George A. Wilson W1OLP
318 Fisher Street
Walpole MA 02081

D'Arsonval Dossier

How these meters work and how to make them work for you is no mystery. Discover the inner machinations of the D'Arsonval movement for yourself.

This article covers the basic aspects of the panel meters most frequently used by amateurs. These meters indicate voltage and current. The article will not address itself to alternating-current meters and meters combined with electronic circuits that measure values such as FM frequency deviation, resistance, signal strength, and the like. However, a little knowledge of how the simple voltage- and current-measuring devices work may turn your junk box or your next flea-market visit into something very profitable.

Panel meters are made in a large variety of ranges, and when the desired range is not available, it is possible to adapt what is on hand to provide the necessary service. Voltmeters can be bought with ranges from millivolts to kilovolts and ammeters from microamperes to a hundred Amperes. However, by judicious buying at auctions and flea markets, low-current meters (typically, 0-1 milliampere) can be purchased that can be adapted to a wide range of currents and voltages. Read on!

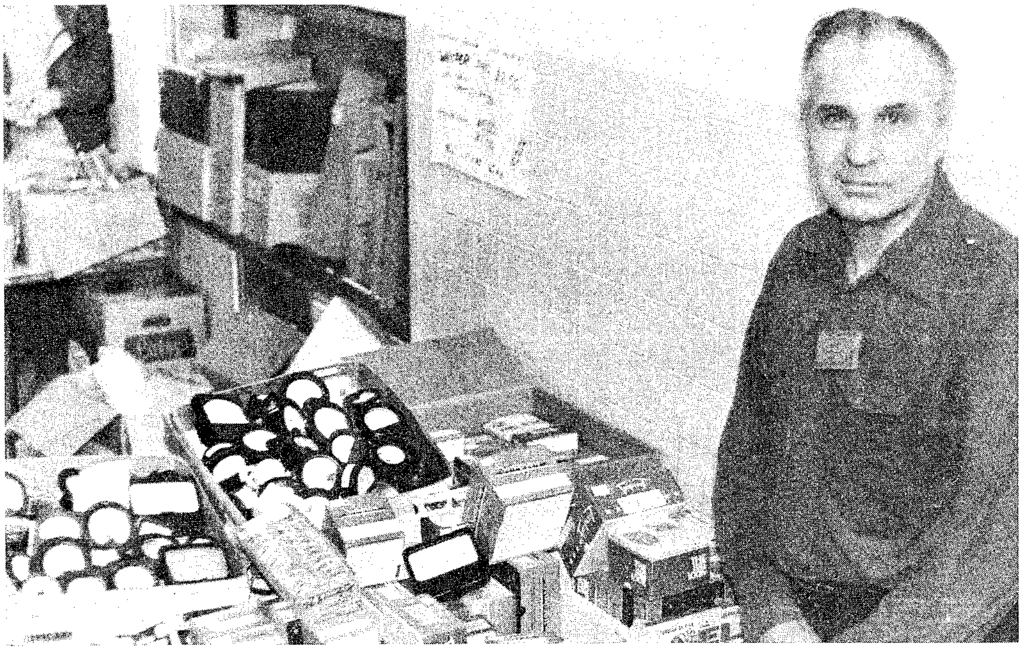
Flea-market meters come in all shapes, sizes, and ranges. Some really large units are frequently seen. Six- and 10-inch sizes make great bench meters; how about an oversize S-meter for your next QRP rig? It may take a bit of patience, but even matching meters can be found if you keep your eye out for them. There are thousands of low-price, high-quality meters like the Weston 301 type available in junk boxes and flea markets.

How They Work

Meters measure current even when they are actually indicating voltage. Their needle deflection is nominally proportional to the flow of current through them. In the case of meters using D'Arsonval moving coil movements, the meter deflection is strictly proportional to the current through them. This is the most popular type of meter and will be the type primarily discussed in this article.

The only other type of meter that is normally seen by amateurs is the iron-vane type. This type is used frequently for ac measurements. It does not deflect strictly proportionally with current through its coil. Its major claim to fame (for amateur use) is its low cost. Unlike the D'Arsonval type, the current in an iron-vane meter flows through a fixed rather than a moving coil. The common, low-cost type is generally plagued with calibration problems caused by magnetic material (e.g., iron or steel) in its vicinity. D'Arsonval movements are relatively but not entirely free of this sort of problem.

Meters deflect when current passes through them because the current creates a magnetic field that opposes a permanent magnetic field built into the meter. The vane in an iron-vane meter is a permanent magnet and is attached to the indicator needle. The metered current flows in a fixed coil that is wound around (but not on) the vane. The field created by the current in the coil opposes that of the vane, and the vane moves until force from its field balances the force from the field of the coil.



Flea marketeer with his meter display. Excellent sources of meters of all descriptions, flea markets and auctions offer the lowest prices. In most cases, meters work properly or do not work at all. Flea-market and auction prices are generally low enough to risk as-it-is purchasing. However, most sellers will honor your request for your money back.

D'Arsonval meters have moving coils that rotate within a permanent magnetic field. In this configuration, the fields can be properly arranged to cause the needle (attached to the rotating coil) to move in a manner that is strictly proportional to the current flowing in the coil. The proportionality of the D'Arsonval meter allows its scale to be divided into equal divisions for equal changes in current throughout its scale. The typical iron-vane meter provides more motion for a given current change at the low end of its scale than at the top end. The scale at the top end of a typical iron-vane meter is crowded and difficult to read.

