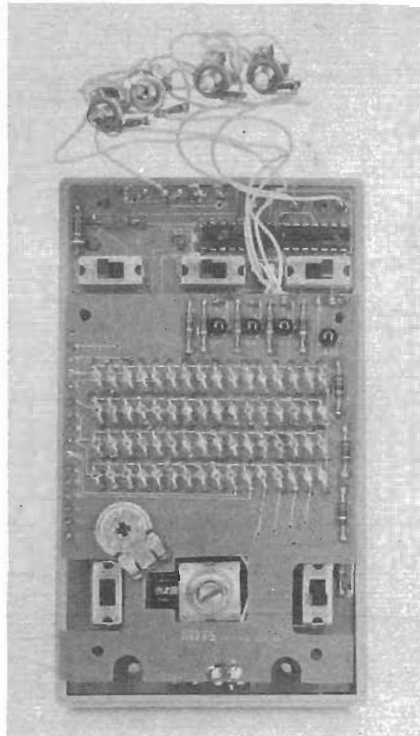
IN A KIT

4-Channel Storage

Using LED indicators, this has full storage triggering. The LED matrix with 16

THE MS-416 has a time-base range of .5 μs to 200 ms that will cover most digital circuit needs.



INTERIOR VIEW of the MS-416. Calibration of the unit is a simple one setting operation.

WITH THE RAPID INCREASE IN INTEGRATED circuit technology, more and more electronic equipment is being designed around digital circuitry. These new circuits are full of complex timing sequences and elusive pulses. Elusive because the pulses occur one-time and one-time only.

There are many three- and four-channel oscilloscopes on the market which can handle complex timing relationships. But they are generally very expensive, cumbersome instruments and are usually found only in very well-equipped labs.

Another instrument sometimes used in testing digital circuitry is the logic probe. Many logic probes have built-in pulse catchers for those one-time pulses. However, they are inadequate for most circuit testing and nearly useless in complex timing situations.

As a result, a new instrument has been developed. It is called the MS-416, and it incorporates the best features of both the oscilloscope and the logic probe.

The MS-416 is an inexpensive, four channel, hand-held, digital logic oriented scope with full memory capability. The time-base range from .5μs to 200ms will cover most digital circuit needs. With four channels, extensive timing relationships can be easily observed. Signals are displayed on a 4 $\times$ 16 LED matrix; 4 channels, with 16 LED's per channel.

In addition to the normal mode of operation, the MS-416 can be switched into storage operation at any time during testing and will "remember" the information present on all four channels of its display. It will hold this information until it is switched back to normal operation or turned off. The storage mode also serves as an excellent pulse catcher for those elusive one-time pulses. The MS-416 will wait until the pulse occurs and then hold it in its memory as long as it is desired.

Together with positive- or negative-edge triggering, an auto-sweep mode for steady-state logic measurements and a Ni-Cad battery supply, the MS-416 becomes quite a versatile piece of equipment.

The MS-416 is available in kit form for $127.50, or assembled for $189.50, from MITS, Inc., 6328 Linn, N.E., P.O. Box 8636, Albuquerque, NM 87108.

Circuit operation

The MS-416 consists basically of eight interconnecting circuits. The block diagram in Fig. 1 shows a power supply, a memory, a clock oscillator, a counter, a decoder, a mode select circuit, a sync circuit and a display.

The complete schematic of the MS-416 is shown in Fig. 2. The power supply will run on 117 Vac with an ac adapter. Using the adapter (a standard 9V unit), the supply is regulated by D1, a 5.1 V Zener diode. C1 provides filtering, and a separate filtering network (R6 and C2) is used for the clock oscillator IC-g. When the power switch S1 is in the OFF position, the adapter is used to charge the Ni-Cads through R1 and R2. To run on Ni-Cads, simply unplug the adapter, which shorts the A and C contacts of the ac jack, and switches the unit on. In battery operation, the supply is essentially unregulated to eliminate unnecessary current drain. It takes approximately 14 hours to charge the batteries, and with a full charge they will power the unit for about 1½ hours of continuous use.

The memory consists of a 64-bit RAM (Random Access Memory), Am31L01 (IC-a). The signal inputs are buffered through IC-b and the inverted signal is fed directly into the four word bit inputs of the RAM. Each word consists of 4 bits, one bit for each channel.

The 4 bit word is selected by the binary outputs of the counter (IC-c) connected to the four address inputs of the RAM. The RAM is addressed simultaneously with the 4 $\times$ 16 decoder (IC-f). As the 16 words are addressed one at a time, the signal present at each of the 4 inputs is written into the memory and fed, inverted, to the RAM outputs. The chip-enable input of the RAM is pulsed high at the end of each 16 count, disabling the memory while the counter resets. This will cycle continuously as long as the unit is in the normal operation mode, and the mode select circuit holds the RAM in the Write mode. In the storage mode, the mode select circuit switches the read/write input of the RAM to Read after one full 16 count. The signals present on the RAM inputs will then be continuously displayed as long as the unit is in the store mode.

The clock oscillator uses four inverter gates of IC-g, along with two variable resistors (R4 and R5), and two capacitors (C3 and C4) to produce the variable frequency signal used for the time-base. Switch S4 selects either a 620-pF capacitor (C3) for the X1 range or a .68μf capacitor (C4) for the X1000 range as part of the time constant for the oscillator. A 50-ohm trim pot R5 is used for calibration, and a 5K ohm linear taper pot is used to vary the time constant to select the initial sweep rate for the time-base. Switch S5 either sends the clock signal to IC-e in the X1 position or, in the X20 position, sends it through IC-j for a divide by 10 and IC-h for a divide by 2 before sending it to IC-e. Using S4, S5 and R4 you can produce a time-base from 0.5-μs. to 200 ms. The final signal is fed through a NAND

Digital Scope

4-channel digital scope capability and automatic readout is a 4 X 16 LED's per channel.

by JAMES B. VICE

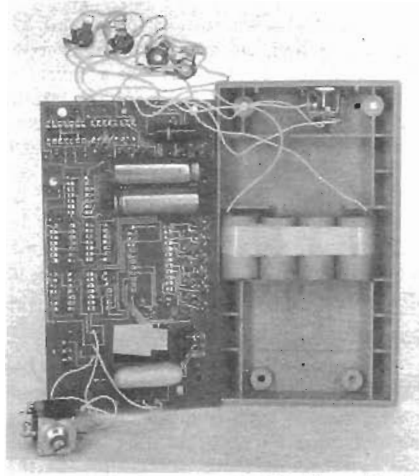
gate and an inverter gate to the counter.

The counter is a 7493 4-bit binary counter (IC-c) operated in the ripple-through configuration (series of flip flops), providing simultaneous divisions of 2, 4, 8 and 16 of the clock frequency on its four outputs. The outputs are fed to both the 4 × 16 decoder and the RAM address inputs, keeping the two synchronized. The divide by 16 output, pin 11, is also fed to the clock inputs of the flip-flops (IC-d) in the sync and mode select circuits. As the 7493 counts up, the d output goes high on the 9 count and falls after the 16 count. This falling edge is used to toggle the flip-flops.

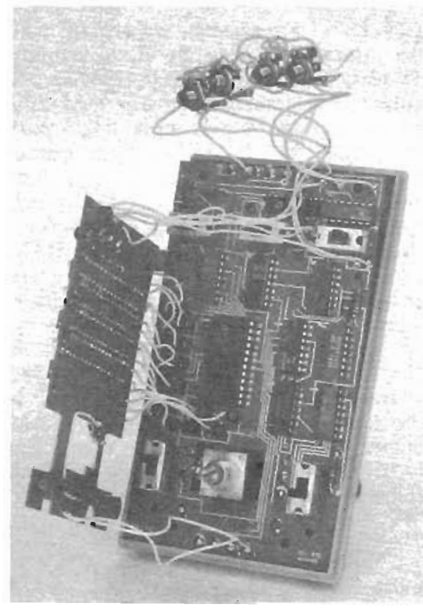
The decoder is an Am93L11 4-line to 16-line decoder/demultiplexer. As the counter feeds information into the decoder's four binary coded inputs, its outputs 0 through 15 are strobed low sequentially at the rate determined by the clock oscillator frequency. These outputs are fed through transistors to the display. The decoder is disabled at the end of each 16 count by the same signal that resets the counter.

The mode select circuit consists of switch S3 and one flip-flop of IC-d. In the normal mode of operation, the clear input of the flip-flop is held low by S3 to ground, keeping the flip-flop in the clear state. This prevents the clock input of the flip-flop, which is connected to the D output of the counter, from having any effect while in the normal mode. When S3 is switched to store, the clear input goes high so that when the signal on the counter D output falls after the 16 count, the flip-flop will toggle. The flip-flop is connected so that it latches, and it will stay latched until S3 is returned to the normal position. When the flip-flop latches, the Q output goes high, switching the RAM to the Read mode. Simultaneously, the Q output goes low and is used to block the signals on the input buffer (IC-b) and to block pulses from the sync circuit at pin 10 of IC-e. When S3 is switched back to normal the flip-flop immediately goes back to its clear state.

The sync circuit is both the most complex and the most important circuitry in the unit. It consists of a 9601 retriggerable one-shot (IC-k), four NAND gates of IC-e, two inverter gates of IC-g and one flip-flop of IC-d. The signal for the



INTERIOR VIEW of the MS-416. The main circuit board is swung away to show the underside of the main board and the batteries.



INTERIOR VIEW of the MS-416. The display board is swung away to reveal the main printed circuit board.

sync is taken from the output of the channel one buffer (pin 3 IC-b). The sync signal is fed to S2 and one gate of IC-e which is connected as an inverter. The input to the one-shot is taken from S2. In this manner, switch S2 is used to select either the rising edge or falling edge of the input signal for synchronizing the MS-416.

The one-shot has an output pulse duration of approximately 160 ns. The Q output of the one-shot is fed into pin 5 of one NAND gate of IC-e where it is gated together with the Q output of one flip-flop of IC-d.

This gate is used to prevent any one-shot pulses from passing while the counter is counting up. The output of the NAND gate is again fed into one input of another NAND gate where it is gated together with the Q output of the mode select flip-flop. The output of this gate goes through an inverter gate of IC-g and to the clear input of the sync flip-flop. The clock input of the sync flip-flop is connected to the D output of the counter; therefore, when the signal on the counter falls after the 16 count, the flip-flop toggles.

This causes several things to happen at once. The Q output of the flip-flop is connected to another NAND gate of IC-e, together with the clock signal, and then through another inverter to the counter. The NAND gate serves to block the clock pulses from reaching the counter while it is being reset. The Q output of the flip-flop is used to reset the counter, disable the decoder and disable the RAM. It is also used to set conditions at pin 4 of IC-e to allow the next one-shot pulse to pass. When the next one-shot pulse occurs, it will pass through to clear the sync flip-flop, starting the entire sequence over again.

The display consists of 64 RL-50 LED's arranged in a 4 × 16 matrix; along with associated driving circuitry (Q1 through Q20 and resistors R8 through R15). Transistors Q17 to Q20

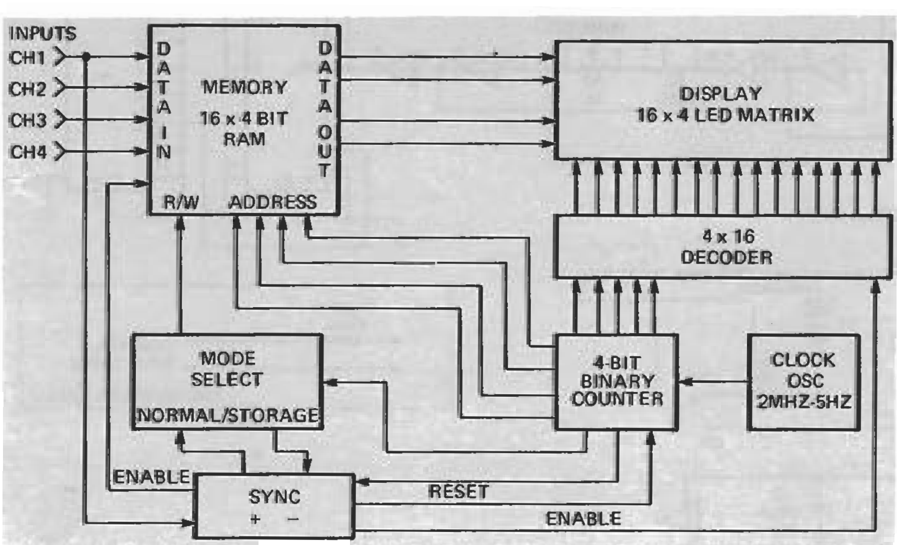


FIG. 1—MS-416 BLOCK DIAGRAM. The trigger circuits are synchronized to the channel-1 signal.

(CS4410's) are switched on and off with the information from the RAM outputs. Transistors Q1 to Q16 (EN2907's) are pulsed low at their bases one at a time by the decoder outputs, providing a path to ground for the LEDs. Each output word from the RAM consists of four bits, each bit corresponds to one channel, and each of the decoder outputs corresponds to one RAM address. The RAM address and the decoder output are changed at whatever rate is predetermined by the clock oscillator frequency. As an example; if the counter is at its 2nd count, the RAM will be at its 2nd address and Q2 will be turned on. If there is a positive signal on the RAM output to Q18 at this time, then LED D23 will light for however long the clock frequency determines.

There is also an auto-sweep circuit for measuring high or low steady-state conditions. Since the sync circuit requires a pulse to function, a steady-state condition has no effect and is never seen. Switch S6 allows the unit to measure these signals by switching the clock oscillator signal into the other A input of the one-shot. This allows the sync to be continuously triggered. When not in auto-sweep operation, S6 holds the input to the one-shot at V_{cc}.

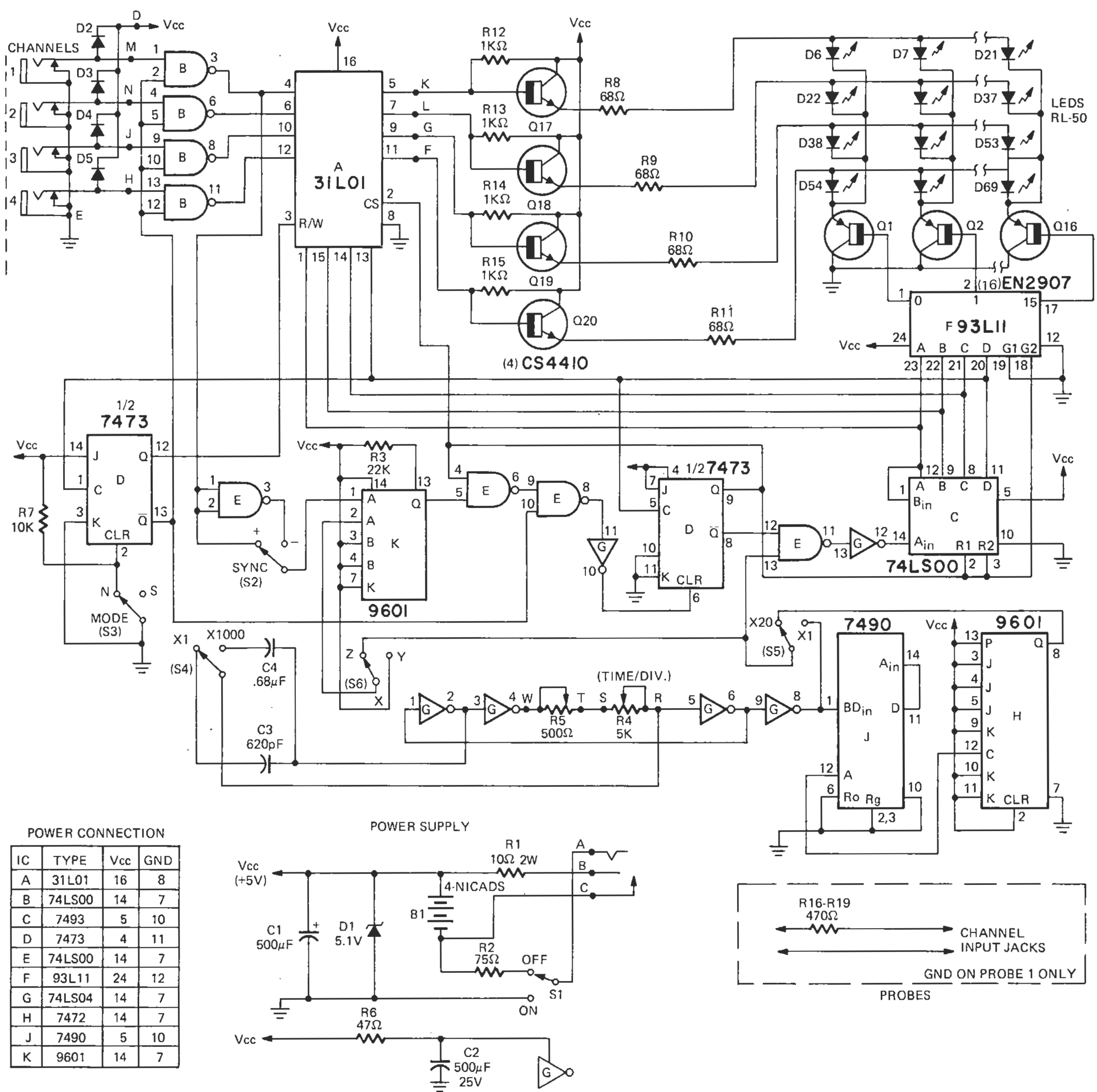
How's it's made

The MS-416 is built around two double sided PC boards with plated-through holes. As the unit is quite compact, the builder must be sure that all components are installed as close as possible to the boards and all excess component leads and IC pins are cut off as short as possible without damaging the connection. The boards are assembled one at a time and then wired together after all the components have been installed on the component side of the boards. (There are five components mounted on the opposite side. These will be mentioned later).

The first step in construction is to install switches S1 to S5 on the main board. These are the only components on the boards that are not installed flat against the boards.

The next step is to install the integrated circuits. Orient them correctly according to the component layout, and be sure to push them down as flat against the board as possible.

At this point it is best to install the



POWER CONNECTION

IC	TYPE	Vcc	GND
A	31L01	16	8
B	74LS00	14	7
C	7493	5	10
D	7473	4	11
E	74LS00	14	7
F	93L11	24	12
G	74LS04	14	7
H	7472	14	7
J	7490	5	10
K	9601	14	7

FIG. 2—COMPLETE SCHEMATIC DIAGRAM of the MS-416. Power can be supplied with an optional 117-Vac adapter.

components that go on the back side of the board (R1 and capacitors C1 through C4). Be sure that the polarity on C1 and C2 are correct.

Install Zener diode D1, and make sure polarity is right.

Resistors R2, R3, R6 and R7 are installed next and then transistors Q1 through Q16. Be sure the base-emitter-collector leads of the transistors are properly aligned. This finishes the main board for the time being.

Assemble the LED board in the following manner. Resistors R8 through R15 and transistors Q17 through Q20 are installed on the LED board in the same manner as those on the main board.

The next step requires the greatest care and takes the most amount of time. LED's D6 through D69 are installed. Be sure to align them in straight rows and columns. It is helpful when doing this to draw lines on the PC board with a ballpoint pen and follow these lines while installing the LED's.

The 500-ohm trim pot, R5, is now installed after bending its three leads downward. Insulate the body of the pot from any copper foil on the board by placing a small piece of tape placed directly underneath it. This finishes assembly on the LED board.

Wire the 5K potentiometer, R4, to the main board. Switch S6, located on the pot is also wired to its respective pads on the board. Insert these wires from the back of the board and solder them on the component side.

The two boards can now be wired together. The pads to be connected are marked the same on both boards to make wiring easier.

Finally, the case top and case bottom are assembled. The four input jacks and diodes D2 through D5, along with the front panel fasten to the case top. It is best to wire the jacks before installing them in the case. The Ni-Cads and the ac jack are installed in the case bottom. Be sure battery polarity is correct. Wire the components in the top and bottom cases to the rest of the circuitry, and you are ready to calibrate the unit.

Calibration is easy

Calibrating the MS-416 is a simple, one-setting operation. In this method, a frequency meter or oscilloscope is needed; although instructions are included with the kit that show how you can set it up without special test equipment, but are less accurate.

For the most accurate calibration, switch S4 should be in the X1000 position and S5 in the X1 position. The TIME/DIV pot R4 should be set in its fully clockwise position. Connect your test instrument ground to the ground on the ac jack and your test probe to the switch terminal on R4 which connects with pad Z on the main board. Connect the unit to the ac adapter and turn the power switch to ON.

Adjust trim pot R5 until the clock oscillator frequency reads exactly 2kHz. Once this frequency is set, the unit requires no further calibration.

The unit can now be completely assembled using the hardware supplied with the kit, and the knob installed on R4. This is done by turning R4 fully clockwise and aligning the pointer on the knob with the .5μs marking of the TIME/DIV scale on the front panel.

Using the MS-416

Although the inputs to the MS-416 are protected against overload, remember this is a digital logic oriented instrument; therefore, you should not measure signals which exceed digital logic voltage levels. In most digital logic, the maximum voltage for a logic "O" is 0.8 volt, the minimum voltage for a logic "1" is 2 volts. The maximum input voltage from the unit you are testing should not exceed 5.5 volts.

When measuring a signal, keep in mind that the sync operates from the channel one input and therefore this channel must be used if you are using less than all four channels. It is best to attach the probe with the ground lead to the channel one jack as a reminder. (Four probes are also supplied with the kit.)

The display of the MS-416 is interpreted in much the same manner as a conventional oscilloscope. The settings on R4 and switches S4 and S5 determine the TIME/DIVISION of the sweep, and each of the 16 LED's in each channel represent one division. Synchronizing from channel one, the signals are displayed showing the logic levels ("1"=LED on, "0"=LED off) and their respective timing relationship.

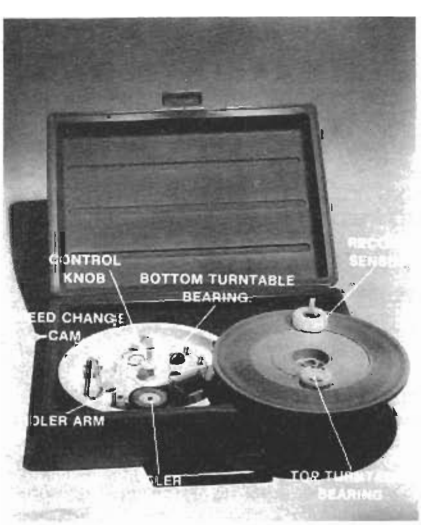
Turning the TIME/DIV knob fully counter-clockwise to AS (auto-sweep) allows the measurement of steady-state conditions by lighting the entire channel for a logic "1", or blanking the entire channel for a logic "0".

For storage operation simply switch the mode switch to "S" at any time, and the next sweep will store any information present.

If you wish to catch that elusive one-time pulse, simply place the unit in the proper conditions for usual storage operation, setting the mode switch to "S" before you place your probe on the test point you wish to measure. As soon as a pulse comes along it will be "caught" in the memory and held there as long for as you wish. **R-E**

Portable record player introduces new ideas

A new portable two-speed record player operates without the need for the conventional on-off switch, and uses



a hither-to-unknown method of changing speeds. The player simply puts on the record and turns the spindle in a clockwise direction to start the machine.

The new automatic speed changer operates around a "Magic Ring," a one-piece component made of *Celcon* (Celanese) plastic, which surrounds a spindle shaft centered within a shallow cupped base. This part acts as a weight sensor, and selects a speed of either 33⅓ or 45 rpm according to the weight of the record.

The center post of the "Magic Ring" is also the off-on switch. Turning it clockwise starts the machine. It is also the shaft of the volume control, and continuing to turn it brings up the volume.

Inventor and designer of the new-idea player is Art Tateishi, president of Seabreeze Products of Canada, a Toronto company which makes the unique player.

Industrial Research Institute honors zone-melting inventor

W. G. Pfann, who invented the zone melting technique for producing the high-purity metals that make modern transistors and integrated circuits possible, has been awarded the second Annual Achievement Award of the Industrial Research Institute. The Bell Labs was given a sculpture symbolizing creativity in industrial research, and was cited for "his vision and leadership in recognizing the requirements for ultra-high purity materials. This foresight resulted in his research on zone melting and refining and crystal growth techniques.

W. G. PFANN, BELL LABS SCIENTIST, center, receives the award, a sculptured work of art, entitled "Man and Technology." from Dr. N. Bruce Hannay, I.R.I. president, right. The presentation address was given by Dr. William P. Slichter, at left in the photo.

LEDs replace CRT in solid-state scope

by Forrest M. Mims, III
Albuquerque, N. M.

Thanks to the availability of low-cost light-emitting diodes, an all-solid-state oscilloscope can now be assembled. Figure 1 is the circuit diagram for a prototype that replaces the conventional CRT with a 10-by-10 array of GaAsP red LEDs. Although resolution of the 100-element screen is poor, pulses, square waves, triangle waves, and ramps are easily identifiable.

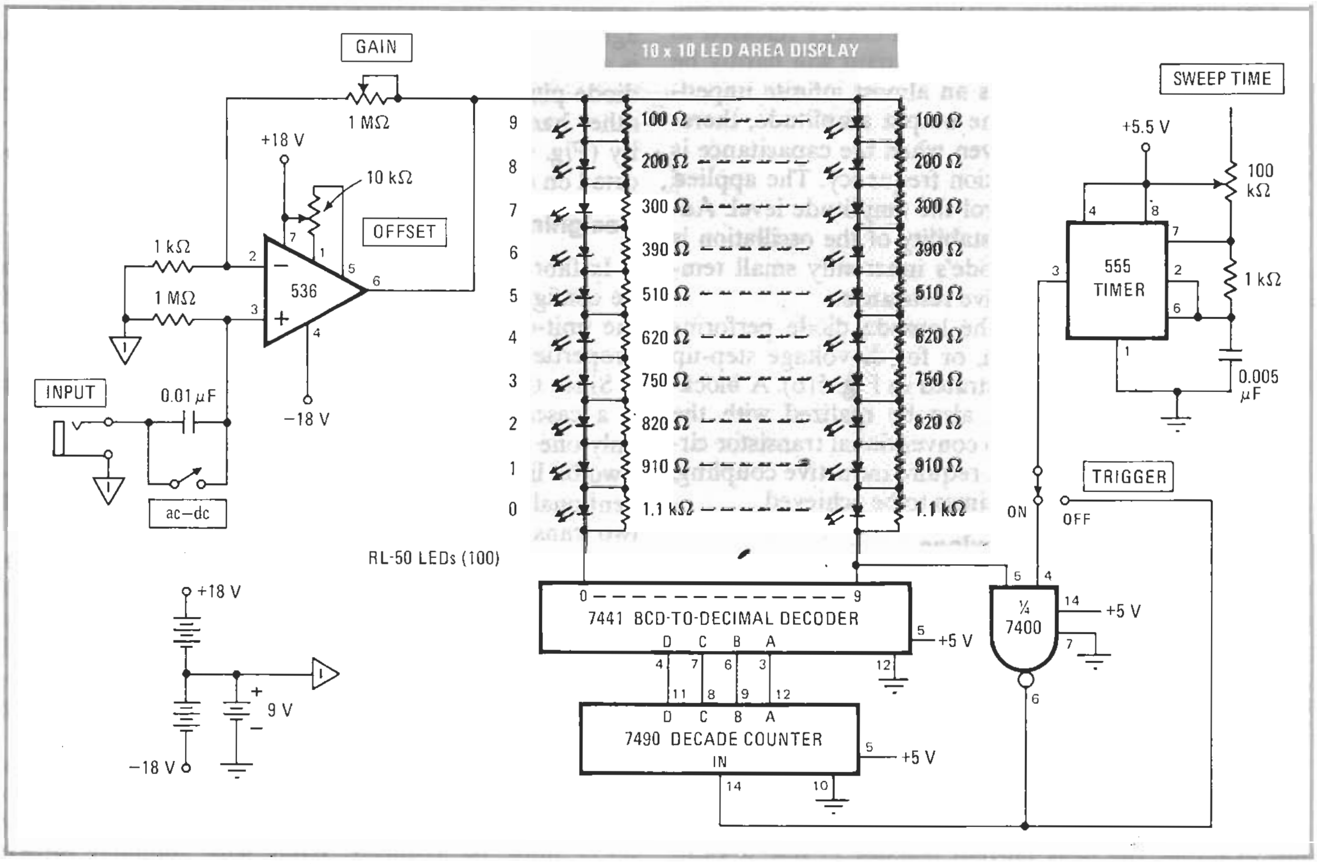
Input signals to the scope are ac- or dc-coupled to a 536 FET-input operational amplifier. The op amp is connected directly to 10 vertical columns of LEDs in series. The LEDs in each column are paired with individual resistors connected in series to form a voltage divider. The result is that each column of LEDs is a voltage sensor with a bar-graph-style readout.

The 10 LED columns are sequentially scanned by a sweep circuit composed of a 555 clock, a 7490 decade counter, and a 7441 one-of-10 decoder. A single NAND gate provides an optional automatic trigger feature for synchronizing the sweep with incoming waveforms from the op amp.

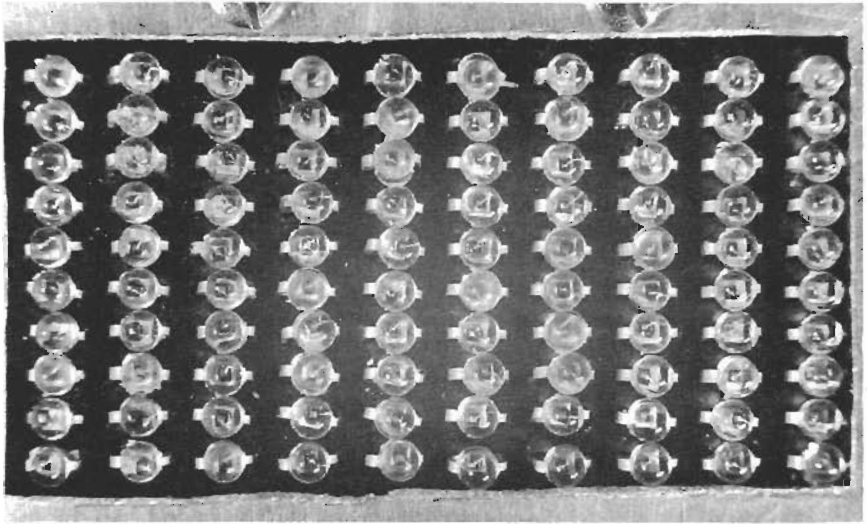
A pocket-sized version of the scope, measuring 4 by 6 by 13 centimeters, has front-panel controls that include vertical voltage sensitivity, horizontal time sweep, trigger, ac-dc, and power. The voltage sensitivity is adjustable from 0.01 volt per division to 1.0 V/division, where each LED is a division. The sweep is adjustable from 20 microseconds/division to 1.0 second/division. The amplifier and sweep circuits consume a maximum of 54 milliwatts, and the display consumes a maximum of 308 mW when all of the LEDs are on.

Figure 2 is a photograph of the scope's LED screen. The prototype scope shows only half of a bipolar waveform, and the input connections must be reversed to view the other half. □

Engineer's Notebook is a regular feature in Electronics. We invite readers to submit original design shortcuts, calculation aids, measurement and test techniques, and other ideas for saving engineering time or cost. We'll pay $50 for each item published.



1. Solid-state scope. Waveforms are displayed on 10-by-10 array of LEDs in this scope. Incoming signal is amplified and applied to all 10 columns of LEDs, and decoder completes circuit through each column in sequence to provide scanning. Display shows only the positive half of an ac waveform. The pattern is like a bar graph in that all lights below top of waveform are lighted; thus in a ramp, the bottom two LEDs might be lit in the first column, the bottom three LEDs in the second column, the bottom four in the next column, and so forth.



2. LED array. Light-emitting diodes are mounted on perforated board painted black to provide good contrast. Holes in board are 0.1 inch apart, so 10-by-10 array occupies area of approximately 1 by 2 in. Resistors for voltage divider are mounted right behind the LEDs, allowing compact packaging. A second board of similar size, stacked behind the LED board, holds the amplifier and scanning circuitry. Entire scope, including batteries, is about the size of a pocket calculator. Author built prototype for less than $40.

