

Build this Simple, High-Resolution DC Voltmeter

Here's an easy-to-build, computer-read, six-digit voltmeter based on a new ADC chip and a precise voltage reference.

By Ron Tipton, ex-K5UJC

Last year, Linear Technology Corporation¹ introduced a single-chip, 24-bit analog-to-digital converter (ADC), the LTC2400. I requested a demo board to see what it would do. This project and article are the results.

Although the chip has 24-bits of resolution, it isn't really a 24-bit converter. The specification sheet says the typical output noise is 1.5 μV RMS. Gaussian random noise has a crest factor (peak divided by RMS) of about five so $1.5 \times 5 \times 2 = 15 \mu\text{V}$ pk-pk. At 5 V full scale, the least-significant bit is just 0.3 μV so the

converter noise effectively "uses up" the lower five bits; at best we have a 19-bit converter, which is really quite good for an SO-8 IC!

Selecting a Voltage Reference

However, we also need to find a voltage reference for the converter that adds minimum noise. Since the ADC and reference noise will be uncorrelated, the noise powers add directly. The noise voltage, therefore, will increase as the square root of the sum of the squares of the individual noise voltages, that is, the RMS sum. The demo board uses an LTC1236A 5-V reference chip for the converter reference and for the converter supply voltage. The LTC1236A "spec" sheet lists an initial uncertainty of $\pm 2.5 \text{ mV}$, a temperature coefficient of 5 ppm/ $^{\circ}\text{C}$,

and a maximum output noise of 3.5 μV rms. The RMS sum of 1.5 μV and 3.5 μV is 3.8 μV or about 38 μV pk-pk (assuming a crest factor of five).

Using an input of +2.000 V from a voltage reference, I measured an output variation about the mean of about 60 μV pk-pk. See the graph in Fig 1. This is greater than the predicted 38 μV pk-pk, but the 2-V input contributes some noise, too, so these numbers are in the right ballpark. Even so, I thought I could do better with a quieter reference supply. Thaler Corporation² makes a precision 5-V reference IC, the VRE305A, that I've used in other projects.³ Its specs are quite good. The initial voltage uncertainty is only $\pm 0.5 \text{ mV}$, the temperature coefficient is 0.6 ppm/ $^{\circ}\text{C}$, and the output noise is typically 3 μV RMS without

¹Notes appear on page 43.

the optional external noise-reduction capacitor. The only drawback to this chip is its need for a 13.5 to 22 V supply, but I deemed this a worthwhile trade for its superior performance.

An output noise level of 3 μV RMS is pretty good, but what about summing the outputs of several references and dividing each reference output by the number being summed? The total noise voltage decreases and the dc output remains constant at 5 V. By summing three outputs, the initial uncertainty of the 5 V may decrease, too, since it's equal to the average of the three references. Using 3 μV RMS from the specification sheet, we get the curve in Fig 2 for multiple references. Three references looked like a good compromise, as

the improvement becomes increasingly smaller beyond four or five. Three is manageable in cost, circuit-board space and summing-resistor values. Another look at Fig 1 shows a decrease to about 30 μV pk-pk variation for the three-reference voltmeter, which I'm calling a model 251. The result is a solid 6-digit meter—not bad for a cost of about \$150!

Comments on the Circuit Diagrams

The circuit diagram is shown in Figs 3, 4 and 5. Let's take a look at how it works. In Fig 3, U1 is a very-low-noise, chopper-stabilized op amp connected for non-inverting operation. Slide switch S1 sets the input gain to 0.1, 1 or 10 for full scale ranges of 50, 5 and

0.5 V. The circuit-board common is not internally connected to the case, as this makes it easier to control ground loops. You may get more stable operation by placing a low-resistance jumper between the black and green (case) binding posts. The ADC uses an internal conversion oscillator and digital filter to reject either 50- or 60-Hz input signals. For 50-Hz rejection, pin 8 is connected to +5 V; it is grounded for 60-Hz rejection. The demo board and my board have jumpers to make this selection.

Input Protection

Resistor R2 and diode D1 protect the ADC from negative input voltages on the 50-V and 5-V ranges. The voltage drop across R2 from positive-voltage leakage current is measurable, but the error is so small I consider it negligible. There is no negative input protection on the 0.5-V range because of the gain of 10 in U1. You can connect a Schottky diode (such as a 1N5817) in parallel with R7 with the cathode end on U1, pin 6. This protects the ADC but the positive voltage leakage current causes a -0.4% error at +5 V into the ADC. I consider this unacceptable, but it would protect the ADC from destruction.

