VOL. 50. No. 5
RADIO-ELECTRONICS
MAY 1979

$1.25 ■ MAY 1979

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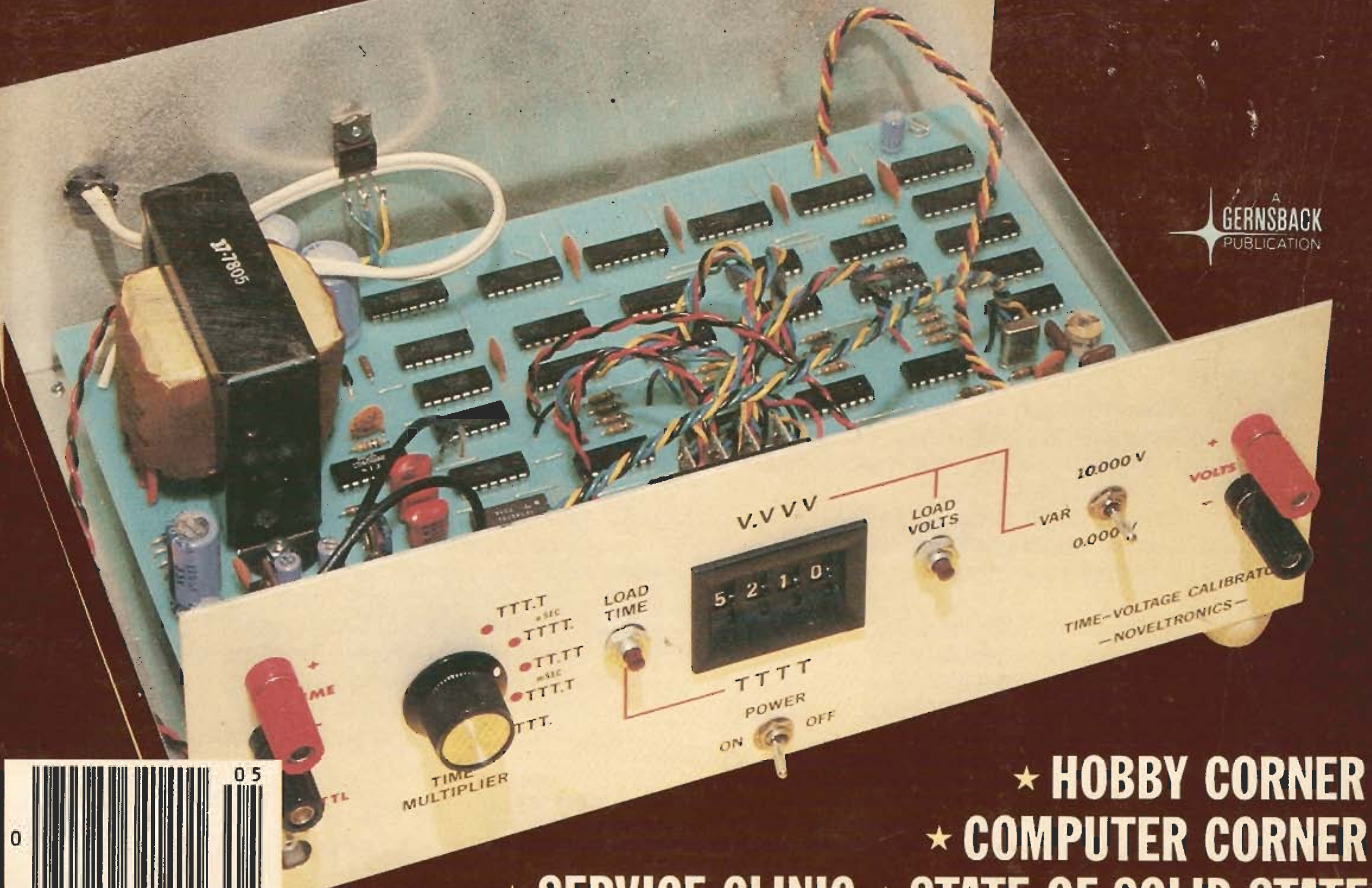

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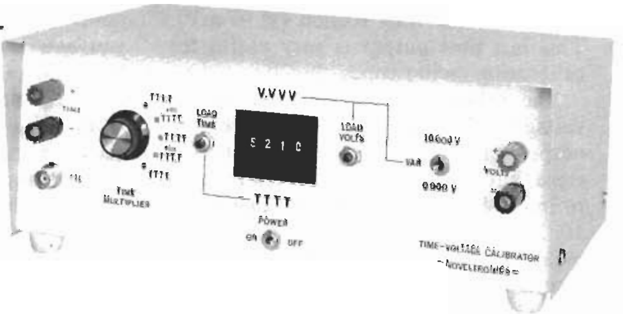


Time/Voltage Calibrator

Precision digital test equipment requires special test instruments to insure that calibrations are within specified tolerances. This calibrator supplies time and voltage references you'll need.

DOUG FARRAR

FOR YEARS LARGE COMPANIES HAVE ENjoyed the benefits of highly accurate digital test equipment because only they could afford the substantial initial capital outlay and the periodic maintenance and calibration required in using this equipment. Recently, however, advances in digital and linear-integrated-circuit technology have brought the cost of these test instruments down to a price affordable to even the hobbyist.

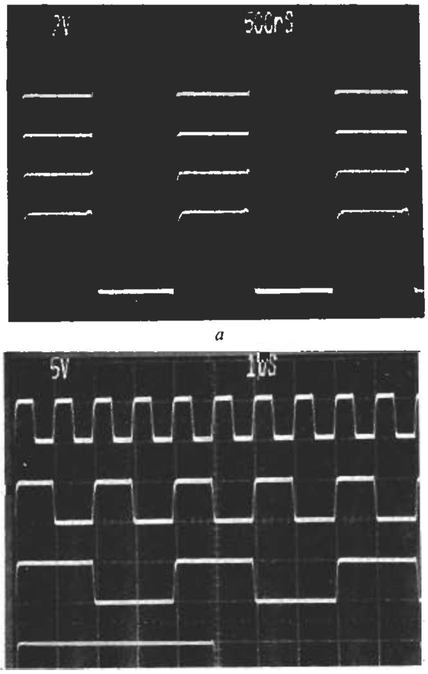


FIG. 1—MULTIPLE EXPOSURES of "time" outputs. At *a* programmed voltages are 4, 6, 8 and 10 with 2.0-μs period. At *b* we have 5-volt swings at 1, 2, 4 and 10 μs programmed periods.

However, there is a side to this story that is never mentioned: How is a hobbyist going to keep his new gear calibrated? In the days of 1% to 5% accuracy, the known voltage of a battery or the approximate resonant frequency of a crystal were adequate enough for calibration standards. Nowadays, a 3½-digit digital voltmeter (DVM) needs a 0.1%-voltage standard; newer scopes need 1% (or better) time standards. And even inexpensive frequency meters need .01% time standards.

Of course, you can routinely send an instrument to a calibration lab (as the manuals tell you to do!), but this could easily become more expensive than the cost of the unit itself. Even if you're willing to do that, you may not have such a lab near you. What's the hobbyist to do?

The Time-Voltage Calibrator described in this article can be the answer to your calibration problems, and could pay for itself many times over. This instrument has two separate sections for time and voltage, each controlled by a standard 4-digit thumbwheel-switch network. When you dial in the desired voltage and press the LOAD VOLTS pushbutton, a DC-voltage output is produced that is accurate to better than 0.1%. Dialing in the desired time and pressing the LOAD TIME pushbutton produces two time outputs with 0.005% accuracy. The first output is a standard TTL output with a duty cycle within 5 ns of 50%. The second time output has slower rise and falltimes than the first, but its voltage swing is highly accurate. The time period is controlled from the front panel, while the voltage

SPECIFICATIONS

VOLT SPECIFICATIONS	
Range	0.000 to 10.000 volts in 1-mV steps
Total error	<±0.1% of setting (untrimmed) <±0.05% of setting (trimmed)
Settling time	stable to 1 mV within 15 seconds
Trim range	±20 mV
TIME SPECIFICATIONS	
Range	000.0 to 999.9 μs in 0.1-μs steps
Multiplier	×1, ×10, ×100, ×1,000, ×10,000
Total error	<50 ppm (.005%) of setting (untrimmed) <5 ppm (.0005%) of setting (trimmed)
Trim range	±30 ppm, typical

	Time	TTL
V_{OL}	0 volts	<0.4 volts
V_{OH}	programmed by VOLTS section; approx. 4 volts (min.), +10 volts (max.), ±10 mV	>2.4 volts
Output impedance	<100 ohms (typ.)	normal TTL
Rise/falltimes	<50 ns (typ.)	<5 ns
Duty cycle	within 20 ns of 50%	within 5 ns of 50%

swing is between ground and whatever is dialed into the volts section (±10 mV). This last time output is very useful for calibrating oscilloscopes.