One-shot and flip-flop add single-sweep option to scope

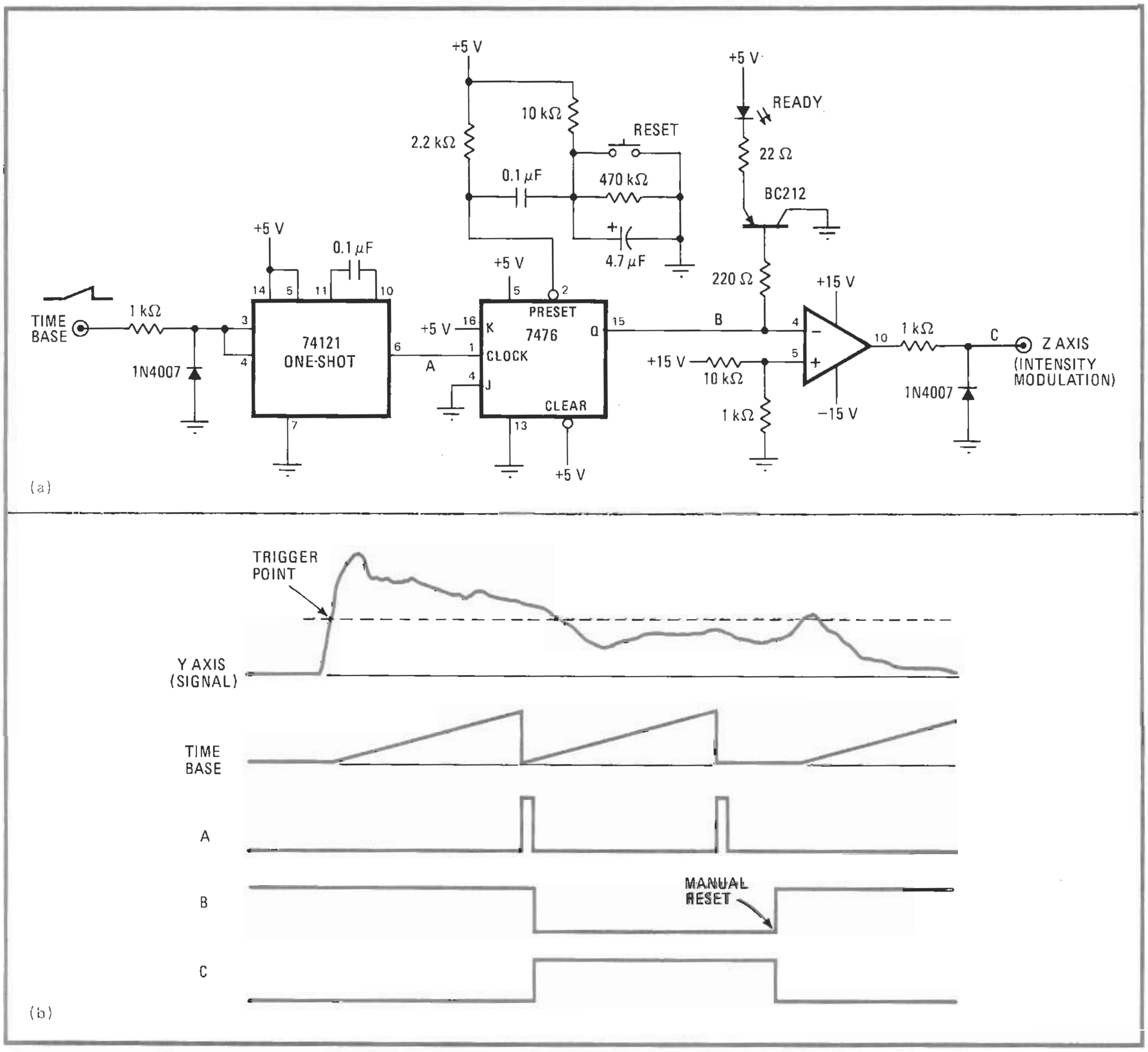
by M.C.W. Moerdijk
N. V. Kema, Arnhem, the Netherlands

Oscilloscopes that have a Z axis, or intensity modulation, input can easily be modified for the single-sweep option if needed, provided the scope's sweep (time-base) signal is externally available. This inexpensive Z-axis blanking circuit has been used successfully with the popular Philips PM3210 oscilloscope and can be used with the older Dumont scopes as well.

As shown in the figure, the internal sweep signal is connected to the time-base terminal of the circuit. The scope is placed in the external trigger mode and preset to a suitable triggering level.

Input (Y-axis) signals exceeding the trigger point initialize the internal sweep, and the signal is traced across the scope face. The negative edge of the ramp (X-axis) signal terminates the trace period, firing the 74121 one-shot multivibrator, which in turn resets the 7476 J-K flip-flop. The flip-flop drives the following comparator high, generating a signal to the scope's Z axis that blanks the trace before the time base can sweep again (if the input signal is above the set threshold).

Depressing the momentary-contact switch generates a negative-going pulse to the preset input of the flip-flop, thereby setting Q and resetting the Z-axis line. This reset scheme is most effective in applications where Y-axis signals trigger the ramp generator only occasionally, even if the signals exceed the threshold point for a considerable length of time thereafter. When the trigger threshold is exceeded periodically, a partial sweep will often be generated—the result of initiating the manual reset while the ramp generator is running. □



One sweep per trigger. Adding single-sweep option to Z-axis scope requires a one-shot, J-K flip-flop, and comparator, assuming that external time-base option is available. Trigger signal initiates ramp, and scope then displays signal for one cycle of the time base. Falling edge of ramp generates signal to Z axis, blanking trace until circuit is reset manually.

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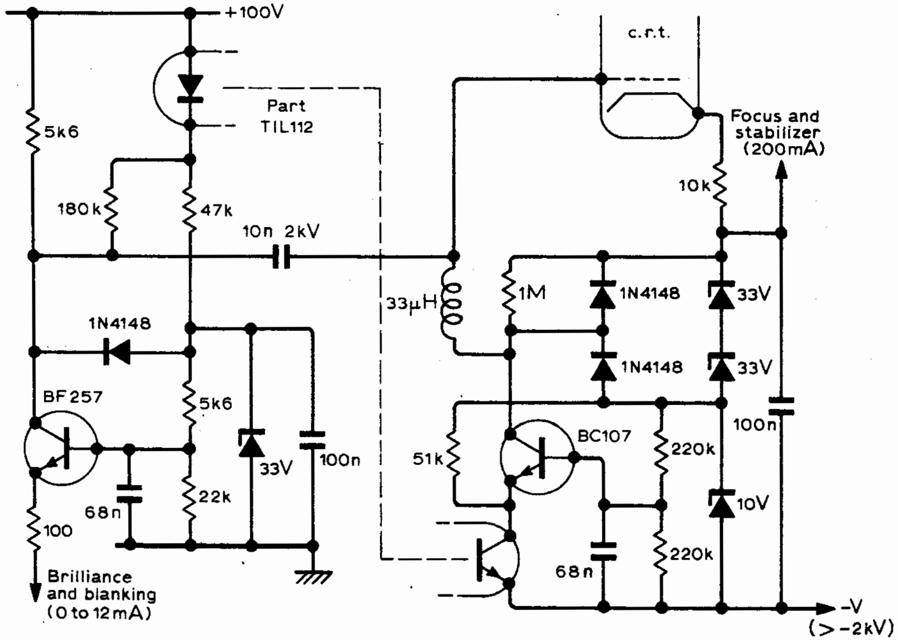


Optically coupled grid blanking

Grid blanking for c.r.ts can be a problem due to the high direct voltage difference between the blanking amplifier and c.r.t. grid. This often necessitates the use of a second h.t. winding to provide a floating supply. In this circuit an opto isolator is used with unity gain loading to provide d.c. and low frequency control. the 10nF capacitor takes over at higher frequencies. In order to maintain linearity within 5%, the isolator is biased to deliver 130μA and can deliver 60 p.i.v. at the c.r.t. grid. Temperature stability is adequate, and the brilliance control can be mounted in the low voltage section of the circuit. It is advisable to mount the blanking amplifier as close to the tube base as possible in order to maintain bandwidth and immunity to interference.

J. M. Rubery,
Rotterdam,
Holland.

Trace Quadrupler for D.C. 'scopes

by D. Bollen

The quadrupler unit can be added to a single-beam scope to give four independent *Y* traces, or a pair of *XY* traces, without sacrificing sensitivity or d.c. coupling. All traces can be positioned anywhere on the screen without interaction. The principle of the quadrupler is to sample four inputs, by means of linear transmission gates switched by a *JK* flip-flop ring-counter. Inputs are sampled one at a time (quad mode) or two at a time (dual-pair mode), at switching frequencies extending to 2MHz.

Fig. 1 shows two methods of sampling four *Y* inputs one at a time. In Fig. 1(a), a free-running oscillator triggers the ring-counter and causes each gate to open in turn. Provided that the sampling frequency is not harmonically related to the timebase frequency, the display will appear to be four continuous input waveforms. The quality of this chopped display depends on a clean switching waveform with fast rise and fall times and a minimum of under- or over-shoot contributed by the 'scope. However, it is difficult to avoid some trace thickening at high 'scope sensitivities, and a screen glow due to the finite rise and fall times of the switching waveform at sampling frequencies in excess of 100kHz.

A much better display at fast sampling rates can be achieved if the traces appear alternately, triggered by timebase flyback, see Fig. 1(b). Here the unwanted transients occur only at the edges of the screen, so there is no trace thickening or glow. The limitations with timebase triggered sampling are break-up of the display when switching and propagation delays exceed flyback time, and a display flicker below 5ms/cm, with average persistence screen coatings, due to the natural time division of four.

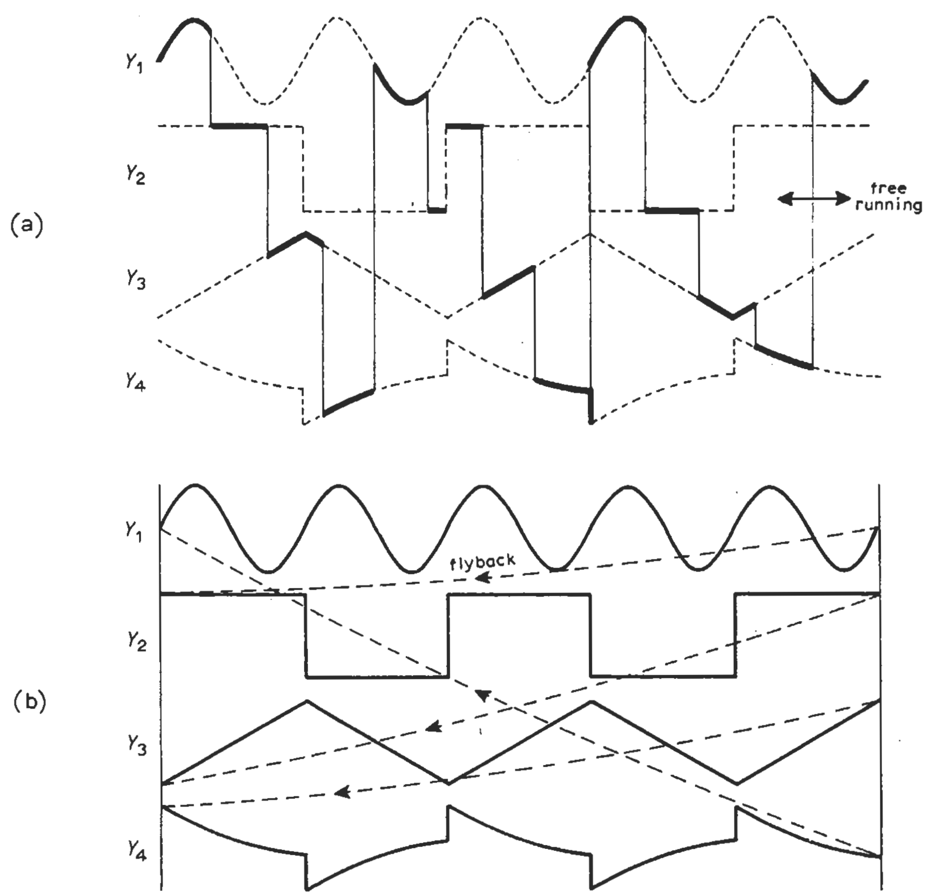
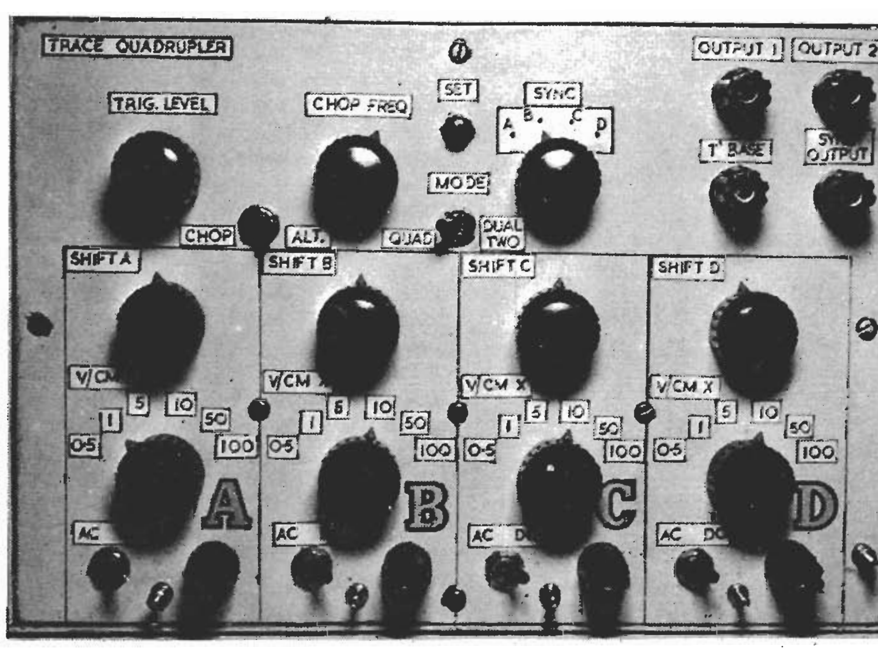


Fig. 1. How a four-trace display is built up, (a) in the chopped trace mode, and (b) in the alternate trace mode.



The block diagram of the quadrupler is given in Fig. 2. Input signals are applied, via frequency compensated attenuators, to four identical non-inverting pre-amplifiers, each having a gain of two, an f.e.t. input, a low output impedance, and variable d.c. output shifting. The four-position switch S_1 allows a sync. signal to be taken from any pre-amp. output, prior to gating. Gates are opened by the ring counter in a sequence selected by S_2, in response to clock pulses derived from either a square-wave oscillator with six switch-selected chop frequencies, or from a timebase triggered Schmitt. The wide choice of chopping frequencies ensures freedom from harmonic locking with the timebase.

Gating

The basic circuit of the quadrupler four-diode gate is given in Fig. 3. When the gate pulse goes positive all four diodes conduct, and R_1 and R_2 are connected to the signal path. The input does not actually drive the gate output, but merely allows R_1 and R_2 to 'pull up' and 'pull down' the output terminal. Thus, when $R_1 = R_2 = R_3$ the maximum amplitude the gate will handle will be half the gate pulse amplitude, beyond which there will be clipping of signal peaks. With the gate open a signal passes from input to output with virtually no shift of d.c. level and very little attenuation.

All diodes are rendered non-conducting when the gate pulse goes negative, thus closing the gate. Each diode can then be represented by a small capacitor of about 3pF, in series-parallel with input, output, R_1 and R_2. This small value of capacitance accounts for the intermodulation between channels at high input frequencies, typically 10% at 8MHz. Fig. 4 gives the display sequences for quad and dual-pair operation.

Ring counter

The action of the ring counter in circuit Fig. 5 is to transfer a pulse, or a group of pulses, from left to right along outputs A to D when triggered by clock pulses.

A brief description of *JK* flip-flops will help to explain the chain of events in the ring-counter. Each *JK* element consists of inputs *J* and *K* feeding a master bistable, which in turn feeds a slave bistable having outputs Q and $\bar{Q}$. On the leading edge of a positive-going clock pulse, master and slave are first disconnected from each other, then information present at *J* and *K* terminals is entered into the master. As the clock pulse trailing edge arrives, *J* and *K* terminals are first isolated from the master then the previous information is transferred from master to slave, and appears at Q and $\bar{Q}$.

In the ring counter of Fig. 5, any *JK* element will assume the 'state' of the *JK* in front of it at the termination of a clock pulse. Meanwhile the preceding *JK* may well have changed state in response to the *JK* in front of it.

The action of preset and clear inputs is to override clock pulses and hold the slave bistable in a known condition. With preset earthed Q will be held on, and $\bar{Q}$ is held on by the clear input. In the quadrupler ring counter, clock pulses are continuous and the mode of operation is first selected by S_1 and then implemented by pressing S_2. If S_1 is placed in the quad position while the ring counter is running, all the outputs A to D

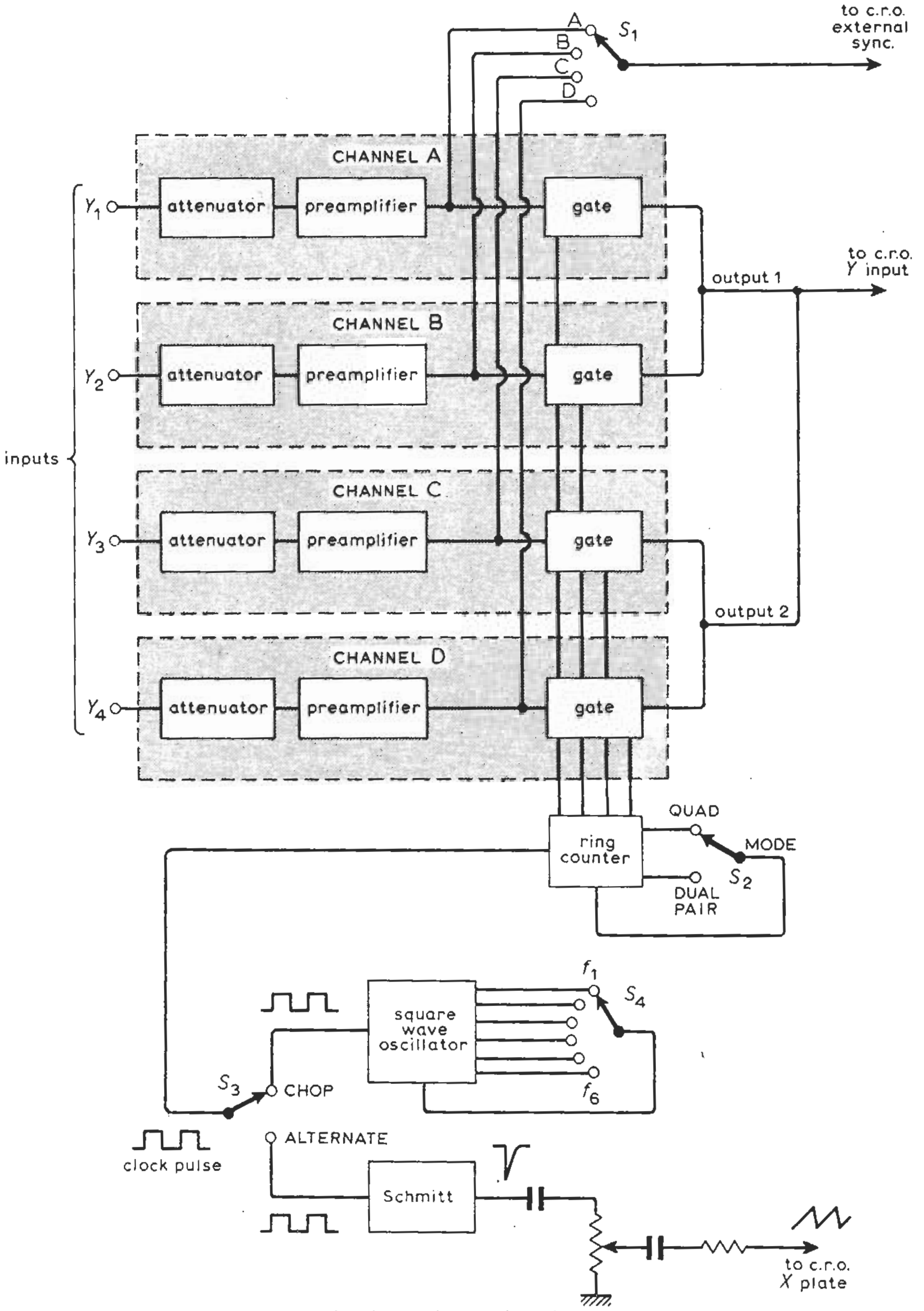


Fig. 2. Block diagram of the quadrupler in the quad mode.

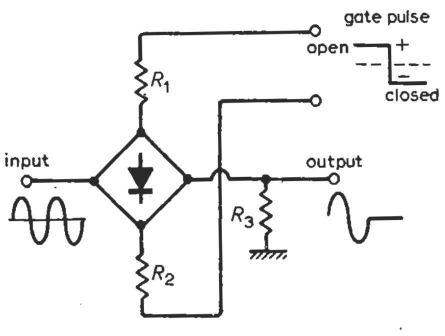
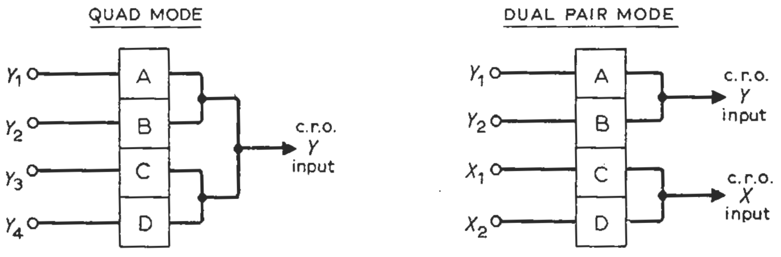


Fig. 3. Linear transmission gate. The input signal is controlled by the gate pulse.



sequence	gate open	display
1	A	Y_1
2	B	Y_2
3	C	Y_3
4	D	Y_4

sequence	gate open	display
1	A,C	Y_1, X_1
2	B,D	Y_2, X_2

Fig. 4. Gate switching sequences in the quad and dual-pair mode.

will freeze as soon as S_2 is pressed, with A 'on' (about 4V) and B, C, and D 'off' (about 0.2V). As S_2 is released, the first clock pulse transfers the 'on' condition from A to B, and thence to C and D on receipt of further clock pulses. If S_1 had been set to dual pair, pressing S_2 would have caused A and C to turn on, with B and D off, After releasing S_2, the first clock pulse would then shift 'on' from A and C to B and D, and back again with the second clock pulse.

Pre-amplifier

In the following circuit diagrams, quadrupled components are suffixed with the letters A, B, C or D, to correspond with the channel in which they are used. Components common to all channels have no suffix.

The pre-amplifier circuit of Fig. 6 has input attenuators designed around an impedance of 3MΩ shunted by 10pF, plus another 5pF from circuit strays. Maximum error is +3.3% −3% using 2% resistors selected on the basis of ±5% preferred value increments. In choosing attenuator division ratios consideration was given to achieving the widest possible range with only six steps, by omitting the 2 from a 1, 2, 5 sequence. With 'scope sensitivity set to 100mV/cm, each quadrupler input will, for example, offer 50mV, 100mV, 500mV, 1V, 5V, and 10V/cm.

The amplifier section of Fig. 6 uses parallel derived, series injected d.c. negative feedback, controlled by R_{39A}, to hold the gain down to two and reduce output impedance to less than 100 ohms. Capacitive shunting of the feedback path (C_{13} and C_{14} assisted by C_{15}) maintains gain up to 5MHz.

Ideally the pre-amplifier shift controls R_{40} should permit adjustment of Tr_2 collector voltage without influencing gain, but in practice there is some attenuation of signals with shift voltages greater than −4V, but this is apparent only with 'scopes having 10cm vertical scale at 1V/cm.

Quad-gate

It was noted earlier that gate pulse amplitude should exceed maximum signal amplitude if clipping is to be avoided. Also, a large gate pulse will tend to give cleaner switching. In the circuit of Fig. 7, the diode gates are switched by transistor pairs Tr_3 and Tr_4, with the base of each transistor driven from ring counter Q and $\bar{Q}$ outputs, thus achieving a gate pulse of more than twice the maximum signal amplitude.

As the need for fast gate opening and closing is mainly dictated by minimum timebase flyback time when working with alternate traces, 300ns for the quadrupler gates should be adequate with timebase sweeps of 50ns/cm or more. However, this gating time can be halved, if so desired, by omitting i.c. output protection resistors R_{25} and R_{26} from the circuit of Fig. 8.

Ring-counter and clock

In Fig. 8, flip-flop ground connections are taken to the −12V rail, instead of to earth, so that d.c. coupling can exist between ring counter outputs and the gate switching transistors, thus allowing the quadrupler to

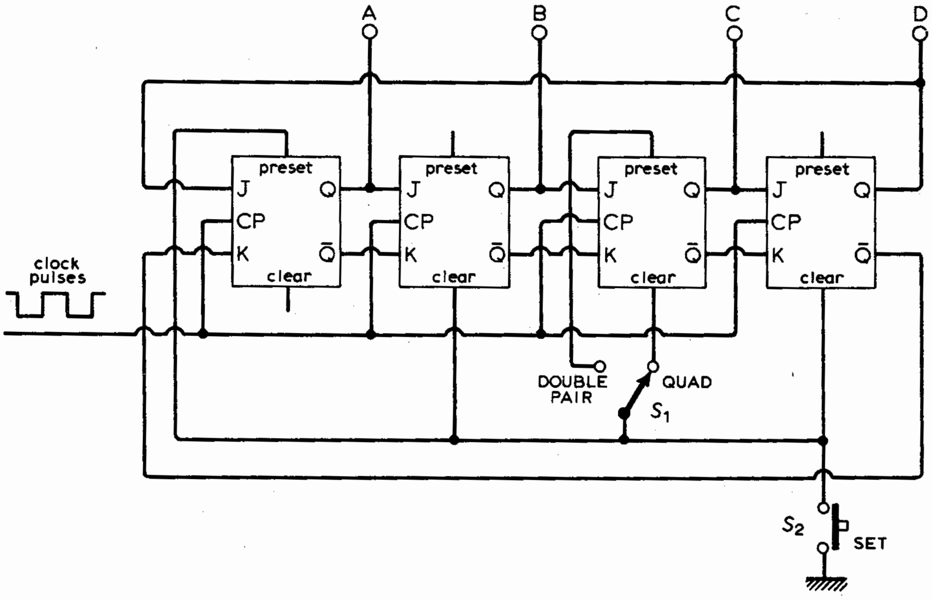


Fig. 5. The ring counter showing the set and reset arrangements.

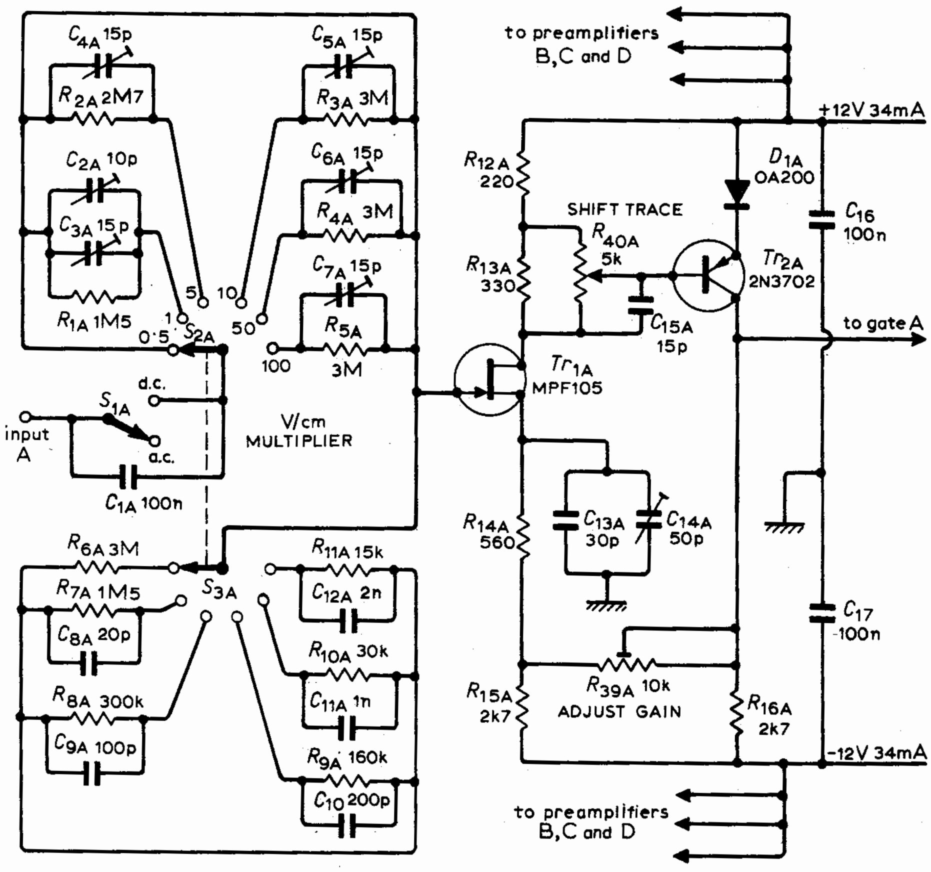


Fig. 6. One of the four input pre-amplifiers.

be used with long-persistence tubes at very slow sampling rates. Therefore, if resistors R_{25} and R_{26} are removed to improve gate switching times, accidental shorting to earth of ring counter outputs will almost certainly result in catastrophic failure of i.cs; a point to be borne in mind. Transistor Tr_5 in Fig. 8 supplies a roughly stabilized +5V to the ring counter, relative to the −12V rail.

If the quadrupler ring counter was susceptible to random noise pulses it would tend to assume an unwanted mode during use, and switch the wrong gate at the wrong time. The series 74N family demands a clock pulse with rise and fall times of less than 150ns for good noise immunity, and clock pulses should also originate from a low impedance source with a logic 0 of less than 0.4V and a logic 1 of more than 2.4V. The above conditions are satisfied by the clocking circuits of Fig. 8. Complementary emitter followers Tr_6 and Tr_7 ensure a low impedance, and provide a logic 0 and 1 of 0.2V and 4.5V respectively, when overdriven by the square-wave oscillator and Schmitt trigger. The 2N3702 used for Tr_7 saturates at around 0.2V.

The somewhat unusual square-wave

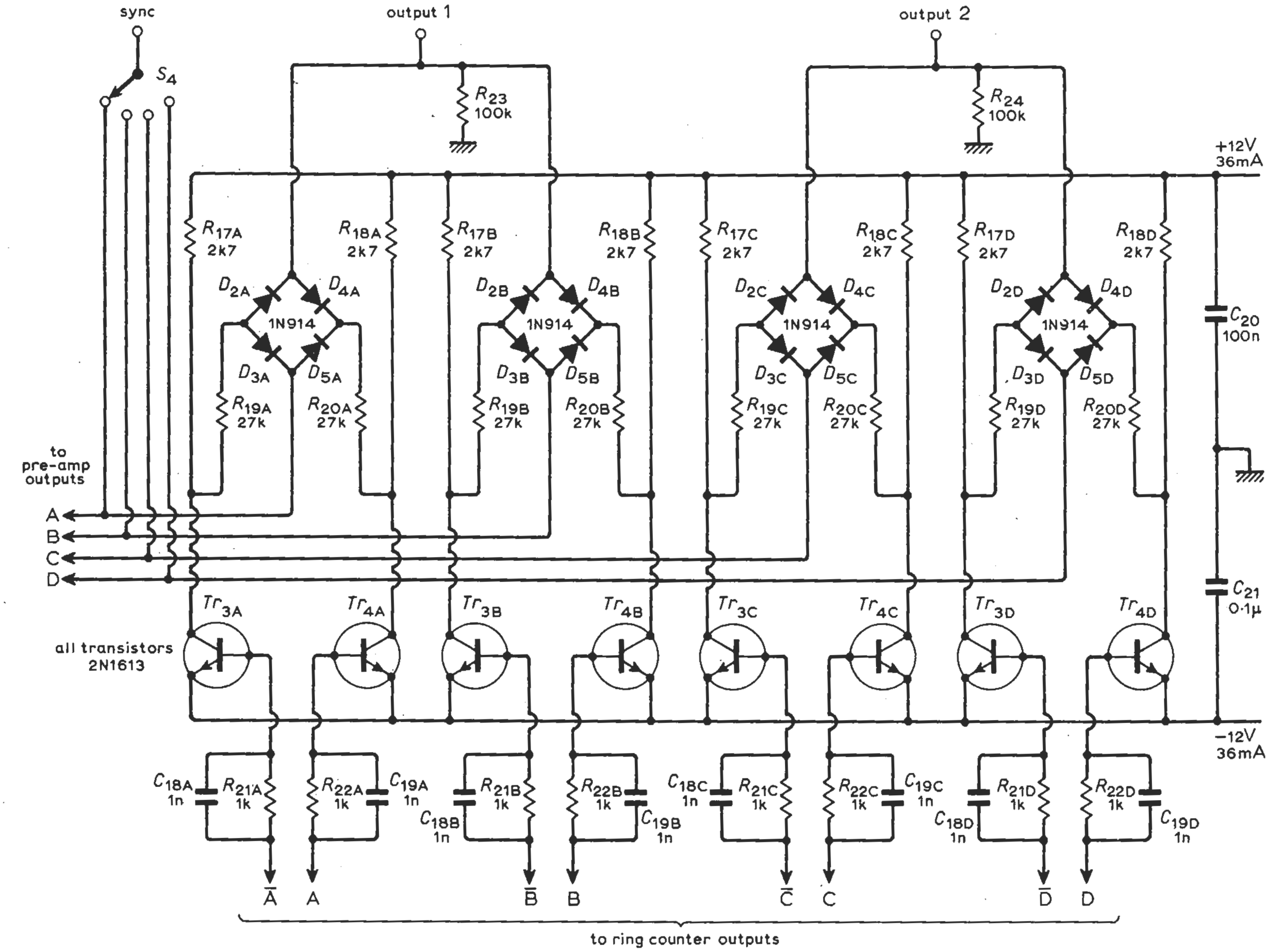


Fig. 7. The four linear transmission gates with the components for interfacing with the counter.