The 5-V range is the most accurate because U1 is just a voltage follower, and there are no resistor tolerances to worry about. On the other two ranges, gain-setting resistors are used. Although they are 0.1%-tolerance units, there will be a small gain uncertainty.

Serial Interface

The serial data interface to the computer copies the demo-board interface except I added optocouplers to isolate computer common from voltmeter common. That gives another option for controlling ground loops. A common interface was intentionally included so that the demo software would also

Resistor Matching

You can use stock 0.1% resistors for the whole project, but you can get better performance by matching them when same-valued sets or pairs are needed (see the Parts List). In these cases, the specific values are not as important as the degree to which the values match. This matching can be easily done with another digital multimeter (DMM). In fact, the DMM need not be very accurate, as long as its readings are stable. A 4½-digit meter gives you a resolution of 1 Ω (0.01%) at 10 k Ω and 5½ digits is 10 times better. You can easily determine stability by rechecking matched pairs after 30 minutes or so.

The 0.1% resistors from Mouser Electronics have a temperature coefficient (TC) of ± 25 ppm/°C. This amounts to ± 0.25 Ω /°C for a 10-k Ω resistor. So matching to better than $\pm 0.01\%$ is probably useless because of the resistance change with temperature. Inexpensive 1% metal-film resistors could also be matched in this way, but their TC is ± 50 ppm/°C, so we should avoid the temptation to save money this way.

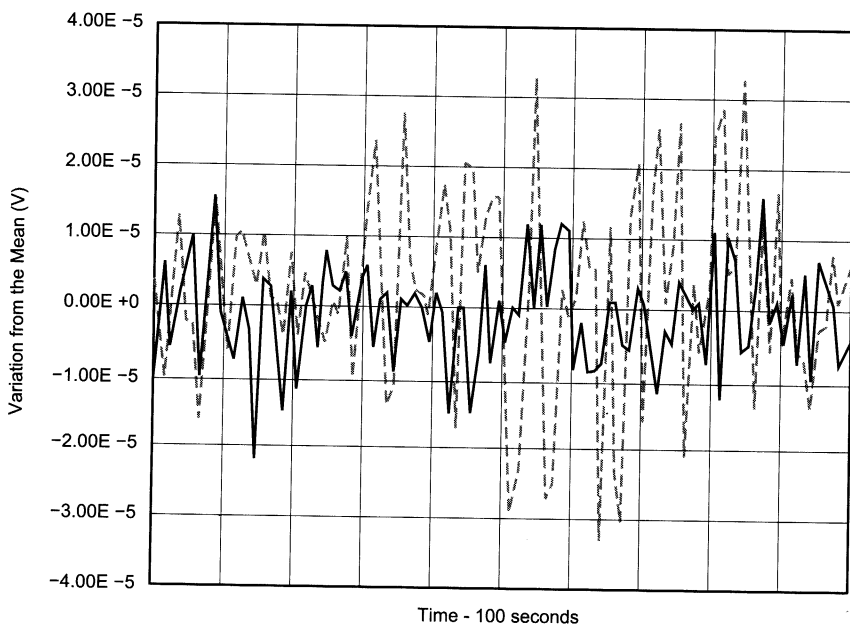


Fig 1—Comparison of short-term variation in voltage reading. The solid line is for the model 251 voltmeter and the dashed line is for the LTC2400 demo board. Input voltage was 2.000 V in both cases.

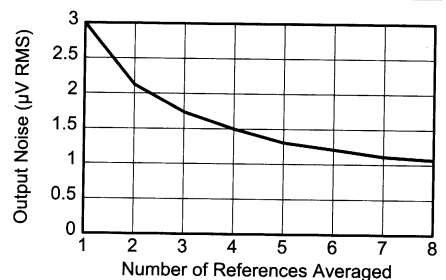


Fig 2—Total noise decreases as the number of uncorrelated sources increase. Three sources seems a good compromise between performance and circuit complexity.

work with this circuit. Remember, though, that the computer display will always be zero to +5 V, so you will have to mentally correct the decimal point unless you are on the $\times 1$ scale. The demo software is for *Windows95* and *98*, so I have written a companion *MS-DOS* program to also display the voltage and record data files.⁴ This could give new life to that old laptop computer gathering dust in your closet.

Reference

Fig 4 shows the 5-V reference circuit. The outputs of three Thaler VRE305As are summed by op amp U7 and then inverted back to +5 V by U8. These are very-low-noise chopper op amps; don't substitute another type. R11 through R16 are 10-k Ω , 0.1% metal-film resistors matched to 0.01% (see the sidebar "Resistor Matching"). Performance will be somewhat poorer with stock 0.1% resistors, so use a matched set if you can. To help with this, I'm making matched sets available.⁵ Actually, these resistors seem to group quite well. Fig 6 shows the results of matching the resistors I had on hand.