The maximum programmable output voltage is 10.000 in 1-mV steps. The time output is from 0.1 μs to 999.9 μs in 0.1-μs steps; but a multiplier switch can be used to multiply all these time increments by 10, 100, 1000, or 10,000, even while maintaining the 0.005% accuracy. This results in a maximum time output of 9.999 seconds. The scope photos in Fig. 1 show some of the waveforms obtainable with the Time and Voltage Calibrator.

The best part about the entire project is that it requires no calibration to meet these specifications! Using the components called out in the parts list, means you now have your own secondary time and voltage standards that are traceable to the National Bureau of Standards (NBS). But if you do have access to very accurate time- and voltage-measuring equipment, the calibrator can be trimmed to even tighter specs.

How it works

There are two almost separate sections to the calibrator: time (Fig. 2) and voltage (Fig. 3). Both sections are loaded with the thumbwheel-switch network, S1–S4 (Fig. 4). Two separate sets of latches (IC1–IC4 and IC5–IC8) latch the state of the thumbwheels when their respective LOAD switches (LOAD VOLTS, S6 and LOAD TIME, S7) are depressed and then released. So, after a value is loaded into either set of latches, the thumbwheels can be set to any other value.

Let's examine the time section first. The design goals for this circuitry were:

Time increments of 0.1 μs;
A squarewave output;
A time range of 000.0 through 999.9 μs, with a time multiplier on top of this.

To accomplish the first two goals, a divide-by-n counter, where n is the thumbwheel-latch value, is clocked at a 20-MHz rate (50-ns time period), and

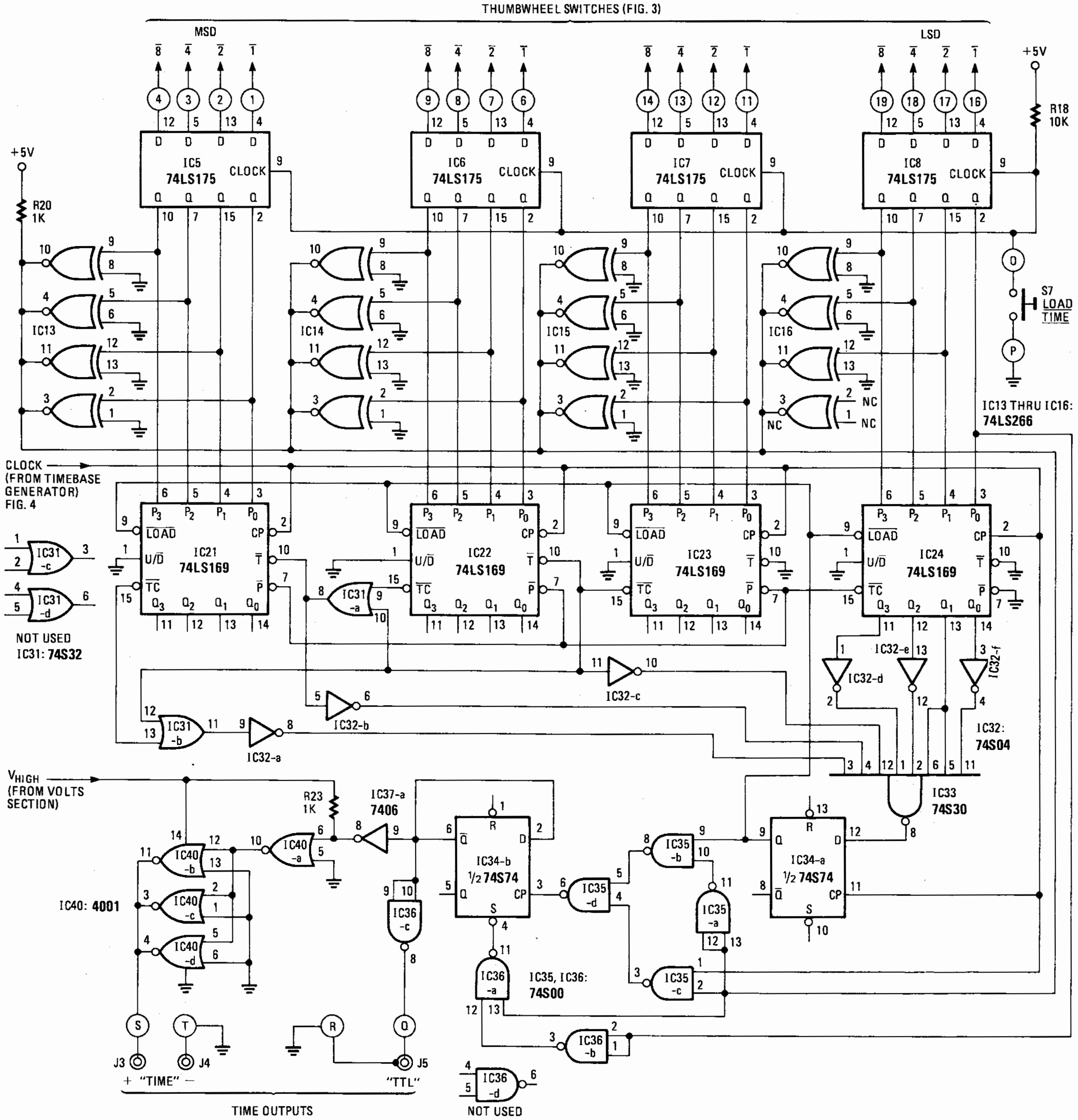


FIG. 2—THE TIME SECTION of the calibrator. Four thumbwheel switches select the time period of the waveforms at the TIME and TTL outputs when pushbutton S7 is depressed.

the counter output is divided by two to produce a squarewave with a time step of 2 × 50 ns = 100 ns (or 0.1 μs). The third and last design goal requires a four-decade counter network. By reducing the counter's clock frequency by 10, 100, 1000 and 10,000, the time output can be multiplied by a similar number.

Decade up/down counters IC21–IC24 are wired in the down-count mode, with IC21 being the most significant stage and IC24 the least significant. These IC's form a divide-by-n counter stage, where the value of n ranges from 2 to 9999. When the counter reaches a value of 0002, all inputs to NAND gate IC33 go high, forcing the gate's output to a logic low level. This output drives the data input of the D-type flip-flop, IC34-a. On the next clock, IC34-a's output (Q) goes low, while the counter decrements to 0001. The output of IC34-a is connected to all four counters' synchronous parallel load inputs, so the counters are now prepared for a synchronous load on the next clock cycle, and will load the latched value of n from the thumbwheel switches at that time. The counter stage decrements in the following sequence:

n→(n − 1)→(n − 2) · · · 3→2→1→n · · ·

So loading the n-value produces a low output from IC34-a every n clock cycles. Dividing this signal with a divide-by-two flip-flop (IC34-b) produces the desired squarewave output, and every step in n is a 0.1-μs change in the resulting squarewave output.