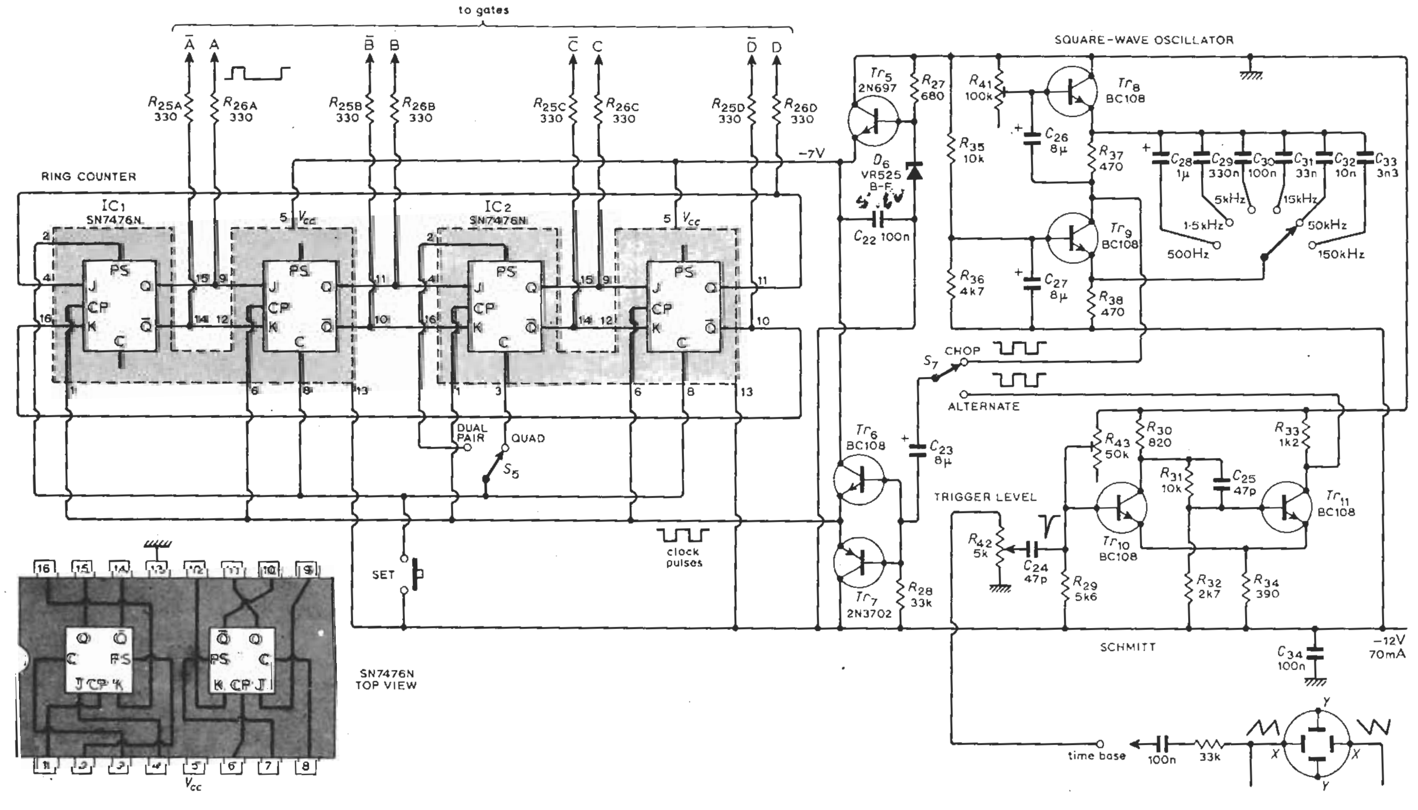
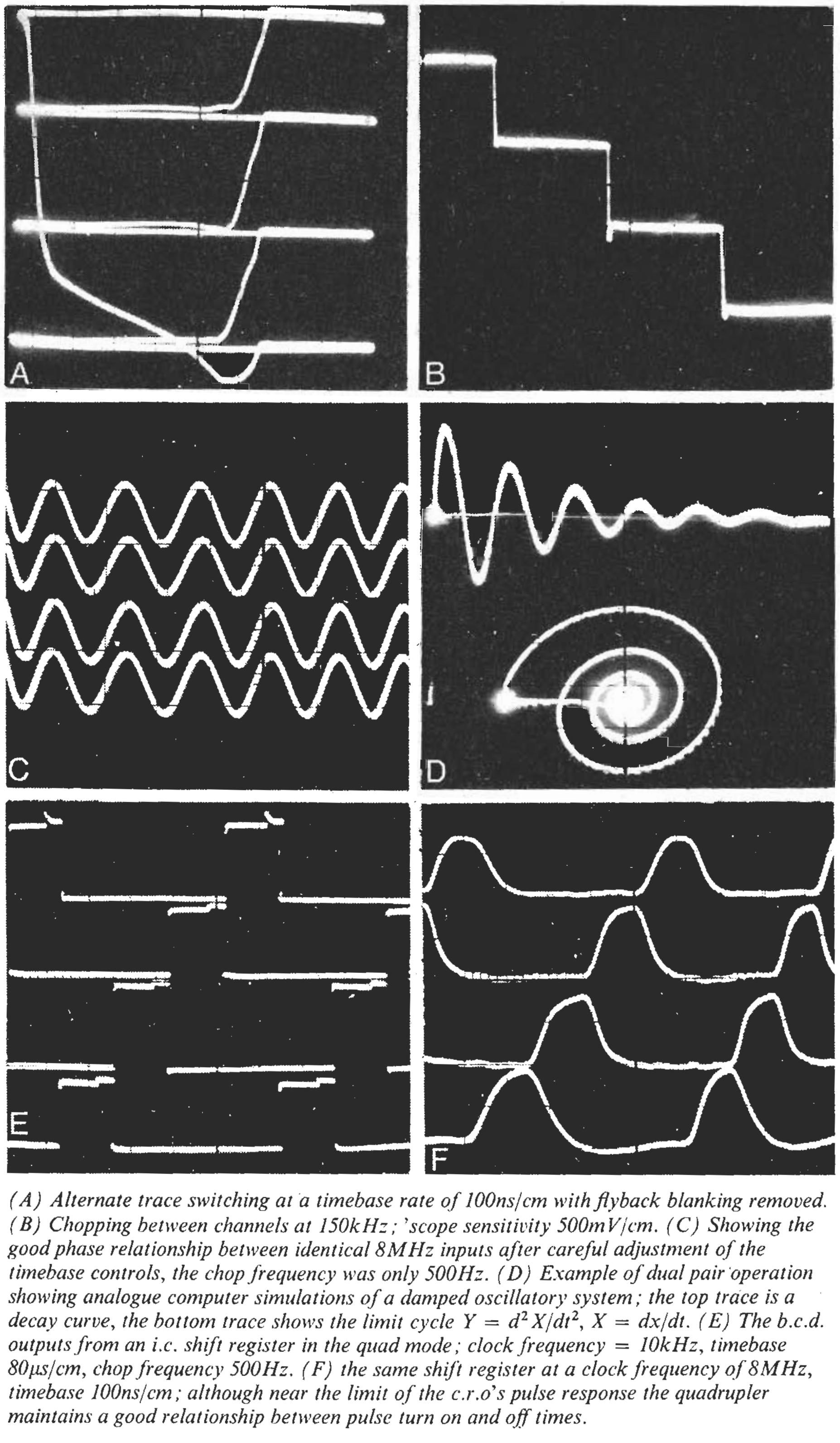


Fig. 8. Ring counter and clock pulse circuits.



(A) Alternate trace switching at a timebase rate of 100ns/cm with flyback blanking removed. (B) Chopping between channels at 150kHz; 'scope sensitivity 500mV/cm. (C) Showing the good phase relationship between identical 8MHz inputs after careful adjustment of the timebase controls, the chop frequency was only 500Hz. (D) Example of dual pair operation showing analogue computer simulations of a damped oscillatory system; the top trace is a decay curve, the bottom trace shows the limit cycle $Y = d^2X/dt^2$, $X = dx/dt$. (E) The b.c.d. outputs from an i.c. shift register in the quad mode; clock frequency = 10kHz, timebase 80µs/cm, chop frequency 500Hz. (F) the same shift register at a clock frequency of 8MHz, timebase 100ns/cm; although near the limit of the c.r.o's pulse response the quadrupler maintains a good relationship between pulse turn on and off times.

oscillator of Fig. 8 offers the following advantages over a conventional astable multivibrator; approximately equal rise and fall times of less than 150ns, and frequency selection by single capacitors. Potentiometer R_{41} establishes the mark-space ratio.

Looking next at the Schmitt, this is designed to operate beyond 2MHz, with capacitor C_{24} differentiating the timebase sawtooth to provide a steep negative-going pulse from the flyback edge. An output from the 'scope to the trigger control R_{42} is most conveniently taken from one of the X plates via a resistor of about 33kΩ in series with a 100nF isolating capacitor, but it might be preferable with transistor 'scopes to omit the resistor and tap off the sawtooth from the low-voltage timebase circuit.

Construction

Signal paths and ring counter output leads should be kept as short as possible, as should the connection from the timebase input socket to the Schmitt. It is, of course, essential to screen pre-amplifier inputs and attenuators against hum and pulse transients. The circuits of Figs. 6, 7, and 8 can be assembled on separate panels and positioned close to their controls and switches.

Capacitors C_{16}, C_{17}, C_{20}, C_{21}, C_{22}, and C_{34} are ceramic discs, and, apart from polyesters C_1 and C_{29}–C_{32} and electrolytics, all remaining fixed capacitors are polystyrene. Trimmer capacitors used in the attenuators and pre-amplifiers should be either ceramic or air-spaced, *not* mica compression.

All resistors, excluding the 2% metal oxide or high-stability used in the attenuators, are 10% 0.5W carbon. Pre-sets R_{39}, R_{41} and R_{43} can be sub-miniature skeleton types.

Power supply

The quadrupler should be run from a well stabilized 12–0–12V power supply capable of 200mA output. In the absence of such a supply, two 12V dry batteries will give tolerable results when shunted by 2500µF capacitors, for initial testing at reduced accuracy and increased drift.

Alignment

An audio, r.f., and square-wave generator will aid quick and accurate alignment of the quadrupler. Failing such test instruments simple oscillators can be made up in breadboard form to yield sine wave outputs of 1kHz and 5MHz, and a square wave of 1kHz; 5kΩ carbon potentiometers can be used as oscillator output attenuators, with the slider output shunted to earth by a 100Ω resistor in the case of the 5MHz oscillator.

First, check that the quadrupler functions correctly in the quad and dual pair modes with chopped and alternate traces. Ignore for the time being the amount of trace shift given by R_{40A-D} as this is dependent on pre-amp. gain.

Connect the quadrupler to the oscilloscope as shown in Fig. 9. Inject a 1kHz sine wave signal into the 'scope and adjust controls for a display of 4cm peak to peak. Set the quadrupler attenuators to 1V/cm and switch the 'scope input to the quadrupler outputs. Adjust R_{39A-D} for four identical waveforms of 4cm peak-to-peak. Superimpose the waveforms to check gain uniformity, and ensure that R_{40A-D} will deflect their traces off the screen when the 'scope is set to 1V/cm.

Now set quadrupler attenuators to 0.5V/cm and inject a 5MHz signal from a low impedance source into the 'scope input. Adjust 'scope sensitivity for a display of 2cm peak-to-peak. Switch this same signal through the quadrupler and trim C_{14A-D} for four identical waveforms of 4cm peak-to-peak. If the 'scope has insufficient bandwidth to display an undistorted 5MHz waveform of 4cm, either reduce signal amplitude or use a lower frequency.

The final test uses a square-wave generator to align attenuator capacitors for optimum pulse response. With quadrupler attenuators at 0.5V/cm apply a 1kHz square wave of about 1V to inputs A–D and adjust 'scope sensitivity for a display of about 4cm peak-to-peak. Assuming that the 'scope itself is correctly aligned, there should be virtually no over or undershoot, see Fig. 9. Now switch quadrupler attenuators to 1V/cm and increase signal amplitude to again give a display of 4cm peak-to-peak. Adjust C_{3A-D} to obtain a correct square-wave response. The same process is then

Each channel	
input impedance	3MΩ and 15pF
frequency response	Flat d.c.-5MHz, −3dB at 8MHz
rise time	⩽ 10ns
intermodulation between channels	< 0.15% at 100kHz
	< 4.5% at 4MHz
	< 10% at 8MHz
maximum output	±5V into 100kΩ (quad mode) or into 50kΩ (dual pair mode)
trace shift	±6V
attenuator error	< ±3.3%
attenuator range	V/cm times 0.5, 1.5, 10, 50, 100
scope input drift	3mV/°C after warm-up
interchannel drift	0.5mV/°C
trace 'noise'	about 2mV, depending on 'scope and layout
Sampling	
chop frequencies	0.5, 1.5, 5, 15, 50, 150kHz
maximum alternate trace frequency	⩾ 2MHz, depending on flyback time

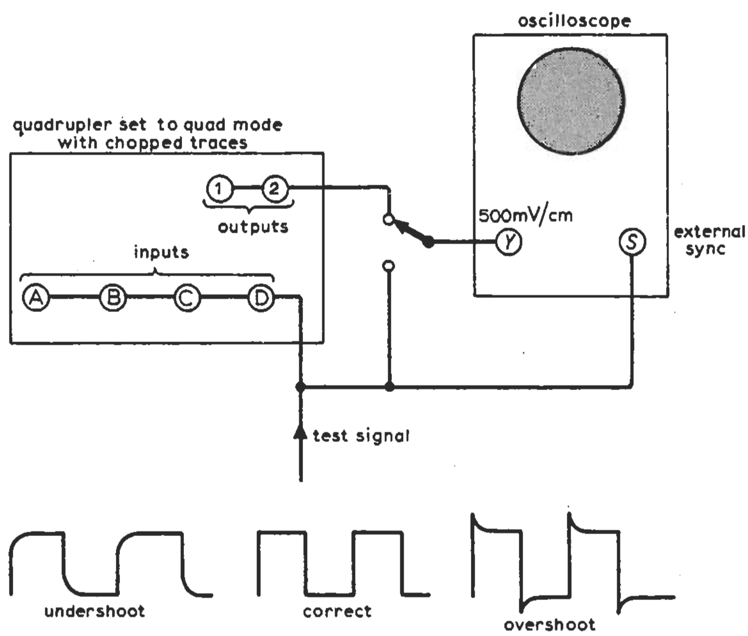


Fig. 9. Quadrupler alignment test circuit. Waveforms show the effect of attenuator trimming capacitor adjustment.

repeated for the remaining attenuator positions, by trimming appropriate capacitors ($C_{4A\text{-}D}$–$C_{7A\text{-}D}$). It will be necessary to increase 'scope sensitivity for an adequate display when the highest attenuator ranges are being trimmed.

The quadrupler in use

There is little to be gained in trying to operate the quadrupler with 'scope sensitivities of less than 50mV/cm as drift and trace noise will then prove troublesome. At the other end of the scale, severe waveform distortion can result if the 'scope is set higher than 1V/cm. With 'scope sensitivities confined to 100mV–1V/cm, quadrupler attenuators will still cater for inputs of from 50mV–100V/cm, and this should be more than adequate for most purposes.

Pre-amplifiers will begin to overload when input voltages exceed five times the V/cm attenuator setting and catastrophic failure of f.e.ts may result as voltages approach fifty times V/cm. Care must therefore be exercised in the choice of low attenuator settings when dealing with inputs of more than 20V amplitude.

With all electronic switch trace multipliers there can be some doubt that a correct phase relationship exists between independent input signals. Alternate trace working is more convenient to operate over a wide range of timebase speeds, and gives a better quality display, but it carries with it the penalty of 'phase slipping' at low audio frequencies and high r.f. Chopped trace working, on the other hand, ensures perfect phasing as long as the chop frequency exceeds that of the timebase, thus covering all signals up to a few hundred kilohertz.

Careful adjustment of timebase stability and trigger controls will usually minimize phase errors between high-frequency signals to within a few degrees. The technique is to first link quadrupler inputs together and inject a common signal, then the timebase is adjusted for a 'slip free' display while deriving a sync. signal from one of the pre-amplifier outputs.

Announcements

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The Electronics Division of the Institution of Electrical Engineers are organizing a residential vacation school on **M.O.S. Circuit Design,** to be held at the University of Edinburgh from 25-29 September. Further details can be obtained from the Divisional Secretary (Electronics), I.E.E., Savoy Place, London WC2R OBL.

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maximum output	±5V into 100kΩ (quad mode) or into 50kΩ (dual pair mode)
trace shift	±6V
attenuator error	< ±3.3%
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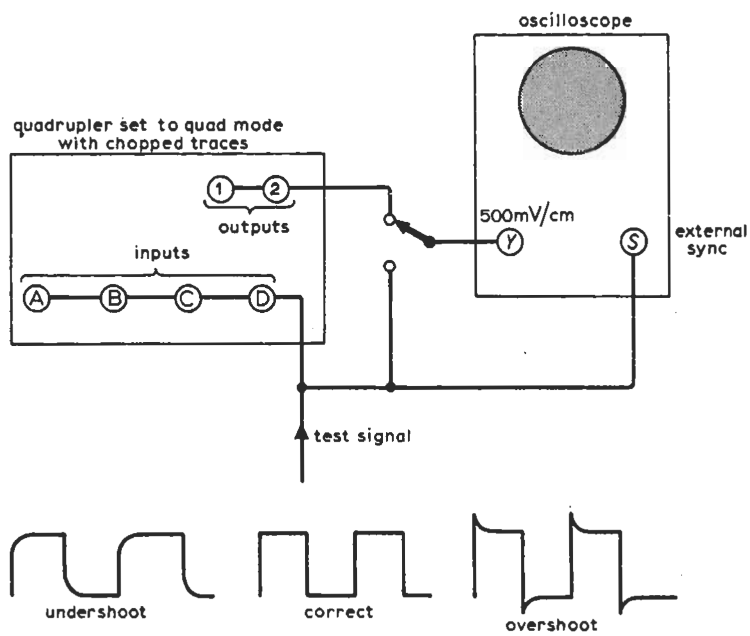

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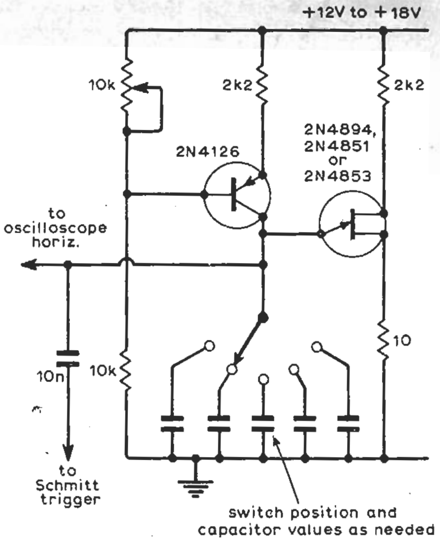
Trace quadrupler

I enjoyed reading D. Bollen's article on a trace quadrupler for d.c. 'scopes, in the May issue of *Wireless World*. I recently built a similar unit that used m.o.s. f.e.t. switches rather than the diode bridge. Mr Bollen shows the X plate used as the source for the trigger when the unit is in the alternate mode. Since many experimenters may not want to add an extra terminal to their 'scopes, or are reluctant to add anything to it I would suggest an alternative method.



Mr Titus u.j.t. oscillator for an oscilloscope trace quadrupler.

A constant current, unijunction transistor oscillator will produce a very linear sawtooth wave which may be used to trigger the Schmitt trigger. This sawtooth wave also supplies the horizontal sweep voltage for the 'scope when it is applied to the horizontal terminal. In this way it provides the trigger and the sweep. The frequency is varied through the use of a switched set of capacitors and a variable resistor.

J. A. Titus,
Blacksburg,
Virginia, U.S.A.

The author replies:
The trouble with 'scopes is that they come in all shapes and functions. Mr Titus' 'scope obviously has no external X plate connection, but is endowed with an X amplifier input, in which case the idea of a separate sweep oscillator is certainly worth considering. Being of a lazy disposition, I would rather add a few components to the 'scope than build a sweep oscillator, on the principle that the more terminals there are the greater flexibility there is.

Assuming that an external sweep oscillator is either desirable or unavoidable, my main objection to the u.j.t. circuit is that it will operate only up to 100kHz or so, with a sluggish flyback. Even cheap 'scopes can usually muster a timebase rate of 500kHz, and the trace quadrupler will respond to 2MHz, so it does seem to be rather a waste of top-end performance. An emitter follower should

Test Equipment Scene

By Leslie Solomon, Technical Editor

4-Channel CRT Viewing

ALTHOUGH we, as serious electronics experimenters and service technicians, have access to the latest in test equipment, quite often our needs are one step ahead of the available instruments. Take the case of waveform analysis as an example.

Although two-channel scopes are readily available, as are dual-trace converters for single-trace scopes, there are many occasions when even two traces are not enough. This is especially true when observing several signals in a digital counter, aligning an i-f strip, servicing audio systems—any occasion when it is necessary that a number of signals have certain specific and accurate relationships in order for the complete system to operate properly.

Since multiple trace displays are not readily available now, we have cooked up a small circuit that does the job at reasonable cost. Because 5-inch scopes seem to be so popular and since four traces fit nicely on such a scope, the circuit is designed for four traces. (Most of the readers we have contacted on this subject seem to be interested in displaying four traces.) The circuit (Fig. 1) uses CMOS IC's so the power requirements are minimal. Only the circuit is shown —the serious instrument builder can readily design his own pc or perf board layout.

The heart of the 4-channel switcher is the 4016 transmission gate, also known as a quad bilateral switch—which has no equivalent in any other type of logic. Essentially, each transmission gate (TG) consists of a CMOS device that is connected in series with an input signal and the scope. (There are four such gates in a 4016).

Each TG acts as a conventional mechanical switch, in that, when its control element is driven one way, the CMOS device looks like an open circuit; and when the control element is driven the other way, the device looks like a short circuit. Also, like a mechanical switch, either end of a TG can be the input or output.

The circuit uses a pair of flip-flops (4013) and a set of two-input NOR gates (4001) used as a decoder and arranged to deliver four independent successive gate signals—one for each input trigger signal (pin 3 of the 4013). Each NOR output turns on its pair of associated TG's in sequence, with only one pair of TG's operating at the same time.

The four audio inputs are passed through their own gain controls and then to one of the four lower TG's. The four outputs are connected to the common summing output through isolation resistors. In this way, each audio channel is sampled successively and presented to the scope.

Each audio TG has an associated bias TG (upper 4016) which is turned on simultaneously. The bias TG's deliver a predetermined dc voltage (set by the associated positioning control) to the summing output. In this way, each channel can be independently positioned on the scope. By keeping the audio input level low and properly spacing the four traces, they will easily fit on a 5-inch scope.

Trigger Source. The 4013 requires a positive going input trigger on pin 3. This can be provided in one of two ways—either in a

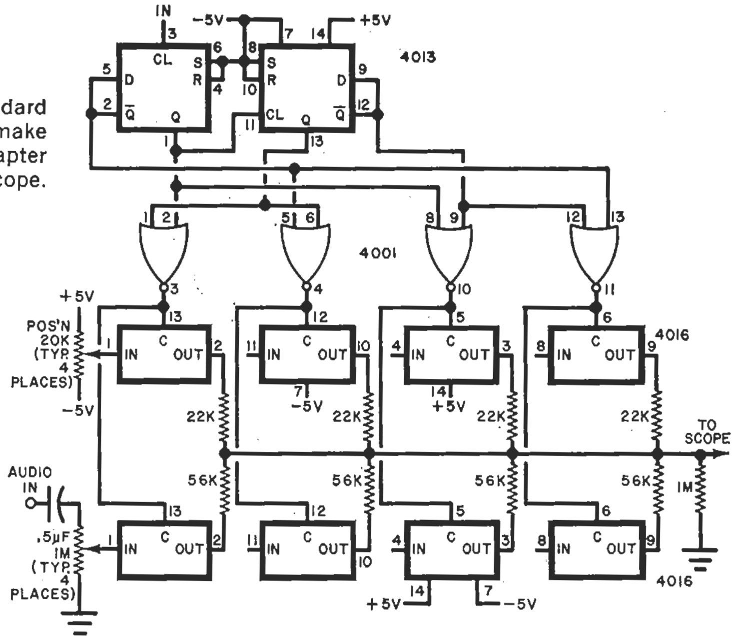


Fig. 1. Just four standard CMOS IC's are used to make a handy four-trace adapter for a single-channel scope.

chopped mode or an alternate mode. Both arrangements are shown in Fig. 2.

In Fig. 2A, the chopped mode, a 4009 CMOS chip is arranged as a free-running multivibrator whose frequency is dependent on the value of *R* and *C*. The buffered output is connected to pin 3 of the 4013.

For alternate-mode triggering, with one channel for each sweep of the scope CRT, it is necessary to get to the scope's horizontal oscillator and pick off a pulse that occurs during the retrace. (The particular scope that we used had such an output provided on the rear apron.) The way in which this pulse is processed to drive the flip-flops depends on the pulse from the scope. In our case, we had a 2-volt negative-going pulse from the scope. The circuit is shown in Fig. 2B. Another transistor will provide phase inversion if necessary.

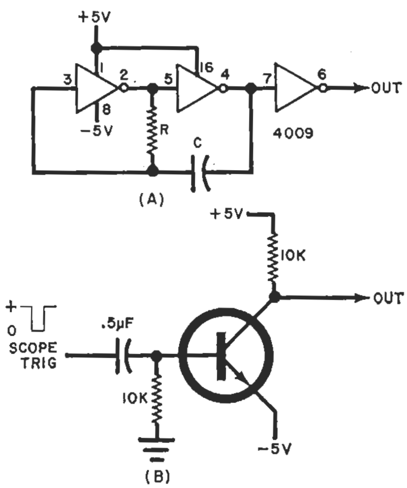


Fig. 2. Chopped mode of triggering uses a CMOS oscillator (A). Simpler circuit (B) is for alternate trigger.

Keep in mind that, in the alternate mode, the four traces will follow each other in time. Thus they will be dimmer than usual. However, we found that there was enough brightness left in the scope intensity control to compensate.

Generating Sync Pulse. Figure 3 shows one approach to generating a sync pulse for

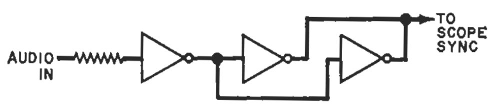


Fig. 3. Three CMOS inverters are used to make a sync generator for four-channel trace. Output inverters are in parallel.

the scope. Here, the selected audio channel is coupled into an inverter (4009) through an isolation resistor, and the output is taken from a pair of inverters in parallel to provide a heftier output signal to drive the scope sync. ◈

Chopping mode improves multiple-trace display

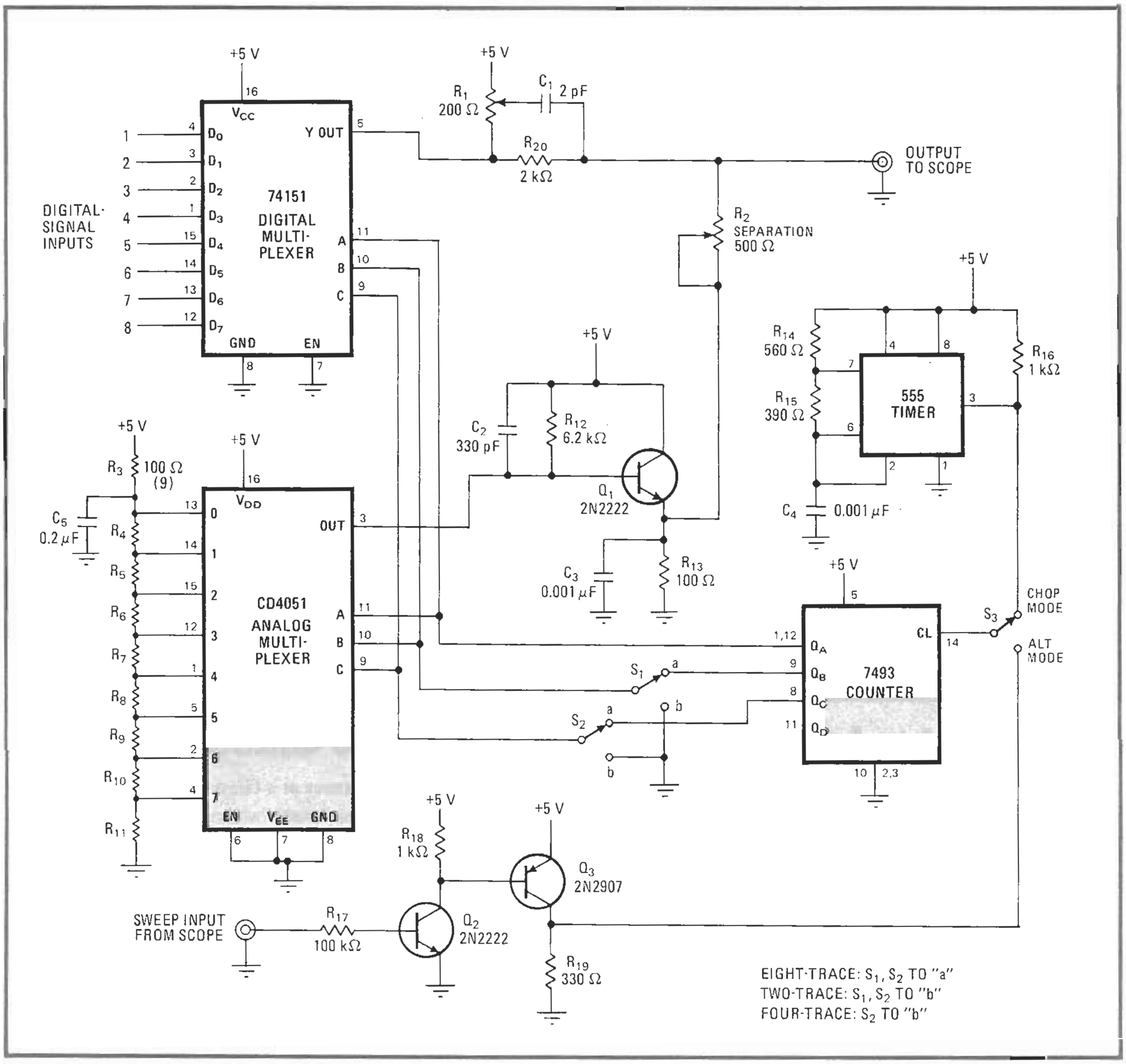
by C. S. Pepper
IRT Corp., San Diego, Calif.

A chopped mode of signal sampling extends the usefulness and versatility of an oscilloscope display that shows several signals simultaneously. The eight-trace oscilloscope switch described in [*Electronics* Dec. 25, 1975, p. 75] operates in an alternating mode that uses both beams of a dual-beam scope. One beam repeats as usual, and the second steps through a repeating pattern of eight vertical levels. Each level displays one line of digital data; the result is a nine-channel trace-sequential display.

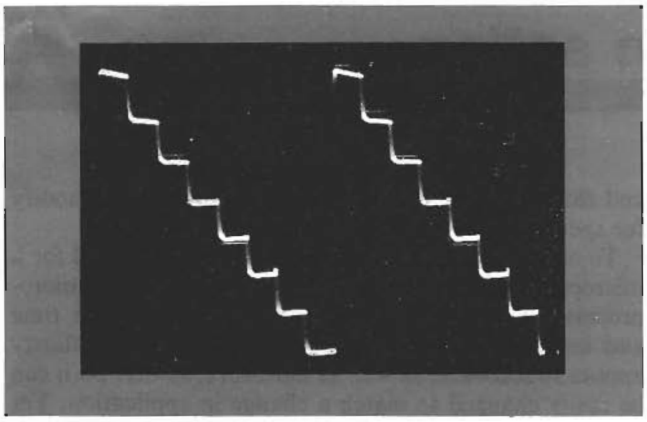
The sequential mode of sampling is satisfactory for data that is repeated at a sufficiently high rate. But, if data repeats slowly or occurs only once, all of the signals must be sampled at high speed and displayed during a single sweep. The circuit shown in Fig. 1 provides for both the chopped and alternate-sweep modes of signal sampling and display.