C11, C12 and C14 are the optional external noise-reduction capacitors, suggested on the VRE305A datasheet. Charge-storage capacitors C16, C17, C19 and C20, as well as C3 and C4 have polypropylene-film dielectric; for best performance, do not substitute another type.

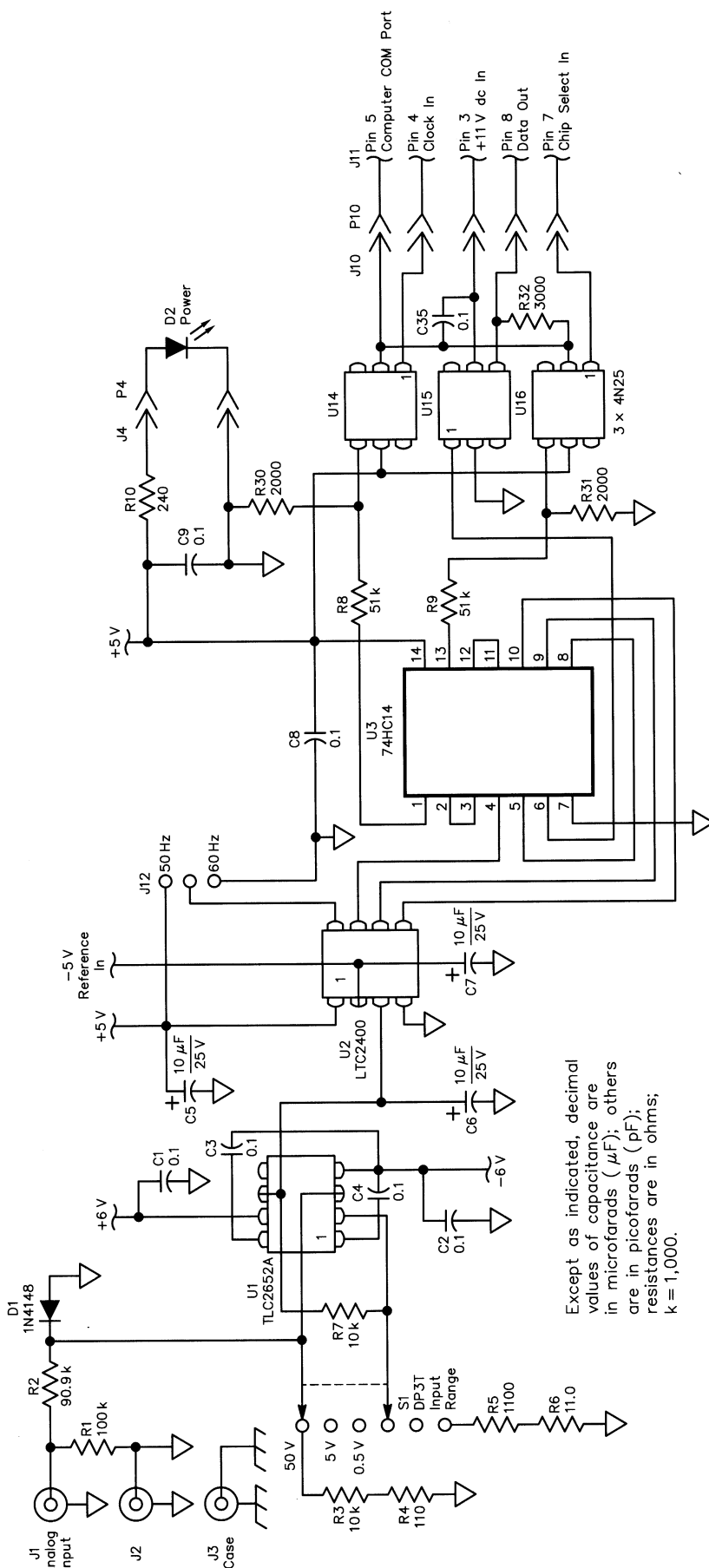
Power Supply

The power supply is shown in Fig 5. The incoming low-voltage ac is rectified by U17 and filtered by C22. The resulting dc voltage is then split by power op amp U9 into ± 17 V. The +15 V regulator, U10, must be a low-drop-out-voltage type. The regulated +5 V powers the ADC and interface logic and the ± 6 V goes to the op amps. Using separate regulators provides high isolation between the digital and analog parts of the circuit, and the low ac power supply voltage minimizes 60- and 120-Hz feedthrough.