Invariably, a value of 0000 or 0001 will be loaded into the time section. Since a divide-by-zero or a divide-by-one counter does not exist, the circuitry would produce 'an ambiguous output. To circum-

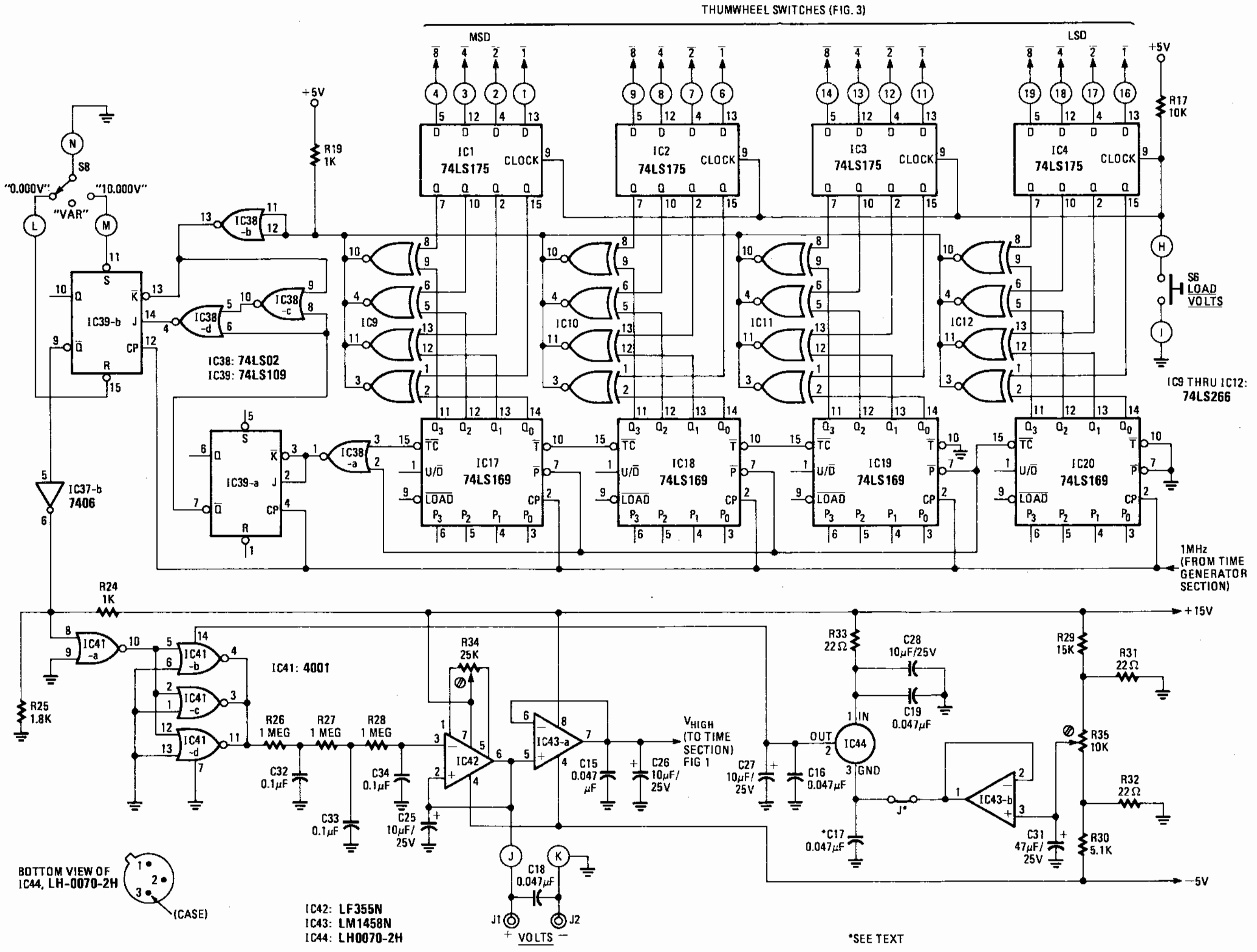


FIG. 3—THE VOLTAGE CALIBRATOR is based on a precision 10-volt reference that can be processed to deliver voltages down to 0 in 10-mV steps.

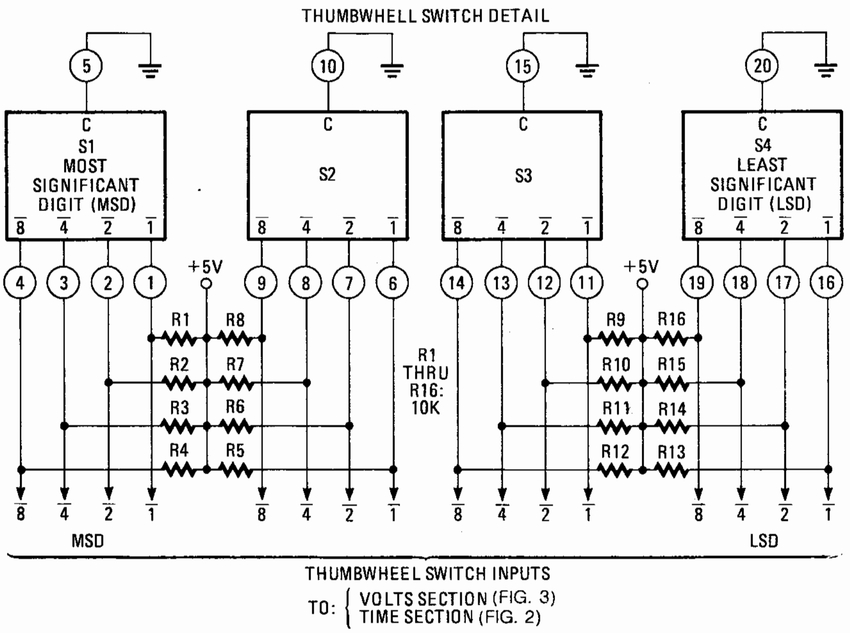


FIG. 4—THUMBWHEEL SWITCHES are BCD-complement types that provide the binary equivalent of analog numbers selected. Resistors R1 though R13 are pull-up resistors.

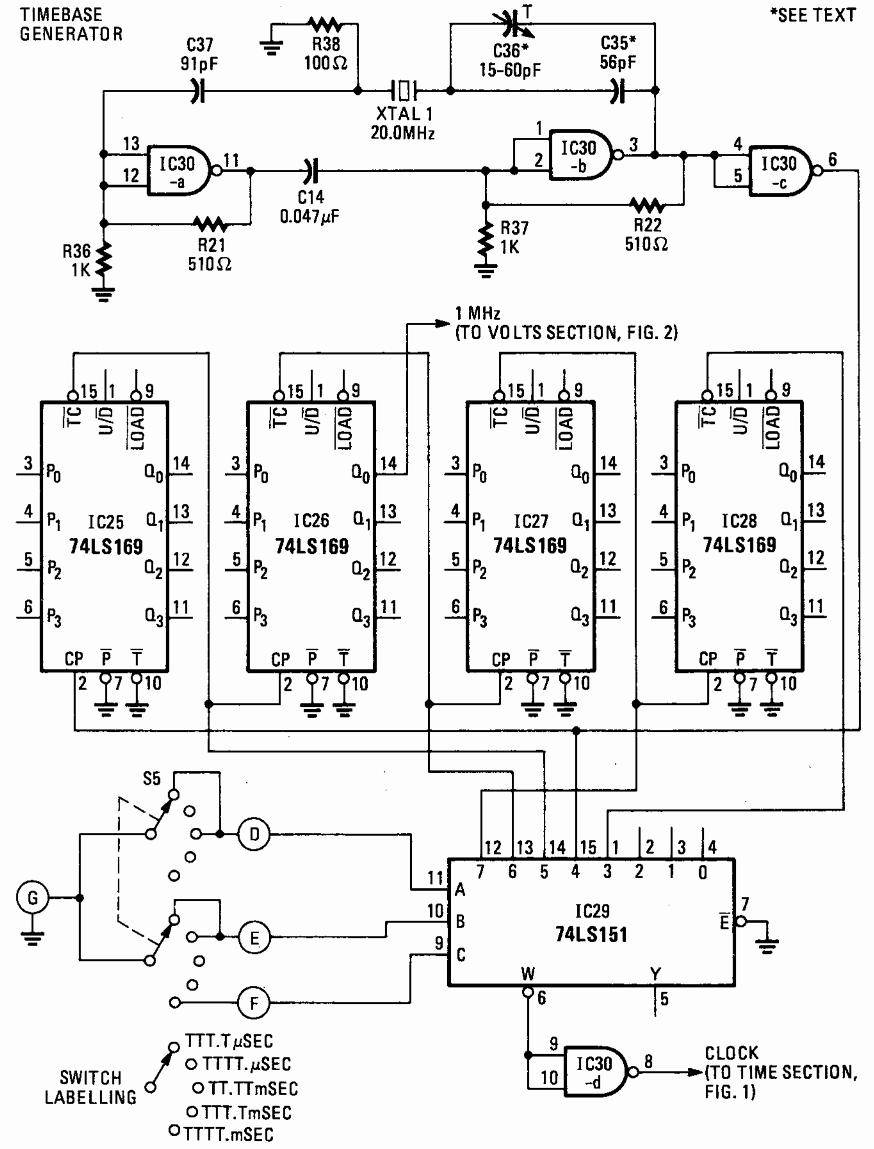


FIG. 5—DECADE COUNTERS in ripple configuration divide the 20-MHz clock frequency by a factor of 10 per counter.