In this circuit, the 74S151 is an 8-line digital multiplexer. Inputs A, B, and C pick one of the eight digital signals for connection to the output at pin 5. A 74151 may be used if the faster Schottky device is not required.

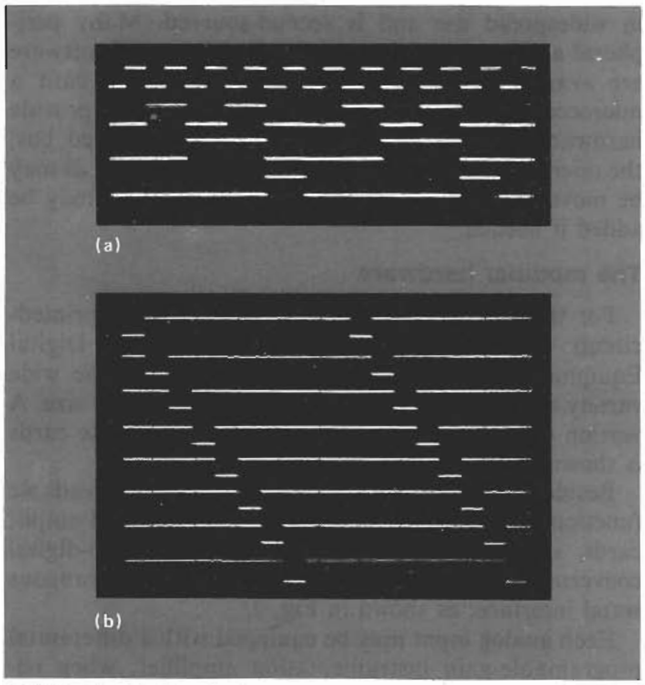
The CD4051 analog multiplexer takes its inputs from



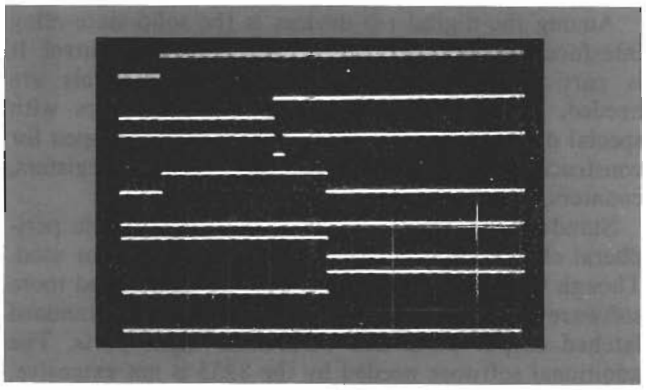
1. Signal traces. Scope displays two, four, or eight digital input signals, timeshared on either a chopped or sequential basis. The digital multiplexer selects individual inputs in cyclic succession, and the analog multiplexer separates their traces vertically. Both multiplexers are driven by a counter that counts pulses from a 555 timer for the chopped mode or sweeps from the scope for the alternate-sweep mode.



2. Fast steps. Staircase waveform positions scope trace in the chopped mode. Each step is 5 microseconds wide.



3. Outputs displayed. the chopped mode produced these waveforms of (a) the four outputs from a 7490 decade counter, and (b) the first eight outputs from a 7442 decimal decoder driven by the 7490. Input pulse rate was 1 kHz.



4. Slow process. Timing diagram of a slow speed controller with total trace length of 0.5 second was photographed by use of chopped mode. Display was triggered from the negative transition of the upper trace.

a resistance-chain divider that establishes a set of eight equally divided voltage levels. These levels appear at the output in the same sequence as the digital signals from the 74S151 because the two multiplexers have common addressing. A 2N2222 transistor, Q_1, provides drive power for the analog output, and the digital and analog signals are summed at the output to the oscilloscope.

Addressing is obtained from the 7493 counter. The circuit utilizes a single channel of the oscilloscope, with external triggering from one of the signals or a related source. The Q_A, Q_B, and Q_C outputs provide fast chopping of the data. If a slower chop signal can be used, dropping back to Q_B, Q_C and Q_D will double the ON time for the same chop frequency.

Switches S_1 and S_2 provide options of eight, four, or two traces. For eight traces, both switches are in position (a), and for a two-trace display, both switches must be in the grounded (b) position. If only switch S_1 is in the (b) position a four-trace pattern, composed of traces 1, 2, 5, and 6, will appear. This can be a useful option because, at times, eight traces are too many, and the switches provide a means of momentarily reducing the clutter. Note that only addressing is changed; a two-trace display spaces the traces the same as the original eight.

A simple 555 timer circuit provides the counter input when switch S_3 is set for the chop mode. The values shown will provide a trace-bit time of about 5 microseconds, or a staircase time of 40 μs. The chop waveform is shown in Fig. 2. Each step is 5 μs—fast enough to cover the line breaks in the traces. Since the chop is not in synchronism with the data, surprisingly fast data can be viewed in the chop mode. The trace of Fig. 3a shows the four outputs from a 7490 decade counter with a 1-kilohertz input. Figure 3b shows the first eight outputs from a 7442 decimal decoder tracking the 7490.

The waveforms in Fig. 4 are those of a very slow control system, with a total sweep time of 0.5 second. The sequences shown are all for one single event. The only way to identify these scope traces is by photography—the single sweep goes by much too fast to begin to track the events taking place on the eight traces. The eight-channel switch and Polaroid film make the photography simple.

For operation in the alternate-sweep mode, the scope sawtooth provides the clock input to the 7490 counter. Because the signal level from some scopes is much too high for the 5-volt transistor-transistor-logic counter, the drive circuit with Q_2 and Q_3 is included. This circuit works well with a 30-V sweep in, but for other voltages, a revision of R_{17} may be needed.

Three compensation elements are included in the circuit. The first of these is C_5, which may require some tweaking to best flatten the top step of the staircase shown in Fig. 2. The second is C_2, which eliminates overshoot at the end of each step. The effect of overshoot is to draw a thick trace; the 330-picofarad value shown may require trimming to produce the narrowest trace and to eliminate ringing. Finally, R_1 and C_1 should be trimmed to produce the narrowest trace. □

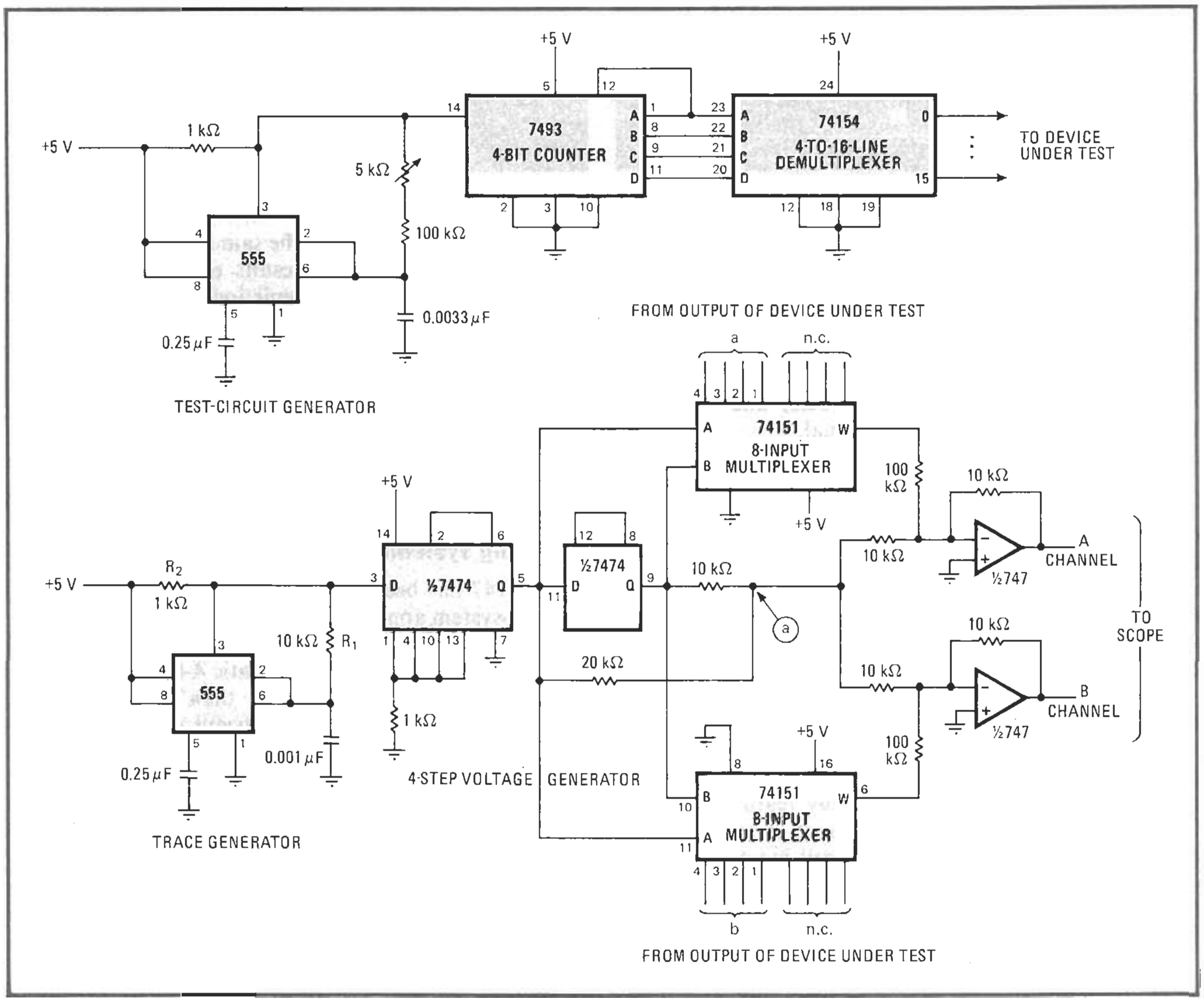
Designer's casebook is a regular feature in Electronics. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay $50 for each item published.

Eight-trace scope display checks analog or digital signals

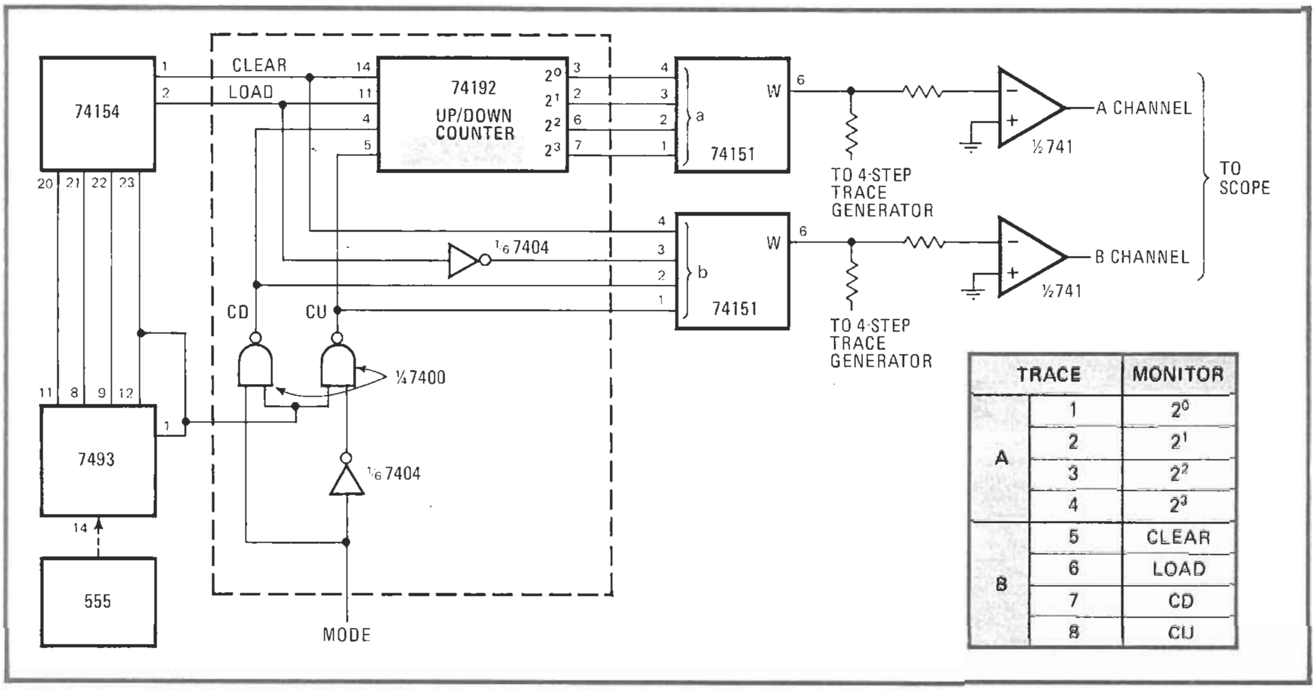
by George O. Wright
Washington, D. C.

Of all the circuits that enable a dual-trace oscilloscope to display multiple signals simultaneously, none yet provides the versatility of this one. It can be configured to monitor analog as well as digital signals. It does not require the use of the scope's sweep trigger voltage (which may not be available on some instruments) to drive the input-signal multiplexer. It also generates logic signals for stimulating devices under test. Thus the devices may be examined apart from their operating systems, which would normally supply the necessary stimulus. The circuit uses readily available integrated circuits, too, and can be built for less than $50.

The basic circuit for observing digital signals is easily implemented, as shown in Fig. 1. A trace generator using the 555 timer and operating at 60 kilohertz drives a 7474 dual D flip-flop to produce a four-step dc voltage. The output of each flip-flop is summed across the junction of the 10- and 20-kilohm resistors at point (a) to generate an output of 1, 2, 3, and 4 volts. These voltages are then synchronously added with the signal from the output of the two 74151 multiplexers, which are driven by the selected outputs of the device under test. One flip-flop also switches the multiplexers directly, so that a total of

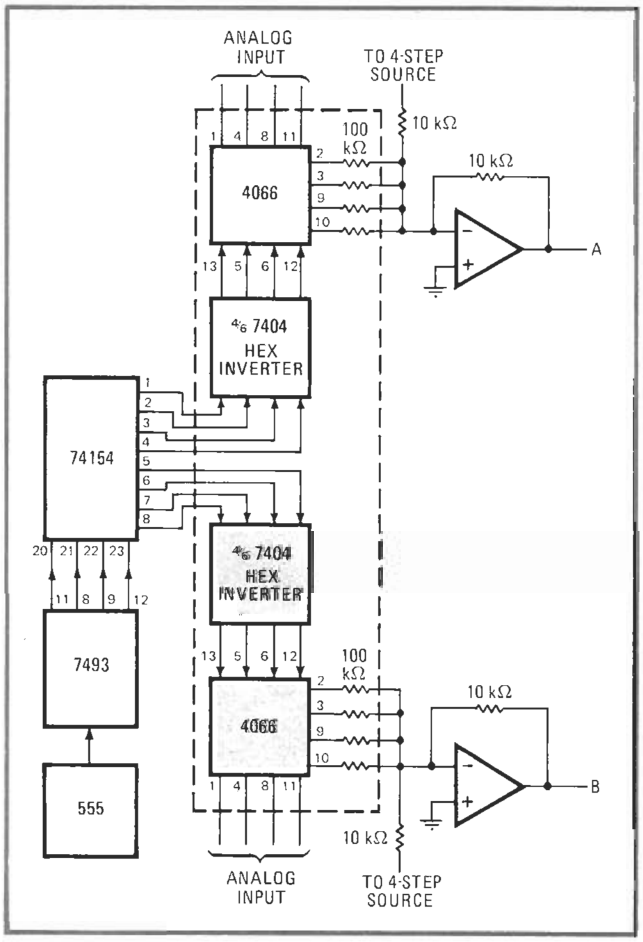


1. Low-cost analyzer. Four-step voltage generator, clocks, and counters generate eight-trace display for dual-input scope. Cost is under $50. Trace generator positions scope beam, while test-circuit generator derives logic signals to control device under test. Output of test circuit is digitally multiplexed through 74151s; alternatively, transmission gates may be used for observation of analog signals.



TRACE		MONITOR
A	1	2^0
	2	2^1
	3	2^2
	4	2^3
B	5	CLEAR
	6	LOAD
	7	CD
	8	CU

2. Digital application. Test of 74192 counter requires addition of inverters and NAND gates as shown, to derive logic signals for desired test sequence. Table specifies signal monitored by oscilloscope. Sync signal for scope is obtained from any point in trace generator chain.



3. Analog application. Replacement of 74151 multiplexers by transmission gates permits observation of eight analog signals, as shown. Logic generator continues to function in same capacity, driving 4066 analog switches with digital gating signals.

eight possible input signals can be displayed once every viewing cycle.

The test-circuit generator is similar to the trace generator but operates at 1,500 hertz. In conjunction with the 7493 decoder and 74154 multiplexer, it produces 16 logic signals for controlling the test pattern generated for the circuit under examination. The output signals from the multiplexer are sequential, each separated from its predecessor by one clock period.

Figure 2 shows a typical application of the circuit—testing the performance of an 8-bit synchronous up/down counter, in this case the 74192. Two NAND gates and two inverters have been added to derive signals that the 74154 could not itself generate, to cycle the test counter. The 74154 produces the clear and load signals, while the 7493, in conjunction with the NAND gates, derives the count-up and count-down signals (CU and CD in Fig. 2). All signals drive the 74151 multiplexers, either directly, through the counter, or through the logic gates. All eight output signals from the 74192 are multiplexed, four inputs per channel, to the oscilloscope.

As shown in Fig. 3, eight analog signals may also be observed if a slight modification is made to the basic circuit. This time, the 74154 provides the logic signals for the 7404 inverters, so that the 4066 transmission gates may be periodically sampled. The 74151 multiplexers are bypassed.

The trace generator frequency was initially set to provide acceptable scope viewing at minimum flicker rate. Step transitions of the four-value generator are not noticeable on the cathode-ray tube. The test-circuit oscillator frequency is 1/40 of the trace generator frequency to permit display of a sufficient number of events from the device under test; a 5-kilohm potentiometer has been added to permit small-range adjustments.

Both clocks should be separate and nonsynchronous to permit the scope's sync trigger input from locking-in to the output frequency of the four-step generator. Sync for the CRT can be obtained from any point in the trace generator chain. (Both oscillators were described in *Electronics*, May 13, 1976, p. 95). As mentioned, R_1 should be at least 10 times R_2. The current through R_2 should be minimized, so that the 555 can generate sufficient drive to trigger transistor-transistor logic circuits. □

Logic Trigger

Debug complex logic circuitry with this unit.

WHEN USING AN oscilloscope to examine or fault find digital circuitry, it is often desirable to see what happens just before a pulse or edge occurs. An example of this is when measuring the propagation delay in a ripple counter. Here it is easy to trigger on the last output but the edge of the counter input which initiated the change in the output may have occurred over 100 ns earlier. Even with the delay line built into modern oscilloscopes the edge is too early to see.

Triggering on the input waveform allows this edge to be seen but if the output pulse occurs only once every thousand or so pulses it will not be seen. With this unit, the output of all the stages in the divider can be examined and a pulse can be generated anywhere in the cycle. By selecting a pulse very close to, but before, the edge in question and using it to trigger the oscilloscope (use ext trigger) both the clock waveform and output waveform can be seen.

With the advent of microprocessors it has become increasingly difficult to fault find as things happen (e.g. the CE input to a memory may go low) only when a particular address is given. As the address bus is always in motion it is almost impossible to trigger the scope on any one address. Again with this unit the address bus is interrogated along with the necessary write or read lines, and its output can be used to trigger the oscilloscope only when the correct sequencer is received.

SPECIFICATIONS

Modes	Asynchronous or synchronous
No. of inputs	12 address, 1 clock
Loading	
address	0.4 UL (TTL)
clock	0.4 UL (TTL)
Pulse extension mono	10 ms
Pulse indication	LED
Minimum pulse detectable	<40 ns
Propagation delay	<45 ns
Trigger (synchronous)	positive or negative edge of clock input
Set up time (synchronous) address to clock	<40 ns
Output	logical "1" when input agrees with switch setting and/or clock (synchronous only)
Power requriement	+5V @ 50 mA

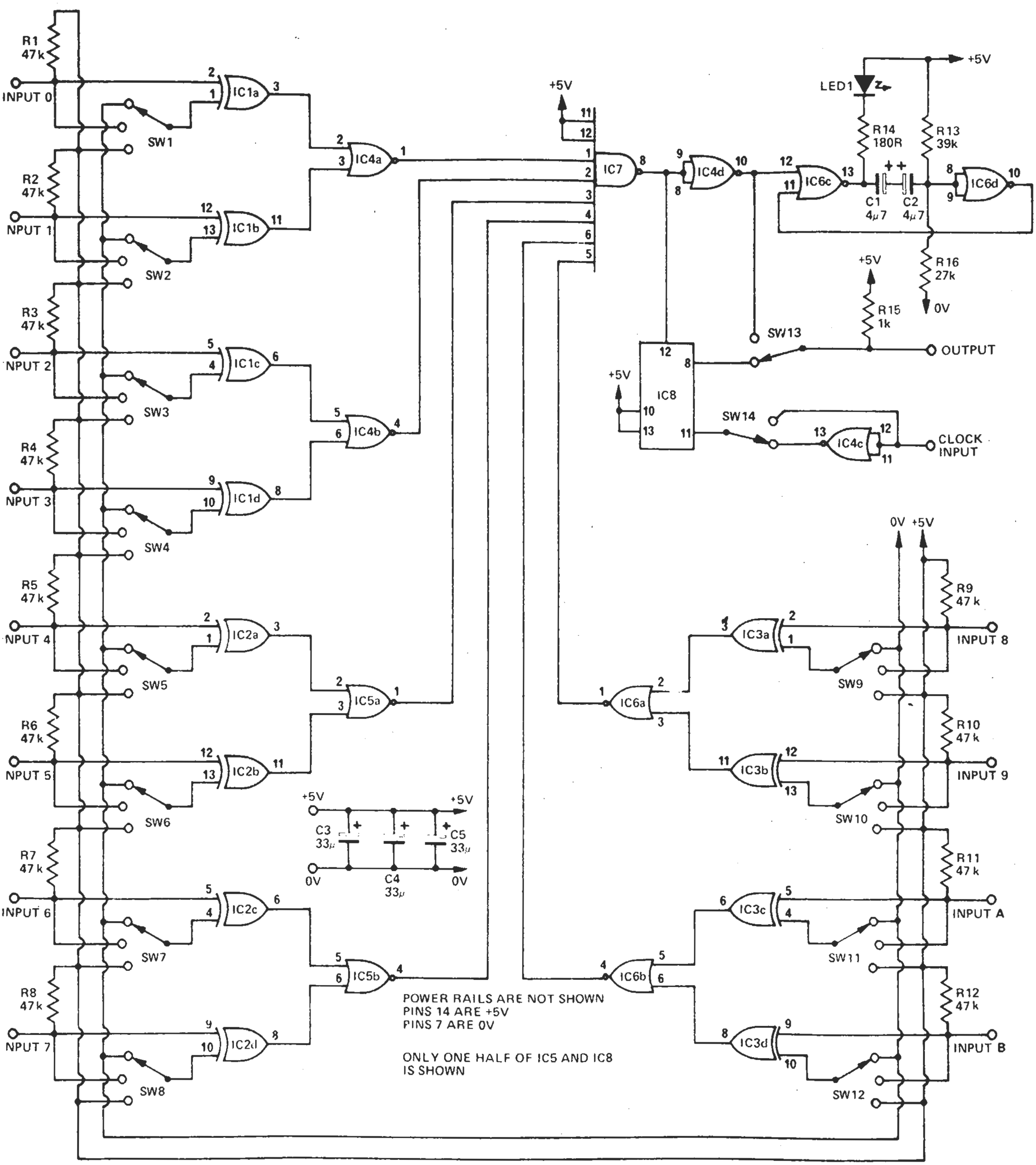


Fig. 1. Circuit diagram of the Logic Trigger.

PARTS LIST

RESISTORS all ½ W, 5%
- R1—R12 . . . . 47k
- R13. . . . . 39k
- R14. . . . . 180R
- R15. . . . . 1k
- R16. . . . . 27k

CAPACITORS
- C1,2 . . . . 4μ7 25V electro
- C3—C5 . . . . . 33μ 16V tantalum

SEMICONDUCTORS
- IC1—IC3 . . . . 74LS86
- IC4—IC6 . . . . 74LS02
- IC7 . . . . 74LS30
- IC8 . . . . 74LS74

LED 1 . . . . . Red LED

MISCELLANEOUS
- PC board ETI 141
- Twelve 3 position slide switches
- Two 2 position slide switches
- Front panel
- Box to suit

HOW IT WORKS

The twelve inputs are compared to the levels set on the slide switches SW1-SW12 by the exclusive OR gates IC1-IC3. These ICs have a high output only if the two inputs differ. If they are the same, either both low or both high, the output will be low. If the two inputs are joined together, as when the switches are in the don't care position, the output will always be low.

The outputs from the exclusive OR gates are combined in pairs by the NOR gates IC4-IC6. If the 12 input signals match the preset selection, the output of all 6 NOR gates will be high. If any one is not in agreement with the selection one or more of the NOR gates will have a low output.

These NOR gate outputs are combined by IC7 which is an eight input NAND gate. The output of this gate will low only if all 12 inputs match. The output of this IC is inverted by IC4/d to provide the asynchronous output.

This output also triggers the monostable formed by IC6/c and IC6/d. This gives a 10 ms long pulse to light the LED indicating a pulse was received. If it is a steady state signal the LED will stay on.

The output of the NAND gate, IC7, also joins the data input of IC8 (D type flip flop). This IC is toggled on the positive edge of the clock waveform transfering the data to the output. This is the synchronous output. To allow for either positive or negative synchronization an inverter is used on the clock input and either polarity can be selected by SW13.

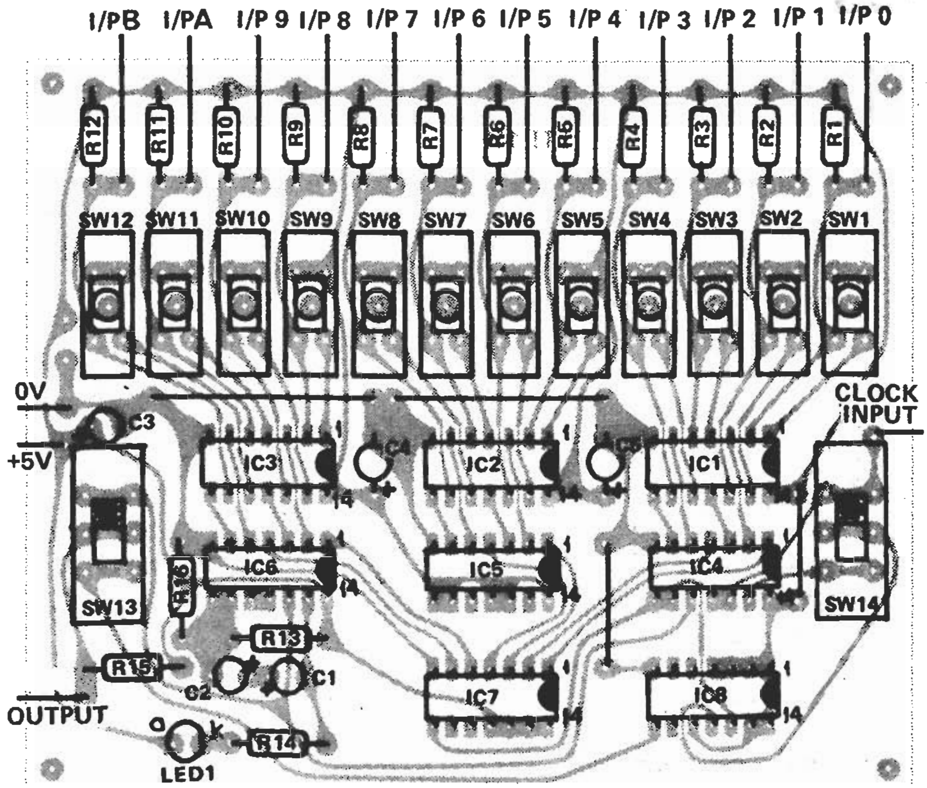


Fig. 2 Overlay of the PCB

For pcbs for this project please contact: Spectrum Electronics, P. O. Box 4166D, Hamilton Ontario L8V 4L5, or B & R Electronics, P. O. Box 6326F, Hamilton Ontario L9C 6L9.

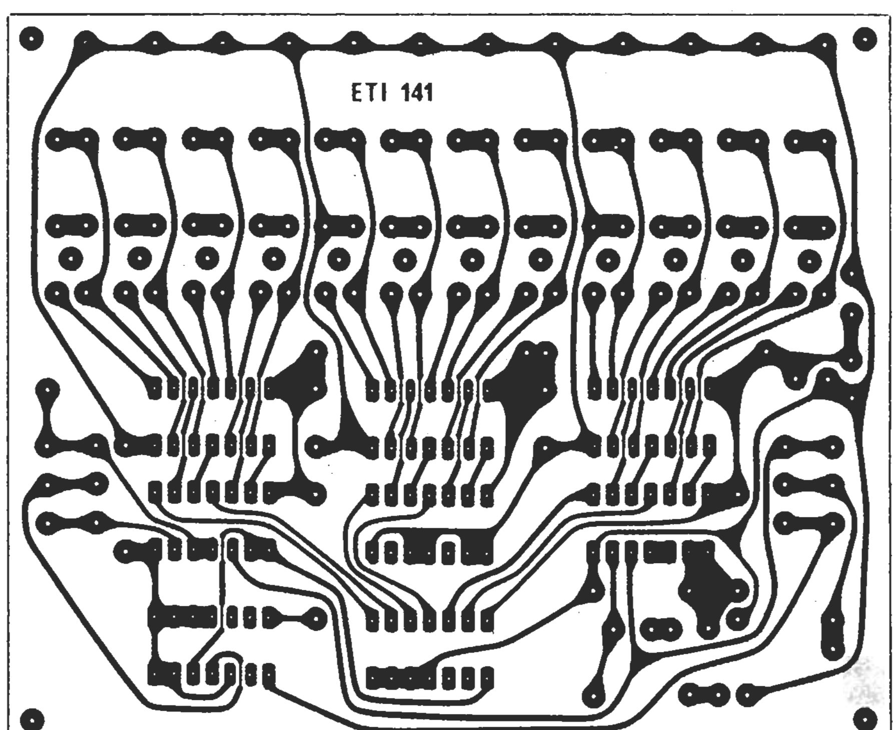


Fig. 3 PCB pattern shown full size.

Rise-Time Measurements

BY RAYMOND E. HERZOG

WHAT YOU SEE MAY NOT BE WHAT YOU'VE REALLY GOT

SUPPOSE you feed the output of a pulse generator through a probe to an oscilloscope. You adjust the scope time base for a fast sweep. (This is the typical setup for measurement of rise time.) The result is the easily recognized rise-time waveform shown in Fig. 1.

Question: If the time base is set for a sweep of 50 nanoseconds per division, what is the rise time of the generator's output pulse—ignoring any inherent scope inaccuracies.

"That's easy," you say, quickly multiplying 50 ns/div times the two divisions covered by the pulse's leading edge. "100 ns is the rise time of the pulse. Right?"

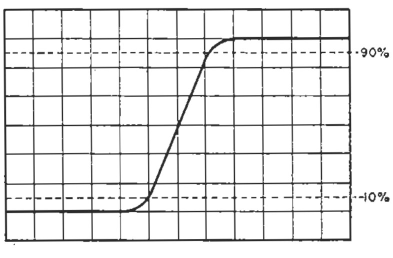
Maybe yes; and maybe no!

Although 100 ns is the correct reading of the scope display, this value may not be the true rise time of the pulse. So ignoring scope inaccuracies, what other reason is there for suspecting that the measurement is not the real rise time?

Basically it is that, when the pulse passes through the probe, the scope amplifier, and even the scope CRT, it suffers rise time deterioration. Thus, the displayed waveform can't represent the true, original signal.

Although this is an unfortunate circumstance, it has one saving grace: it can be predicted. So, if you erroneously said that the rise time in the example was 100 ns, it should be both interesting and informative to learn how to determine what the error might be.

Fig. 1. Pulse rise time is measured between the 10% and 90% points on the leading edge of oscilloscope trace. In this case, rise time is 100 nanosec.



