CRT. In the STORE mode, the acquisition readout information is converted to ASCII and stored in the processor memory, providing a permanent record of waveform scale factors. Thus, whenever a stored waveform is displayed, so are its scale factors.

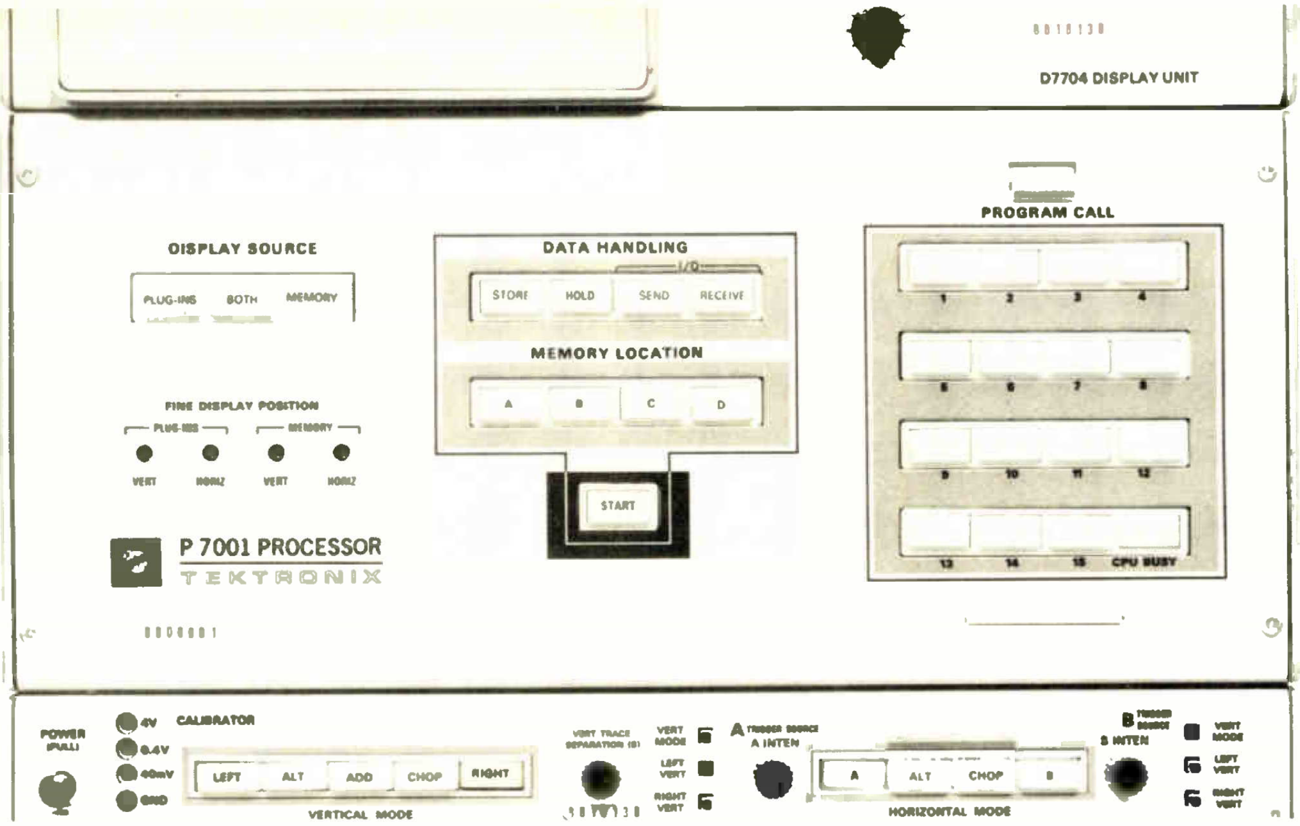
Sixteen 80-character messages may be stored in the processor memory. Four of these are allocated to the A, B, C, and D memory locations and are addressable from the front panel. Normally, these contain only scale factors. The remaining 12 messages may be used for computer-to-operator communication. These messages, once stored, may be displayed with one command.

Controlling the processor

Push buttons on the front panel provide access to logic circuits in the processor, allowing simple control of the Digital Processing Oscilloscope and its computer interface (Fig. 3). Each time a new mode is selected (STORE, START, etc.), the processor generates a computer interrupt, which allows complete operator-processor-computer interaction. The computer constantly monitors processor status, which is indicated by the lighted buttons. The buttons are also controlled by the



2. The processor. Signal interface allows display to be fed from acquisition units, or by processed signal, or both. Up to eight waveforms—four real-time, four processed—can be viewed at once.