vent the problem, an open-collector exclusive-NOR network consisting of IC13–IC16 is used as a comparator to monitor the latches' loaded value. When a 0000 or a 0001 is loaded, the OR-tied output of the comparator gates goes high, signaling the logic that this special condition now exists. The comparator output drives IC35-c-2, IC35-a and IC36-a (IC35 is wired as a 1-of-2 multiplexer). When the comparator output is low, the multiplexer selects the divide-by-n output to be applied to the clock input of divide-by-two flip-flop IC34-b, as discussed above. But when the comparator output is high, the multiplexer selects the down-counters' clock input as the clocking signal to IC34-b. This produces a divide-by-2 squarewave of 20 MHz, or 10 MHz, which is a 0.1-μs period. But if a 0000 is loaded into the time thumbwheel latches, the input of NAND gate IC36-b is low, causing its output to go high. This means that both inputs to IC36-a are high, and the overriding asynchronous $\overline{\text{SET}}$ input to IC34-b is activated. The divide-by-two flip-flop output is now always low, regardless of the inputs on the synchronous inputs, producing a period of 0, as required.

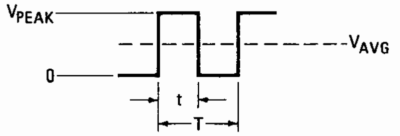
The time-counter network can generate the correct squarewave for any value from 0 to 9999. All that remains to be done is to buffer the squarewave before applying the signal to the front panel. Buffer IC36-c inverts IC34-b's output, and is a standard TTL output (i.e., it has a precise time but no amplitude control). Open-collector buffer IC37-a drives CMOS buffer network IC40. This output swings between ground and its V_{DD} input (indicated as V_{HIGH} on the schematic diagram), which is a DC signal coming from the volts section (to be discussed shortly). While the rise and falltimes from buffer IC40 are slower than that of a TTL output, the amplitude and period are very accurate. However, reliable operation below about 4.5 volts cannot be expected.

Getting the time-counter network to operate at 20 MHz is not easy and requires more circuitry than a slower counter chain. Integrated circuit 31, IC32, IC33 and IC34 perform the necessary high-speed logic operations. It is important that these IC's be Schottky-type IC's, and not low-power Schottky or standard TTL types. Furthermore, if you believe in worst-case numbers, down-counters IC21–IC24 should be manufactured by either Fairchild, Motorola, or Raytheon, since the worst-case speed specifications of these companies are tighter than those of other makes. The "slower" devices may result in the counters not working with some n counts!

Up to this point, it has been assumed that the time counters work with a 20-MHz clock input. If a 2-MHz clock rate is used instead, each least-significant thumbwheel step would be 1.0 μs, rather than 0.1 μs. Furthermore, 200-kHz, 20-kHz and 2-kHz clock inputs would produce minimum steps of 10 μs, 0.1 ms and 1.0 ms, respectively. Generating these clock rates is a simple task, assuming that the 20-MHz frequency already exists. Decade counters IC25–IC28 (Fig. 5) are hooked up to divide the 20-MHz clock by factors of 10-per-counter.

The 20-MHz signal and the four counter outputs are connected to multiplexer IC29. Use of the multiplexer and TIME MULTIPLIER switch S5 allows front-panel "cold-switch" selection of a single clock to be applied to the time section. That is, a set of DC signals can select one AC signal to be applied to the time counters, thus avoiding the need to route the noise-producing AC signals to the chassis's front panel. The output of the multiplexer is buffered by IC30-d before being applied to the time calibrator's clock inputs.

The NAND gates, IC30-a and IC30-b, are the amplifying components of the crystal oscillator, whose frequency is set by the 20.0-MHz crystal. The NAND gates introduce a small amount of loop delay that is compensated for by the paralleled capacitor combination of C35, trimmer C36, capacitor C37 and resistor R38. Resistors R21, R22, R36 and R37 bias the gates in their linear regions. The oscillator output is buffered by IC30-c before being applied to the multiplexer and countdown string.



$V_{AVG} = V_{PEAK} \times DC/100$

WHERE V_{PEAK} IS THE PEAK VOLTAGE

DC IS THE WAVEFORM DUTY CYCLE $(=\frac{t}{T})$

FIG. 6—CHARACTERISTICS of the squarewave that determines the average voltage.

The volts calibrator: how it works

Anyone who has designed an automobile dwellmeter will recognize the operational principle behind the programmable

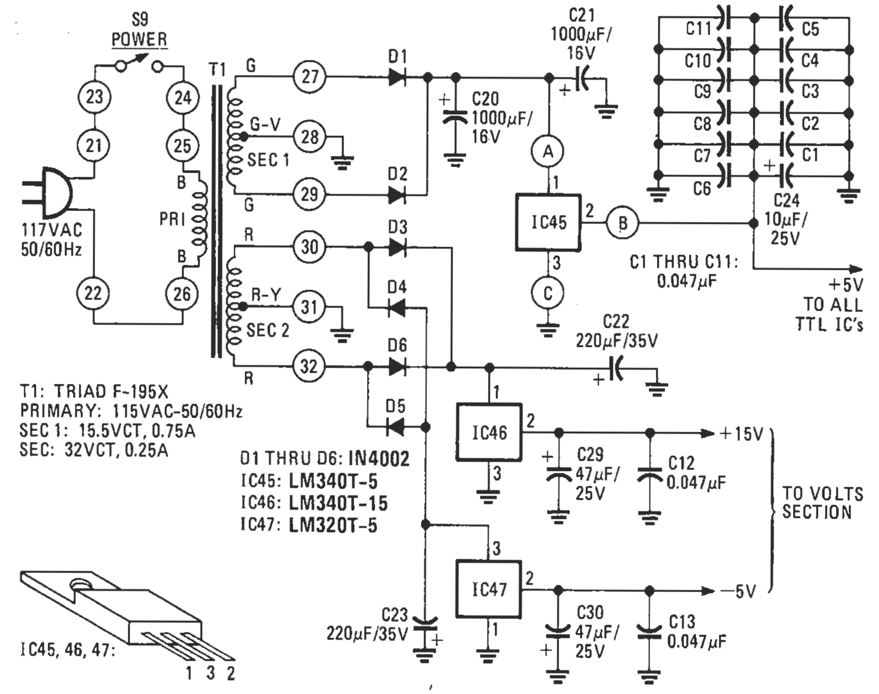


FIG. 7—POWER SUPPLY CIRCUIT. The power transformer with its two secondaries, supplies the IC voltage regulators that deliver the three regulated voltages used in the calibrator.

voltage generator. If a rectangular-wave voltage is allowed to swing between ground and some known voltage with some known duty-cycle, then the average voltage is given by the equations shown in Fig. 6.

So, with a duty-cycle of 0, the waveform never switches but remains at ground, and $V_{AVG} = 0$. A duty-cycle of 100 means that the waveform remains at V_{PEAK}, so $V_{AVG} = V_{PEAK}$. A duty-cycle at any point between the two extremes produces an average voltage between 0 and V_{PEAK}, as shown by the Fig. 6 equation.

How can this principle be used here? It's easy to generate an extremely accurate duty-cycle using standard digital technology. However, where do you obtain an accurate voltage source? Here comes linear IC technology to the rescue! National Semiconductor produces a linear IC voltage reference that is laser-trimmed to 10.000 volts. This IC comes in two accuracy grades: −1H is 10.000 volts ±10 mV (±0.1%), while −2H is ±5 mV (±0.05%). The latter value is specified here for the ultimate in untrimmed accuracy.