Rise-Time Formula. True rise time can be determined by the use of the tongue-twisting formula known as "the square root of the sum of the squares." In mathematical terms:

$$T_{RG} = \sqrt{T_{RD}^2 - T_{RP}^2 - T_{RO}^2}$$

where T_{RG} = true signal generator rise time
T_{RD} = displayed rise time
T_{RP} = probe rise time
T_{RO} = oscilloscope (amplifier and CRT) rise time

For a low- to medium-priced general-purpose oscilloscope, a typical rise time is 35 ns.

For a standard probe, rise time is 5 or 10 ns. Putting these values into the formula, we get

$$T_{RG} = \sqrt{100^2 - 35^2 - 10^2}$$
$$= 93.1 \text{ ns}$$

Thus, the actual rise time of the generator pulse is 93.1 ns and not the 100 ns displayed on the scope; and the measurement was in error by 7.4%.

It is important, therefore, to keep in mind that the displayed rise time is greater than the actual rise time. The amount of error is shown in Fig. 2, where per cent of error is plotted against the ratio of the input signal's rise time to test equipment rise time. In our example, this rise time ratio would be 93.1 divided by the square root of $35^2 + 10^2$ or 2.56.

Knowing that the measurement devices do introduce an error and with the aid of Fig. 2, you can determine just what error to expect. Conversely, to make a measurement within a given accuracy, Fig. 2 can be used to find what rise time response is needed in the test equipment.

More About Rise Time. We often concern ourselves with only the frequency response of an oscilloscope or an amplifier when, as we have seen, rise time is also important.

In using Fig. 1, we measured rise time between the 10% and 90% points of peak value on the leading edge of the pulse. These two points are used as standards for waveform measurement in the industry.

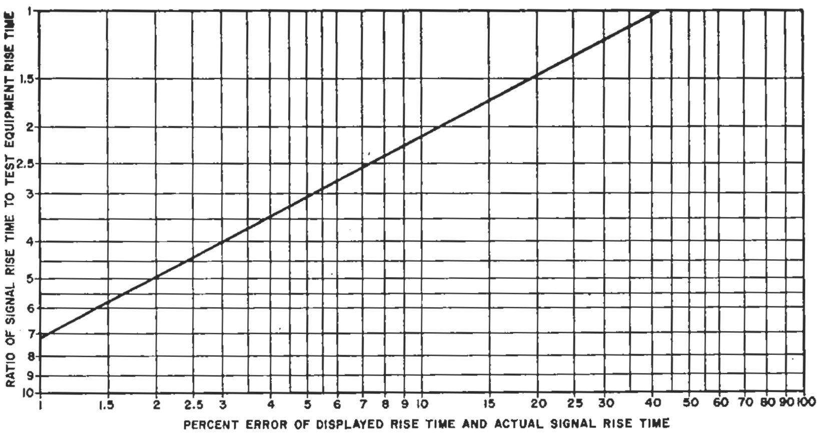


Fig. 2. Measurement error is inversely proportional to the rise-time ratio.

Looking at Fig. 1 again, you will note that the pulse rises linearly from the 10% voltage level to the 90% level. Such a characteristic is known as a Gaussian response. When an ideal unit step pulse (one with zero rise time) is applied to an amplifier (or cascaded amplifiers) whose frequency response is RC limited, the response is Gaussian. For a Gaussian response, there is a relationship between rise time and frequency (also called bandwidth):

$0.35 = t_r \times bw$

where t_r = rise time in microseconds

bw = frequency bandwidth in MHz

Oscilloscope vertical amplifiers consist of cascaded RC stages so the above formula applies. For instance, if a scope has a 10-MHz bandwidth, its corresponding rise time would be 0.035 microseconds or 35 ns.

The 0.35 constant in the formula results from a combination of two factors:

RC rise time $= t_r = 2.2RC$

-3 dB frequency $= F_c = 1/(2\pi RC)$

Consider first the 2.2RC factor and look at the universal time constant curve in Fig. 3. This curve will readily be recognized as the capacitor charging voltage in a series RC network with an applied ideal step pulse. Recalling that, in rise time measurements, the 10% and 90% points were used, we find the corresponding RC value for these two points: namely 0.1 RC and 2.3 RC. Taking the difference between these two values, we get 2.2RC—the time in which rise time is resolved.

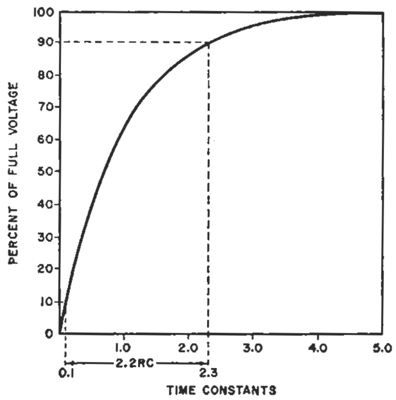
But wait just a moment! The curve in Fig. 3 is not Gaussian, so how can it be used in our calculations? Well, irrespective of Gaussian—or whatever—the universal time constant curve serves only as a reference for the 2.2 RC value. It is not the signal pulse to be measured (as in Fig. 1) and thus does not have to be Gaussian.

Remember that what we did say about Gaussian response was that it pertained to an amplifier stage whose frequency response is RC limited.

This brings us to the second factor in the 0.35 constant: the -3-dB frequency, or the frequency at which an amplifier's gain is down 3 dB from mid-frequency gain. The influence of the stage's resistance and capacitance is shown in the -3-dB frequency formula: $F_c = 1/(2\pi RC)$.

Having defined these two factors, let's see how they determine the 0.35 constant. First, transpose $F_c = 1/(2\pi RC)$ into $RC = 1/(2\pi F_c)$. Then from $t_r = 2.2RC$, we get $t_r = 2.2. [1/(2\pi F_c)] = 0.35/F_c$. Finally, $0.35 = t_r \times F_c$. Or since frequency response is bandwidth, $0.35 = t_r \times bw$. ◈

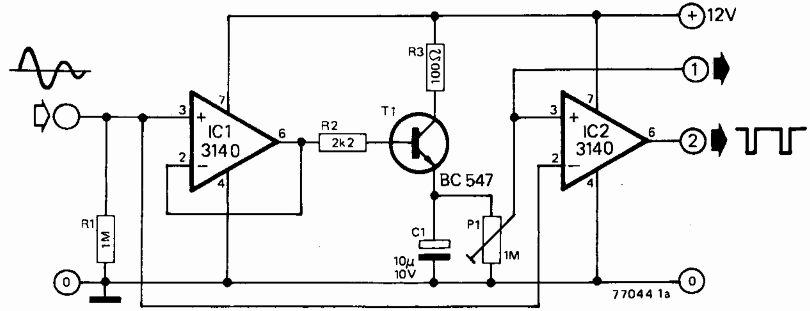
Fig. 3. This is time constant curve for charging capacitor in series RC circuit.



66

auto trigger level control

1a



Oscilloscopes, frequency counters and other instruments triggered by AC signals almost invariably have a manual trigger level control, to adjust the point on the waveform at which triggering occurs. When making measurements where the signal level varies, for example at different places in a circuit, it is tedious to have to make frequent adjustments to this control.

The circuit described here provides a trigger signal at a fixed percentage of the peak input level, irrespective of what that level is, so the frustration of having the trace disappear from an oscilloscope when the signal level falls below the trigger level is avoided.

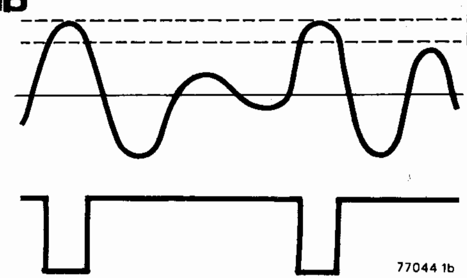
The circuit consists basically of a peak rectifier that provides one input of a comparator with a DC voltage equal to a fixed percentage of the peak signal level. The other input of the comparator is fed with the signal. When the signal level exceeds the DC reference level the comparator output will go low. When it falls below the reference level the comparator output will go high.

The peak rectifier consists of IC1 and T1. On positive half cycles of the signal waveform the output of IC1 will swing positive until T1 starts to conduct, after which IC1/T1 will act as a voltage follower, charging up C1 to the peak value of the signal.

A portion of this voltage is taken from the slider of P1 and applied to the non-inverting input of IC2, which functions as a comparator. The AC signal is fed to the inverting input. When the signal level exceeds the reference voltage the comparator output will go low; when the signal level falls below the reference level the comparator output will go high. (see figure 1b)

P1 may be used to set the trigger level to any desired percentage of the signal level. The DC level at the slider of P1 may also be fed to the comparator input of an existing trigger level circuit. In this case this circuit should have a high input impedance to avoid discharging C1. Alternatively the output from P1 can be buffered by an op-amp connected as a voltage follower.

1b



One-chip multiplexer simplifies eight-trace scope

by Sam Curchack
EDO Corp., Government Products Division, College Point, N. Y.

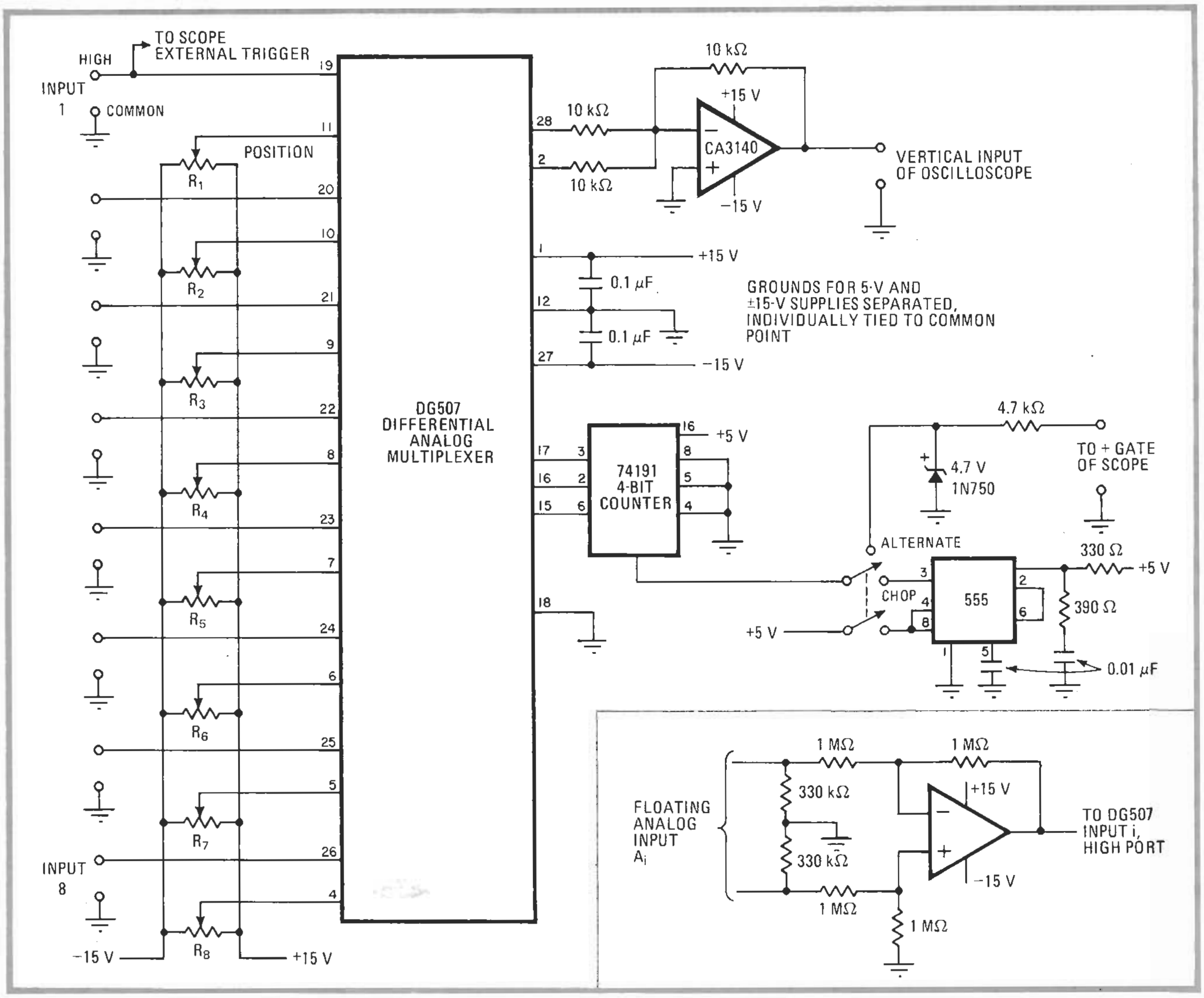
Displaying eight analog signals simultaneously with only a single-trace oscilloscope, this switching circuit can be built for even less ($35) than the one proposed by Wright.[1] Circuitry is simplified, too, by the use of a one-chip, eight-channel differential multiplexer. And unlike most other arrangements, this unit is more versatile, having a chopped-mode and alternate-mode option and trace-positioning controls for each analog input.

In the chopped mode, which can be used at sweep speeds up to 50 microseconds/centimeter, all traces are referenced in time to input 1, which is the signal used to trigger the scope. Operational amplifiers (see inset) may be added for handling floating inputs. The 555 timer, operating as an astable multivibrator, switches the 74191 4-bit counter at a 9-μs rate, the sampling-bit time. This action in turn sequentially switches the DG507 multiplexer. As each input is selected, it is added to the dc output voltage of its positioning potentiometer (R_1–R_8).

At sweep speeds of 1 millisecond/cm and faster, the unit's alternate-mode option may be used. The 555 is deactivated and each analog input is switched in turn at any sweep speed selected by the user. The resulting display, devoid of most switching transients, is somewhat cleaner than can be achieved in the chopped mode. All other settings remain the same. A gating signal is required to synchronize the 4-bit counter, however. This signal is supplied by the scope's +GATE port.

More than 8 traces can be displayed on a dual-trace scope. With an additional 8-trace switching unit of the type previously described, 16 traces can be displayed. A large screen scope such as the Tektronix 7603 will be required for suitable resolution in this case. □

References
1. George O. Wright, "Eight-trace scope display checks analog or digital signals," *Electronics*, Aug. 4, 1977, p. 108.



Sweep switch. Low-cost circuit displays eight analog signals on single-trace scope with aid of one-chip analog multiplexer. Alternate-mode (flicker-free above 200 μs/cm) and chopped-mode options are available. Each trace may be individually positioned on screen.

Experimenter's Corner

By Forrest M. Mims

SOLID-STATE OSCILLOSCOPE WRAP-UP

ONE OF the most popular topics that has been covered in this column is the solid-state oscilloscope. Many readers have requested additional information on this subject. Others have designed and built scopes of their own. This month, we'll review the recent history of solid-state scopes and describe several reader-designed versions. First, let's review a few basics.

How They Work. Figure 1 is a block diagram of a basic solid-state scope. The horizontal sweep circuit is very straightforward and can be made up of standard TTL or CMOS ICs. An advantage of the CMOS logic family is its low power consumption and the flexibility of one of its members, the 4017, a chip that combines a counter and 1-of-10 decoder in a single package. The clock can be a simple 2-gate oscillator or an IC timer.

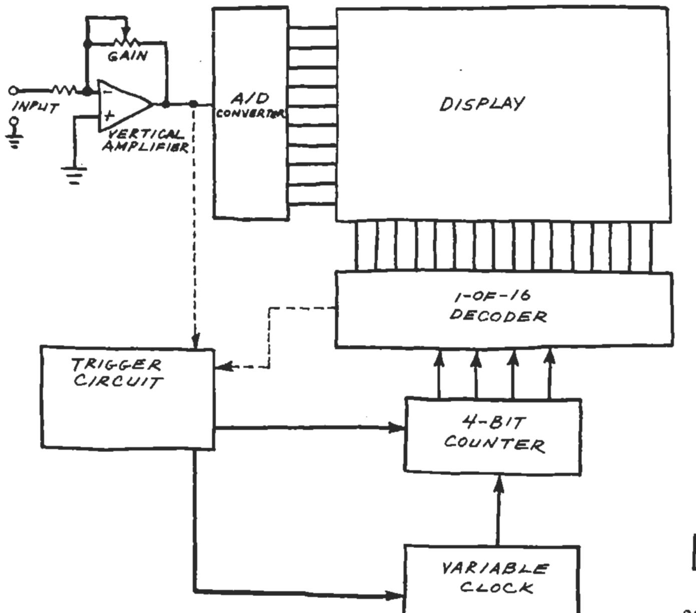


Fig. 1. Block diagram of typical solid-state scope.

Most of the design variations in solid-state scopes occur in the vertical section's analog-to-digital converter. Early scopes required complicated voltage divider/comparator/decoder networks. Now, however, all of these functions are available in chips such as National Semiconductor's LM3914.

The operation of most solid-state scopes is straightforward. The display consists of an array of optical elements such as LEDs or liquid crystals. Only one vertical column in the display is enabled at any instant, and the instantaneous amplitude of the applied waveform determines which element within that column is activated. If the horizontal sweep is synchronized with the frequency of the input signals, the outline of the applied waveform will be displayed as a pattern of dots. Synchronization can be achieved either by manually adjusting the timebase or by means of an automatic trigger circuit that starts the sweep when the amplitude of the input signal exceeds a preselected value.

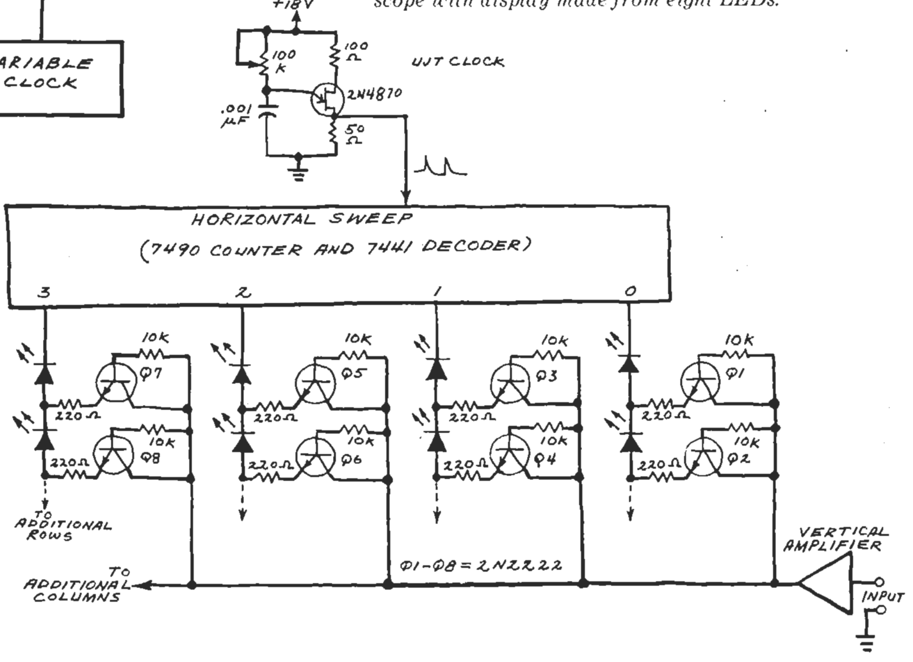
Early Solid-State Scopes. The development of visible LEDs in the early 1960's made possible compact graphic displays that could serve as the screens of solid-state scopes if teamed up with suitable driving and scanning circuitry. Back then, however, LEDs cost $10 *each* and the necessary drive circuits would have been very complex. Accordingly, most work in the area of LED displays was limited to military projects.

I began experimenting with solid-state scope designs when LED prices began to tumble in the early 1970's. For those readers who have requested additional information, here's a condensed history of the solid-state scopes that have appeared in POPULAR ELECTRONICS and *Electronics* magazines:

In February 1974, I assembled a crude scope with a display made from eight LEDs. Figure 2 is a simplified schematic of this scope. The vertical drive circuit was far too complex for convenient expansion, so I experimented with series-connected LEDs having slightly different turn-on voltages. A rising voltage applied to a string of such LEDs causes them to light up in sequence. In spite of its simplicity, this method proved impractical because the LEDs had to be selected for various turn-on voltages.

Another simple way to create a bar-graph display is to connect LEDs across each of the resistors in a voltage divider, as shown in Fig. 3. As the voltage applied across the divider is increased, the voltage drop across each resistor increases proportionally. If the resistance of each resistor in the chain is larger than the one above it, then the LEDs will light up in bar-graph fashion as the voltage applied across the entire divider net-

Fig. 2. Simplified schematic of an original scope with display made from eight LEDs.



work increases. For example, using the resistance values shown in Fig. 3, I constructed a circuit in which the LEDs began to glow when the applied voltage was increased to the values shown below.

Led	Voltage
1	8.1
2	9.0
3	10.0
4	10.7
5	11.7
6	12.7
7	14.0
8	15.0
9	16.0
10	17.5

This vertical-axis circuit is very simple, but it has some major drawbacks. The input voltage must attain a relatively high value before the first LED begins to glow. Also, only bar-graph (not moving-dot) operation is possible. Nevertheless, I've used this method to make a miniature solid-state scope with a 10 × 10 LED screen. Figure 4 shows the circuit in simplified form. Excluding its power supply, this scope fits with room to spare in a pocket-calculator-size enclosure. Vertical sensitivity is adjustable from 0.01-volt per LED to 1.0 volt per LED, and horizontal sweep is adjustable from 20 microseconds per LED to 1.0 second per LED. Total power consumption of the display with all LEDs on is 308 milliwatts. The drive electronics consume another 54 mW. For more information about this scope, refer to "LEDs Replace CRT in Solid-State Scope" (*Electronics*, June 26, 1975, p. 110) and my book *LED Projects* (Howard W. Sams & Co., 1976, pp. 92-95).

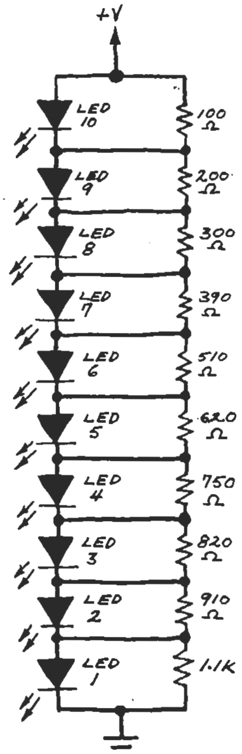


Fig. 3. Voltage-divider LED bargraph display.

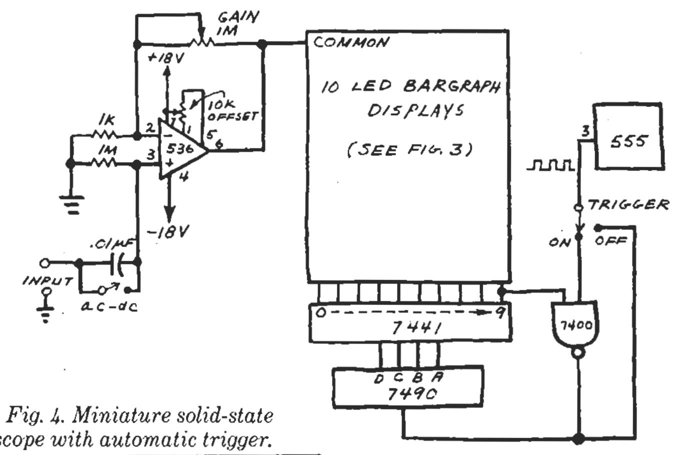


Fig. 4. Miniature solid-state scope with automatic trigger.

A few years ago, Vernon Boyd described an improved solid-state scope in *Electronics* (November 24, 1977, pp. 128-130). His circuit employed a string of comparators and a decoder/driver network to generate a moving-dot readout. Almost one year later, the October 1978 installment of this column briefly described an improved scope with a 10 × 16 LED screen. Construction and operating details followed in the April 1979 "Project of the Month."

The August 1979 "Project of the Month" was a "matchbox" LED oscilloscope. The key to the simplicity and tiny size of this scope was the use of the new LM3914 dot/bar display driver. Additional information about this scope, which can easily be expanded to provide a larger, more useful display, can be found in a brief article I wrote for *Electronics* (May 24, 1979, p. 169).

The most recent article in POPULAR ELECTRONICS related to solid-state scope technology was the hand-held LED spectrum analyzer featured on the cover of the September 1979 issue. This circuit's vertical driver is an LM3915, the logarithmic version of the LM3914.

Taken together, these articles will give you a good background in solid-state scope operation. If you don't have back issues of the various magazines that have been mentioned, consult a public or technical library.

Readers' Solid-State Scopes. Several readers have designed and built various solid-state scopes. For example, Bill Cikas, a self-taught electronics enthusiast

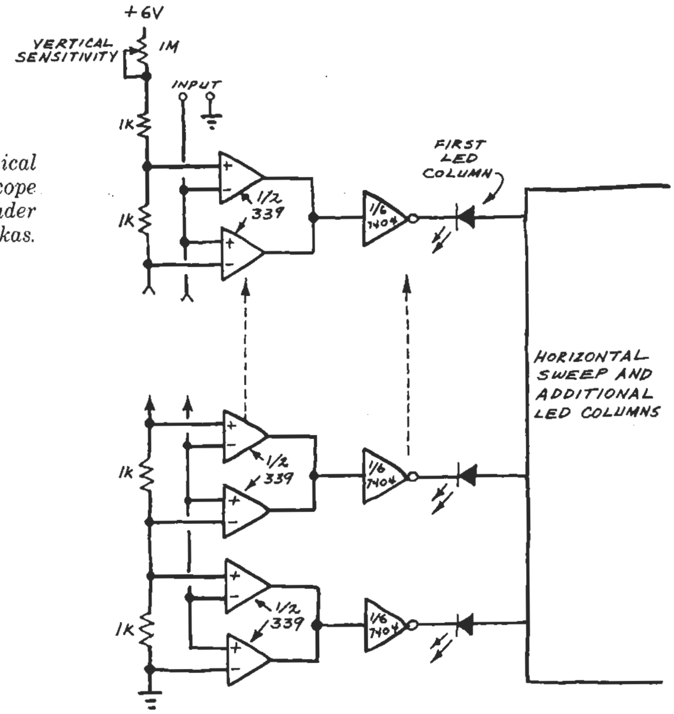
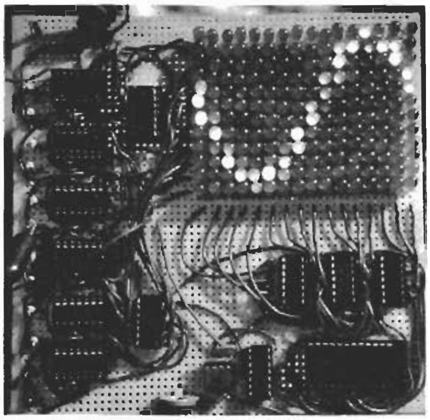


Fig. 5. Vertical section of scope designed by reader Bill Cikas.

Fig. 6. Photo below is of solid-state scope whose circuit is shown in Fig. 5.



living in Rockford, Illinois, has designed a scope with a 12 × 16 element LED display that fits on a 6" × 6" (15.3 × 15.3 cm) perforated board. A portion of the scope's vertical section is shown in Fig. 5, and a photo of the scope displaying a well defined sine wave appears in Fig. 6.

Steven Bolotin, a Chicago high school student, modified the scope described in the April 1979 installment of this column to permit both the negative and positive halves of a waveform to be displayed. The modification, which is shown in Fig. 7, is inserted between the vertical amplifier and analog-to-digital converter and causes the incoming wave to ride on an adjustable dc level.

Joe Sharp of Orange, Virginia, has worked on the resolution problem caused by the limited number of display elements in the screen of a solid-state scope. He has determined that at least thirty display columns are required for every ten display rows to minimize smearing of the trace. Joe's scope employs three cascaded LM3914s, thirty 10-element LED bar arrays, and provides automatic trigger, ac/dc operation and various other features.

Gregory Kovacs, a student at Eric Hamber Secondary School in Vancouver, British Columbia, has provided details of a sophisticated solid-state scope project he has undertaken. For his half-term electronics project, Greg designed and assembled a scope that can display the waveforms of signals with frequencies of several hundred kilohertz.

A noteworthy feature of Greg's scope is the use of a Siemens UAA170 IC dot generator. Like the more recently introduced

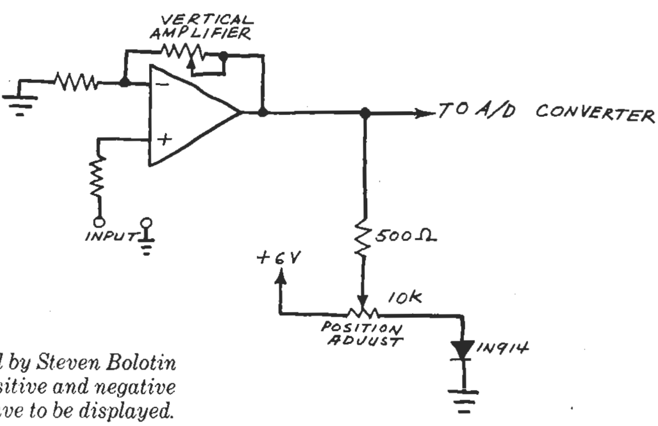


Fig. 7. Circuit designed by Steven Bolotin that permits positive and negative halves of a wave to be displayed.

LM3914, the UAA170 eliminates the complicated voltage divider/comparator/decoder network that would otherwise be required for the scope's vertical section. In a paper describing his project, Gary observes that a scope using a single UAA170 vertical display driver would be limited to a maximum input frequency of only 50 Hz or so. Therefore, he assembled ten separate vertical display boards, each with its own UAA170 and column of 16 LEDs, and scanned each board with a conventional counter/decoder circuit.

Each display board contains an op-amp sample-and-hold circuit controlled by a Siliconix DG181 analog switch. A horizontal sweep sequentially strobes each display board's sample-and-hold circuit and the sampled voltage level is held until the next strobe pulse arrives. The result is the capability of displaying input waveforms having frequencies of up to 1 MHz.

An important consequence of Greg's decision to use individual sample-and-hold circuits is that his circuit can function as an analog *storage scope.* It can sample and display on its screen for several minutes any waveform before degradation caused by leakage in the sample-and-hold capacitors occurs. Figure 8 is a photo that shows the high-quality trace the circuit provides.

Looking Ahead. Solid-state scopes have a very bright future. Thanks to the LM3914 and similar moving-dot display drivers, experimenters and hobbyists can easily design their own scopes. By cascading vertical and horizontal driver ICs, oscilloscopes with displays containing hundreds of LEDs are possible. Although building such a scope would be tedious (the display board in one of my scopes has more than 650 solder connections), cost is no longer the limiting factor it was before LEDs could be purchased in volume for less than 10¢ each.

Homebrew scopes will become even simpler when manufacturers produce LED dot/bar displays with integral solid-state decoder/drivers. A complete scope could then be assembled in building-block fashion simply by connecting display columns to a standard horizontal sweep circuit. Individual, discrete LEDs are fine for low-resolution scopes, but are for a few reasons unattractive if high resolution is desired. Several alternative display technologies are available, the least costly being liquid crystals. Unfortunately, liquid-crystal displays are too slow for conventional multiplexing techniques.

Recently, however, Ian A. Shanks of the Royal Signals and Radar Establishment in Malvern, England, solved the liquid-crystal addressing problem with a design that continuously applies signals to all elements of the display. Shanks has assembled a prototype storage oscilloscope with a 100 × 100 element display measuring 2.5" × 2.5" (6.45 cm × 6.45 cm). The waveform is displayed as a black line on a light background. It can be projected onto a screen by removing the display's reflective back and using it like a transparency in a slide projector. Shanks is building a new scope with a 128 × 256 element display and believes that a 1,000 × 1,000 element display can be made.

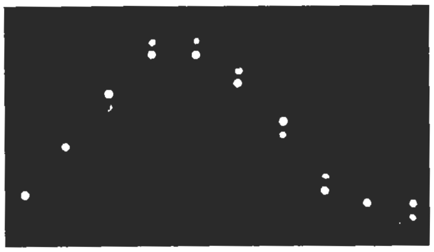


Fig. 8. Photo of waveform displayed on scope designed by Gregory Kovacs.