3. Front-panel controls. Ten of these 28 buttons control the processor. The remainder are used to request computer action. The 16 program call buttons are used to direct the computer to execute user-definable programs and do not directly affect the processor unit itself.

I/O device to inform the operator of computer-initiated processor modes.

Ten of the 28 front-panel buttons directly control the processor. Two buttons set the status to STORE or HOLD, four buttons are used to designate the waveform memory locations, and three buttons set the CRT display source—PLUG-INS, BOTH, MEMORY.

The START button is used to initiate any processor or computer mode that will destroy previously stored waveform data (contents of A, B, C, or D), and thereby reduces the possibility of inadvertent destruction of stored data. The remaining 18 buttons are used to request computer action. The SEND and RECEIVE buttons direct the computer to input from the processor or to output desired waveforms. Each time SEND or RECEIVE is used, the processor is set into a HOLD mode, where acquired data is retained, and then a START command sends an interrupt to the I/O unit. The 16 program call buttons are used to direct the computer to execute user-definable programs and do not directly affect the processor.

The computer, through I/O control, can access any individual device in the processor and change any of its modes. This allows, under program control, operations such as simultaneous storage in and display from different memory locations. In addition, single-sweep reset and end-of-sweep interrupt are available to the computer, allowing further programing flexibility.

The software

The BASIC language was chosen as a starting point for the software because it is a simple, interactive language that is easy to use. An operator can write a program, run it, modify it, and run it again without reentering or recompiling the program. Some of the elements of BASIC were expanded to adapt the language to the needs of the Digital Processing Oscilloscope. New statements were added to improve waveform processing, and special features were added to support the oscilloscope hardware. Where possible, the software was designed to minimize waveform storage requirements and speed up waveform processing. The software is called APD BASIC, and it is written for the Digital Equipment Corp. PDP-11 series of minicomputers.

APD BASIC has four permanently defined arrays—that is, four portions of the core memory—for storing the waveforms from the processor. Four arrays are necessary for transferring waveforms with the SEND and RECEIVE buttons on the processor front panel. The floating-point format of the arrays gives the user access to waveforms for computation. Individual elements or the whole waveform can be examined or changed. A number of variables have been permanently defined to give the user access to waveform scale factors and units, as well as to scale factors from any of the acquisition unit's digital plug-ins, such as digital multimeters and counters.

One of the central features of APD BASIC is the LET statement, which has been greatly expanded from the LET in BASIC. In addition to the standard equivalence function, LET may be used to transfer waveforms and scale factors between any of the memory locations, either in the processor or the PDP-11 minicomputer. Typing the simple statement:

```
LET C = PA
```

will transfer a waveform and its scale factors from processor memory location A to APD BASIC array C.

The LET statement may also be used to perform scalar-array operations, using any combination of the mathematical functions of BASIC. To generate a waveform that is the vector magnitude of two other waveforms, the simple statement:

```
LET PC = SQR(A*A + B*B)
```

results in each element of array A being squared and added to the corresponding element of array B squared. The square root of the sum is then stored in the corresponding element of processor memory location C.

The functions of the PRINT statement in BASIC have been expanded to form the DISPLAY statement, which may be used to display text, variables, and waveforms simultaneously on the scope's CRT. The statement

```
DISPLAY "THE PEAK VALUE IS", B(50), WB
```

displays the message "THE PEAK VALUE IS", the value of the 50th element of array B, and the waveform in processor memory location B simultaneously on the CRT. The DISPLAY statement is the key to programing interaction between the user and the program, and the previous program statement is a simple example of how this interaction might be programed.