Construction

All components, except the connectors, are on one double-sided circuit board as shown in Fig 7.⁶ Fig 8 is the parts location diagram, while Figs 9 and 10 show how the connectors are mounted. Enclosure drilling and circuit board layout drawings can be

Fig 3—Input amplifier, ADC and serial data interface. U1 is an eight-pin DIP, but U2 and U3 are surface-mount devices.



downloaded; see Note 4.

Although most of the ICs are somewhat expensive, don't use sockets. The added (and variable) contact resistance will degrade accuracy and long-term stability. It's also better to use solder from the same roll for the whole board as this, too, can affect accuracy.

I used a cast-aluminum enclosure to provide electrical shielding and a reasonably constant temperature for the whole voltmeter. The power op amp, U9, and +15 V regulator, U10, are connected to one of the enclosure walls through an aluminum bracket so their heat isn't dissipated inside the case.

Surface leakage on the circuit board can also degrade performance, so clean off the flux and oily fingerprints before mounting it in the enclosure. Mechanical stress on the board can produce cyclic variations as the board reacts to changes in its environment. To minimize this effect, I kept board mounting as simple as I could. The heat-sink bracket is attached to the case wall with two #4-40 machine screws and nuts. The other, output-end corner is supported by a 3/8-inch-long nylon snap-in post that attaches to the enclosure bottom with a sheet-metal screw, but just snaps into an oversize hole in the circuit board. The voltage-input end of the board is supported by two 3/8-inch nylon spacers that aren't attached to the enclosure bottom.

into any convenient outlet and attach its cord to the power-input connector. Connect the DB9 connector to your computer's serial port. Turn on the voltmeter's power and start the computer program (*Windows* or *MS-DOS*

version). You should see the input voltage displayed on the screen.

Software

Both versions of the software let you select either COM1 or COM2. Both

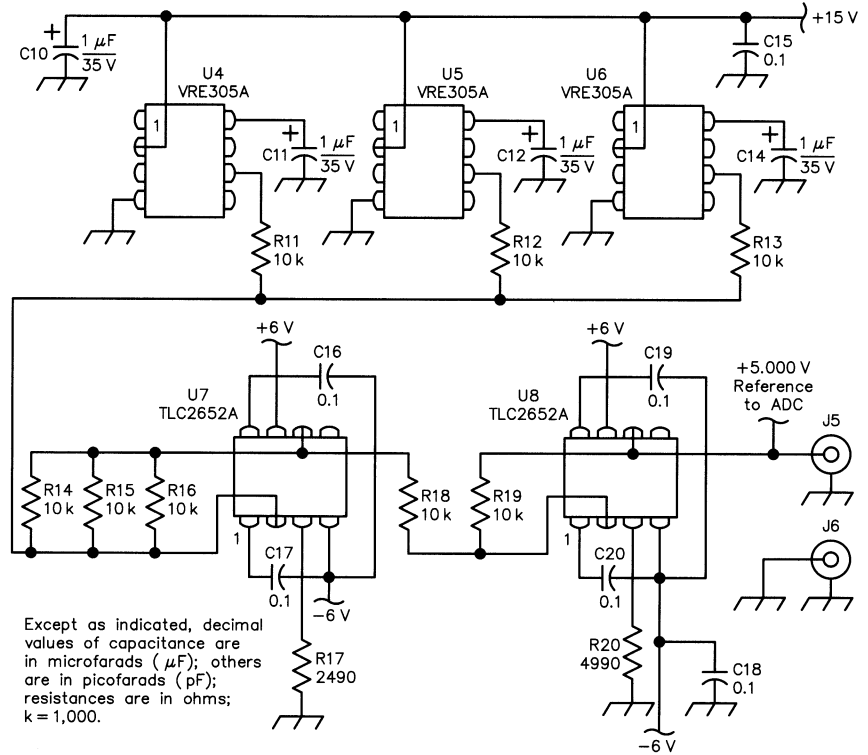


Fig 4—The 5-V reference supply averages three outputs to reduce short-term variations. The op amps are chopper-stabilized with very little output noise.