In Conclusion. The oscilloscope is the most important and useful piece of test equipment available. Hopefully, these solid-state scope developments will lead to pocket-size, high-resolution, full-feature scopes affordable by most experimenters and hobbyists. In the meantime, those described here show how *you* can make contributions to this new technology. ◇

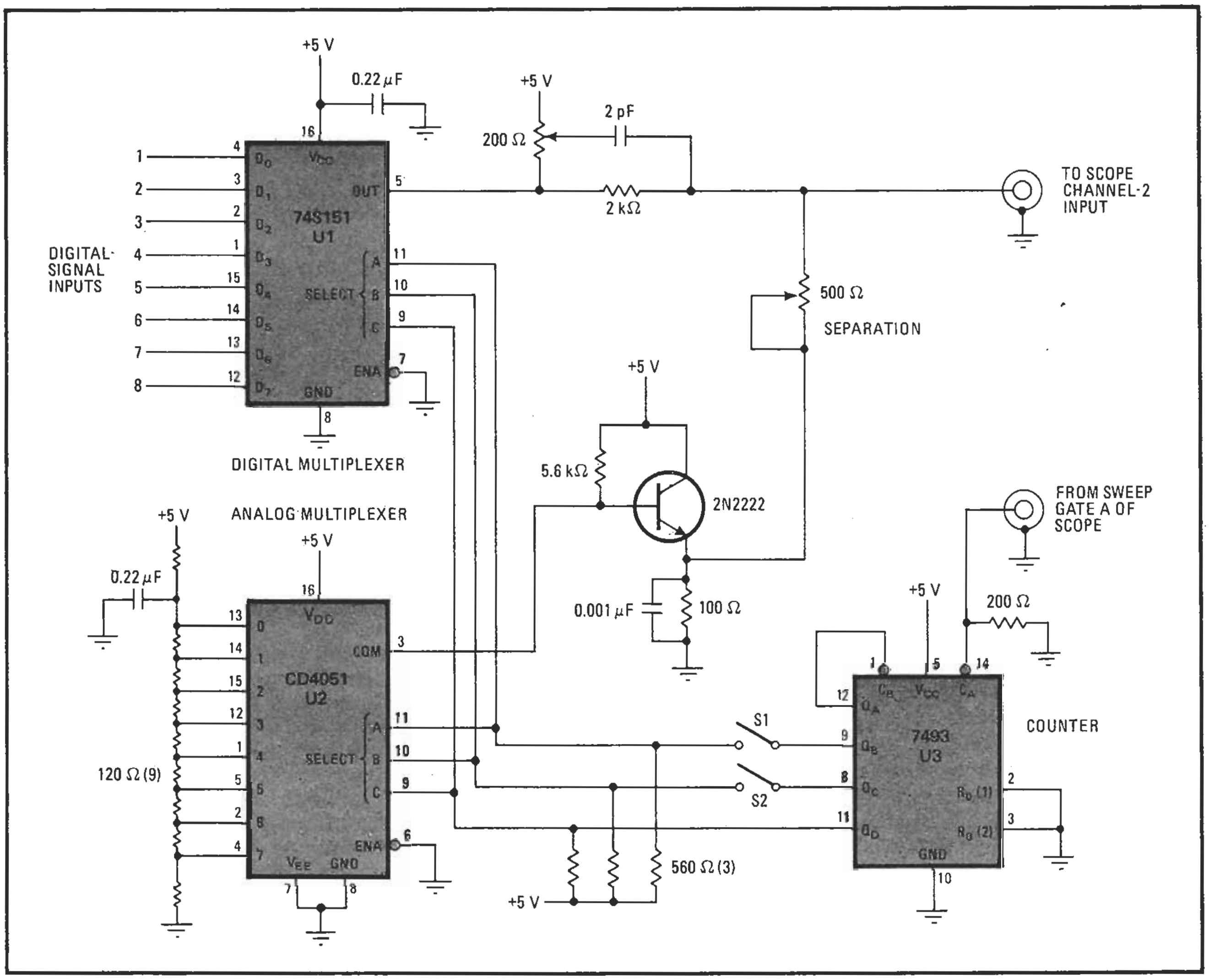
Scope display of eight signals helps debug sequential logic

by Matthew L. Fichtenbaum
General Radio Co., Concord, Mass.

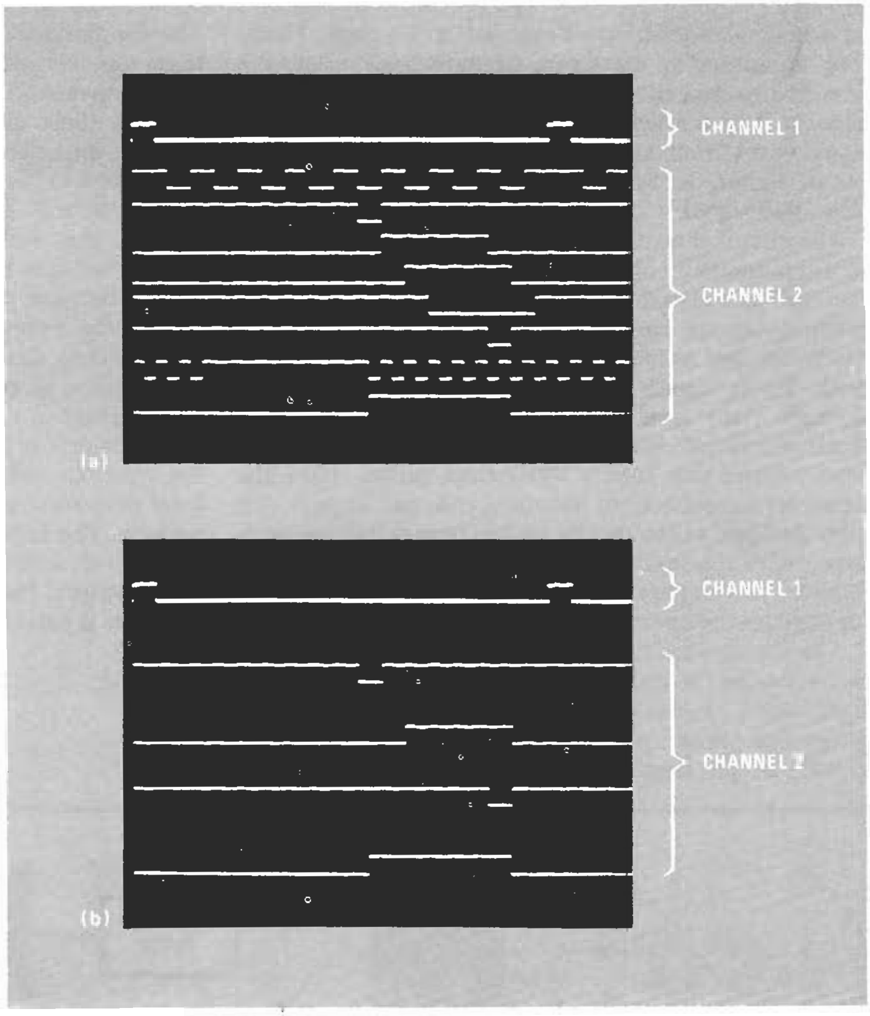
When debugging sequential logic, an engineer may have to observe several signals simultaneously. Logical states and the times that they change are of primary importance in the visual display; the exact values of voltage levels and the duration of rise times and fall times are of lesser importance.

Two, four, or eight digital signals can be displayed on one of the two channels of a Tektronix 454 or similar dual-trace oscilloscope, as demonstrated in the photographs on the next page. The other channel may then be used for triggering or for observation of a ninth signal. The eight signals are treated as logic levels and are gated by a digital multiplexer. Although this procedure does not preserve voltage levels and wave shapes, it does achieve maximum speed with simple circuitry.

The circuit for displaying the signals on the scope is illustrated in Fig. 1. The 7493 divide-by-16 counter (U3) is incremented after each scope sweep. The counter steps through the eight inputs sequentially, and the extra stage compensates for the use of every other sweep in the "alternate" display mode. The counter's highest three bits select an input signal via digital multiplexer U1, which is a 74S151 TTL Schottky type. At the same time, the CD4051 C-MOS analog multiplexer U2 picks a dc voltage off a resistor chain. This voltage is summed



1. Multi-trace adapter. Two, four, or eight digital input signals time-share the channel-2 trace of a dual-trace oscilloscope by means of this circuit. The digital multiplexer selects individual digital inputs in cyclic succession, and the analog multiplexer separates their wave forms vertically; sweep counter drives multiplexers. Switches S_1 and S_2 permit display of only two or four digital wave forms, instead of eight.



2. Signal tracing. Channel 2 of dual-trace scope is multiplexed to display eight different logic wave forms in (a) and four wave forms in (b). The channel-1 trace, used for triggering, appears at top in both photos; it is brighter than the channel-2 traces because of its higher duty ratio. This simultaneous display of several signals is convenient for logic-circuit debugging. High and low states, and the timing of their changes, are indicated accurately even though the multiplexing does not preserve voltage levels and wave shapes. The multi-trace adapter circuit is shown in Fig. 1 on the preceding page.

with the digital signal, providing a different reference level for each trace and thus separating the traces vertically from each other on the screen, as shown in Fig. 1.

The 500-ohm variable resistor adjusts the magnitude of the dc offset, varying the trace separation. The scope's variable vertical-sensitivity control may be used to adjust the over-all display amplitude. The 200-ohm potentiometer is adjusted for best transient response. Both the 500-ohm and 200-ohm pots should be cermet or other noninductive types. The three 560-ohm resistors pull up the levels of the inputs to the multiplexers.

The resistor chain could be replaced by eight potentiometers in parallel, with their wipers connected to the input terminals of the CD4051, for separate adjustments of the vertical positions of the individual traces.

If switch S_1 is open, the scope displays only four traces (digital inputs 1, 3, 5, 7). If both S_1 and S_2 are open, only two inputs (3 and 7) are displayed.

This time-division-multiplexing of channel 2 on the dual-trace scope of course makes the signal wave forms less bright than the channel-1 trace. In Fig. 2(a), the top trace is scanned eight times as often as each of the lower eight traces, and in Fig. 2(b), channel 1 is scanned four times as often as any one of the four offset wave forms that share channel 2.

The circuit may be built in a small box, with appropriate connectors to the scope and inputs. It should be used near the logic circuit under test to minimize signal-lead length and circuit-loading. Only 5 volts of dc power are required. □

4-TRACE CONVERTER FOR OSCILLOSCOPES

Make your single-trace instrument more useful with this low-cost circuit

BY JIM MORGAN

HAVE you ever found yourself staring at the nonworking "innards" of a stereo audio amplifier or a complex digital circuit, wishing you had a multi-channel oscilloscope? Now, for about $70, you can build an oscilloscope switch that can display 2, 3, or 4 channels of inputs on a single-trace scope.

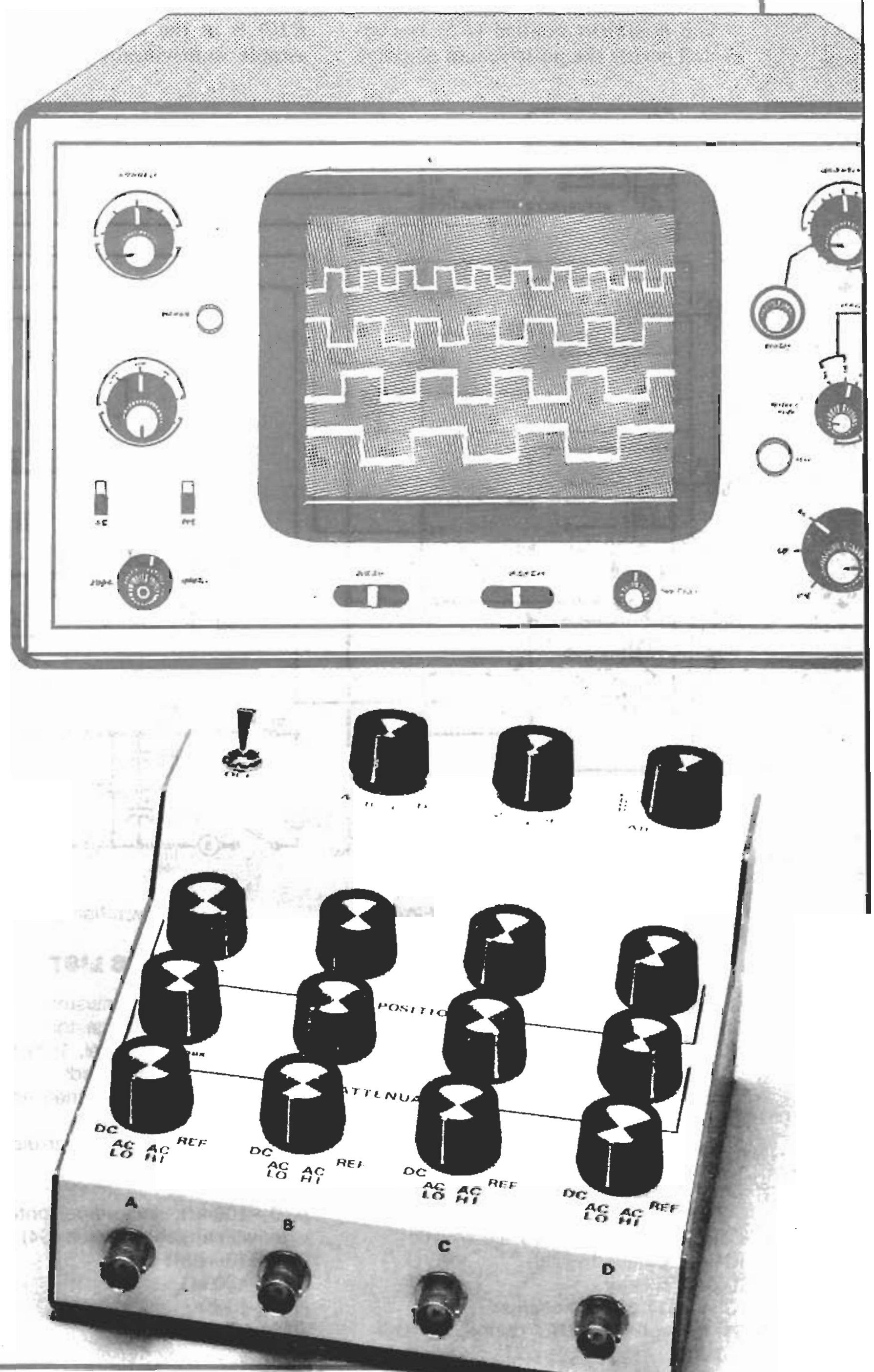
Bandwidth at the 3-dB point is about 4.5 MHz, but the scope switch is usable with signals up to about 20 MHz. Isolation between switches approaches 65 dB, and the input impedance is 98 kilohms (which can be improved if desired). On ac, the switcher will accept signals to 15 V peak-to-peak, while on dc, signals can be ±7.5 V. The display can be chopped at adjustable frequencies from 12 to 210 kHz, and a fixed 200-Hz rate is also available. A built-in trigger processor provides a choice of input channel to do the oscilloscope triggering.

Power requirement is ±9 V from alkaline cells or a simple line-operated power supply.

The switcher can also be used as the staircase generator for a transistor curve tracer, or it can produce four outputs from a single source so that a single audio preamplifier can drive four power amplifiers. A single video source can also be used to drive four video monitors. The complete schematic is shown in Fig. 1.

Circuit Operation. The central element of the oscilloscope switcher is *IC1*, a CMOS quad analog switch. This chip contains four independent spst switches (electronic), each controlled by its own flip-flop. When a CMOS switch is "open," its impedance approaches 2000 megohms, which provides ample isolation between the input and output. In the closed condition the series resistance is approximately 80 ohms, and the attenuation of conducted signals is insignificant.

Since the switcher's four input chan-



nels are similar, we will discuss only channel A. The desired input signal, applied to *J1*, is coupled to DC/LO/HI/REF selector switch *S1*. In the DC position, the input signal is directly coupled to *IC1*, while in the LO or HI positions, the signal is ac-coupled through either *C1* for low frequencies or *C2* for high frequencies. In the REF position, the switch is fed a dc voltage determined by the setting of POSITION control *R5* to allow for trace positioning. The signal at *J1* is also coupled to the trigger-processing circuit to synchronize the scope to the selected signal.

The POSITION control (*R5*) is connected across the positive and negative voltage sources so that each trace can be positioned as desired on the scope CRT display. Capacitor *C3* bypasses the input signal away from the POSITION control and effectively places the lower end of the ATTENUATION potentiometer at ground level. The POSITION control applies a selected dc bias to the switch input to determine trace position.

The four switch outputs (pins 2, 3, 9, and 10 of *IC1*) are connected in parallel and feed the SCOPE VERTICAL INPUT (*J5*).

When CHOP-ALTERNATE switch *S5* (fitted to STABILITY potentiometer *R10*) is in the CHOP (open) position, astable multivibrator *IC2* can be adjusted via STABILITY control *R10* to generate pulses whose frequency ranges from 12 to 210 kHz. When *S5* is in the ALTERNATE (closed) position, the large value of *C13* is placed in the timing circuit, reducing the *IC2* output frequency to approximately 200 Hz.

The CHOP mode of *S5* is used when observing low-frequency signals, while the ALTERNATE mode is used for observing high frequencies. STABILITY control *R10* can be adjusted to remove any flicker or display breakup when the input frequency is similar to the *IC2* pulse frequency or one of its harmonics.

The output of *IC2* drives decade counter *IC3*, whose outputs, in turn, drive the four flip-flops within *IC1*.

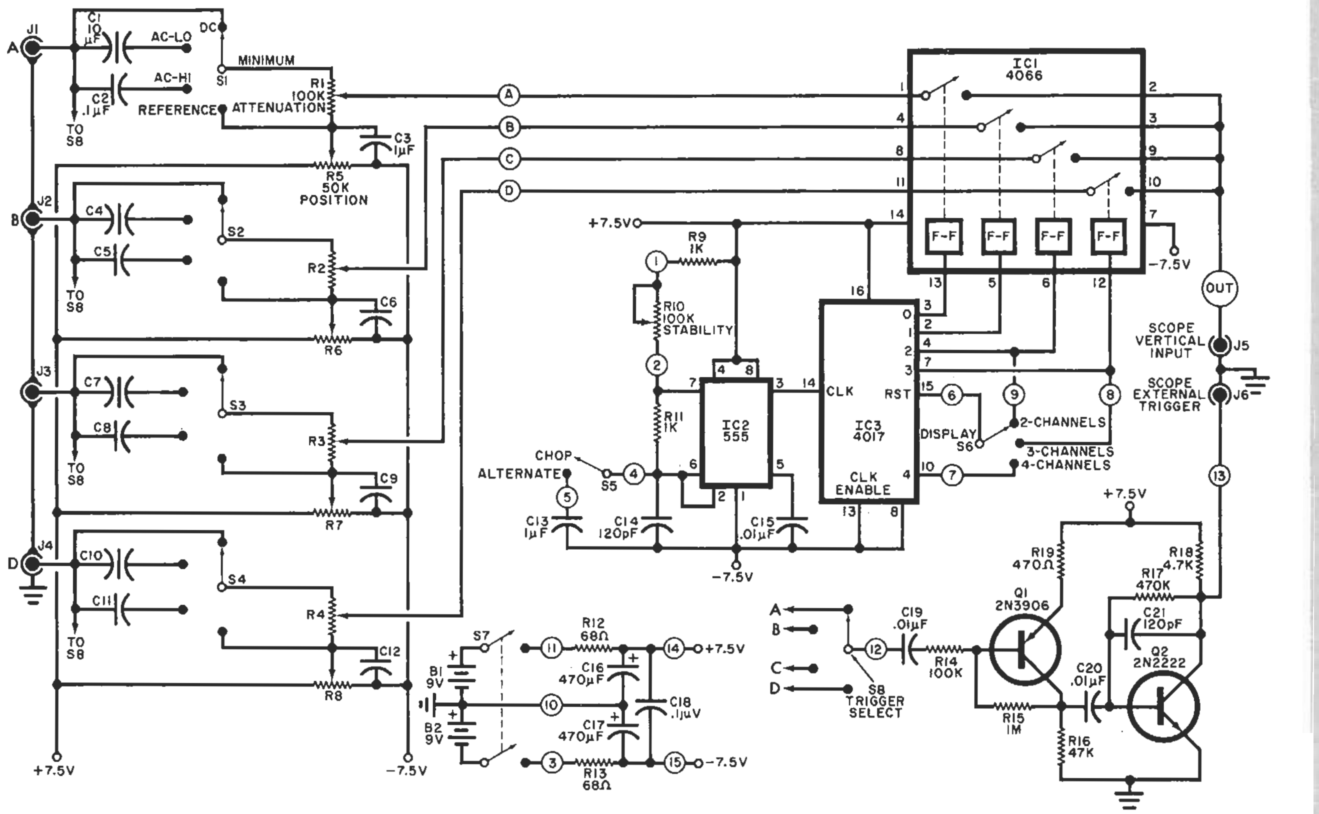


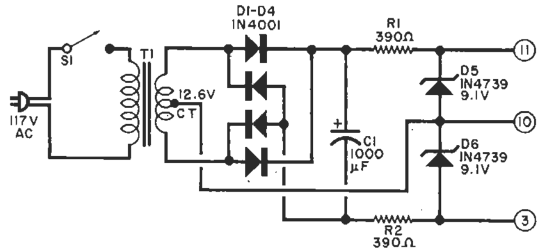
Fig. 1. The heart of the scope switcher is a CMOS quad analog switch.

PARTS LIST

B1,B2—Six 1.5-V alkaline cells
C1,C4,C7,C10—10-μF, 30-V nonpolarized capacitor
C2,C5,C8,C11,C18—0.1-μF, 50-V Mylar capacitor
C3,C6,C9,C12,C13—1-μF, 30-V tantalum capacitor
C14,C21—120-pF, 50-V disc capacitor
C15,C19,C20—0.01-μF, 50-V Mylar capacitor
C16,C17—470-μF, 16-V electrolytic
IC1—4066 quad switch
IC2—555 timer
IC3—4017 decade counter
J1 through J6—BNC connector, UG-1094
Q1—2N3906 pnp transistor
Q2—2N2222 npn transistor
The following are ¼-W, 10% resistors unless otherwise noted:
R1,R2,R3,R4—100-kΩ linear-taper potentiometer
R5,R6,R7,R8—50-kΩ linear-taper potentiometer
R9, R11—1 kΩ
R10—100-kΩ, audio-taper potentiometer with attached switch (S4)
R12,R13—68Ω
R14—100 kΩ
R15—1 MΩ
R16—47 kΩ
R17—470 kΩ
R18—4.7 kΩ
R19—470 Ω
S1,S2,S3,S4,S8—4-position rotary switch
S5—Spst switch (part of R10)
S6—3-position rotary switch
S7—Dpdt slide switch
Misc.—Suitable case (6½" × 6" × 3", Sprague QEP-1715-01 or similar), hook-up wire, battery holders, knobs, press-on type, mounting hardware, etc.

Note: The following is available from Hi-Technology Designs, Box 457, Fairview, OR 97024: etched and drilled pc board for $6.95.

Fig. 2. Optional ac-powered dc supply can be used instead of batteries.



Construction. The project can be assembled using point-to-point wiring or the pc board shown in Fig. 3. Component installation is shown in Fig. 4. The circled letters in Fig. 1 and Fig. 2 refer to pads on the pc board. Note that some resistors are mounted on end to conserve board space. Note also that input capacitors *C1, C4, C7,* and *C10* are nonpolarized types, while the STABILITY control has an associated switch (*S5*) that closes when this control is at its extreme counterclockwise position. If you take care with lead dress, frequencies up to and beyond 4.5 MHz can be displayed. Use BNC connectors for the inputs, and 20-gauge wire to make the necessary switch/control-to-board connections.

The board is then installed within a suitable enclosure whose front panel can accommodate the various controls and the input and output connectors. Each should be suitably identified as to use. Many components can be directly mounted on the switches and potentiometers. Either the battery pack or the line-powered dc supply can be located within the enclosure. If the supply circuit is used, its power cord can exit via a grommetted hole at the rear of the enclosure. Install fresh alkaline cells if battery operation is desired.

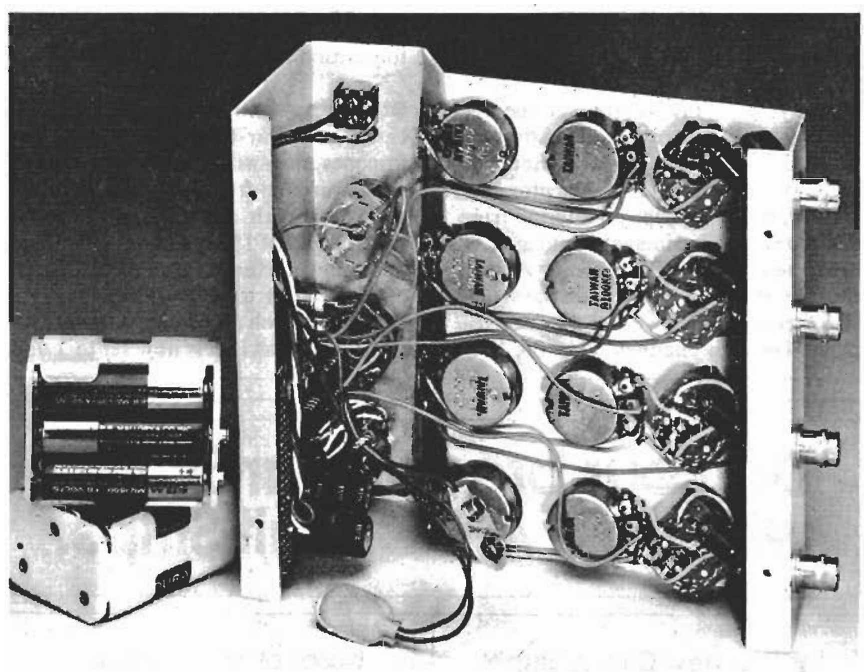
PARTS LIST (Power Supply)

C1—1000-μF, 50-V electrolytic
D1 through D4—1N4001
D5,D6—1N4739, 9.1-V zener
R1,R2—390-Ω, ¼-W resistor
S1—Spst switch
T1—12.6-V, 1.2-A transformer (Radio Shack 273-1505 or similar)
Misc.—Line cord, hook-up wire, tie lugs, etc.

DISPLAY switch *S6* is connected to the reset input of *IC3* and enables selection of three of the *IC3* outputs to allow the display of two, three, or four traces on the scope display. The use of the decade counter ensures that only one flip-flop within *IC1* is enabled at a time.

TRIGGER SELECT switch *S8* selects one of the inputs from *J1* through *J4* and applies the selected signal to the trigger processor formed by *Q1, Q2,* and their associated components. Essentially, the two-transistor circuit forms a high-gain amplifier/shaper whose output is coupled via *J6* to the scope's external trigger input. The two-transistor circuit will operate with inputs as low as 10-mV rms.

Since the current requirement is less than 20 mA, a pair of 9-V batteries can be used for the power supply. If *B1* and *B2* are formed from six 1.5-V alkaline cells in series, up to 80 hours of intermittent duty can be expected. An optional ac-powered dc supply is shown in Fig. 2.



Internal view of the author's prototype.

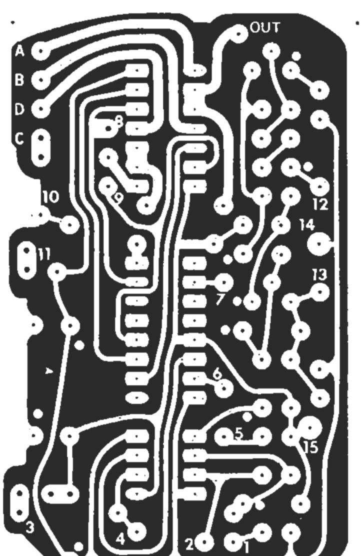


Fig. 3. Exact-size foil pattern.

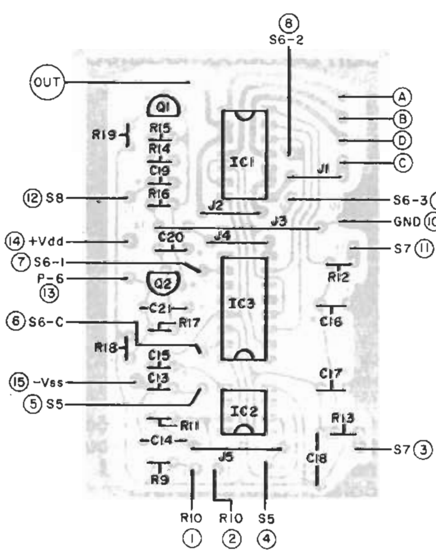


Fig. 4. Component placement diagram.

Checkout. Turn on power to the switcher (*S1* in the ac supply or *S7* in the battery version) and measure +7.5 V between pins 14 (+) and 10 (GND), and − 7.5 V between pads 15 (−) and 10 (GND). Also check that the correct dc input voltage appears at the pertinent pads of the three ICs.

Connect a scope between pin 3 of *IC2* and ground. A series of pulses should be displayed. Now, by starting at the maximum clockwise position of STABILITY control *R10*, and rotating this control counterclockwise, the displayed pulse frequency should increase. When the associated switch (*S5*) closes, the pulse frequency should drop to about 200 Hz. You may have to reverse the connections to *R10* to get the desired result.

Set the scope vertical attenuator to 1 V/division, dc input, and position the trace on the center graticule line. On the switcher, set all the POSITION controls fully counterclockwise, DISPLAY (*S6*) switch to 4 CHANNELS, and the ATTENUATION controls to maximum. Connect the scope vertical input to SCOPE VERTICAL INPUT connector *J5*.

Now, with the scope on internal trigger, a straight-line image should appear near the bottom of the screen. Adjust the four POSITION controls on the scope switcher to create a staircase of convenient size with channel A on the bottom, channel B above it, then channel C, and finally channel D on the top. Adjust the scope's vertical attenuator and position controls to center the display. Each step of the staircase should be about a 2-V increment.

Connect the switcher's SCOPE EXTERNAL TRIGGER jack (*J6*) to the scope's external trigger input and set the scope trigger controls accordingly. Using a signal generator, apply analog or digital signals to the four input connectors and note that they appear on the four traces. Use the TRIGGER SELECT switch (*S8*) to select the desired trigger signal and adjust the scope trigger controls for a stable CRT display. You can now adjust the ATTENUATION and POSITION controls on the switcher to position the image as desired.

Other Applications. Besides its application as a four-trace add-on for oscilloscopes, the switcher can also be used as a variable-frequency square-wave generator with a maximum peak-to-peak output of 15 V. To implement this operation, set the input selector switches (*S1* to *S4*) to REFERENCE and the DISPLAY switch (*S6*) to 2 CHANNELS. If the DISPLAY switch is now set to 3 or 4 CHANNELS, and the scope traces are centered, the frequency present at SCOPE VERTICAL INPUT connector *J5* will be lowered by one-third and one-half, respectively. The staircase output can be used as a driver for a transistor curve tracer.

Since *IC1* is bilateral, a signal can be applied to *J5* and then distributed to four different circuits connected to *J1* through *J4*. This setup wil also work with digital signals—you can drive four displays from one computer (or video game).

Some design tradeoffs were made to keep the cost down. For example, the ATTENUATION controls are low-cost 100-kilohm units, which in conjunction with the scope input impedance, produces a 98-kilohm input impedance for the switcher. The input attenuators (*R1-R4*) may be increased to 1-megohm units, but circuit response time will increase because it will take longer to change the input capacitors. This approach could be used when monitoring high-impedance circuits. However, a high input impedance will cause some rolloff on the edges of observed pulses if the ATTENUATION controls are in other than their MINIMUM positions. ◇

Scope Bargraph Unit

Graeme Durant

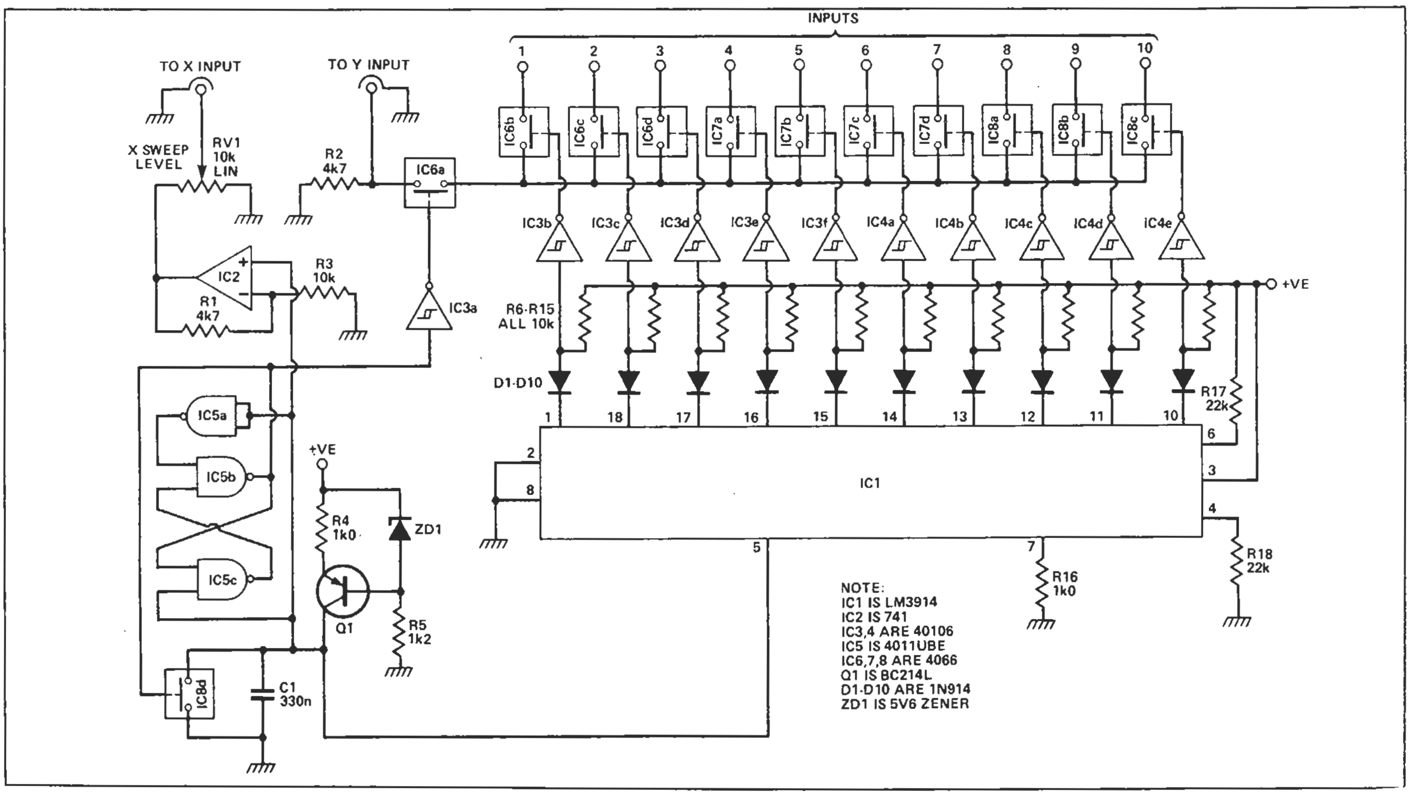
This circuit is designed to be used in conjunction with any ordinary oscilloscope which has an X-deflection input, and allows it to be used as a bargraph display. The screen has 10 useable columns.