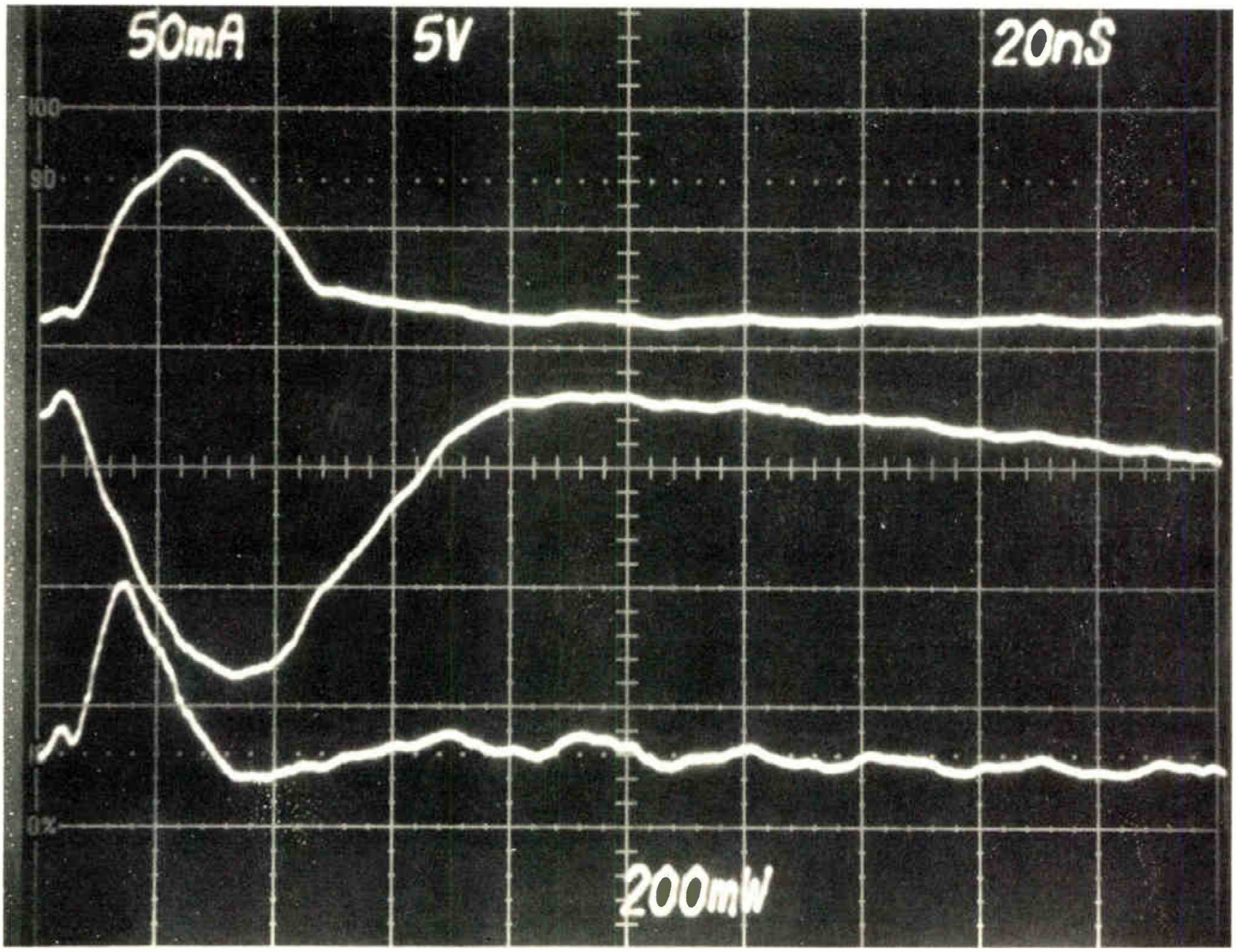
APD BASIC maintains correct waveform calibration at all times. When waveforms are transferred from the processor into an APD BASIC array, the vertical scale factor is combined with the waveform to give the actual values that came into the acquisition plug-in. Transfer of an APD BASIC array to a processor memory location results in the waveform being scaled to a standard oscilloscope scale factor, so that the waveform is completely visible on the CRT without interfering with the readout. This automatic scaling can be overridden by the user to position or scale the waveform on the display as desired.

Correct calibration of the units associated with scale factors is also maintained. For example, multiplying two voltage waveforms results in a waveform with units of "vv" (volts * volts).