Operation

Plug the "wall wart" transformer

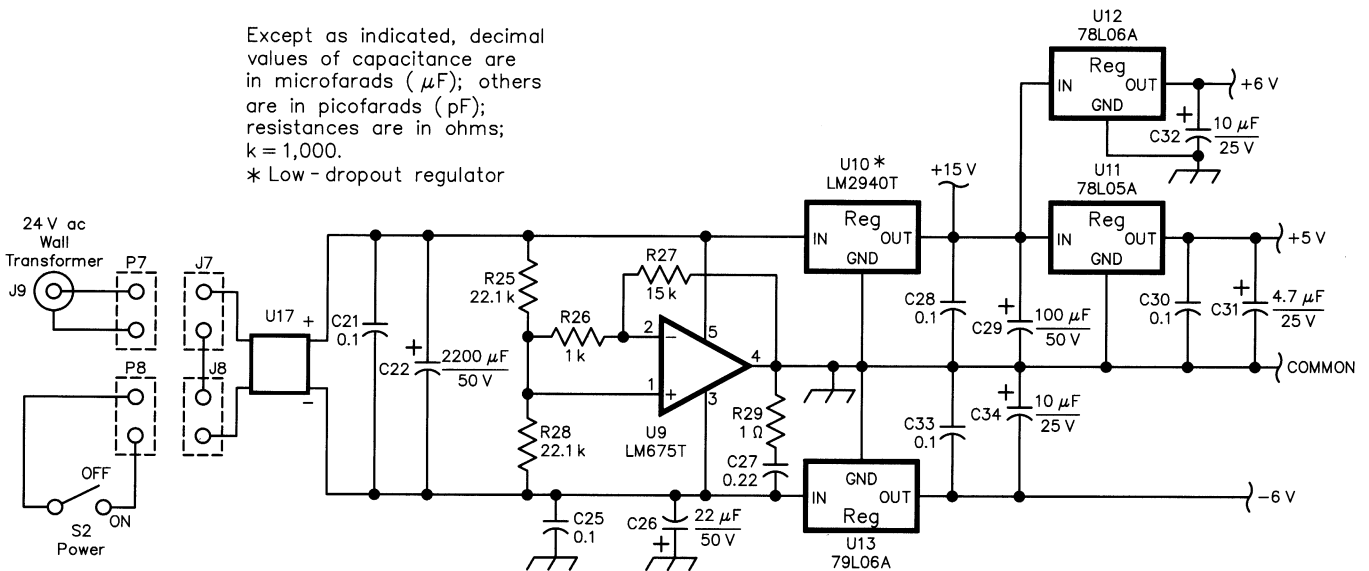


Fig 5—The LTC2400 voltmeter power supply. U9 splits the dc to +17 V and -17 V. U10 is a low-dropout voltage regulator.

versions let you do an N -point running average if you want to. Both versions also let you record a data file. The recorded data format uses ASCII numbers separated by tab and new line characters, so the files are easy to import into a spreadsheet or math program. For the *MS-DOS* version to work correctly you must have ANSI.SYS or an equivalent loaded. That is, you need a line in your config.sys file that reads: DEVICE=C:\DOS\ANSI.SYS (or wherever the file is located).

I wrote the *MS-DOS* program in MIX Software *PowerC*,⁷ and I used a serial-communications library from MarshallSoft named *PCLAC*.⁸ The source code is included in the SVMETER.ZIP file (see Note 4). The

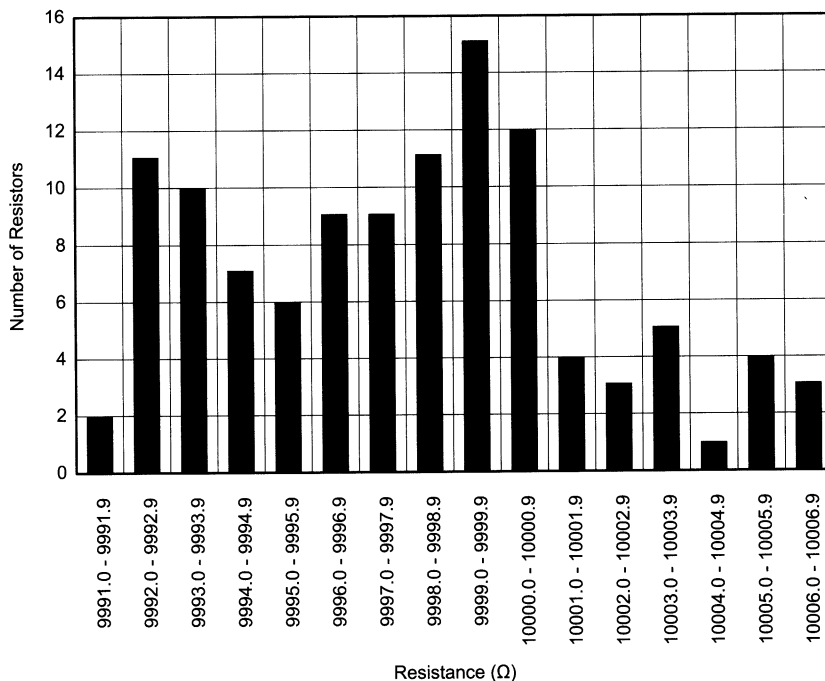


Fig 6(right)—This graph shows the result of measuring 112 10-kΩ, 0.1% metal-film resistors. The resistors in each “bin” are matched to 0.01%.