The heart of the circuit is IC1, and LM3914 bargraph driver. The input to this, pin 5, is connected to a sawtooth generator running at about 1 kHz, formed around Q1. Q1 is a constant current generator supplying 5 mA and charging a 330nF capacitor to create a linear sweep. As the voltage on this capacitor reaches the upper CMOS threshold, about two-thirds supply, a latch formed by IC5b and c is triggered by IC5a. This rapidly discharges the capacitor through IC8d. When the voltage has dropped to the lower CMOS level, about one-third supply, the latch is reset and the capacitor starts to charge up again. Thus a linear sawtooth waveform is produced.

This is buffered by IC2 and fed out to drive the X amplifier in the scope. However, as this sweep also drives a bargraph IC which has its upper and lower limits set to be similar to the two CMOS switching levels, the 10 outputs go low, one at a time, in sequence. These outputs are used to drive a multiplexing system: a set of 10 analogue switches (IC6b to IC8c). These are driven via inverting Schmitt triggers, diodes and pull-up resistors due to the limited drive capability of IC1 at logic 1.

The multiplexed output is sent to the scope's Y input via another analogue switch, which is normally on, but cut off while the sweep capacitor discharges so as to blank out the 'flyback'. Alternatively, the 'Z modulation' input of the scope could be used if one is available.

In use, the internal sweep generator in the scope is turned off and the circuit is connected. It is recommended that a regulated supply of 15 V is used so as to provide adequate X output drive. The X sweep level is adjusted until a suitable width of display is produced (this being a horizontal line at the present), which should be moved to the bottom of the screen. Now the inputs to the scope may be connected and the Y sensitivity of the scope adjusted to give a good display.



TECH TIPS

Eight Traces On A Single Trace Scope

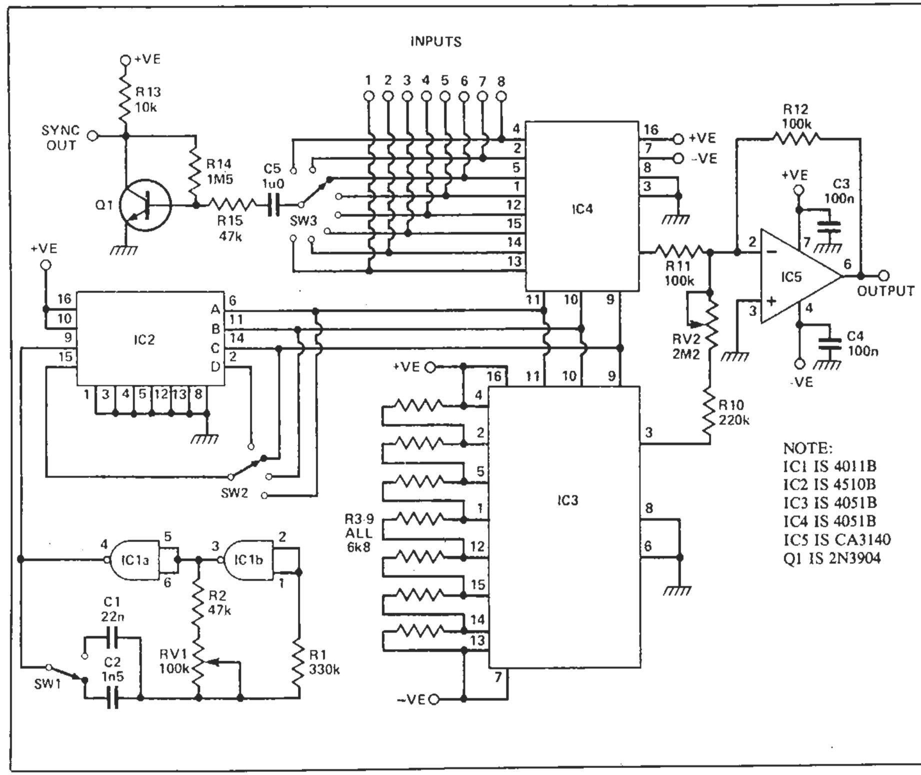
Tore Solheim

This simple and inexpensive circuit can display up to eight traces on a single beam oscilloscope. Even though the capacity of such a simple circuit is limited, it will be fine as part of a home workshop. The frequency response is DC to 100 kHz with the circuit shown, and the scope sensitivity should be 0V5 per division, preferably DC-coupled.

IC1 is the clock oscillator: SW1 selects chopped or alternate mode. RV1 allows the frequency to be adjusted over the range 10-30 kHz or 200-700 Hz depending on the setting of SW1. The counter IC2 controls the two analogue multiplexers IC3, 4. One, two, four or eight traces may be selected using SW2, which couples one of the counter outputs back to the reset pin to reset the IC after the desired count length. The analogue inputs of IC3 are connected to a voltage divider, R3-9, and the output is connected, via R10 and RV2, to the negative input of the op-amp, IC5. This allows the offset voltage of the op-amp to be adjusted over a wide range. The trace changes position by changing the offset voltage, which has no effect on the gain of the op-amp. RV2 allows the voltage offset between the upper and lower traces to be adjusted from ±0V3 to ±3 V, ie RV2 is the position control. Separate controls aren't needed here. The eight channel inputs are connected to the analogue inputs of IC4.

The circuitry around Q1 and SW3 is to allow external triggering of the scope. This circuit isn't strictly necessary, but will often give a better display. The whole circuit is designed for a ±6 V power supply, and the inclusion of IC3, 4 means that ±7V5 should never be exceeded.

Why is IC5 wired in the inverting mode, when the non-inverting mode would give better results? The offset adjustment of a non-inverting low-gain amplifier using the method shown here would affect the gain. Also, the inputs should not be left open-circuit as this will cause notches on the traces. The inputs should therefore be connected to an inverting amplifier, preferably with an attenuator due to the low sensitivity.



Advances in CRT design augur improved oscilloscopes

by A.G. Shephard, Thomson-CSF
Electron Tube Division, Paris, France

☐ The oscilloscope has become an indispensable measuring tool in all fields of science and technology, at least partly because of improvements in the oscilloscope's basic component—the cathode-ray tube. Although some CRTs being manufactured today are little different from those introduced in the first scopes in the 1930s, during the early days of television, the capabilities of some modern CRTs have outpaced the electronics used in scope design. And recent developments, chiefly charge-coupled devices, will probably bring about an oscilloscope generation that is more likely to be integrated into data-collection systems than to stand alone as isolated instruments.

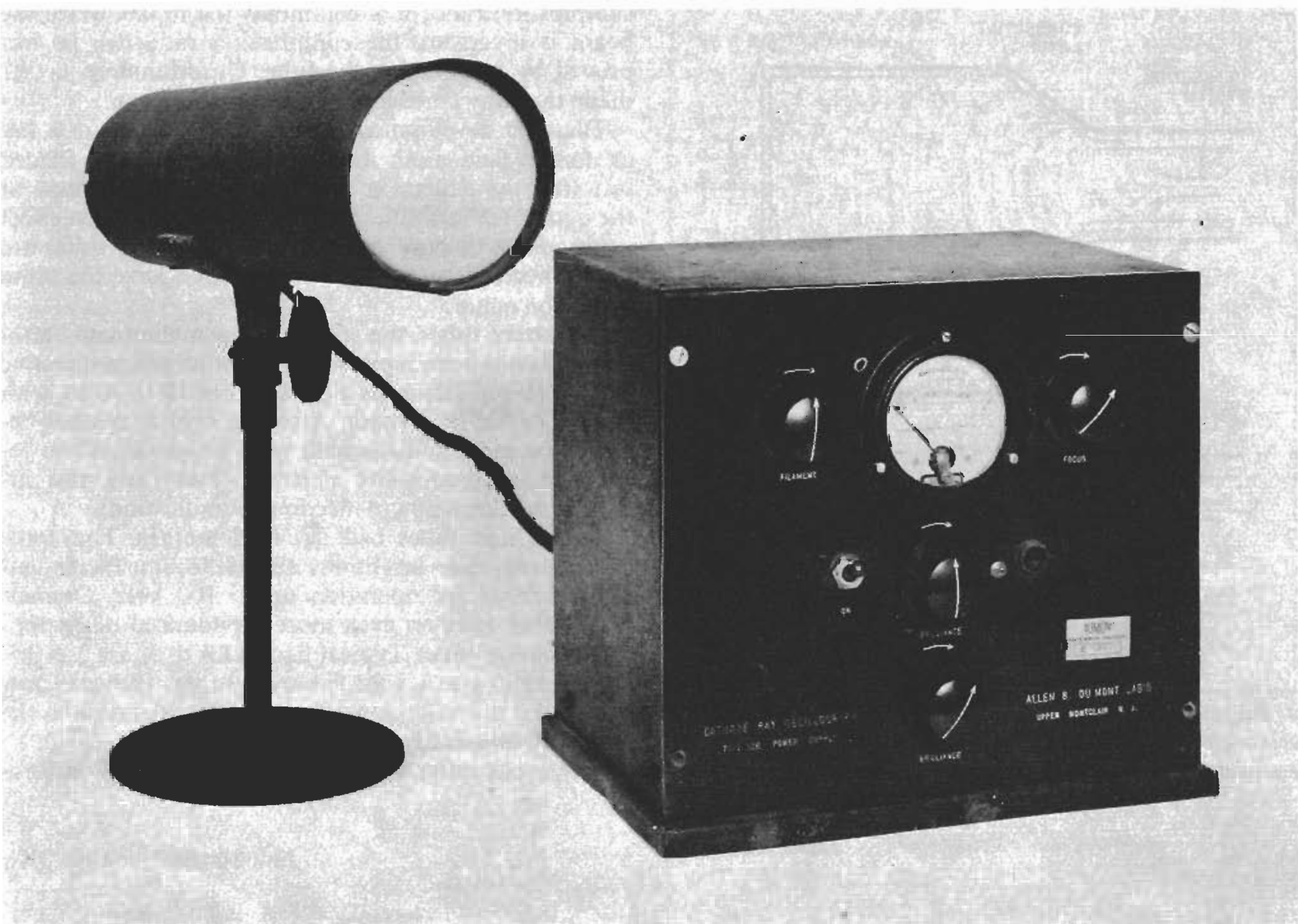
In choosing a cathode-ray tube, the scope maker considers deflection factor, bandwidth, storage capability, reliability, and display quality, which includes screen dimensions, trace brightness, spatial resolution, and geometric distortion. With the variety of CRTs now available, the manufacturer can satisfy most requirements on these counts.

The remaining headaches mainly concern bandwidth. The upper limit is being raised constantly. Whereas a 30-megahertz laboratory oscilloscope was considered exceptional in 1955, 350-MHz models are now in common use, and a demand, admittedly limited, exists even for gigahertz capability. Working in close liaison with oscilloscope designers, CRT manufacturers have played, and are still playing, an important role in this evolution.

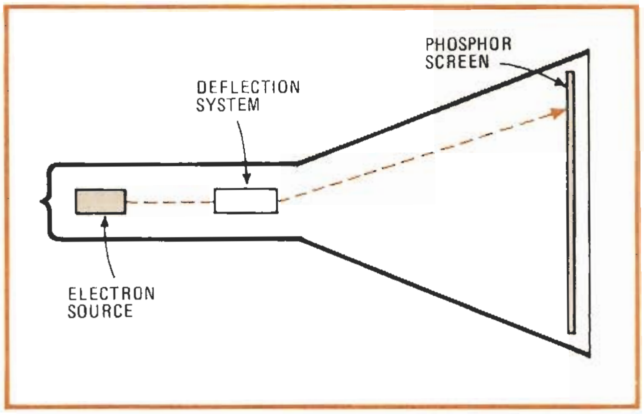
Simple beginnings

Many of the requirements of educational institutions and repair shops can be satisfied by 10-MHz oscilloscopes that use CRTs of relatively simple design (Fig. 1), differing little in principle from the first tubes ever to be manufactured. Electrons from a hot cathode are collimated into a fine beam and accelerated toward a phosphor screen that is several kilovolts positive with respect to the cathode.

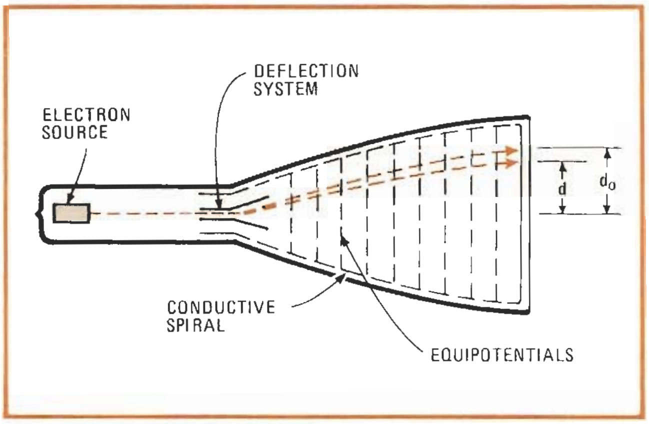
The electron beam is deflected so as to graphically display the incoming signal information (usually as a function of time) along horizontal and vertical axes. Electrostatic deflection is nearly always used. Although



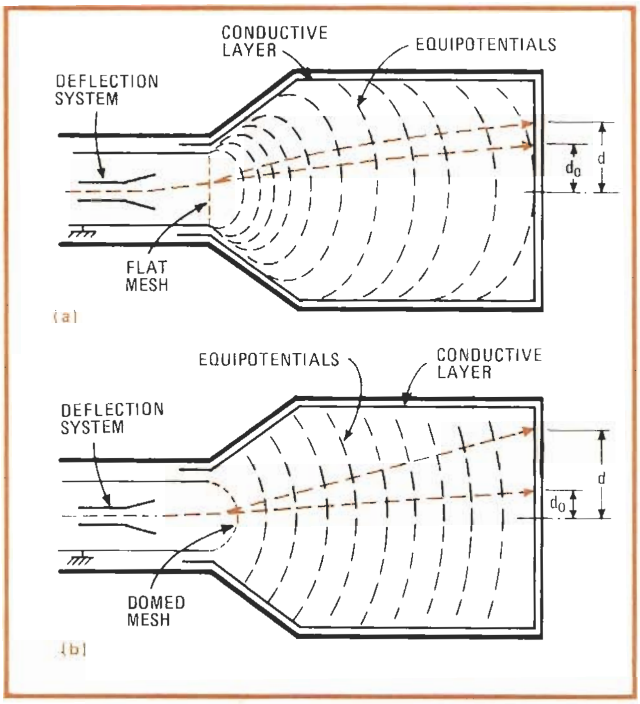
1. On screen. The first commercial oscilloscope, of which an example is in the Smithsonian Institution, was introduced by Allen B. DuMont Labs in the 1930s. Deflection connections were made directly to the CRT, the box shown acting only as a high-voltage power supply.



1. Simple CRT. The most common oscilloscope CRT, still widely used in low-frequency instruments, differs little from early units.



2. Spinning a field. The voltage across a conductive spiral on the inside surface of the CRT creates a field that accelerates the beam.



3. Magnifying through a mesh. Either a flat or curved mesh helps improve the deflection factor of a scope CRT. The radially traversed equipotentials of the domed-mesh tube increase this effect.

magnetic deflection gives a slightly smaller spot size, coil-design problems and excessive power consumption impose an upper limit on useful operating frequency of 2 to 3 MHz. Tubes using this principle are normally found only in oscilloscopes that have limited frequency response and large screens.

Because of their unsophisticated design, these simple tubes are relatively cheap to manufacture, but their low trace brightness makes them totally unsuitable for operation above 20 MHz. Since trace brightness depends on the energy imparted to the screen by the electron beam, and hence on accelerating voltage, the only way to improve trace brightness would be to increase the accelerating voltage. But to do so would automatically increase the already high value of the deflection factor (see "Measuring deflection," p. 116). Increasing the length of the deflection plate could reduce the deflection factor, but the increased interplate capacitance would hurt the CRT's high-frequency performance.

Post-deflection acceleration

In an attempt to increase trace brightness without unduly affecting the deflection factor, CRT manufacturers long ago introduced tubes in which the energy of relatively low-voltage electrons was increased after deflection. This technique is known as post-deflection acceleration, or PDA.

The first tubes of this kind had a resistive spiral electrode painted on the inner surface of the glass bulb (Fig. 2), and the potential difference across the two ends was about 10 kilovolts. The spiral creates equipotentials that act as a converging lens, progressively accelerating while bending the beam toward the tube axis. The deflection that would occur if there were no convergence, d_0, divided into the actual deflection, d, is known as the compression ratio; it is commonly 0.4 to 0.6. Since the beam is divergent, the compression ratio can be improved by lengthening the tube. Unfortunately, a CRT made that way tends to be rather cumbersome.

The next development was the introduction of a flat or domed field mesh into the spiral PDA tube. Placed just after the deflection plates, it modifies the shape of the equipotentials, thus avoiding the compression effect associated with pure spiral PDA tubes. These tubes are much shorter than spiral PDA CRTs that have the same deflection factor.

In modern tubes, the spiral has been eliminated altogether. It has been replaced by a continuous conductive coating (Fig. 3) that has a potential of 15 to 20 kV with respect to the field mesh. A strong field is created between the mesh and the bulb wall, which yields two results: it accelerates the electrons (PDA) and also increases the deflection (deflection magnification).

The earliest tubes had flat field meshes. They provided good trace brightness and deflection factor and were suitable for operation up to 100 MHz. Domed-mesh tubes have an even more pronounced deflection-amplification effect. Typical figures for d/d_0 are 2 to 3.5, compared to 1 to 1.5 for flat-mesh tubes. They are now being used in oscilloscopes designed for operation in the 50-to-300-MHz range.

Both types suffer from disadvantages that directly result from the use of field meshes. First, the beam is diffracted by the grid-like form of the mesh, increasing spot size and reducing contrast. Second, an appreciable part of the beam is intercepted by the mesh, which then emits secondary electrons that reduce control further and can also cause a halo effect on the screen. This halo, although always present, is not noticeable under most conditions. However, when the time base is unusually slow, the halo is clearly visible. The effect is more pronounced with domed-mesh than with flat-mesh tubes.

Quadripolar Lenses

An improvement in the tubes, the use of quadripolar and slot lenses, was developed in 1967 by Thomson-CSF. These tubes, which are extremely compact, have a very low deflection factor, wide frequency response, excellent trace brightness and geometry, and complete absence of the problems that characterize mesh-type tubes. The secret lies in their PDA/deflection-magnification system, consisting of a set of quadripolar lenses followed by a slot lens (Fig. 4).

This tube design greatly reduces the problems encountered in developing large-bandwith oscilloscopes. Yielding a bright trace because beam-attenuating meshes are eliminated, it allows signals with very fast rise times to be displayed. Because of the extremely low deflection factor, the deflection sections can be driven by amplifiers that have moderate gain. The low deflection factor also makes possible compact, large-screen tubes, which are ideal for the growing market in large-display portable oscilloscopes. Spatial resolution is excellent because there is neither beam diffraction nor secondary emissions. And because tubes of this design are lighter and more robust than field-mesh tubes, they are ideal for applications where weight and mechanical reliability are of utmost importance.

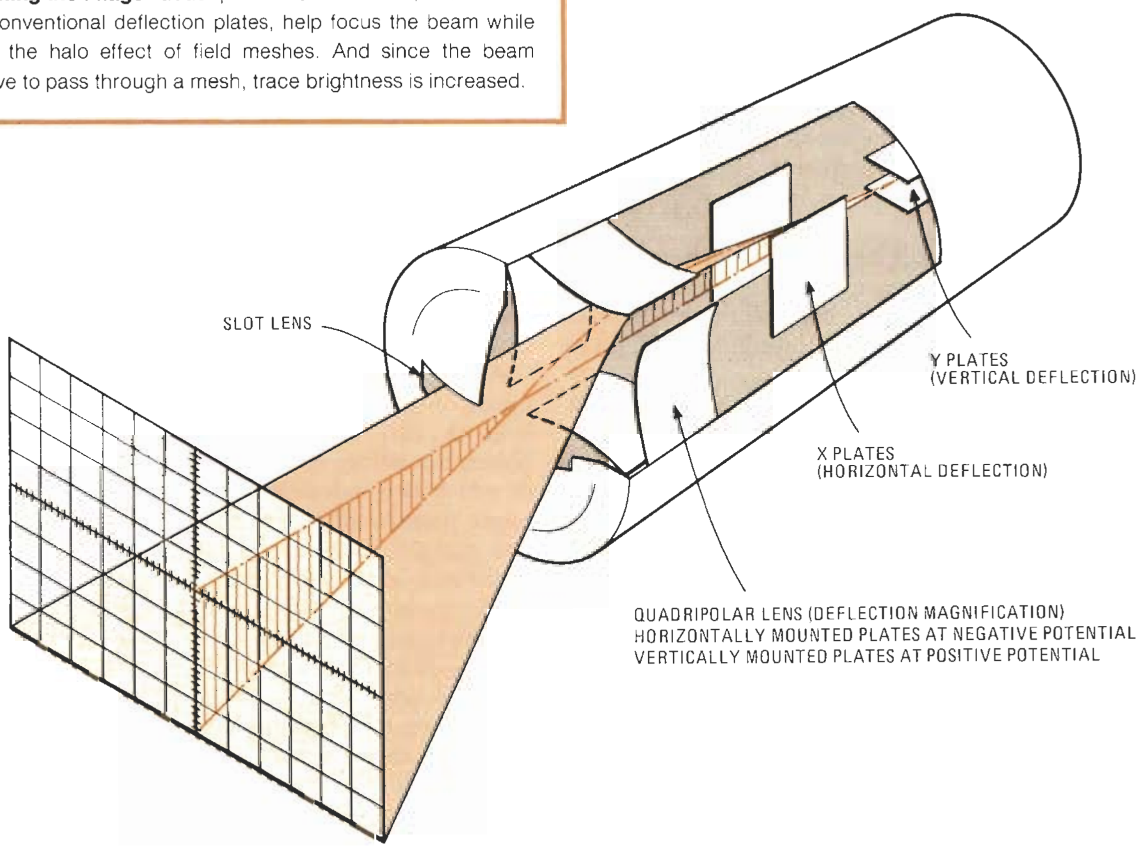
Deflecting the beam

So far, little has been said about the primary deflection system, and, for the sake of simplicity, all of the drawings have shown conventional deflection plates. The maximum frequency response of a set of conventional plates depends on the time taken by an electron to pass between them. If it takes more than an appreciable fraction of the signal cycle time, then the net deflection will be either reduced or zero.

Frequency response could be improved by reducing transit time by means of a reduction in plate length or an increase in electron velocity, but either technique would adversely effect the deflection factor. Because of the high degree of deflection amplification obtained in quadripolar lens tubes, the deflection factor may be sacrificed to a certain extent. For that reason, such tubes, even with conventional plates, have a larger bandwidth than their domed-mesh counterparts.

Another problem becomes apparent when the CRT is judged as part of an oscilloscope, instead of alone. Because the impedance of the plates is inversely proportional to the signal frequency, the amplifier that drives them must be capable of functioning correctively with a

4. Sharpening the image. Quadripolar and slot lenses, shown here following conventional deflection plates, help focus the beam while eliminating the halo effect of field meshes. And since the beam doesn't have to pass through a mesh, trace brightness is increased.



Measuring deflection

Two terms to describe the capability of a deflection system to alter electrons' trajectories are deflection factor and its inverse, deflection sensitivity. The meanings of the two terms are sometimes reversed. An electron of energy eV_0, passing through an electrostatic field V_s that is perpendicular to its original trajectory (V being the potential difference across the deflection plates), will be deflected. The deflection, d, is $(V/V_0)(Ll/2s)$.

The deflection factor of a CRT, V/d, is the number of volts required for a 1-centimeter (or graticule division) deflection:

$$V/d = (2sV_0)/(Ll)$$

This capability can also be expressed in terms of deflection sensitivity as the number of centimeters or graticule divisions of deflection obtained with a deflection voltage of 1 volt.

TABLE 1: OSCILLOSCOPE CRTs

CRT type	Advantages	Disadvantages	Frequency range
Simple	Low cost Fairly small spot (0.4 mm)	Low deflection factor (30 V/cm) Low trace brightness	Up to 10 MHz
Spiral PDA	Medium price Small spot (0.2 to 0.3 mm) Bright trace	Medium deflection factor (10 V/cm) Bulky	Up to 50 MHz
Flat-mesh lens	Medium price (higher than spiral PDA) Fairly small spot (0.4 mm) Good deflection factor (6 V/cm)	Medium trace brightness Halo caused by mesh	50 to 100 MHz
Domed-mesh lens	Medium-sized spot (0.45 mm) Compact Very good deflection factor (4 V/cm)	High price Medium trace brightness Halo caused by mesh	50 to 300 MHz 500 MHz possible
Quadripolar lens	Fairly small spot (0.4 mm) No halo Compact Excellent deflection factor (1.5 V/cm)	High price Medium trace brightness	50 to 500 MHz 800 MHz possible

wide range of loads. The design of such amplifiers becomes difficult, if not impossible, for large-bandwidth oscilloscopes.

For these reasons, conventional plate systems are not to be recommended beyond 150 MHz for domed-mesh tubes and 250 to 300 MHz for quadripolar-lens tubes, which have shorter deflection plates and less plate-to-plate capacitance. For frequencies higher than these, transmission-line systems are used (Fig. 5).

Instead of one relatively long plate, a series of short plates is used. These are interconnected by inductive/capacitive delay elements to match the signal propagation time to the electron transit time so that the electron is constantly deflected during its passage between the plates. In addition, and of major importance to the oscilloscope designer, correctly adapted transmission-line systems have a frequency-independent impedance, which greatly simplifies design of the deflection amplifier.

In addition to the previously mentioned improvements, which are largely concerned with electron optics, the actual presentatation of the visible image has changed over the years. The P1 phosphor, in common use for a long time, has now been replaced to a great extent by P31. which exhibits superior characteristics for most oscilloscope applications. The color is more agreeable to the eye and better matched to the spectral sensitivity of films used in oscilloscope cameras. In addition, P31 has a more rapid rise time and higher luminosity, which makes it superior for display of fast transients.

Trace brightness has been nearly doubled by coating the back surface (electron-gun side) of the phosphor with a thin layer of aluminum. The metal acts as a mirror, reflecting outward the light that is emitted from the phosphor back in the tube.

Adding a grid

Until the late 1960s, most oscilloscope measurements were made by reading along a plastic graticule in front of the CRT. This graticule was easily damaged, and parallax resulting from the separation between the image on the phosphor and the graticule caused reading errors. In later CRTs, the graticule is being placed inside the tube in the same plane as the phosphor.

Although increasing accuracy, internal graticules caused unexpected problems for the CRT manufacturer. The slightest errors in trace geometry, not noticeable with an external graticule, became immediately obvious and reason for complaint. However, accuracy in mounting and the general precision of the electron optics have been improved, so that the accuracy of the modern oscilloscope CRT is becoming more and more accepted.

Many oscilloscopes can display two or more traces at the same time. The simplest technique with a standard CRT is to chop or alternate the incoming signals at a high frequency and apply them at different times to the vertical-deflection plates. The traces are separated by dc-level controls.

Another technique provides two continuous traces by means of a special CRT in which the electron beam is split in two after leaving the horizontal-deflection plates, but before reaching the vertical-deflection plates, of which two independent sets are used. A third technique permits all parameters to be varied by means of two completely independent sets of electron guns and horizontal- and vertical-deflection plates.

The most recent change has been made possible by the availability of large-screen CRTs. For many years, the standard display format has been 8 by 10 centimeters, but new CRT screens are 10 by 12.5 cm, and even larger sizes are becoming available. Although the absolute resolution remains the same, the readability has been greatly improved by 10-by-12.5-cm screens, so that this format may rapidly replace its predecessor as a standard.

All of the CRTs described so far have one thing in common: when an electron strikes the phosphor screen, the resulting luminous spot is only visible for an instant. When looking at sufficiently fast, repetitive phenomena, the eye integrates the successive traces to give an impression of continuity. With very slowly evolving signals or fast nonrecurrent phenomena, some form of image-storage system is required. When required for use with a conventional oscilloscope, storage is usually provided by a camera.

Capturing the image . . .

However, another type of instrument is available for these applications. This is the storage oscilloscope in which a direct-view storage tube (DVST) replaces the conventional CRT. And even though a DVST can store incoming signals and display a continuous image, the stored data can be totally erased in a few milliseconds.

The main difference between the two basic classes of DVST is where the signal is stored. In one, the phosphor-target tube, the storage medium is the phosphor of the screen. This system is inexpensive because it is simple to construct and also simple to operate. Because of the way it works, the phosphor-target tube is commonly called a bistable tube. Since the operation of this class of tube has been extensively described elsewhere, it won't be dealt with here.

Capable of much better performance is a class of tube, in commercial production at Thomson-CSF since 1962, in which the storage medium is a special mesh that is placed near to the phosphor (see Table 2). Because of the principle of operation, this tube is known as the variable-persistence (or half-tone) storage tube.

The basic structure of a variable-persistence DVST resembles that of a conventional CRT with several components added (Fig. 6). The storage-and-display section consists of a phosphor viewing screen, a metal-mesh collector electrode, and a metal-mesh backing electrode that has a thin layer of dielectric (the storage surface) deposited on the side facing the writing gun.

Operation of the tube depends on the secondary-emission characteristics of this dielectric so that the storage surface can be charged either positively or negatively, according to the energy of the incident electrons.

The flood guns (normally two) continuously emit a wide-angled beam of low-velocity electrons that is shaped by the collimator so that the meshes and phosphor are evenly and orthogonally irradiated. Electrons approach positively charged areas of the storage mesh, then will pass through the holes in the backing electrode, be accelerated, and strike the phosphor.

Those approaching negatively charged areas will be repelled back toward the collector. The storage mesh acts like the control grid of a triode in that the transmitted beam of electrons will be modulated by varying levels of positive charge present on the storage surface. In this way, half-tone information can be displayed on the phosphor screen.

. . . storing it . . .

To write and store information, the storage surface is locally charged in a positive-going sense by the beam from the writing gun. The electrons are energetic enough to give a secondary-emission ratio that is greater than one.

The resulting trace of positive charges can be turned into an image by the flooding beam. Because the flooding-beam electrons don't remain on the storage surface (they are either repelled or transmitted through the holes), an infinite-duration display seems to be possible. But in practice, residual gas molecules inside the tube are ionized by the flooding beam, positive ions are deposited on the storage surface, and display contrast is reduced by the appearance of a luminous "stain" of increasing intensity until, eventually, the information is lost. This phenomenon is called "fading positive." Long-term retention can be accomplished by switching off the flood guns so that written information is stored indefinitely before being displayed.

