PROJECT: A Compensated, Modular RF Voltmeter

This versatile and yet simple voltmeter measures levels from 100 mV to 300 V, from 30 MHz to audio frequencies, and is accurate to ± 0.5 dB. The design allows for either a built-in analog meter or an externally connected DVM—or both! This portable, simple, and inexpensive project was originally featured in the March/April 2001 issue of *QEX*. Like the original article, the project described below includes several refinements implemented by its author, Sid Cooper, K2QHE that evolved from a suggestion by then *QEX* Managing Editor, Robert Schetgen, KU7G, to increase the voltage range of the instrument.

The requirements for this RF voltmeter (RFVM, **Fig 25.46**) are many:

- Provide accurate, stable measurements
- Measure voltage at frequencies from audio through HF
- Measure voltage levels from QRP to QRO
- Measure voltages inside equipment or in coax
- Operate portably or from ac lines
- Be flexible: work with digital voltmeters already in the shack, or independently
- Be inexpensive

DESIGN APPROACH

To achieve stability, the RFVM uses op amps and any drift in the probe's diode detector is compensated by a matched diode in the RF op amp. This stretches the sensitivity to QRP levels. The dynamic range extends linearly from 0.1 V to 300 V (RMS) by using a series of compensated voltage multipliers.

The frequency response was flattened by using Schottky diodes, which easily reach from 60 Hz to 30 MHz. Both the basic probe and the multipliers very simply adapt to function as a probe, clip to various measurement points on the chassis or to screw onto UHF connectors. The active devices are only two op amps. They draw 800 µA of resting current and a maximum of 4.0 mA during operation from a 9-V battery, which is disconnected when a 9-V wall unit is plugged into a jack on the back panel. As designed, the RFVM has a small sloping panel cabinet with a microammeter display. A pair of front-panel banana OUTPUT jacks can be used with a DVM; this eliminates one op amp, the meter and a multiposition switch. Since the meter and switch are the most expensive parts (when they are not bought at a hamfest), how low-cost can this RF voltmeter get?

THE PROBE

The low-voltage probe is a detector circuit that uses a Schottky diode and a high-impedance filter circuit (**Fig 25.45**). The diode is matched with the one in the feedback circuit of the CA3160 shown in **Fig 25.64**. This match reduces the diode's threshold voltage from about 0.34 V to less than 0.1 V, making the voltage drop comparable to that of a germanium diode. Since I think 0.1 V adequately covers QRP requirements, I made no further tests with germanium diodes to determine how much lower in voltage we could go.[1]

Use the low voltage probe and the output of the CA3160 in the meter unit (Fig 25.64) to find a matched diode pair. Build the CA3160 circuit first for this purpose. Select a diode and place it in the feedback loop of the CA3160, then test each of the remaining diodes in the probe with the three pots set about midrange. Test each diode, first at probe inputs of 100 mV, then at 3.00 V, at 400 Hz. Record the dc output from the CA3160, using the OUTPUT terminals. A bag of 20 diodes from Mouser Electronics[2] contained seven matched pairs, with identical readings at both low and high voltages. My tests used the ac scale (good to 500 Hz) of a Heath 2372 DVM to read the input voltage, and its dc scale to read the output. The number of matched pairs is surprising, but the diodes in the bag may all be from the same production run.

RF PROBE ASSEMBLY

After selecting matched diodes, all components of the RF probe are mounted on a piece of perf board that is inserted in an aluminum tube (**Fig 25.47**). Since the circuit board is very light, it is supported on each end only by its input and output wires. The input RF wire is soldered to the center pin of the SO-239 connector. The two dc-output wires are held to the board by a small tie wrap, consisting of a piece of the #26 insulated wire, after having been passed through the plug cap and grommet. Cut a slit in the aluminum tube, perpendicular to its end. Make it at least ⅛-inch long and ¹⁄₃₂-inch wide to allow a bare

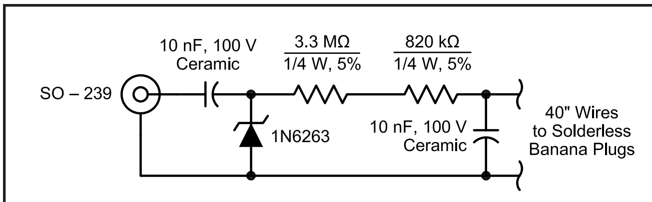


Fig 25.45 — A schematic diagram of the RF probe.

Fig 25.46 — The RF voltmeter with meter unit, RF probe and voltage multipliers.