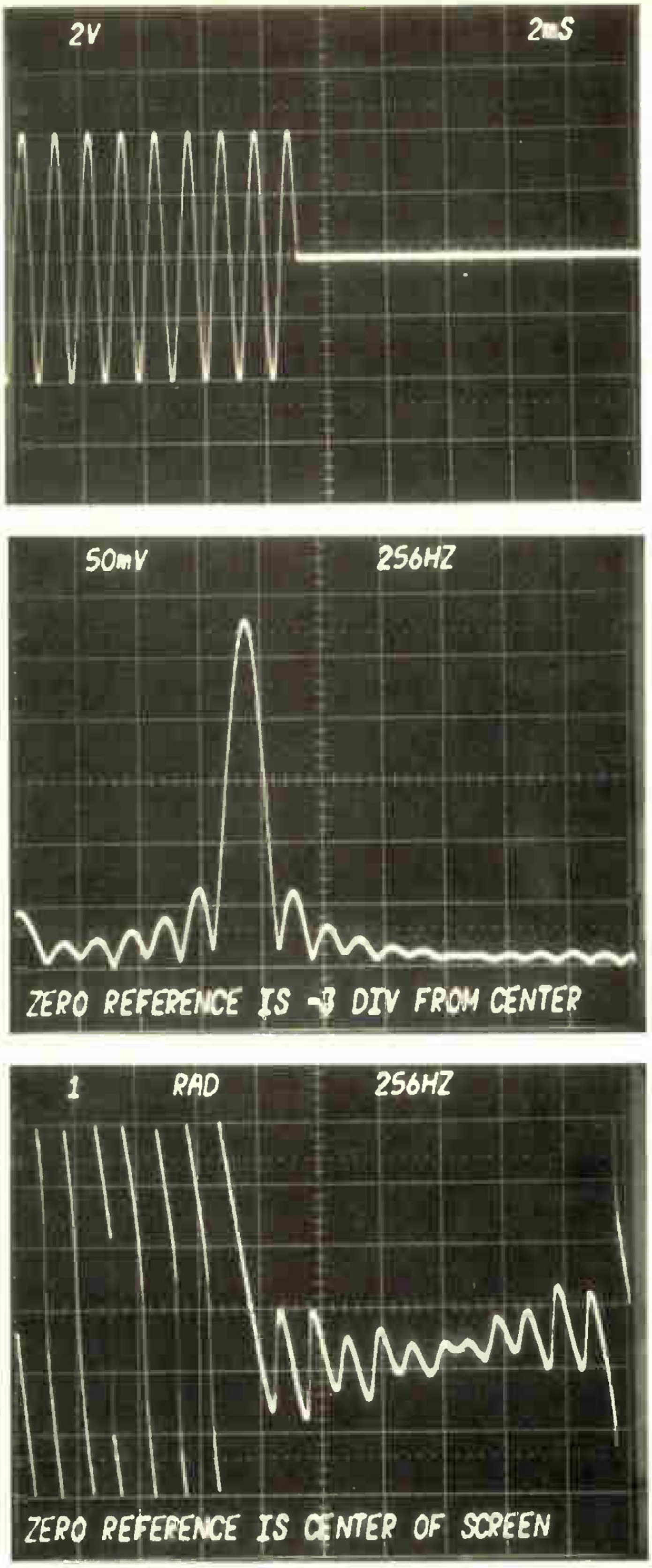
Special features have been added to APD BASIC to support the hardware functions of the scope. The interrupts sent to the computer from front-panel buttons are recognized by the software, which performs the action requested. The SEND and RECEIVE buttons transfer waveforms between APD BASIC arrays and the processor.

With the program call buttons on the front panel, the user may execute APD BASIC programs previously entered in the PDP-11. Button number 1 starts program execution at the lowest line number in the range 100 to 199, number 2 starts execution at the lowest line number in the range 200 to 299, and so on through button number 13. The user merely starts writing the program at the line number corresponding to the button he wants to execute the program.

Buttons 14, 15, and 16 are reserved for special pur-



4. Calculating power dissipation. Processor acquires collector current (top trace) and collector-to-emitter voltage (middle trace) waveforms from plug-in vertical amplifiers. Computer multiplies the two waveforms to get the instantaneous power displayed in the bottom trace.



5. Fourier transforms on display. A 9-millisecond burst of low-frequency sinusoid (top) is analyzed into its magnitude (middle) and phase spectra by a simple two-line program in APD BASIC.

poses. Number 14 is a CONTINUE control that allows the operator to interact with the computer in running a program. It is used, among other things, to provide the computer with a ground reference level—in the same manner that touching a probe to ground tells a human operator where ground is on a regular scope. Button 15, called RESET, is a sort of universal panic button. Pushing it stops the execution of any program and returns the software to its initial idle mode. Button 16 is simply a computer-busy indicator lamp.