How do you generate an AC rectangular waveform that swings accurately between 0 and 10.000 volts; does it with the desired duty-cycle; and exhibits insignificant rise and falltimes between the two voltages? The answer is surprisingly simple: All CMOS circuits switch their outputs between ground and their supply voltage, V_{DD}. Because FET's behave in a resistive manner, there is no offset voltage at the outputs to contend with, as in TTL logic circuits. Thus, by applying the 10.000-volt reference to V_{DD} of a CMOS gate, and applying the specified duty-cycle to the gate's input, the desired signal conditioning appears at the CMOS output. All that remains to be done is to

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PARTS LIST

Resistors are 5%, ¼ watt unless otherwise noted
R1-R18—10,000 ohms
R19,R20,R23,R24,R36,R37—1000 ohms
R21, R22—510 ohms
R25—1800 ohms
R26-R28—1 megohm
R29—15,000 ohms
R30—5100 ohms
R31-R33—22 ohms
R34—25,000-ohm, PC-mount trimmer
R35—10,000-ohm, PC-mount trimmer
R38—100 ohms
Capacitors
C1-C19—0.047 μF, 25 volts, ceramic disc
C20, C21—1000 μF, 16 volts, radial electrolytic
C22, C23—220 μF, 35 volts, radial electrolytic
C24-C28—10 μF, 25 volts, radial electrolytic
C29-C31—47 μF, 25 volts, radial electrolytic
C32-C34—0.1 μF, 50 volts, Mylar
C35—56 pF (or 91 pF), 50 volts, mica (see text)
C36—15-60-pF trimmer (see text)
C37—91 pF, 50 volts, mica
Semiconductors
D1-D6—1N4002, 1A, 100-volt diode
IC1-IC8—74LS175, quad D-type flip-flop
IC9-IC16—74LS266, quad exclusive NOR gate
IC17-IC20—74LS169, 4-bit up-down decade-counter
IC21-IC28—74LS169 (Fairchild, Motorola or Raytheon, see text) 4-bit up-down counter
IC29—74LS151, 8-input multiplexer
IC30, IC35, IC36—74S00, quad 2-input NAND gate
IC31—74S32, quad 2-input OR gate
IC32—74S04, hex inverter
IC33—74S30, 8-input NAND gate
IC34—74S74, dual D-type flip-flop
IC37—7406, hex inverter, open-collector
IC38—74LS02, quad 2-input NOR gate
IC39—74LS109, dual J-$\overline{K}$ flip-flop
IC40, IC41—CD4001, quad 2-input CMOS NOR gate
IC42—LF355N (National) JFET op-amp
IC43—LM1458N (National) dual op-amp
IC44—LH0070-2H (National) 10-volt reference
IC45—LM340T-5 (National) 5-volt positive regulator
IC46—LM340T-15 (National) 15-volt positive regulator
IC47—LM320T-5 (National) 5-volt negative regulator
Miscellaneous
S1-S4—Thumbwheel switches, BCD-complement, Unimax SF-18 or equal (Unimax Switch Corp., Ives Rd., Wallingford, CT 06492)
S5—2-pole, 5-position rotary switch (CTS T-206 or equal)
S6, S7—Momentary, normally open switch
S8—SPDT, ON-OFF-ON switch
S9—SPST switch
J1-J4—5-way binding post
J5—BNC female, panel-mount connector
XTAL1—20.0-MHz quartz crystal, series-resonant, .005% or better tolerance, HC18/U holder
Thumbwheel switch end plates; line cord; strain relief; case (LMB #ME-7114); 4-40 × ½-in. hardware; knob; ½-in. aluminum strips; wire and coax; BNC receptacle and ground lug; PC board; and dry transfer letters.

The following components are available postpaid from Noveltronics, P.O. Box 4044, Mountain View, CA 94040:

CK-TVC:	**Complete kit of parts and hardware—PC board, special 2-color dry transfer chassis lettering sheet, and unpunched chassis, $150.**
PK-TVC:	**Partial kit—complete thumbwheel switch assembly, LH0070-2H, transformer, crystal, case, special dry transfer lettering sheet, and PC board, $100.**
PCB-TVC:	**Etched, drilled and silk-screened PC board, $25.**

California residents add state and local taxes to the total order. Individual items are not available for sale. Orders paid by money order or bank-certified check can be discounted 5%, and guarantee shipment within 2 shipping days after receipt of order. Allow up to 2 weeks delay for personal check clearance time. No out-of-state P.O. boxes, please. Canadian and Mexican orders add 5% (non-discountable) of order, all other non-USA orders add 10% (non-discountable) to cover additional postage and handling. U.S. funds only.

TIME/VOLTAGE CALIBRATOR

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apply the waveform to a low-pass filter to generate the average DC voltage and then buffer it.

The voltage-calibrator section (Fig. 3) resembles the time section somewhat, but the two circuits are different. Thumbwheel-switch latches IC1–IC4 feed exclusive-NOR inputs. Again, the exclusive-NOR network IC9–IC12 is used as a comparator, but this time it compares the thumbwheel-latch contents to the counter output. When both values agree, the OR-tied output is pulled high by resistor R19. Decade-counters IC17–IC20 are wired as up-counters. For this application, they free-run, starting from 0000, count to 9999, then start over again. Although the clock frequency's accuracy is unimportant in this application, a rather exact 1-MHz signal that is tapped from the 20-MHz timebase count-down section (IC26 pin 14) is used as the volts section's counter clock.

The TTL portion of the volts section must provide a programmable duty-cycle from 0 to 100%, inclusive, in .01 increments (with a 4-decade total). If a flip-flop can be set to 0 when the four decade-counters are at 0000 and then flipped back to 1 when the counter reaches the desired thumbwheel value, this achieves a programmable duty-cycle; the higher the thumbwheel setting the longer the flip-flop stays at 0. Since the counter-clock frequency is 1 MHz, the programmable duty-cycle output has a frequency of 100 Hz.

The duty-cycle flip-flop described above is J-$\overline{K}$ flip-flop IC39-b. When the counter network reaches 9999, the outputs of counters IC17 and IC20 are low, forcing the output of NOR gate IC38-a high. On the next clock pulse, the counters advance to 0000, and the output of J-$\overline{K}$ flip-flop IC39-a goes low for one clock cycle. Assuming that the exclusive-NOR comparator output is low at this time (that is, the thumbwheel latches are loaded with a nonzero value), the output of inverter IC38-b is high, forcing the output of IC38-c low. Therefore, inputs J and $\overline{K}$ to IC39-b are high; so on the next clock input, the duty-cycle flip-flop's output, $\overline{Q}$, goes low and the counter network increments to 0001. This is the first step of the duty-cycle generation.

The J and $\overline{K}$ inputs of IC39-b are held low and high, respectively, when there is no comparator equal output, or when the counter state is nonzero. This is the hold mode, so the duty-cycle flip-flop maintains its state until there is a change on its inputs.

When the counters and the thumbwheel latches agree in value, the comparator output goes high and the output of inverter IC38-b goes low. The output of IC39-a is high for all counts except .0000, so both the J and $\overline{K}$ inputs to IC39-b are low. On the next clock cycle, the flip-flop output is set back to a 1 and remains there until the counters again reach 0000, when the cycle repeats.

The counter sequence and the duty-cycle flip-flop's output proceed as follows:

Counter:
9999→0→1→2 ··· n→(n + 1) ··· 9999→0→1
Duty-Cycle Flip-Flop (IC39-b pin 9)
1→1→0→0 ··· 0→1 ··· 1→0

Thus, the output stays low for $(n + 1) - 1 = n$ times out of 10,000 counts, so the thumbwheel setting directly loads the correct duty-cycle.

In the event that the thumbwheel latches contain 0000, the outputs of IC38-b and IC39-a go low simultaneously. This forces the output of IC38-c high, which, in turn, forces the output of IC38-d low. Then, IC39-b is constantly loading and then holding a 1 (i.e., the flip-flop output is a DC voltage, with a level corresponding to a 0% duty-cycle, as required).

By using the asynchronous $\overline{\text{SET}}$ and $\overline{\text{RESET}}$ inputs of flip-flop IC39-b, the duty-cycle logic can be overridden. The $\overline{\text{SET}}$ input forces the flip-flop output low (duty-cycle = 100%), and the $\overline{\text{RESET}}$ input forces a high output (duty-cycle = 0%). Switch S8 provides the logic signal. When switch S8 is in its center OFF position, the duty-cycle logic performs as described. This switch allows the user to select between the two voltage extremes and any other preloaded value.