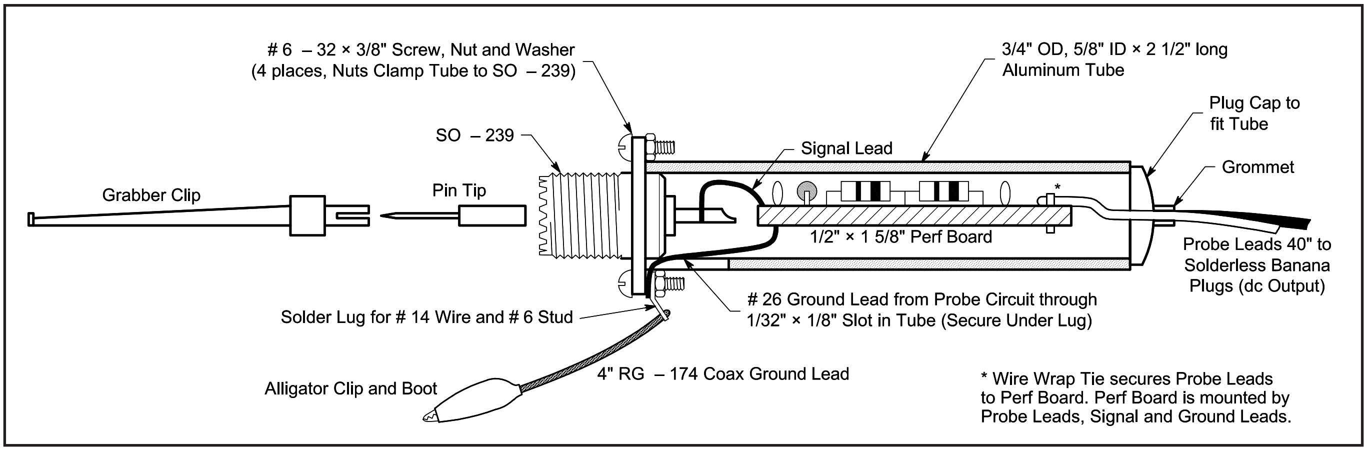


Fig 25.47 — RF probe construction showing the grabber clip (RS 270-334), pin tip (Mouser 534-1600), lug (Mouser 571-34120), for #14-#16 wire and a #6 stud), alligator clip (RS 270-1545), plug cap (Mouser 534-7604), grommet (Mouser 5167-208) and 4-in ground lead made from shield of RG-174.

#26 ground wire to pass through it.

Let's look at how the probe is assembled. The aluminum tube just fits around the back end of the SO-239 connector. When the four #6-32 screws, nuts and washers are installed in the four holes of the SO-239 connector, the flat face of the nut bears down strongly on the aluminum tube and rigidly holds it in place. Most standard SO-239 connector holes easily accept #6-32 screws; if yours do not, enlarge them with a #27 bit. The slit cut in the aluminum tube allows the bare ground wire from the perf board to pass from inside the tube to the outside and around the screw that secures the ground lead of the probe. As can be seen in Fig 25.47, the threaded part of the SO-239 connector faces away from the aluminum tube.

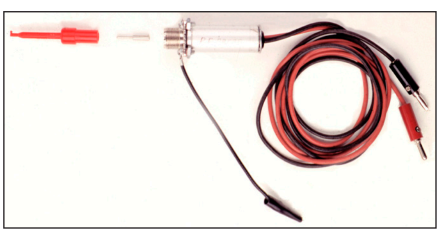


Fig 25.48 — A photo of the grabber clip, pin tip and RF probe.

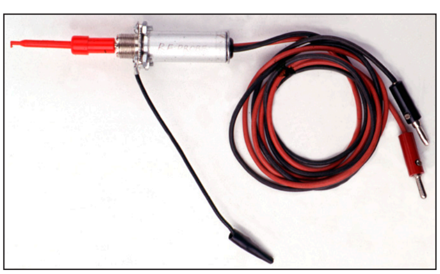


Fig 25.49 — The RF probe with the pin tip and grabber clip in place. The pin tip is not visible, but it provides the physical bridge and electrical connection between the clip and SO-239 of the RF probe.

This probe allows easy voltage measurements in a coaxial cable when the probe SO-239 is secured to a mating T connector. To make a probe reading at any point on a chassis or PC board with this connector, simply insert the larger end of a nicely mating pin tip into the SO-239. The pin tip's diameter is 0.08 inches at the small end and — fittingly — 0.14 inches at the mating end. I made this purely fortuitous discovery while rummaging through a very ancient junk box. Further, to make measurements with the probe clipped to a part or test point on a PC board or chassis, a clip or grabber can be mated to the pin tip that protrudes from the SO-239. This is shown in Figs 25.47 and **25.48**. All this may have been known to people in the connector industry, but it appears not to have been known or used elsewhere. **Fig 25.49** shows the grabber connected to the RF probe using the pin tip to join the two.

PROBE MEASUREMENTS

The probe can accept RF signals up to 20 V (RMS) when there is no dc voltage or a combination of dc voltage and peak ac of about 28 V without exceeding the reverse-voltage rating of the diode. I made linearity measurements of the RF probe from 100 mV to 8.0 V at 400 Hz. (The range was limited by my available signal generator.) **Fig 25.50** is a plot of the error at the probe output versus the input amplitude. This was measured using a digital voltmeter with a 10-MΩ input resistance. This input resistance and the 4.1-MΩ resistor in the probe converts the peak voltage of a sine wave signal to the RMS reading of the DVM. The error is –44% at 100 mV, then 10% (0.9 dB) at 1.0 V and finally 2.9% at 8.0 V. The RF probe and DVM are obviously intended for higher voltage readings where the diode voltage drop doesn't affect the accuracy significantly.

The frequency response of the probe was measured at the midpoint of each ham band from 1.9 to 30 MHz with 650 mV input (see **Fig 25.51**). This time, because the input voltage was low and the absolute error would have been high, the probe was connected to the meter unit, which will be described later. The compensating diode loop of the meter unit reduces the error that would otherwise be read by the DVM from 90 mV (14%) to 4 mV (0.6%). The frequency response, however, is controlled by the probe. Use of the meter unit—which operates entirely on the dc signal—does not affect the frequency response, but it does improve the sensitivity of the readings. The measured response shown goes from –3.6% (–0.32 dB) to +1.2% (+0.1 dB) [A larger input capacitor in the probe will improve accuracy at lower frequencies. Pat McGuire, NO5O, reports good results from 50 kHz to 30 MHz by changing the input capacitor from 10 nF to 0.1 µF and performing the calibration described later at 50 kHz instead of 400 Hz. — Ed].