. . . and letting go

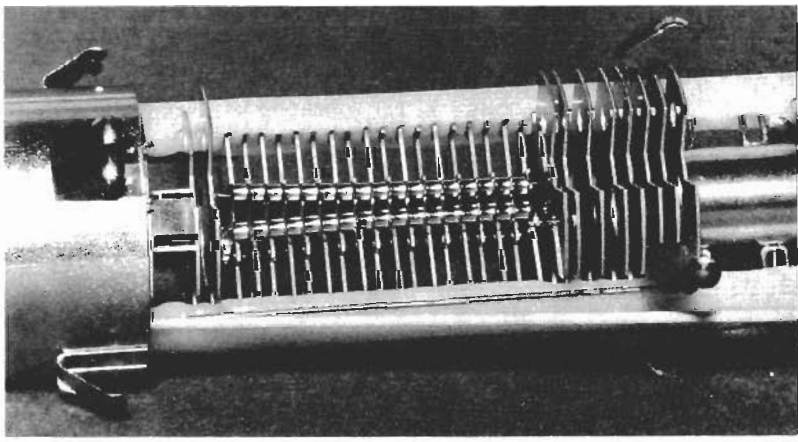
To erase stored information, a positive pulse is applied to the backing electrode. Low-energy flooding-beam electrons are then attracted toward the storage dielectric (the surface potential of which has also been raised because of capacitive coupling) and charge it uniformly to the negative flooding-gun cathode potential. On removal of the positive pulse, the backing-electrode potentials falls to its original value and, because of capacitive coupling, the storage-surface potential falls to the unwritten state. New information can then be written and stored.

If variable-persistence operation is required, the single positive erase pulse is replaced by a train of shorter pulses, each of which partially erases. Persistence may be varied by adjusting the pulse duty cycle.

The DVST can be used as a normal CRT by cutting off the flooding beam and dropping the collector potential (normally around +100 V) to 0 V. To prevent trace broadening, the backing electrode must also be biased negative enough to keep secondary electrons, which are generated by writing-beam electrons striking the storage surface, from reaching the phosphor viewing screen.

Stored writing speed and viewing time are inter-

5. Down the line. Large-bandwidth oscilloscopes demand deflection systems more complicated than simple plates. Electrons are accelerated all along the delay-transmission line shown here.



related. If information is written onto the storage surface by a very fast beam, the displayed trace will be faint, and it will soon be drowned in the increasing background glow of the fading-positive effect. Because of this, the effective writing speed in storage operation is limited to around 500 cm/μs in most tubes. This is equivalent to storing a single-shot 9-ns rise-time signal with 3.5-cm amplitude.

Although this is sufficient for the majority of applications, higher stored writing speeds are desirable in certain domains. In such cases, a fast-transfer storage CRT can be used.

The fast-transfer-storage CRT is similar in principle to a variable-persistence DVST, but it has two storage meshes instead of one. The first has been designed to capture high-speed signals at the expense of viewing time. The stored signal is then transferred to the second mesh, which is designed for long viewing times.

What's coming in scope CRTs

Future developments in CRTs will be aimed at separating the data-gathering from the display functions. In the past, CRT development has been stimulated by the demands for such improvements as increasing bandwidth, sensitivity, brightness, and resolution. Virtually all of those needs can be met by present-day tubes, except for some problems in the gigahertz region. Even there, highly specialized (and also rather expensive) tubes yield reasonable results. However, the total market for oscilloscopes with this level of performance is limited to a handful per country, since their main application is in advanced research into nuclear and laser phenomena. The vast majority of users are more than satisfied by the performance of scopes at 10 to 500 MHz.

For some time, the oscilloscope has been widely considered part of an integrated data-treatment network, rather than an isolated unit. Hence, the demand is increasing for models with digital outputs, compatible with standard data-processing equipment. Various ways have been tried to adapt relatively conventional oscilloscope technology to satisfy this demand. But is this the way to solve the problem, or should the whole function of the CRT and oscilloscope be reconsidered? This question was posed to a group of Thomson-CSF engineers responsible for CRT development, and they tried some crystal-ball gazing.

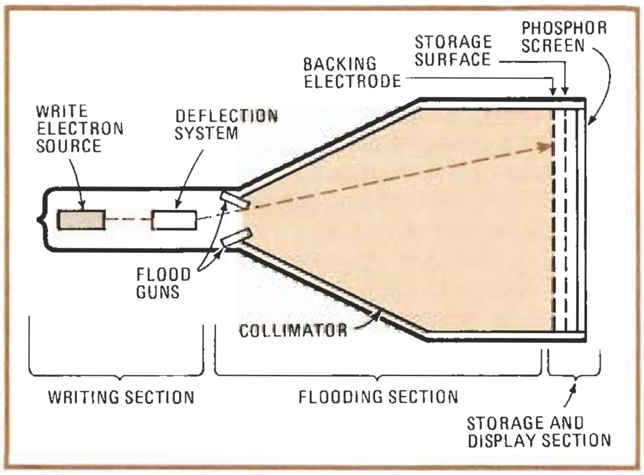
The opinion was unanimous that, although the conventional oscilloscope will continue to be used for the foreseeable future, it will soon be complemented, and for certain applications replaced, by a high-speed data-storage system with digital readout plus an auxiliary display monitor.

How could high-speed data storage with digital readout be obtained? Among the various ideas proposed, three give food for thought; all are based on CCD technology.

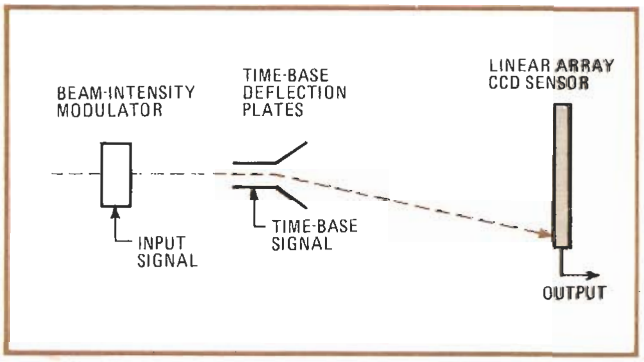
Applying CCDs

The first idea calls for a linear-array CCD to be enclosed in an evacuated glass bulb that also contains an electron gun and horizontal-deflection (time-base) plates (Fig. 7). No vertical-deflection plates would be required because the incoming signal information would modulate the electron-beam current by means of the electron gun's control grid, for example.

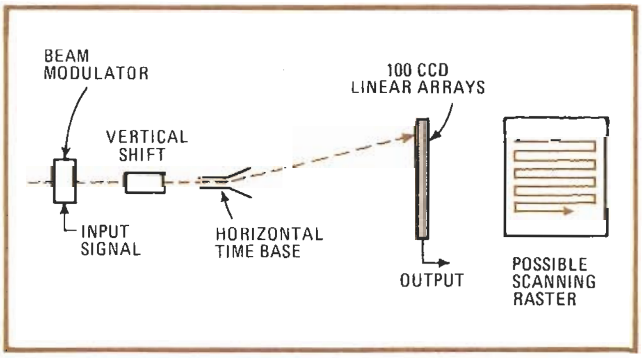
The information would be captured by the linear-array CCD, read out, and stored by a second CCD. It could then be displayed at will by means of a simple, low-cost CRT or digitized for further data treatment. This approach would provide a good digital-output oscilloscope at relatively low cost; the combined cost of the CCD unit and simple CRT monitor could be appreciably less than the cost of today's high-performance CRTs that not only have to display information, but also have to be able to



6. Holding on. The flood guns in a typical direct-view storage tube supply electrons that pass through the storage mesh, on which a trace has been written, before they illuminate the screen.



7. Variable intensity. Future oscilloscopes may use a modulated beam writing on a CCD target instead of on a CRT.



8. More data. Raster scan across a CCD array could extend the recording time of the modulated-beam system.

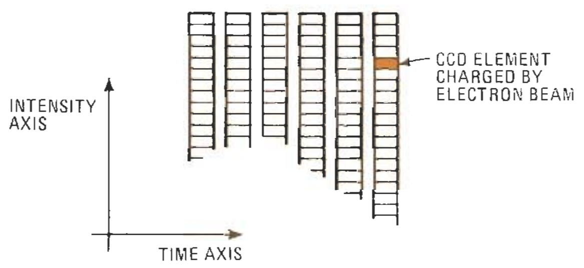
TABLE 2: MESH VS. PHOSPHOR STORAGE		
	TYPICAL MESH STORAGE TUBE	TYPICAL PHOSPHOR STORAGE TUBE
Phosphor	P31: High brightness	PI or similar: less bright
Variable persistence	Yes	No
Half-tone storage (z-axis modulation)	Yes	No
Writing speed	Unaffected by aging	Decreases with aging
Stored brightness	Unaffected by aging	Decreases with aging
Brightness	Up to 100 times higher	
Split-screen capability	No	Yes
Structure	Relatively complex	Simple

capture it. With present CCD technology, models working at 20 to 100 MHz are envisioned.

The next idea is a variation of the first. The single linear array would be replaced by a set of up to 100 parallel linear arrays (Fig. 8). The principle of operation would be the same, but since the time base describes a raster, the possibilities are numerous. For example, the information could be treated as a continuous train of signals so that the capacity would be increased a hundredfold. Alternatively, the information in each linear array could be extracted separately for such signal processing as eliminating noise.

In these two concepts, a sampled analog output would have to be subsequently digitized. The third idea would give a direct digital output (Fig. 9). And, when suitably read out, the output signal could be treated directly by standard data-processing units.

A series of linear-array CCDs would be scanned in both X and Y directions by the electron beam as in a conventional oscilloscope, but the operation would be fundamentally different. Intensity would be indicated by position along the array, and time would be governed by which array the information is stored in. The two previous plans would furnish time information by position along the array and intensity information by the quantity of charge in the CCD elements.



9. CCD CRT. If scanned like a standard CRT, a CCD array can give the same information as the tube but in digital form.

Evaluating CCD potential

The advantages of the three proposed systems over standard CRTs would be:

- An output that would be either digital or sampled and therefore easy to digitize.
- High writing speeds, because an inherent gain of several thousand is possible with CCD targets.
- Readout that could be handled by a cheap standard CRT so that high performance would be possible at a relatively low overall cost.
- Compactness, and low manufacturing costs. By exploiting the technique of the single CCD strip with beam-intensity modulation, it should be possible to construct storage-oscilloscope systems that are cheaper than conventional models.

Such a new-generation oscilloscope would require some form of display unit to provide a visual check of the signal being fed into associated data-processing unit. This check could be made by a simple low-cost CRT for many applications, but an alternative immediately springs to mind—the plasma-discharge display panel.

The plasma panel, which has high writing speed and an inherent memory, is ideally suited for this type of oscilloscope because of its compatibility with digital and sampled signals. And since the typical panel is only about 12 millimeters thick, an instrument using it would be considerably less bulky than one using a CRT.

Research-and-development work now being carried out on these projects will doubtless open up new horizons in signal monitoring and measurement. However, the conventional oscilloscope, with its advantage of immediately showing what is happening, is likely to remain the primary research tool for many years, and the new instruments will be used in a backup role for more detailed or convenient analysis. □

Varying beam thickness in CRT display systems

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Though computer-driven CRT displays have many programable parameters, including intensity, blinking, and dashed- or dotted-line generation, beam thickness is not among them, except indirectly through the display's brightness control. Thickness variability can, however, be provided if the control circuit shown is inserted in the display's stroke vector generator. The circuit superimposes equal-amplitude sine and cosine waves on the generator's X- and Y-deflection ramp signals.

When the CRT beam is stationary, the sine and cosine waves produce a circle. As this circle is moved by the generator ramp signals, a straight line with the thickness of the circle's diameter is displayed. The thickness of the stroke can be programed through digital control of the sine and cosine wave amplitudes.

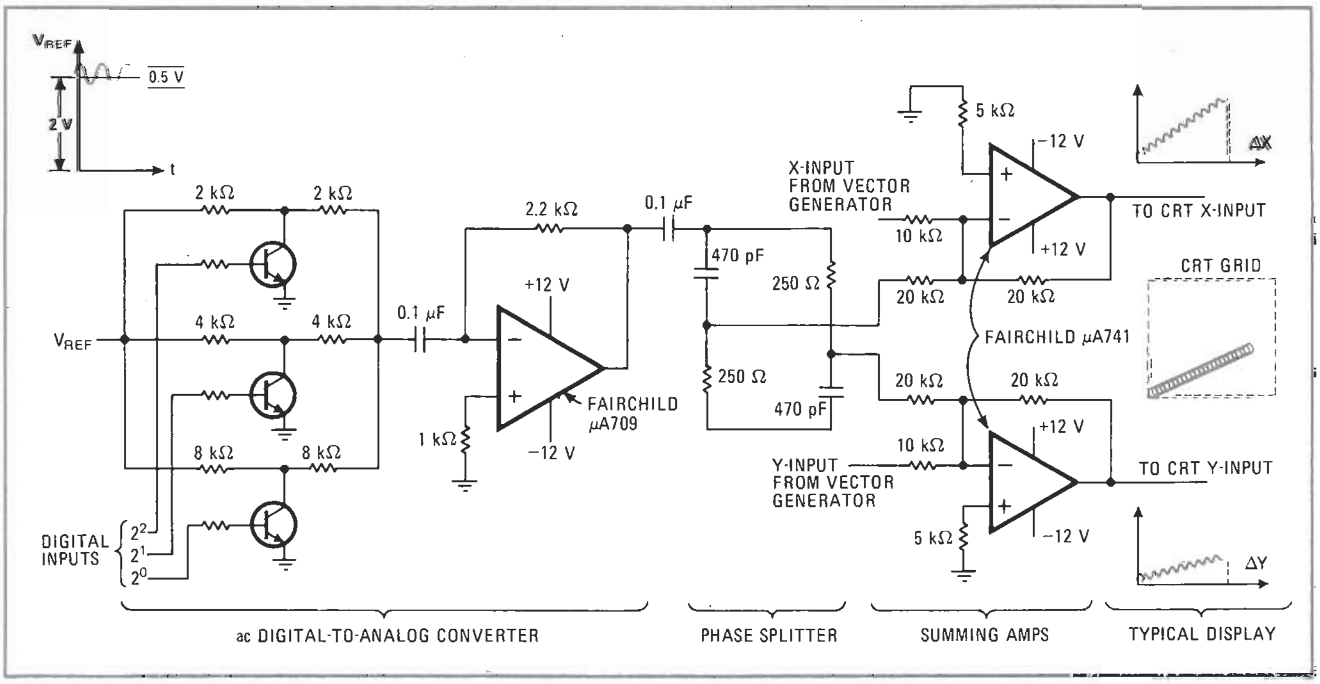
Since a circle is symmetrical, the stroke thickness will be independent of the slope of the stroke. The circles, however, must be closely spaced to prevent ragged edges from being produced in the display. The frequency of the sine and cosine waves, therefore, must be high enough to complete a full circle before the generator ramp signals displace the beam by a distance that is equal to the diameter of the cathode-ray spot.

The stroke vector generator must be the constant-rate type, so that the velocity at which the beam moves over the CRT screen is constant, no matter the length and slope of the stroke being generated. The beam displacement rate for only an X or Y increment is then equal to the displacement rate for any combination of X and Y increments. If the displacement is in either the X or Y direction alone, the corresponding ramp slope will be maximum.

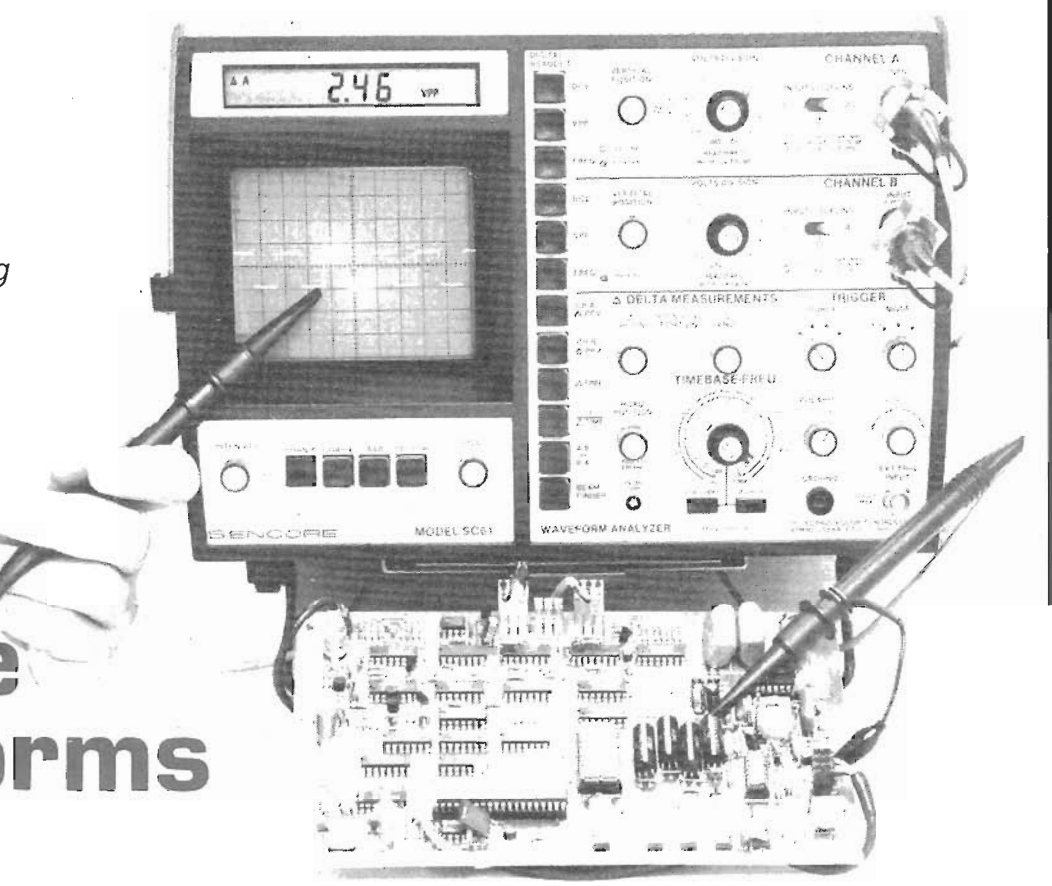
To find the minimum signal frequency of the sine and cosine waves, the maximum X or Y ramp signal slope must be known, as well as the X and Y deflection sensitivity, and the cathode-ray-spot diameter. Suppose these values are 0.01 volt per microsecond, 1 centimeter per volt, and 0.01 cm, respectively. This means that a 0.01-cm displacement can be produced by a 0.01-V signal in 1 μs (for a slope of 0.01 V/μs). The period of a full sine or cosine cycle must then be 1 μs at most, making the minimum signal frequency equal to 1 megahertz. For this case, the maximum stroke thickness is limited to 2.5 millimeters; beyond this, the circles become conspicuous.

In the thickness control circuit given, a 1-MHz sine wave is employed as the reference input to a three-bit digital-to-analog converter, permitting the sine-wave amplitude to be digitally controlled. The phase splitter then produces the sine and cosine waves, which are superimposed on the vector generator's X and Y ramp signals by a pair of op-amp summers. These summing amplifiers drive the X and Y inputs of the CRT display, producing straight-line segments the thickness of which can be varied digitally. □

Controlling display thickness. Circuit converts CRT beam thickness to a digitally programable display parameter. Beam thickness is controlled by superimposing sine and cosine waves to create a circle with a diameter that can be varied in response to a digital input.



An oscilloscope is an indispensable troubleshooting tool. Adding a digital readout makes it ideal.



How to Analyze Waveforms

GREGORY D. CAREY, CET

AN OSCILLOSCOPE IS LIKE AN ELECTRONIC stethoscope—it allows you to confirm a circuit's "health" by examining the signals flowing through it. Whether you are designing a circuit, building a project from a magazine, or repairing circuits for a living, the ability to analyze waveforms quickly, accurately, and without mistakes can let you make the most of your technical skills. Unfortunately, many technicians only use their scopes when absolutely necessary. Because of that, they often are unfamiliar with the unit's operation, making waveform interpretation seem difficult. Combining a digital readout with the scope's graphic display, eliminates most of the problems of waveform interpretation.

What is a waveform?

Before we go on, let's be certain that you understand what the waveform on an oscilloscope's CRT screen represents. The CRT graphically displays the relationship between the voltage and time at the test point you're measuring. The vertical movement (deflection) indicates the signal's voltage, with more deflection representing larger voltages. Simultaneously, the beam is moving horizontally at a constant rate, so that each horizontal division on the CRT represents a constant time interval.

Analyzing the signal helps identify which components are responsible for circuit problems. Let's look at how each part of the waveform helps find different component problems.

The seven waveform parameters

The seven parameters shown in Fig. 1 fully define any signal. Four of those parameters apply to any signal, and the other three apply to complex signals. We will explain how to interpret each parameter and which components are most likely to affect each one.

(1) Waveshape: The signal's waveshape confirms the general operation of a circuit. Waveform distortion is often caused by a problem in a reactive component, such as a coil or a capacitor. Waveform clipping ("flat-topping") may be caused by saturation of a stage or a power supply with low output. After discovering a waveshape problem, other parameters can be used to provide additional clues about the circuit's operation.

(2) DC level: The DC bias at a test point is such an important troubleshooting parameter that many people use their voltmeters as their main piece of test equipment. DC problems may be responsible for problems with any of the other parameters, including distorted waveshape, or incorrect amplitude or frequency. DC problems may be caused by power-supply problems or an open or shorted

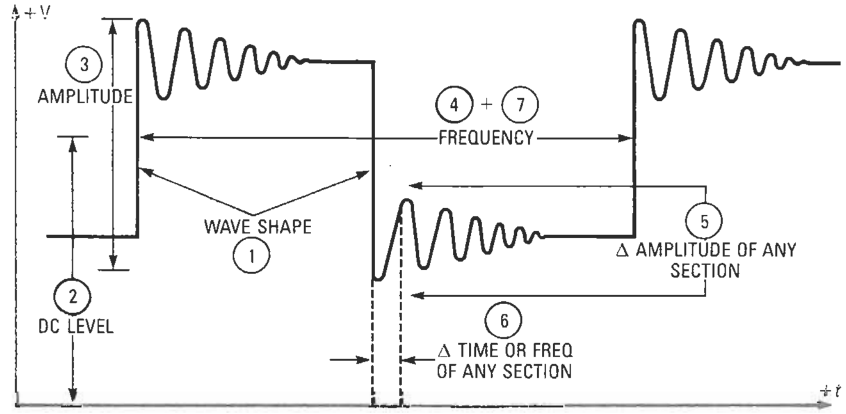


FIG. 1—TO FULLY ANALYZE A WAVEFORM, these seven parameters must be measured or observed.

component somewhere in the circuit. A DC-coupled scope, especially one with a digital readout, allows you to measure DC bias directly, while simultaneously observing the signal's waveshape. The DC and waveform readings also work together when a power supply has excessive ripple, even though its DC output is correct.

(3) Amplitude: The next test is to confirm that the signal has the correct peak-to-peak voltage. Low signal amplitude may be caused by low stage gain or by excessive loading. Poor gain often results from a defective transistor or IC, low power-supply voltage, or a defective emitter-bypass capacitor. Excessive loading may be the result of a component that has shorted or has changed value.

(4) Frequency: Some circuits, such as oscillators, generate signals for use by later stages. Other stages may be referenced to an external source, such as in VCR servo circuits, phase-locked loops, digital counter stages, or television sweep circuits. Testing the frequency of those circuits confirms whether they are working correctly.

Delta measurements

The previous four tests will fully analyze a signal if you are testing a simple waveshape, such as a sinewave or squarewave. If, on the other hand, you are testing a complex signal, you may need to know the details of the secondary parts of the signal to complete the analysis. Those added tests are called *delta* measurements. There are three types of delta measurements as follows:

(5) Delta amplitude: The peak-to-peak voltage test covered earlier measured the total amplitude from the signal's lowest to its highest points. But many signals have additional signals buried within them. For example, an incorrect color-burst level on a composite video waveform (see Fig. 2) may cause color problems. An incorrect sync-pulse level on the same composite signal may cause sync instability. Ripples or glitches, riding along the top of digital squarewaves may cause later circuits to operate incorrectly. Those conditions can be detected by using delta peak-to-peak voltage measurements, which allow the level of secondary signals to be measured independently of the main signal level.

(6) Delta time: Time measurements fall into two categories: those that are part of one signal, and those involving the time difference between two signals. An example of time within one signal would be the duty cycle of a switching power supply, where the "on-time" compared to the "off-time" determines the power delivered to the load. The time delay between two signals is important in many VCR servo adjustments. See Fig. 3. Either of those applications uses a point on the waveform as a reference for a delta-time measurement.

(7) Reciprocal time measurements: You can determine the approximate frequency of a signal by measuring the time for a single cycle and then inverting the time measurement mathematically. You can use that method to determine the time constant of circuits responsible for ringing, or the frequency of an interfering signal to determine its source.

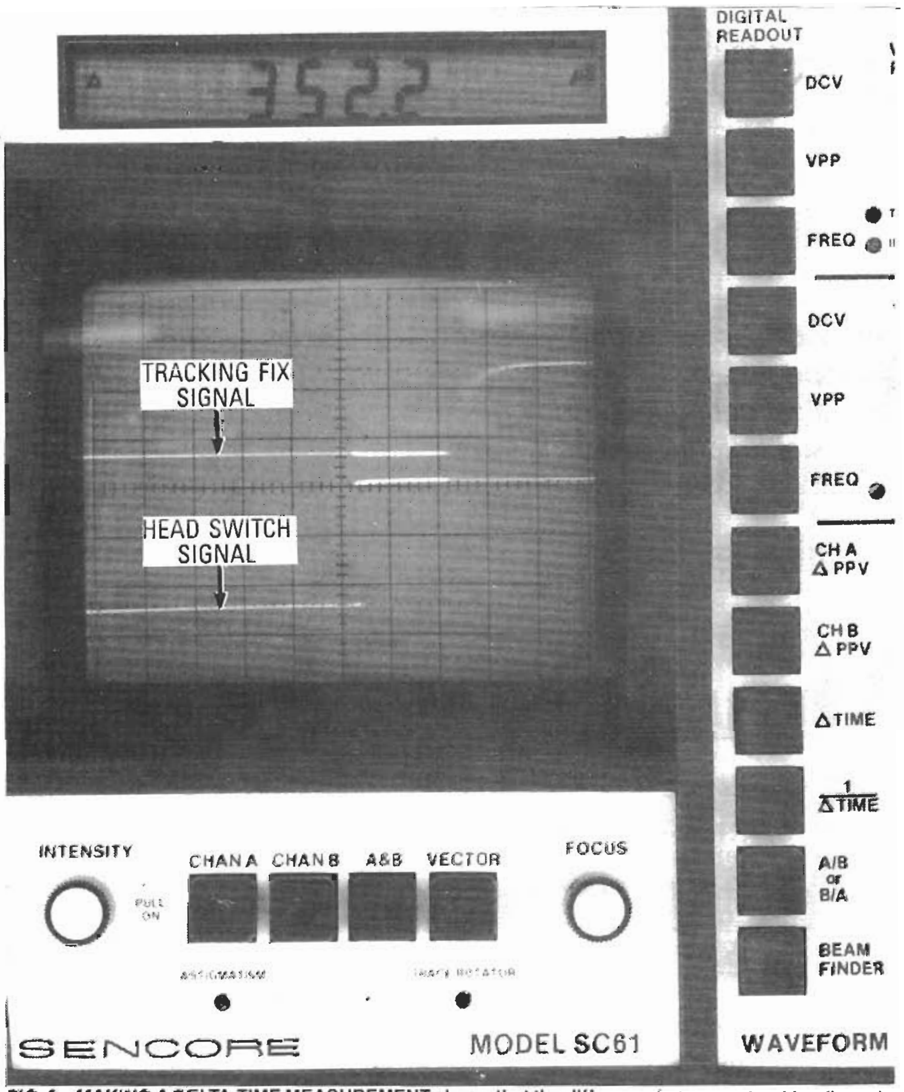


FIG. 3—MAKING A DELTA-TIME MEASUREMENT shows that the difference between a tracking fix and a head-switch signal to be 352 μs; factory specifications call for a 400 μs delay.

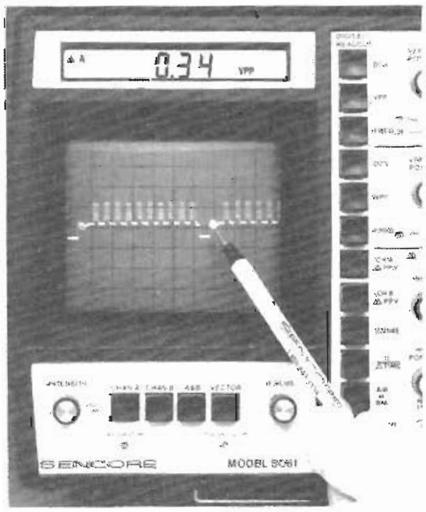


FIG. 2—PERFORMING A DELTA PEAK-TO-PEAK measurement confirms that the color burst of a composite video signal has the correct amplitude.

Digital measurements

You make all seven of those measurements every time you fully analyze a signal with an oscilloscope. Conventional scopes require you to make every parameter reading by measuring beam displacement on the CRT, and multiplying that by the settings of the vertical or horizontal circuit controls. Some scopes with microprocessor-controlled measuring circuits, such as the Sencore *SC61* shown in the opening of this article, allow every parameter to be converted to a direct digital reading. The CRT is then only used to display the overall shape of the signal.

A digital readout offers three advantages over using the CRT for measurements: Speed, accuracy, and freedom from errors. Let's look at each of those advantages in a little more detail.

Speed: You may begin to appreciate the time that direct digital readings save when you look at the number of steps needed to make a single measurement on a conventional CRT. Those steps are outlined in Table 1. If you use an oscilloscope often, you perform those steps without even

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TABLE 1

Peak-to-peak volts

1. Turn vertical vernier to CAL.
2. Lock waveform and adjust horizontal circuits until desired number of waveforms appear.
3. Adjust VOLTS/DIVISION control until waveform is 2 to 4 divisions tall.
4. Adjust VERT POSITION control until the bottom of waveform sits on a horizontal graticule line.
5. Adjust HORIZ POSITION control until tallest portion of waveform is on center CRT graticule.
6. Count divisions between bottom and top of waveform.
7. Multiply number of divisions times VOLTS/DIVISION setting.
8. Multiply times 10 if a $\times 10$ probe is used and input is calibrated for direct readings.

DC volts

1. Set vertical vernier to CAL.
2. Lock waveform and adjust horizontal circuits until desired number of waveforms appear.
3. Adjust VOLTS/DIVISION setting until waveform is 2 to 4 divisions tall.
4. Set INPUT COUPLING switch to ground.
5. Adjust VERT POSITION control until line is on a horizontal graticule line.
6. Move INPUT COUPLING switch to the DC position.
7. Readjust VOLTS/DIVISION switch if has trace moved off screen.
8. Estimate vertical midpoint of waveform.
9. Count number of divisions from reference in step 5 to midpoint of step 8.
10. Multiply number of divisions by the VOLTS/DIVISION setting.
11. Multiply by 10 if a $\times 10$ probe is used and input is calibrated for direct readings.

Time or frequency

1. Turn horizontal vernier to CAL.
2. Lock waveform and adjust horizontal circuits until desired number of waveforms appear.
3. Adjust the HORIZ POSITION control until left edge of signal touches a vertical graticule line.
4. Adjust VERT POSITION control until right edge of signal crosses center CRT graticule.
5. Count number of divisions between left and right edge of waveform.
6. Multiply number of divisions by the setting of the TIMEBASE-FREQ switch.
7. Divide by 10 if the horizontal $\times 10$ expander is on.
8. For frequency, invert results.

ANALYZE WAVEFORM

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thinking about them, but you do go through them.

A properly designed digital readout reduces each measurement to simply pushing a button and reading a number, including the correct decimal placement and the range multiplier. Since the tests are so much easier to do, you will probably analyze waveforms more often, instead of using less effective troubleshooting methods.

Accuracy: Digital readings provide much higher accuracy than a CRT. Most people don't think much about the accuracy of a reading, but errors can add up quickly when using a standard oscilloscope. First, no scope reading can be more accurate than the calibration of the vertical and horizontal circuits. Published accuracies range from 2% to 5%, but only if the scope has been recalibrated within the past few months. If not, the circuit errors may be higher.

Next, consider the errors in determining the displacement of the trace on the CRT. A typical CRT trace has 8 major vertical divisions, each divided into 5 minor divisions. If a waveform is 4 major divisions tall (one-half the screen height), it covers a total of 20 minor divisions. Since the width of the trace is about 1 minor division, the trace thickness adds an extra 5% error to the calibration uncertainly. When we add interpolation and parallax errors, a scope reading will only be accurate to within 10% to 20%.

Digital scope readouts offer a much higher degree of accuracy. For instance, the peak-to-peak voltage function of the Sencore *SC61* is accurate to 2%. The accuracy improvements are even greater for frequency measurements; that is because

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See Roberts Part 12 for END