A special statement has been added to set the status of any of the devices in the processor under program control. With this statement, operation of any of the front-panel push buttons can be duplicated, and the processor can be controlled in many ways that cannot be duplicated from the front panel. The X-Y display capability of the display generator in the processor is supported by the XYDISPLAY statement. Refreshed X-Y displays can be generated on the CRT from APD BASIC arrays.

Momentary power failures will not interfere with program execution even if the program is controlling the operation of the processor. APD BASIC is designed to recognize the power failure, then restore the status of the processor, and resume program execution after the power is restored.

APD BASIC contains a number of new statements to make waveform processing easier. The functions performed by any of these statements can be duplicated with an APD BASIC subroutine, but including them as a statement makes execution faster and programing easier. Some of these special functions are integration, differentiation, signal averaging, and fast Fourier transformations (FFTs).

For example, a fast Fourier transform written in APD BASIC requires about 20 minutes to transform 512 samples to magnitude and phase spectra. The same task requires less than 10 seconds using the FFT statement. Each of these statements may be used as a single command to be executed immediately or as part of a program. Correct calibration of the results including scale factors and units is always maintained.

Using the Digital Processing Oscilloscope

To display, say, the instantaneous power dissipated by a transistor as a function of time, a current-amplifier plug-in and a voltage-amplifier plug-in could be used to obtain traces of I_c and V_{ce} as shown in the top two traces of Fig. 4. Then, by using the short and simple program that follows, the power may be quickly computed and displayed along with an appropriate scale factor (bottom trace).

```
LIST
REMARK PDP-11 APD BASIC VERSION 001
   100 STATUS 250, 17
   110 FOR I = 1 TO 10:NEXT I
   120 LET PD = PA*PC
   130 DISPLAY WA, WC, WD, V1, V3," ",S1," ",V4
   140 FOR I = 1 TO 50:NEXT I
   150 GO TO 100
READY
*
```

Line 100 causes the scope to store the outputs of the current amplifier and the voltage amplifier in memory locations A and C, respectively. Line 110 is a wait loop that gives the processor enough time to store all of the points.

Line 120 multiplies the contents of A and C and places the result (power) in memory location D. Line

130 causes the oscilloscope to display the waveforms of I_c (waveform A), V_{ce} (C), and power (D) along with their scale factors in a specified format.

Line 140 allows time for viewing before allowing the program to proceed to line 150 which causes the whole process to begin again.

Since the program begins with line 100, pushing program call button number 1 causes the program to start. It will loop indefinitely until stopped by pressing button 15, the RESET button.

The fast and visible Fourier transform

One of the most attractive features of the Digital Processing Oscilloscope is its ability to calculate and display the Fourier transform of any acquired waveform. Figure 5a, for example, shows an expanded view of a burst of a low-frequency sine wave. The signal shown in the photograph was actually acquired and stored at a sweep speed of 20 milliseconds per division. It was then expanded to enable it to be shown in greater detail.

The following two-line program is all that is required to transform the signal into magnitude and phase components in the frequency domain.