MULTIPLIERS

To extend the voltage range of the RF probe, use a 10× multiplier, which is a compensated divider, shown in **Fig 25.52**. The electrical design is straightforward and includes a small trimmer capacitor to adjust for a flat frequency response. These components are very lightweight, so they require no perf board and are easily supported by their leads, which are anchored at the two SO-239 connectors. To make measurements, the input connector can be mated to connectors in a coaxial cable, a pin tip can be inserted for probing PC boards or a grabber can be added for connections to components on a chassis. The multiplier can connect to the RF probe

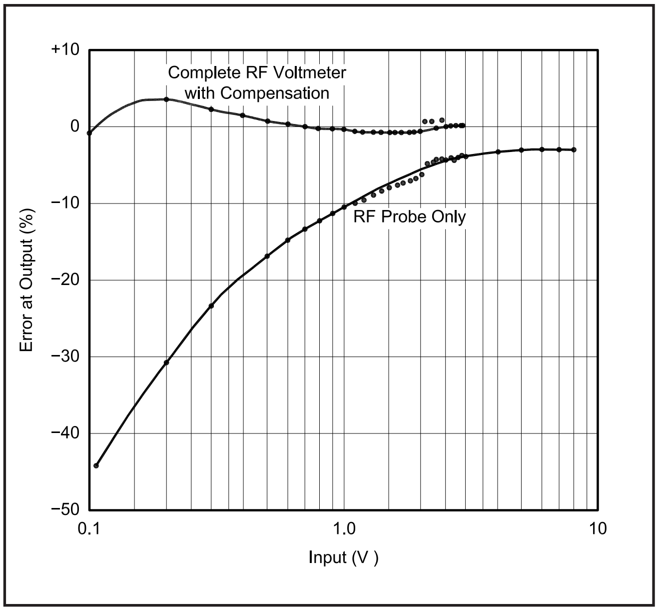


Fig 25.50 — Amplitude linearity of the RF probe alone and in combination with the RF voltmeter.

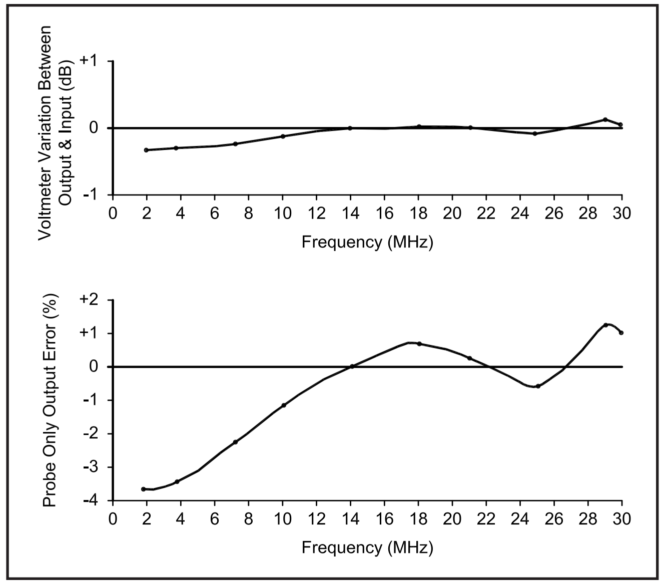


Fig 25.51 — A frequency-response plot for the RF voltmeter. The response of the probe determines the overall system response.

either through a male-to-male UHF fitting or by a piece of coax with a UHF male connector at each end.

The typical way to adjust the trimmer requires a square-wave input and an oscilloscope on the output. The trimmer is then set to produce a flat square-wave output with no overshoots on the leading edges and no droop across the top. An RF signal generator that covers 1.9 MHz to 30 MHz can be used instead, if a square wave generator is not available. Since this is a 10× multiplier, it is reasonable to expect the input to handle up to 200 V (RMS), but the limit is 150 V because the trimmer capacitor is rated at 225 V dc. You may be able to find small trimmers with higher voltage ratings that will take the multiplier to 200 V and still fit inside the tube housing.

Multiplier construction follows the same methods used for the RF probe but with a few differences. My first model used an aluminum tube like that in the RF probe with #6-32 screws to hold it all together, but the frequency response began to drop off at 21 MHz. By replacing the aluminum tube with a phenolic tube[3] having the same dimen-

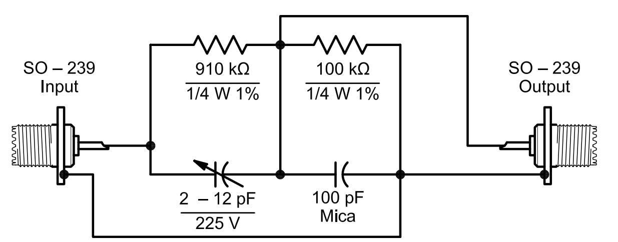


Fig 25.52 — A schematic of the 10× multiplier. The trimmer capacitor is from Ocean State Electronics (see Note 10).