The output of the duty-cycle flip-flop is fed to IC37-b, which converts its TTL-compatible voltage swing to a CMOS-compatible voltage. Resistors R24 and R25 limit the maximum voltage input to the CMOS gate to slightly less than 10. The NOR gate IC41 is the CMOS driver. Its V_{DD} supply lead is connected to the output of IC44, the precision voltage reference. Thus, the precision TTL-generated duty-cycle is voltage-level-shifted by parallel-connected NOR gates IC41-b, IC41-c, and IC41-d to produce the time and voltage requirement described earlier in this section.

A low-pass filter consisting of R26–C32, R27–C33 and R28–C34 produces a DC output whose value is equal to the desired voltage setting. The low-pass filter has a time constant of several seconds, so it takes about 10 seconds for the DC-output value to stabilize. Operational amplifier IC42 has a high-impedance JFET input that will not significantly load the low-pass filter's output. It is connected as a voltage-follower, guaranteeing a low-impedance output at PC board locations J and K. Trimmer resistor R34 nulls the op-amp's input-offset voltage and gives the operator a precise 0-volt setting.

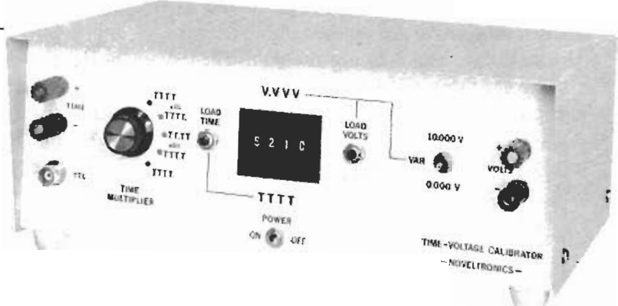
Voltage-follower IC43-a has its input connected to the programmable voltage output. Its output, called "V_{HIGH}", feeds the V_{DD} lead of CMOS gate IC40 in the time section shown in Fig. 1. Thus, whatever value is loaded in the volts section will be the voltage-high output of the time calibrator's 50% waveform.

A low-output-impedance, ±20-mV voltage generator is composed of resistors R29–R32, trimmer R35, capacitors C17 and C31, and voltage-follower IC43-b. The output is used as the ground return for the 10-volt reference IC. Since the precision output is measured with respect to its ground leg, offsetting ground by ±20 mV (with R35) also offsets the output by an equal amount. If you don't trim the volts-calibrator section, most of this section can be omitted.

Thumbwheel switches S1–S4 (Fig. 4) are coded as BCD-complement, meaning that a 0 is a switch closure and a 1 is a switch open. Pull-up resistors R1–R16 pull any open switch node to 5 volts, but any switch closure will force a ground potential on that node. These two voltage levels are TTL-compatible, therefore they directly drive the latch inputs of the time and volts calibrator.

Three power-supply voltages are needed in the calibrator: +5, +15 and −5 volts. The first voltage powers all the TTL circuitry, and the second two voltages power the analog circuitry in the volts section. Transformer T1 (see Fig. 7) has two secondaries. Secondary 1 is full wave rectified by D1 and D2, filtered by C20 and C21 and regulated down to +5 volts by voltage regulator IC45. A bridge rectifier consisting of D3–D6 at secondary 2 provides both positive and negative voltages, which, in turn, are regulated down to +15 and −5 by IC46 and IC47. Separate secondaries in the power supply help minimize the possibility that the high-frequency voltage and current switching transients in the +5-volt power supply will appear in the analog section of the calibrator's time and volts outputs.

This concludes the theory of operation of the Time/Voltage Calibrator. Next month we will go into construction details and will present the PC board pattern and other pertinent information. **R-E**



Time/Voltage Calibrator

Part 2—Precision digital test equipment requires special test instruments to insure that calibrations are within specified tolerances. This calibrator supplies time and voltage references you'll need.

DOUG FARRAR

IN THE MAY ISSUE WE DISCUSSED THE time-voltage calibrator and analyzed its various sections. Now, we are going to cover construction and calibration; along with debugging, if it should be needed.

Construction

Unless you are familiar with low-noise wiring techniques, it is advisable to use the PC board layout shown in Fig. 8. This layout minimizes ground loops and voltage spikes, resulting in very clean DC and AC signal waveforms.

You should prepare the chassis first before stuffing the PC board with parts. The cabinet specified in the Parts List has what is described as a "built-in chassis" (see Fig. 9-a), which consists of another sheet of aluminum mounted to two U-brackets. Because chassis space is limited, you must discard this extra chassis base and the U-brackets as well, which however are required to hold the top of the cabinet in place. The leg of the U-bracket that is exposed is also in the way of the PC board. Use a hacksaw and remove it, as shown in Fig. 9-b, and make an L-bracket. File the edges smooth to avoid cutting yourself later on (NOTE—the chassis supplied with the kit described in the Parts List comes with this procedure already performed).

Remove the L-brackets and set them aside. Place the PC board foil-side down on the bottom of the chassis, so that it rests centered left to right, and about ¼ inch from the chassis' backwall. Mark the PC board's four mounting hole locations on the chassis, then carefully drill the spots with a ⅛-inch drill bit. Refer to Fig. 10 and machine the unit's front side as shown. Remove all burrs. I found it was easier to cover the entire chassis front with neatly placed strips of masking tape and to draw on the tape. Then, when you cut the hole for the thumbwheel switches with a jigsaw, this protects the paint from

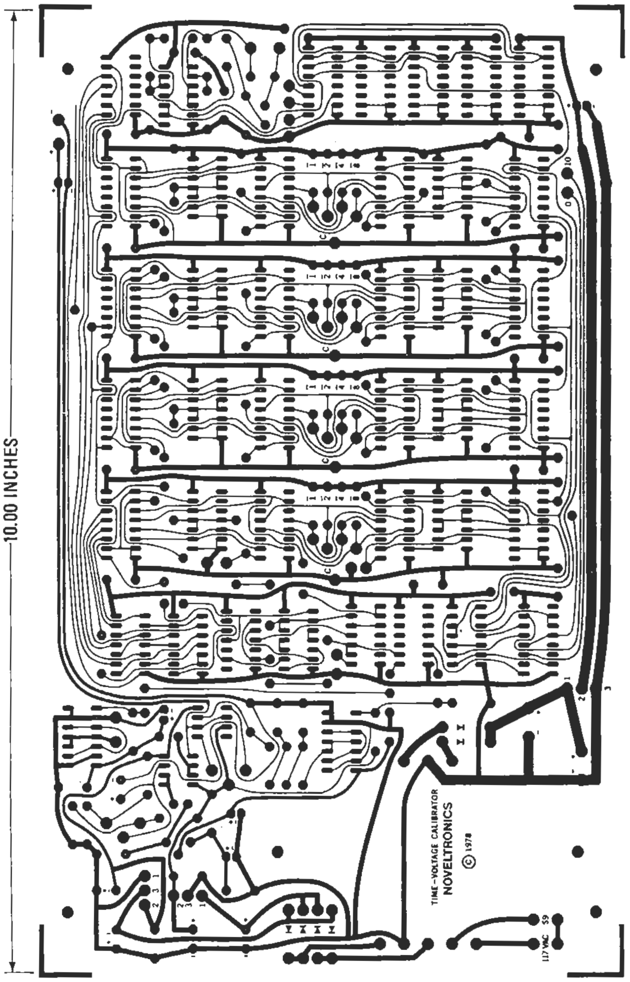
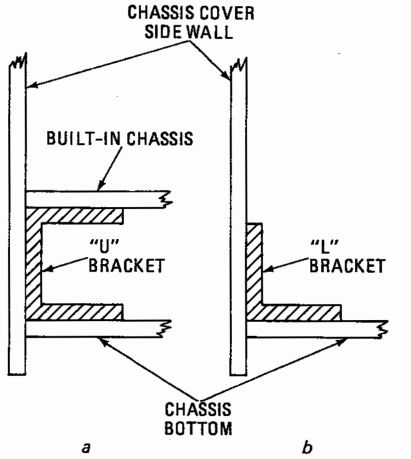


FIG. 8—FOIL PATTERN of the PC board reproduced half-size. This layout was developed to provide low-noise characteristics along with freedom from unwanted ground loops and voltage spikes.

the saw's vibrations. Try hard to keep the thumbwheel-switch hole close to the dimensions shown. An oversize hole defeats the switches' self-locking mechanism.