Parts List

C1, C4, C8, C9, C15, C18, C21, C23, C25, C28, C30, C33, C35—0.1 μF, 50 V ceramic (Jameco 25523)
 C3, C4, C16, C17, C19, C20—0.1 μF, 50 V, 5% polypropylene film (Mouser 1429-1104)
 C5-C7, C32, C31, C34—10 μF, 25 V tantalum electrolytic (Jameco 94078)
 C10-C12, C14—1 μF, 35 V, tantalum electrolytic (Jameco 154860)
 C13—not used
 C22—2200 μF, 50 V electrolytic (Jameco 93841)
 C24, C26—0.22 μF, 50 V polyester film (DigiKey P4667)
 C29—100 μF, 50 V, low-ESR electrolytic (Mouser 140-ESRL50V100)
 D1—1N4148 silicon diode
 D2—Panel-mount red LED (Mouser 35MP062)
 J1, J5—Binding post, red (Mouser 164-4205)
 J2, J6—Binding post, black (Mouser 164-4201)
 J3—Binding post, green (Mouser 164-4204)
 J4, J7, J8—2-pin, 0.1-inch header (DigiKey WM4000)
 J9—DC power jack, insulated, to mate with the connector on the wall transformer (Mouser 163-4303)
 J10—5-pin, 0.1-inch header (DigiKey WM4003)
 J11—Panel-mount, female DB9 connector (Jameco 15780)
 J12—3-pin, 0.1-inch header with shorting jumper (DigiKey 929834-02-36)
 P10—5-pin terminal housing with pins (DigiKey WM2014)
 P4, P7, P8—2-pin terminal housing with pins (DigiKey WM2011) pins are (DigiKey WM2200)
 R1—100 kΩ, 1/4 W, 1% metal film (Mouser 271-100K)
 R2—90.9 kΩ, 1/4 W, 0.1% metal film (Mouser 279-90.9K)
 R3, R7—10 kΩ, 1/4 W, 0.1% metal film (Mouser 279-10K)
 R5—110 Ω, 1/4 W, 0.1% metal film (Mouser 279-110)
 R6—11.0 Ω, 1/4 W, 0.1% metal film (Mouser 279-11)
 R8, R9—51 kΩ, 1/4 W, 5% carbon film (Mouser 291-51K)
 R10—240 Ω, 1/4 W, 5% carbon film (Mouser 291-240)
 R11-R16—10 kΩ, 1/4 W, 0.1% metal film matched to 0.01% or better (Mouser 279-10K)
 R17—2940 Ω, 1/4 W, 0.1% metal film (Mouser 279-2.94K)

R18, R19—10 kΩ, 1/4 W, 0.1% metal film matched to 0.01% or better, see sidebar (Mouser 279-10K)
 R20—4490 Ω, 1/4 W, 0.1% metal film (Mouser 279-4.49K)
 R21 to R24—not used
 R25, R28—22.1 kΩ, 1/4 W, 1% metal film (Mouser 271-22.1K)
 R26—1000 Ω, 1/4 W, 1% metal film (Mouser 271-1K)
 R27—15 kΩ, 1/4 W, 1% metal film (Mouser 271-15K)
 R29—1 Ω, 1 W, 5% carbon film (Mouser 294-1.0)
 R30, R31—2000 Ω, 1/4 W, 1% metal film (Mouser 271-2K)
 R32—3000 Ω, 1/4 W, 1% metal film (Mouser 271-3K)
 S1—DP3T PC-mount slide switch (Mouser 10SL008)
 S2—SPST mini toggle switch (Jameco JMT113)
 T1—24 V ac, 500 mA or higher wall transformer (Mouser 412-224034)
 U1, U7, U8—Texas Instruments TLC2652ACP low-noise chopper op amp (Newark 08F9048)
 U2—Linear Technology LTC2400IS8 24-bit ADC (DigiKey LTC2400IS8)
 U3—74HC14AFN hex inverter (DigiKey TC74HC14AFN)
 U4, U5, U6—Thaler Corp VRE305A +5 V reference (Thaler VRE305AD)
 U9—National Semiconductor LM675T power op amp (Jameco120926)
 U10—LM2940CT +15 V low-dropout voltage regulator (DigiKey LM2940CT-15)
 U11—78L05A +5 V regulator (DigiKey NJM78L05A)
 U12—78L06A +6 V regulator (DigiKey NJM78L06A)
 U13—79L06A -6 V regulator (DigiKey NJM79L06A)
 U14, U15, U16—4N25 optoisolator (DigiKey 4N25QT)
 U17—Bridge rectifier, 50 V, 1 A (Jameco 103000)
 Enclosure—cast aluminum 6.8×4.7×2.2-inch (Mouser 400-4593)
 Heat sink for LM675T power op amp
 Circuit board—See Note 6
 Hardware
 Bumpers (stick-on rubber feet) (DigiKey SJ5523-0)