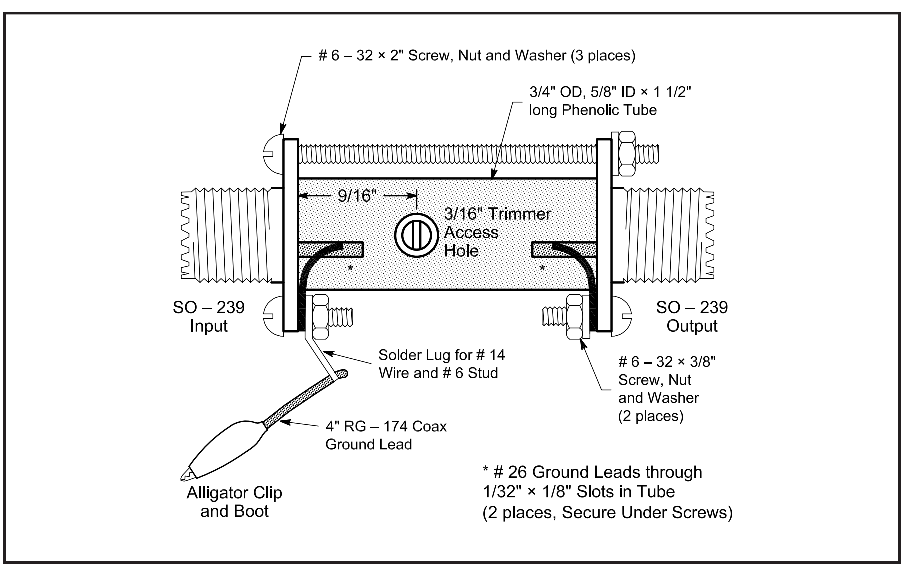


Fig 25.53 — Construction of the 10x multiplier. The phenolic tube is US Plastics #47081, see Note 3. The lug is Mouser 571-34120.

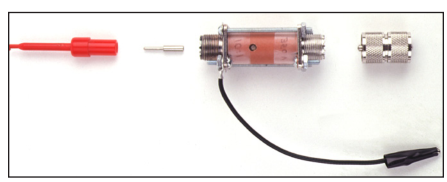


Fig 25.54 — A view showing the 10× multiplier with grabber, pin tip and a male UHF coupler that connects the multiplier to the RF probe.

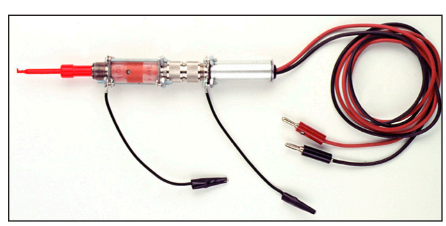


Fig 25.55 — The complete RF probe and 10× multiplier assembly.

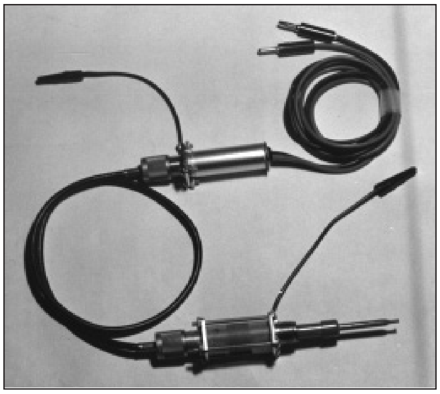


Fig 25.56 — The RF probe and multiplier can be separated by a piece of coax less than 12 inches long if it makes measurements more convenient.

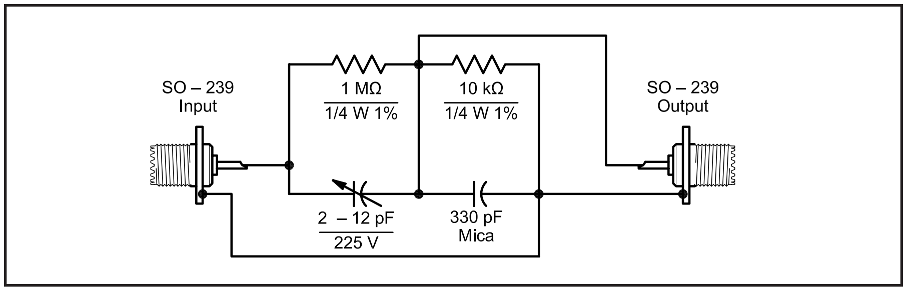


Fig 25.57 — Schematic of the 100x multiplier (maximum allowable input is 150 V RMS). The trimmer capacitor is from Ocean State Electronics (see Note 10).

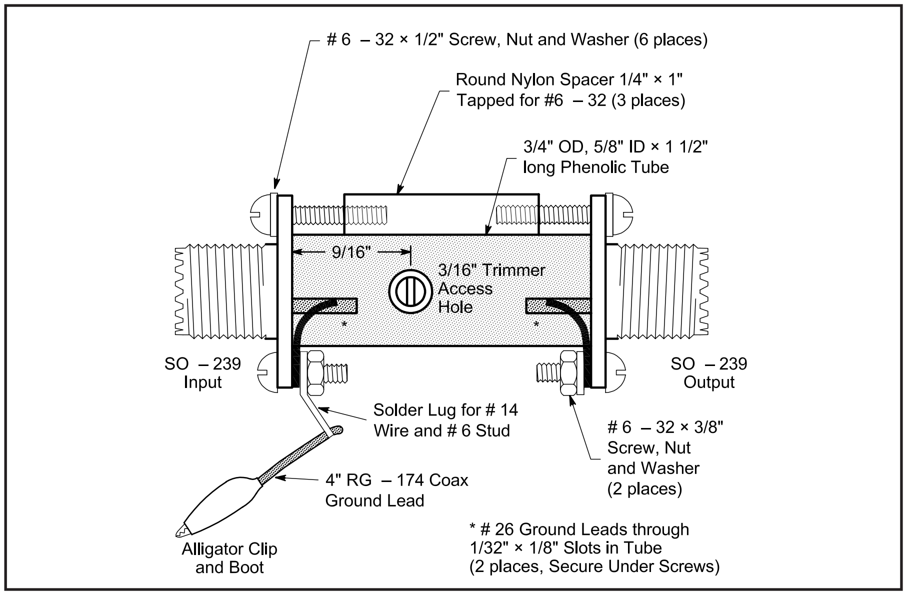


Fig 25.58 — 100× multiplier assembly showing the round Nylon spacer (Mouser 561-TSP10), phenolic tube (US Plastics #47081, see Note 3). The lug is Mouser 571-34120.

sions, the response is adequate to 30 MHz.