CHASSIS MODIFICATIONS

FIG. 9—THE CABINET has a built-in chassis that must be removed and modified before the PC board can be mounted. See text.

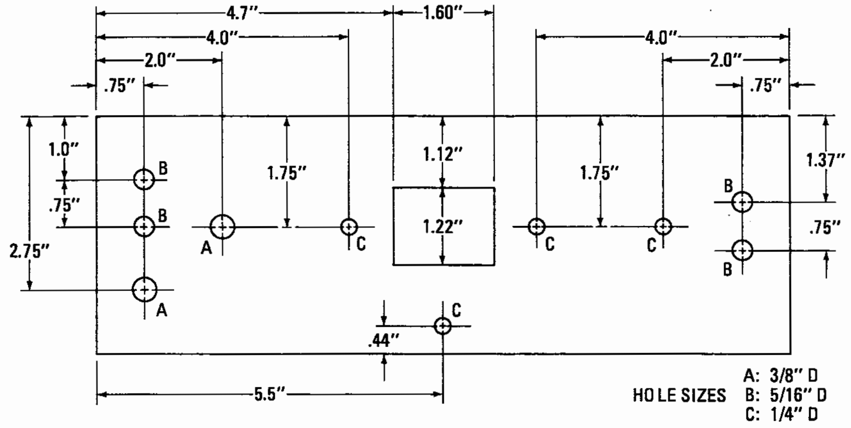
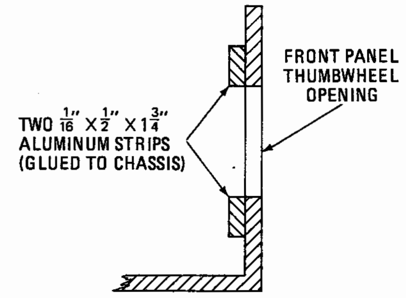


FIG. 10—DRILLING GUIDE for the front panel. We advise protecting the panel's face with masking tape until all holes have been drilled.



THUMBWHEEL SWITCH MOUNTING STOPS

FIG. 11—CROSS-SECTION of the slot for the thumb switches. Add shims as shown so switches fit and are self-locking.

The thumbwheel switches specified are designed to mount through a 1/8-inch-thick panel. Since this chassis is 1/16-inch thick, you must add a 1/16-inch-thick shim to the back of the chassis hole where the thumbwheel switches lock into place (see Fig. 11). Epoxy two strips of 1 3/4 X 1/2 X 1/16-inch aluminum (or PC-board scrap) as shown. Make sure that the strips' edges and front-panel hole edges are aligned.

Lastly, drill two holes through the chassis' backwall, one for the power cord's strain relief, the other for mounting regulator IC45 to the chassis. Both holes should be centered top to bottom. Drill the strain-relief hole 1 inch from the chassis' left edge, and the regulator hole 3 1/2 inch from the same edge.

Past experience has shown that the baked enamel finish on the chassis does not take dry transfer letters very well. I recommend painting the (now-machined) chassis cover with three coats of flat white lacquer, followed by two coats of flat clear lacquer. After a day of drying, you can letter this surface and then coat the letters with two or three more coats of the clear flat finish. The letters sink into the finish and are beautifully protected. This procedure was used on the unit shown in the photograph.

While the paint is drying, you can start stuffing the PC board. Solder the forty-seven jumpers and all the resistors, IC's and capacitors (in that order) on the board (see Fig. 12 and the italicized paragraph below). Only two of these components do not mount on the board: bypass capacitor C18 and +5-voltage regulator IC45. The capacitor should be mounted right on the front-panel VOLTS binding posts. Regulator IC45 needs heat-sinking, so mount it against the chassis' backwall in the hole provided. Solder three wires to the three leads of IC45, and run them to the circled PC board connections—A, B and C. Don't bolt the IC to the chassis until you're ready to mount the board in place on its spacers.

If you have access to an accurate 4 1/2-digit (or greater) DVM, solder capacitors C17 and C31, resistors R29–R32 and trimmer R35 in place. If not, remove all these components, as well as the wire jumper marked "J" (between IC43 and IC44, and next to R29) and insert a jumper wire in the location marked for capacitor C17. Also, if you have access to an accurate frequency meter, mount capacitor C35 and trimmer C36 as shown. If not, then substitute a 91-pF capacitor for C35 and omit the trimmer.*

Transformer T1 mounts directly on the board, but its wire leads must be trimmed down to size first. Hold the transformer near the edge of a table, so that one of its sets of wires hangs over the table edge, then cut each wire to a 1/4-inch length *below* the table top. Repeat this procedure for the other set of wires on the other side, and then strip back the insulation 1/4 inch. The transformer wires will now drop directly into the holes in the PC board, and no wire-crossing is necessary. Secure the transformer to the PC board with 4-40 X 1/2-inch hardware, and then solder the wires in place.

Using an electric drill, twist two 30-inch wires (one black and one red) together and then cut them into 6-, 6-, and 14-inch lengths. Solder these wire pairs into the PC board locations for switches S6, S7 and S9, respectively. Next, twist three color-coded 9-inch wires together and solder them into the PC board location for toggle switch S8. Twist four 11-inch color-coded wires together and solder them into the board locations for rotary switch S5. Lastly, twist five color-coded 20-inch wires together and cut them into four 5-inch pieces. These wires go to the thumbwheel-switch terminals on the PC board.

I strongly recommend using coaxial cable to bring the VOLTS outputs and two TIME outputs from the PC board out to the front panel. Although the characteristic impedance of the coax is not overly important, 50-ohm-impedance cable, such as RG-174/U, is recommended. Using coax cable will reduce the amount of noise pickup from all the TTL circuitry feeding into the VOLTS output. Twisted-pair cable can be used instead, but don't expect the good results from the calibrator that you get using coax cable. Whatever type of cable you choose, cut three 6-inch lengths each of the cabling. Strip 1/2 inch of braid from each end (in the case of coax) of each 6-inch length, then solder the cable into the board. Make sure that the braided shield is inserted into grounded solder pads K, R or T (not the signal end).

At this point, attach the loose ends of the wires to their respective switches (**except** for the thumbwheel switches), but don't actually mount the switches to the front panel yet. Bolt four 3/4-inch spacers, tapped with 4-40 threads on both ends, to the chassis. Bring the power cord in through the strain-relief hole and solder it to its PC board locations, 21 and 22. Now mount the PC board on the spacers and secure in place with four more bolts.

Mount regulator IC45 against the chassis backwall (it has already been wired to the PC board). Snap the thumbwheel switches in place in the chassis panel, and then solder the four 5-wire bundles to the appropriate switches. *Be careful here because the most significant thumbwheel switch is on the left-hand side of the chassis, but it is wired to the right-hand side of the PC board. Simi-*