Linear Technology demo program records data at a fixed rate, but my program lets you select the time—up to 3000 seconds in one-second steps.

Wrapping It Up

The +5 V reference, which is brought out to its own set of binding posts, is good enough to be used as a reference for other instruments. It might be worthwhile to add an input inverter to measure negative voltages; but for its cost, this is useful meter.

Ron got his Technician class license at age 16 as W0MNP and was active on 2 meters. His call became K5UJC when he moved to New Mexico in 1956. He now has degrees in electrical engineering from New Mexico State University and is retired from an engineering position at White Sands Missile Range. In 1957, he started Testronic Development Laboratory (now TDL Technology Inc) to do consulting and electronic product development. He is still the TDL president and keeps busy in "retirement" doing consulting and technical writing.

Notes

- ¹Linear Technology Corporation, 1630 McCarthy Blvd, Milpitas, CA 95035-7417; tel 408-432-1900; www.linear-tech.com.
- ²Thaler Corporation, 2015 N Forbes Blvd, Tucson, AZ 85745; tel 800-827-6006; www.thaler.com.
- ³R. Tipton, "An Improved AC-DC Voltage Reference," *Nuts and Volts* magazine, Jan 2000.

⁴You can download this program along with the circuit-board layout and enclosure drilling drawings from www.zianet.com/tld. Click on Magazine Article Reprints and select SVMETER.ZIP. After unzipping the file, look at contents.txt for information on the other files. You can also download this package from the ARRL Web www.arrl.org/qxfiles/. Look for SVMETER.ZIP.

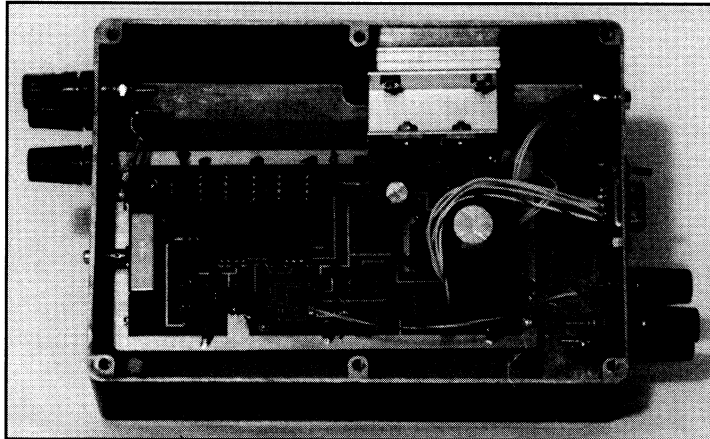


Fig 7—Photo of the circuit board in its enclosure. The heat-sink bracket is a 2-inch length of aluminum channel with two 2-inch lengths of $\frac{1}{8} \times \frac{1}{2}$ -inch bar and one 2-inch length of $\frac{1}{16} \times \frac{1}{2}$ -inch bar as spacers to the enclosure wall. Remember to use insulators and heat-sink compound.