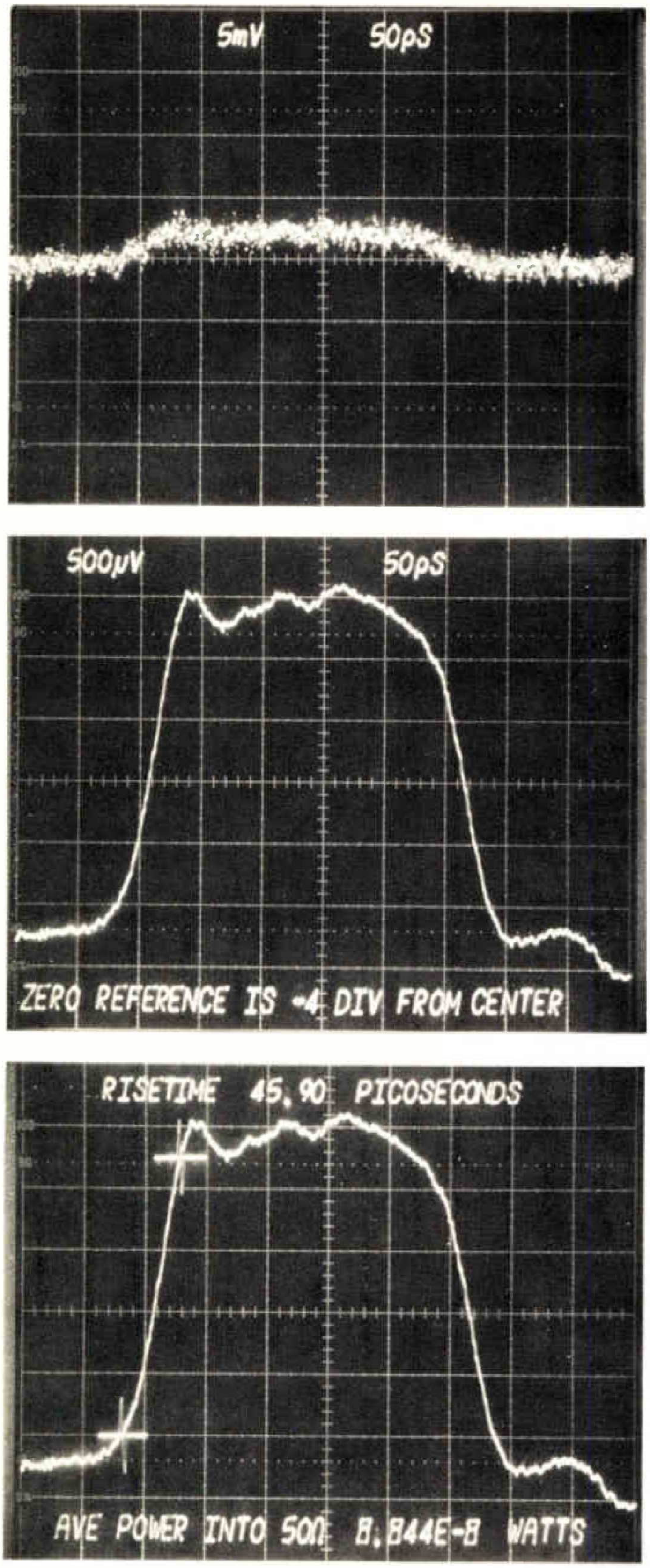
```
100 FFT PA,B,C
110 POLAR B,C,PB,PC
```

Line 100 causes the fast Fourier transform (FFT) algorithm to be applied to the signal stored in memory location A, resulting in 512 complex points which are separated into real and imaginary waveforms stored in arrays B and C, respectively. Line 110 converts the transform waveforms from rectangular coordinates to polar coordinates, and stores the magnitude and phase waveforms in memory locations B and C, respectively.

The displayed results (Figs. 5b and 5c) are as expected. The time-domain waveform is a 9-ms burst of a sinusoid of frequency slightly less than 1 kHz. It can be thought of as the product of a rectangular pulse and a continuous sine wave. Since multiplication in the time domain corresponds to convolution in the frequency domain, the transform is a (sin x)/x waveform convolved with an impulse at the sine wave frequency—that is, it is shifted so as to be centered at the frequency of the sine wave. The phase information is displayed modulo 2π; this is why discontinuities appear at points where the phase angle changes rapidly with frequency.

Computing through the noise

Pulling repetitive signals out of noisy backgrounds by averaging them is not a new technique. But it has probably never before been quite so easy to do as it is with the Digital Processing Oscilloscope, as shown in Fig. 6. Figure 6a shows a single trace, and the signal, a pulse, is barely visible in the noise. After averaging the pulse a thousand times, the greatly improved signal of Fig. 6b is obtained. Note the automatic scaling for best display resolution. Then, as shown in Fig. 6c, the oscilloscope has measured and displayed the rise time and average power into a 50-ohm load of the signal. The markers show the 10% and 90% points picked by the computer.



6. Signal averaging. Single pulse is barely visible in the noise (top). After averaging it 1,000 times, display is enhanced (middle). Rise time and power are calculated and displayed on CRT.

While a complete Digital Processing Oscilloscope, including a minicomputer, can cost anywhere from about $18,000 to about $29,000, without plug-ins, it is worth noting that the owner of a 7704A oscilloscope with an appropriate set of plug-ins and a PDP-11 minicomputer is well on his way to having an operating oscilloscope with brains. The Tektronix P7001 Processor unit costs $5,200, and the least expensive software package—APD BASIC I—costs an additional $650. Added to this is the cost of an I/O device like a teletypewriter. □