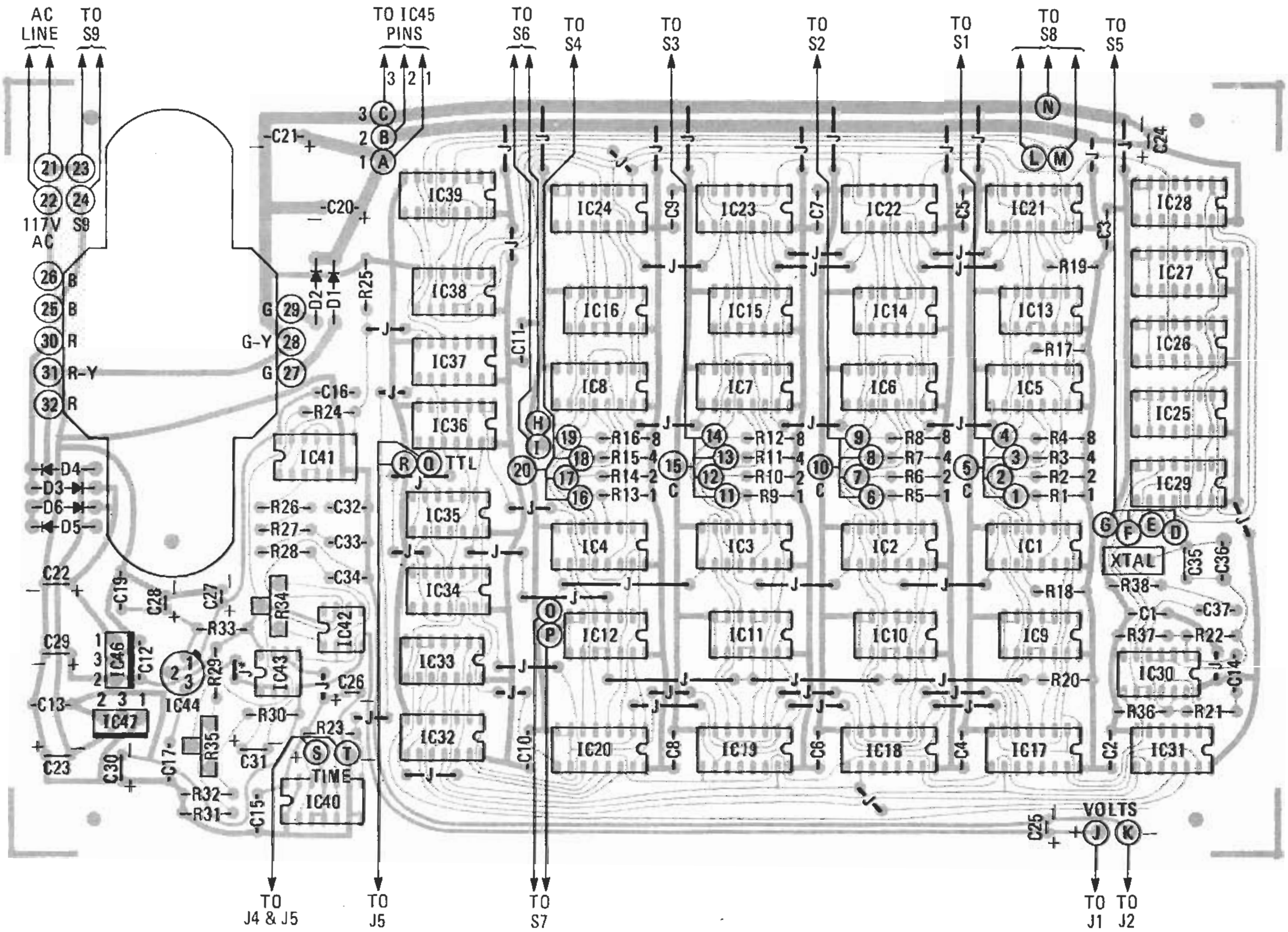


FIG. 12—PARTS PLACEMENT DIAGRAM is superimposed on reverse of PC pattern to show location of parts and to serve as a circuit-tracing aid.

larly, the least-significant counter is located at the left side of the board. So the wires cross, and if you fail to observe this, you will get reversed front-panel digit inputs.

Insert and tighten the four binding posts (J1–J4) and BNC connector J5 to the chassis; then solder the appropriate coax (or twisted-pair) cable to each. Attach the toggle switches and rotary switch to the chassis. Solder capacitor C18 directly to the VOLTS binding-post connectors. This now completes construction of the Time-Voltage Calibrator.

Debugging and calibration

This operation is optional. Before applying power, use an ohmmeter to check each voltage-regulator IC output to make sure that there are no obvious dead shorts to ground. I once encountered an interesting problem with a shorted +5-volt supply line (IC45 pin 2). By progressively removing power wires on the PC board, I traced down the short to one row of IC's. A visual inspection of that row showed nothing wrong, but by desoldering one V_{CC} pin at a time, I found an IC with a dead short between its supply lines.

Also inspect each IC visually to make sure that it is soldered onto the board correctly because if you apply power to a unit that is plugged in backwards, you will ruin the IC.

Apply power and measure all three regulator outputs with a voltmeter to check that you are getting +5, +15 and −5 volts. If not, shut down immediately and correct the problem. Look for open holes in the board where a component or jumper might be missing.

Set TIME MULTIPLIER switch S5 in the TTTT mSEC position, dial 2000 into the thumbwheel switches, and press the LOAD TIME pushbutton. Using a voltmeter on the TTL TIME output, you should observe the meter stay high for 1 second and then low for another. Otherwise, you'll have to debug the time-calibrator section.

Place toggle switch S8 in the 10.000 v position and measure the VOLTS output. After about 10 seconds, the voltmeter should measure very close to 10 volts. If not, something is faulty from IC39-b forward, and you must check it. Place switch S8 in the VAR position, dial in 5000 and press the LOAD VOLTS pushbutton. After 10 seconds, the VOLTS output will read approximately 5 volts. If not, the TTL portion of the volts calibrator section is malfunctioning.

Once the volts and time sections are working, dial and load 5 volts and 4 seconds, then monitor the TIME output (*not* the TTL output). If you don't get a voltage swing between 0 and 5 every 2 seconds, the trouble lies somewhere around IC43-a, IC40 and/or IC37-a.

Of course, an oscilloscope is an invaluable debugging aid, but by dialing in a very long time period (in seconds) you can slow down the time section enough for a voltmeter to be helpful. However, even if the above tests check out OK, there could still be high-frequency problems in the time section. The most difficult timing sequence is with a dialed-in value of 0010 with the time multiplier set in the TTT.T μSEC position (i.e., a 1.0-μs time period). If you can satisfy yourself that this operation works, you're home free. If not, then you may need a scope. As stated earlier, the four time counters, IC21–IC24, must only be those made by the recommended manufacturers. If the time section works from 0.1 μs to 0.9 μs but not 1.0 μs, then your problem lies in the time counter.

Once the two sections are debugged you may (or may not) want to fine-tune the calibrator, depending on the equipment you have available. Apply power to the calibrator for at least 15 minutes before trimming. By this time you have selected the PC board design that matches your trimming capabilities. If you want to adjust the time section, hook up a frequency meter to the calibrator's TTL output and load in a period of 0.1 μs. Adjust trimmer capacitor C36 until the meter measures exactly 10.0 MHz.

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TIME/VOLTAGE CALIBRATOR

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If you find that you cannot trim the frequency properly, you may have to experiment with different values for C35. *Increasing* this capacitance *decreases* the *frequency* of operation. For instance, on a prototype unit, substituting a value of 150 pF for (C35 + C36) dropped the frequency about 700 Hz below center, while a value of 47 pF increased it 1700 Hz above center. Your own results may vary from these values but will follow a similar trend. A couple of trial and error runs will pin down the correct value.

Adjusting the voltage section is a two-step process. Any DVM can be zeroed by shorting its test leads, and this zero accuracy is needed to zero the calibrator. With the DVM connected to the VOLTS output, set toggle switch S8 to the 0.000-volt position, and after one minute, adjust trimmer R34 for a 0.000-volt output. Now, if your DVM is 4½ digits or better and recently calibrated, flip switch S8 to the 10.000-volt setting and after another minute adjust trimmer R35 for a 10.000-volt output; that's all the fine tuning you can do. Attach the chassis top and you're ready to go.

Using the calibrator

Now that you have become used to operating the unit, let's look at how you use the calibrator. Loading a value is as simple as dialing the desired value into the thumbwheel switches and pressing the appropriate LOAD pushbutton. Once a load is performed, the thumbwheel switches can be set to any other value without upsetting the previously latched value.

The volts output takes about 10 to 15 seconds to stabilize when changing from one value to another. Remember that the overall accuracy is specified as a *percentage of the setting* and not a percent of full scale.

The non-TTL time output has an upper frequency limit that is dependent upon the volts section setting. A frequency of 5 MHz is about the highest frequency you can attain, but requires a 10-volt setting. Operation below about 4.5 volts peak-to-peak is uncertain at any frequency. However, the TTL output can operate at any setting.

When you want only a DC output and the time output is a "don't care," then load 0000 into the time section and set the time multiplier to "TTTT mSEC." This minimizes noise in the calibrator and provides the cleanest possible volts output.

Even though you may use the calibrator only a few times per year, you won't ever have to worry about your test gears' accuracy, and the other uses you'll probably find for it may surprise you. You should check your test equipment on a regular basis. **R-E**