Fig 25.53 shows construction methods. Two slits at the ends of the tube allow the ground wires at the input and output ends to exit and wrap around the screws of each connector. A hole in the phenolic tube allows adjustment of the trimmer capacitor.

Fig 25.54 shows the exploded view of the pin tip and grabbers at the input end of the multiplier and a UHF male-to-male connector on the output side to mate with the RF probe. The assembled multiplier and probe are shown in **Fig 25.55**. The whole assembly is only 3½ inches long and is comfortable in the hand. If more flexibility is desired, the two pieces may be separated by as much as one foot of coax (**Fig 25.56**) without doing too much damage to the accuracy of the measurement.

The 100× multiplier follows the same design concepts as the 10× multiplier including the obligatory trimmer capacitor, as in **Fig 25.57**. Here too, the 225 V dc rating of the trimmer limits the maximum RF to 150 V RMS. So, this is not useful should it be used only with the probe and your DVM because the 10× multiplier already covers this range. Later, we will see how it is useful with the RF probe and the meter unit.

The 100× unit also uses a phenolic-tube housing with a hole to adjust the trimmer and a slit at each end to bring out the ground wires, which then wrap around screws in the connectors. In order to reach at least 30 MHz, however, the two-inch steel screws between the two SO-239 connectors must be insulated. Using plastic washers at the connector holes could do this job but would have required #4-40× 2-inch-long screws. After a long search at the biggest hardware stores and catalogs, I found nothing longer than 1½ inches. That's the best way to assemble this multiplier, if you can find the screws. Otherwise, use nylon spacers and shorter screws as shown in **Figs 25.58** and **25.59**. The pin tip and grabber at the input and UHF male-to-male connector or coaxial cable at the output are used as with the 10× multiplier.

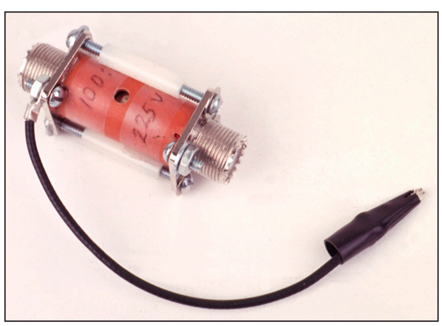


Fig 25.59 — The assembled 100× multiplier.

Table 25.4
Multiplier Range versus Capacitance

Multiplier	10×	100×	200×
Input Cap (pF)	13.3	10.9	13.5

The only purpose of the 2× multiplier is to create a 200× multiplier when used with the 100× multiplier in series, so as to extend the voltage range from 150 V to 300 V (1800 W at 50 Ω only under matched conditions).[4] The trimmer in each multiplier now divides in half the input voltage. **Fig 25.60** shows the 2× multiplier with only one RC section since it relies on the RC sections in the 100× multiplier to complete the division (multiplication).

The construction, **Fig 25.61**, returns to the tubular format as before, but this time there are no slots to pass the ground wires; the four screws are able to do the job. The two multipliers are shown in series in **Fig 25.62**. The input capacitance for each multiplier is shown in **Table 25.4**.

When measurements are made on a load resistance of 50 Ω, the input capacity of the multipliers has no affect on readings below 30 MHz. When the impedance of the load resistance is larger, consider any error it introduces. To get a sense of the affects of the load resistance, use the equation below.

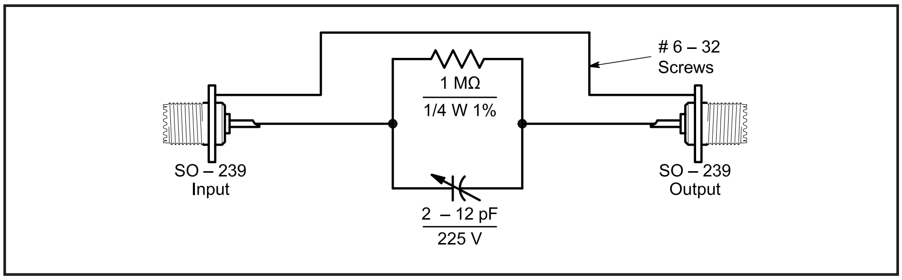


Fig 25.60 — A schematic diagram of the 2× multiplier. Its output connects to the input of the 100× multiplier for 200x measurements up to 300 V RMS. This multiplier is used *only* with the 100× multiplier.

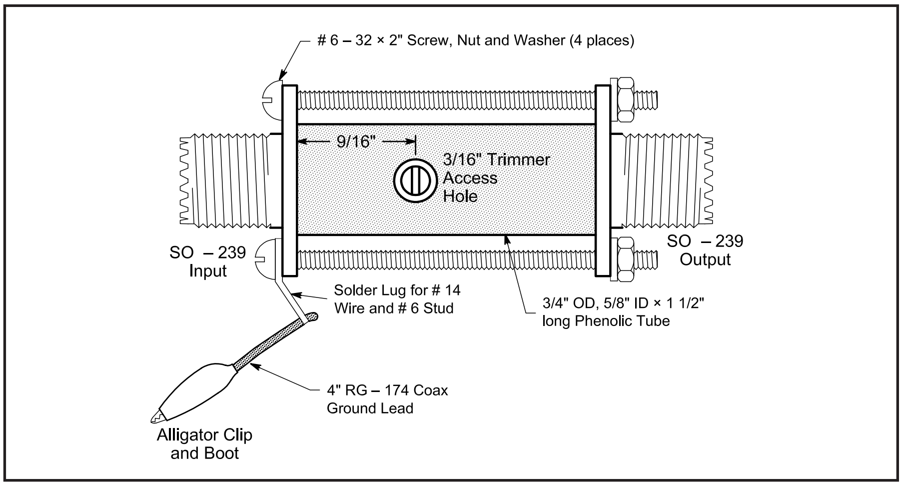


Fig 25.61 — 2× multiplier assembly showing the phenolic tube (US Plastics #47081, see Note 3). The lug is 16-14 #6 stud (Mouser 571-34120).