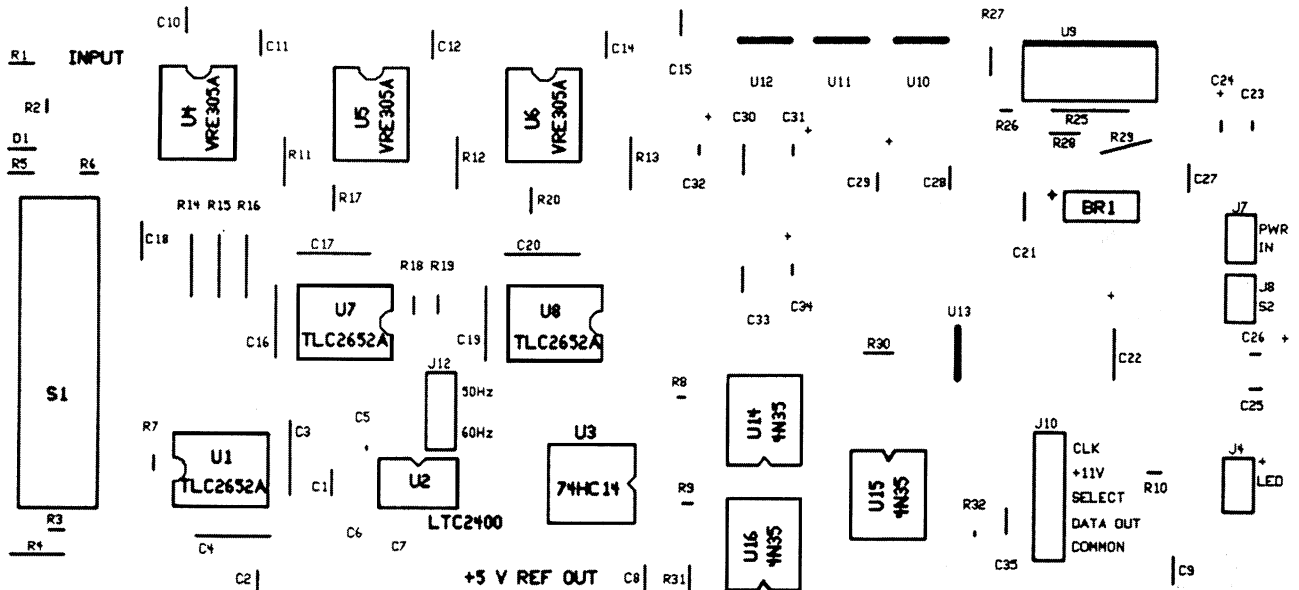


Fig 8—A parts-placement diagram for the LTC2400 voltmeter. All off-board connections use connectors except for the input and reference output.

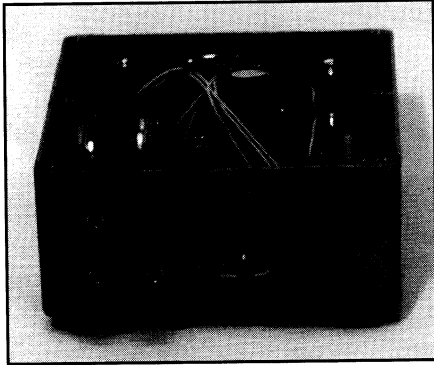


Fig 9—The voltage-input end. The slide switch (gain control) lever extends about $\frac{1}{4}$ -inch through a slot in the enclosure wall.

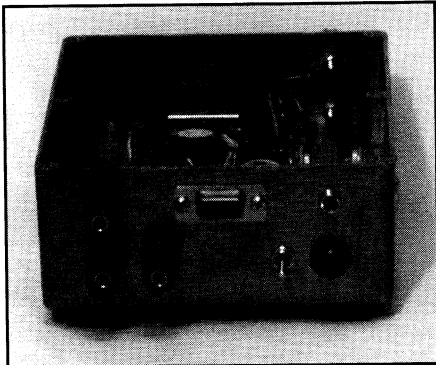


Fig 10—The power-supply end. The wall-wart-input connector, LED and power switch are on the right. The binding posts on the left are for the +5 V reference-voltage output.

Mouser Electronics, 958 N Main, Mansfield, TX 76063-4827; tel 800-346-6873; www.mouser.com.

Newark Electronics, 1919 S Highland Ave, Lombard, IL 60148-6119; tel 800-463-9275; www.newark.com. □□

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⁵A kit of eight matched 10-k Ω , 0.1% resistors is available from the author for US \$12 (postpaid in the US and Canada).

⁶The circuit board is available from FAR Circuits, 18N640 Field Ct, Dundee, IL 60118-9269; tel 847-836-9148 (voice and fax); www.ci.ais.net/farcir/. The boards are \$14 each plus \$1.50 shipping for up to four boards. VISA and MasterCard accepted with a \$3 service charge. This is a solder plated, double-sided board, but the holes are not plated through, so a few component pins must be soldered on both sides. There are also six vias, where short pieces of wire are inserted and soldered on both sides.

⁷MIX Software Inc, 1132 Commerce Dr, Richardson, TX 75081; tel 800-333-0330; www.mixsoftware.com.

⁸MarshallSoft Computing Inc, PO Box 4543, Huntsville, AL 35815; tel 256-881-4630; www.marshallsoft.com.

Parts Distributors

Digi-Key Corporation, 701 Brooks Ave South, Thief River Falls, MN 56701-0677; tel 800-344-4539; www.digikey.com.

Jameco Electronic Components, 1355 Shoreway Rd, Belmont, CA 94002-4100; tel 800-831-4242; www.jameco.com.