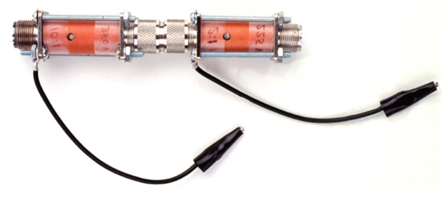


Fig 25.62 — The 2x and 100x multipliers are joined by a male UHF coupler for readings up to 300 V (RMS, 1800 W, see Note 4).

It shows the relationship between the resistance, capacitance and frequency when the measured voltage is 3 dB down from what it would be if it were read by a meter with no input capacity:

$$f = \frac{1}{2\pi R_L C_P} \qquad (21)$$

where
f = 3-dB loss frequency
R_L=load resistance
C_P=probe capacitance

For example, at a load of 1 kΩ and a probe capacity of 13.3 pF, the 3-dB down frequency is about 12 MHz, where the error is 30%. If an attenuator were used instead of the multiplier, it would not have this problem because it works with either a fixed load of 50 Ω at high frequencies or 600 Ω at low frequencies. Probes cannot select their frequency or load impedance and are thereby more flexible in use, so measurements must be made with consideration, but these multipliers would not have a problem at 50 Ω or 600 Ω either.

Table 25.5 summarizes the voltage ranges using only the multiplier with the RF probe and a DVM that has a 10-MΩ input resistance that's available in the shack.

The multipliers are intended for use at high voltages where safety precautions are a primary consideration to avoid personal injury. See the **Safety** chapter of this *Handbook*. In Tektronics' *ABC's of Probes,*[5] an entire section thoroughly covers the hazards and necessary precautions when making measurements with probes. It is worth the little effort to get a copy of it and also the Pomona Catalog,[6] which has some good information on probe use.

The multipliers have panel connectors at both ends and the RF probe has one at one end. Their grounds are connected and brought to the meter unit. This unit is grounded only when the ac-powered 9-V power supply that may be used with it, is grounded. When it is battery operated, the meter unit relies on the ground-clip connection to the ground of the equipment under test. This is satisfactory if there is no unknown break in the chain of ground connections that would make the panel connector hot. Furthermore, as insurance, it is good to wrap these connectors with vinyl tape or to cover the multiplier with a plastic boot to prevent contact with either hands or equipment under test. This is not shown in any photographs because it would have obscured the appearance and construction of the probe and multipliers.

The frequency responses of the multipliers were determined using an RF signal generator set at the midpoint of each ham band from 160 to 10 meters, including 30 MHz. An error of 5.42% (0.46 dB) was measured from 160 to 17 meters, which then decreased to 4.13% (0.35 dB) at 15 meters and then to zero through 30 MHz. The constant error from 160 to 17 meters is probably due to the inherent errors in the test equipment. The oscilloscope has a 60 MHz bandwidth, an input impedance of 1 MΩ and 30 pF, which introduces a load effect on the multiplier outputs. It also has a reading accuracy of ±3%. When the multiplier-components accuracy of 1% is included, it is not surprising to find the overall inaccuracy to be at most 5.42%.[7] The error of the multiplier itself could be inherently less than this. Before the overall frequency response

Table 25.5
Multiplier versus Voltage Range

Probe Configuration	*Range (V)*	*Maximum Voltage*
Probe Alone*	1.0-20 V ac	20 V ac
With 10× Multiplier*	10-150 V ac	225 V (ac + dc)
With 100× and 2× Multiplier†	150-200 V ac	450 V (ac + dc)
With 100× and 2× Multiplier††	200-300 V ac	450 V (ac + dc)

*error less than –10% or –0.83 dB
†with error of –45% to –10% or less than 3.2 dB. A trimmer capacitor with a rating of 300 V dc increases the 10× range to 200 V ac and reduces the error from 45% to 10%. The RF probe and meter unit reduces the error to less than –3.5% or less than –0.3 dB.
††with error less than –6% or –0.54 dB

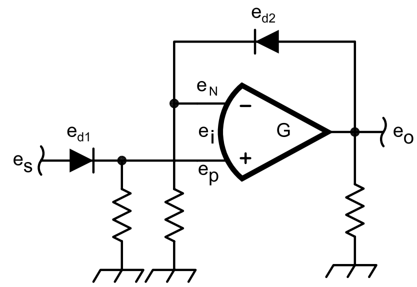
$$e_s - e_{d1} = e_p$$

$$e_o - e_{d2} = e_n$$

$$e_i = e_p - e_n = e_s - e_{d1} - e_o + e_{d2}$$

$$e_i = \frac{e_o}{G} = 0$$

$$e_s - e_o = e_{d1} - e_{d2}$$



e_s represents the input of the RF probe as a dc signal.
e_o represents the output from the high-gain CA3160 op amp.
e_{d1} is the voltage drop across the diode in the RF probe.
e_{d2} is the voltage drop across the diode in the feedback loop.
G = 320,000 for the CA3160.
The last equation shows that any difference between the signal and output results from unequal diode drops when the diodes are not matched.

Fig 25.63 — Basics of the diode-compensation method to improve measurement accuracy at low input voltages. It also provides a measure of temperature compensation and drift reduction. See Fig 25.50.

was measured, the trimmer capacitor was adjusted with the input frequency set mid-frequency at 15 MHz. If your interest in RF probes and multipliers has been raised and you have more questions, see the references in Notes 5 and 6.

THE METER UNIT

The meter unit serves several purposes when used with the RF probe. It increases the accuracy of the probe and DVM from –45% to –3.5% at a voltage of 100 mV RF. At higher voltages, it maintains a minimum advantage of 5:1 in reducing the error, when the probe is used with a DVM. This is an increase in both sensitivity and accuracy. The usual non-linearity caused by the diode in the probe is reduced when used with the meter unit. The technique also incidentally provides temperature compensation for diode drift. The meter unit has a ±5% panel meter to display measurements, but it also contains a pair of OUTPUT terminals for a DVM. Add a DVM when more accuracy is desired at the low end of the range or when you want a bit more resolution. Finally, since the meter unit is fully portable, low-level field-strength measurements are possible with a whip antenna at the probe input connector. Due to its sensitivity and accuracy, the probe can be adapted for use in many places around the shack.

The non-linear response of the probe diode is compensated (improved) by a circuit in the meter unit. The feedback loop of a CA3160 op amp contains a diode matched to the one in the probe (see Note 1). **Fig 25.63** and its sequence of equations present a very simple sketch of how matched diodes do this when dc is applied through a diode. The final equation shows that any difference between the op amp input and output is due to a difference in voltage drops across the two diodes. When the diodes are matched, the error disappears. When RF is applied, the average currents through the diodes must be equal to keep the voltage drops equal. Articles by Kuzdrall (Note 1) Grebenkemper[8] and Lewallen[9] are first-class descriptions of the principles used in this RF voltmeter.

Fig 25.64 shows three pots for calibrating the meter unit. This should be performed at 400 Hz to avoid any effects due to RF. The 100-kΩ pot is typically used to

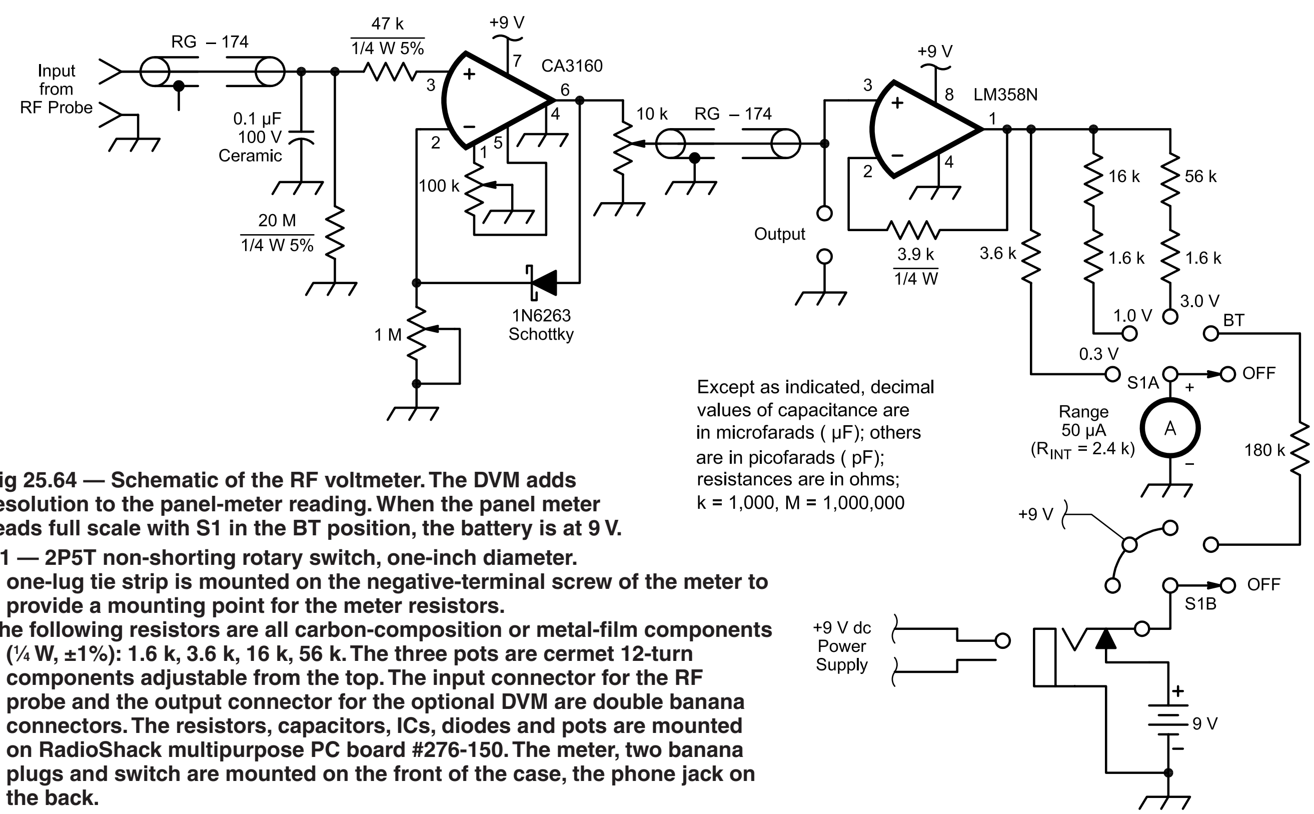


Fig 25.64 — Schematic of the RF voltmeter. The DVM adds resolution to the panel-meter reading. When the panel meter reads full scale with S1 in the BT position, the battery is at 9 V.

S1 — 2P5T non-shorting rotary switch, one-inch diameter.

A one-lug tie strip is mounted on the negative-terminal screw of the meter to provide a mounting point for the meter resistors.

The following resistors are all carbon-composition or metal-film components (¼ W, ±1%): 1.6 k, 3.6 k, 16 k, 56 k. The three pots are cermet 12-turn components adjustable from the top. The input connector for the RF probe and the output connector for the optional DVM are double banana connectors. The resistors, capacitors, ICs, diodes and pots are mounted on RadioShack multipurpose PC board #276-150. The meter, two banana plugs and switch are mounted on the front of the case, the phone jack on the back.

null the offset of the CA3160, but is used here to initially set the offset to about 0.5 mV to 1.0 mV with 100 mV input. Then the 1-MΩ pot sets the output to 100 mV with 100 mV input, and the 10 kΩ pot sets the output to 3.0 V when the input is 3.0 V. Finally, the three pots are alternately adjusted until the 100 mV and 3.0 V set points occur together. The 100-kΩ pot is helpful in fine tuning the 100-mV point. A DVM was used at the optional OUTPUT sockets during calibration.

A CA3160 was selected for the input op amp because of its high input impedance of 1.5 TΩ and high gain of 320,000. Although it has diodes that provide protection, I think it could be sensitive to electrostatic discharge, so handle it carefully. Use IC sockets to permit easy replacement of the ICs in case of damage. An LM358N IC follows the CA3160 (see Fig 25.64), primarily to drive the panel meter. If you use a DVM as the display, you can omit the LM358N circuit, meter and multi-position switch. The only functions lost are the battery-voltage check and power on/off switch. Add an on/off switch to the circuit when the multi-position switch is omitted. The CA3160 op amp circuit easily spans the range from 100 mV to 3.0 V without the need for a range switch.

CONSTRUCTION

A 5×5×4½-inch sloping-front instrument case was used to house the components of the meter unit. The meter on the front panel has a 2×2-inch face and requires a 1½-inch hole in the panel. Although a 50-µA meter from the junk box is used here, a 1-mA movement will work as well, provided the series resistors are changed accordingly.

The rotary switch has two poles and five positions for changing the meter range, testing the battery condition and switching the power off. Two sets of double banana binding posts are used, the INPUT pair accepts the dc signal from the RF probe. The OUTPUT pair provides a voltage for a DVM display, whether the panel meter is used or not. On the rear of the case, a miniature phone jack accepts 9-V power from either a battery or a 9-V dc supply. The ICs and other parts are mounted on a RadioShack multipurpose PC board that has very convenient holes and traces. The board is bolted to the back of the case via standoff insulators and wired to the front panel components (see **Fig 25.65**).

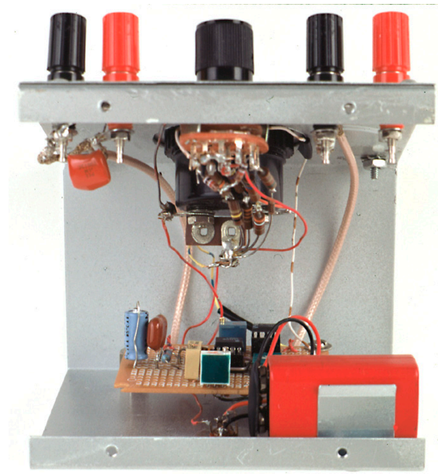


Fig 25.65 — Inside view of the meter unit. RG-174 connects the INPUT and OUTPUT banana binding posts to the circuit board. The rotary switch, one-lug tie strip and battery are also visible.

Notes

[1]J. A. Kuzdrall, "Linearized RF Detector Spans 50-to-1 Range," Analog Applications Issue, *Electronic Design*, June 27, 1994.

[2]Mouser Electronics, 2401 Hwy 287 N, Mansfield, TX 76063; tel 800-346-6873, fax 817-483-0931; E-mail **sales@mouser.com**; **www.mouser.com**.

[3]United States Plastics Corp, 1390 Neubrecht Road, Lima, OH 45801-3196, tel 419-228-2242, fax 419-228-5034.

[4]Load mismatch changes the measured voltage depending on the phase angle of the load impedance. In the worst-case, the mismatch multiplies the voltage by the square root of the SWR. With 1800 W, a 2:1 SWR (100-ohm load) increases the voltage from 300 to 424 V_{RMS} and a 3:1 SWR (150-ohm load) would give 520 V_{RMS}.

[5]*ABCs of Probes*, Tektronix Inc, Literature number 60W-6053-7, July 1998. Tektronix, Inc. Export Sales, PO Box 500 M/S 50-255 Beaverton, OR 97707-0001; 503-627-6877. Johnny Parham, "How to Select the Proper Probe," Electronic Products, July 1997.

[6]Pomona Test and Measurement Accessories catalog. ITT Pomona Electronics, 1500 E Ninth St, Pomona, CA 91766-3835.

[7]A. Frost, "Are You Measuring Your Circuit or Your Scope Probe?" *EDN*, July 22, 1999. E. Feign, "High-Frequency Probes Drive 50-Ω Measurements," *RF Design*, Oct 1998.

[8]J. Grebenkemper, KI6WX, "The Tandem Match — An Accurate Directional Wattmeter," *QST*, Jan 1987, pp 18-26; and "Tandem Match Corrections," *QST*, Jan 1988, p 49.

[9]R. Lewallen, W7EL, "A Simplified and Accurate QRP Directional Wattmeter," *QST*, Feb 1990, pp 19-23, 36.

[10]Ocean State Electronics, 6 Industrial Dr, PO Box 1458, Westerly, RI 02891; tel 800-866-6626, fax 401-596-3590.