Meter Resistance

The flow of current through a meter obeys Ohm's Law. The meter itself has resistance and, therefore, the current through it will be proportional to the voltage across it—see Fig. 1(a). If resistance is added in series with a meter—see Fig. 1(b), more voltage will be required to cause the original amount of meter current to flow. It will be shown later that this is the way to turn a sensitive current meter into a voltmeter. If a resistance is added in parallel with the meter—see Fig. 1(c), the input voltage still occurs across the meter, but a portion of the input current is bypassed (or shunted) through the parallel resistance. The parallel resistance is known as a shunt. This is the method for turning a sensitive current meter into a less sensitive (or higher) current meter.

If meters are to be modified with series or parallel resistance, it is obvious that the resistance of the meter must be known. Examination of meter characteristics, as given in manufacturers' catalogs, gives us the ranges shown in Table 1.

Full Scale Current	Resistance (Typical)
100 microamps	1000-2000 Ohms
200 microamps	400-1000 Ohms
500 microamps	100-200 Ohms
1 milliamp	40-60 Ohms
3 milliamps	20-40 Ohms
5 milliamps	10-20 Ohms

Table 1. Typical sensitive current meter resistances (D'Arsonval type).

In no case should an ohmmeter be connected across a sensitive meter to determine its resistance. The current from the ohmmeter will overrange the meter and may destroy it. A convenient and safe method of determining the resistance of a meter is shown in Fig. 2. It consists of causing full-scale current to flow in the meter and then adding a variable resistance (shunt) across the meter and adjusting it until the meter reads half-scale. If the series resistance (R_{SE}) is much higher than the meter resis-

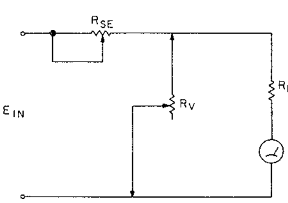


Fig. 2. Determining meter resistance. Set E_{IN} and/or R_{SE} for full scale with R_V disconnected. (R_{SE} should be at least 100 × R_M.) Connect R_V and adjust it until the meter reads one-half scale. Disconnect R_V and measure its resistance with an ohmmeter. R_V will equal R_M.

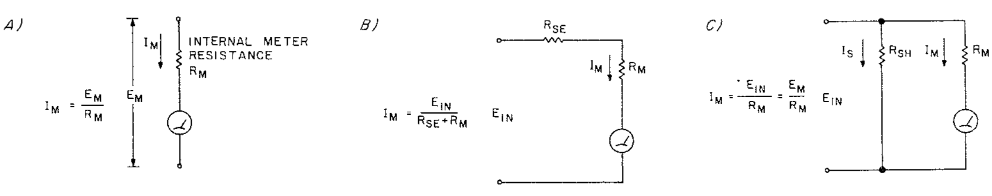
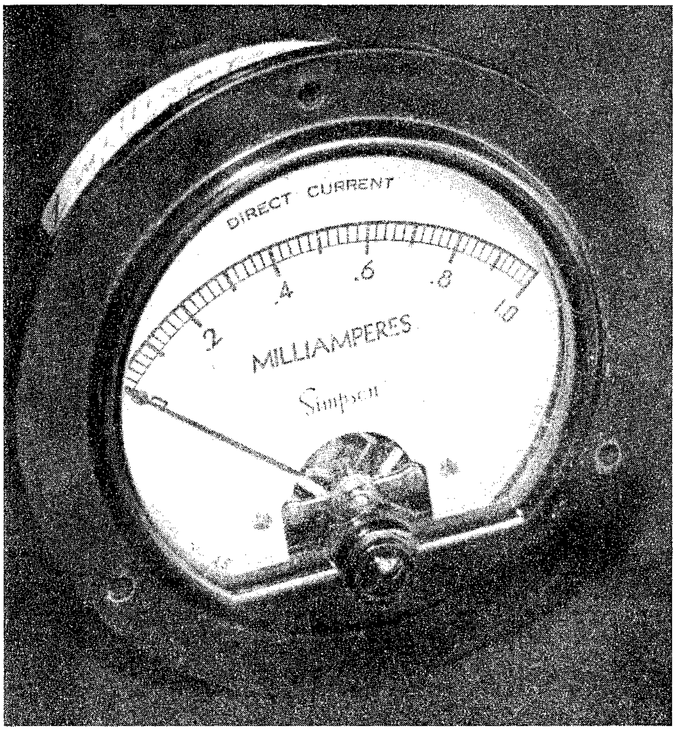


Fig. 1. Basic meter circuits. (a) Electrical characteristics of meter alone. (b) The meter with resistors in series. (c) The meter with resistance (R_{SH}) shunting current around it.



A typical D'Arsonval meter movement is shown above. Note the even (linear) scale. All of the divisions are the same size. This type of meter is the most used by amateurs. The ordinary variety balances the force resulting from a fixed magnet and a moving current coil against a pair of hair springs. Recently, a new type using taut-band springs has been introduced. Both types operate similarly and have linear needle motion with respect to current.

tance (use Table 1 as a guide), the total current will not vary significantly when the variable resistance is added. It can be shown that when the variable resistance is adjusted for half-scale current, the meter resistance is equal to the external shunting resistance. The external resistance can then be disconnected and (safely) measured with an ohmmeter.

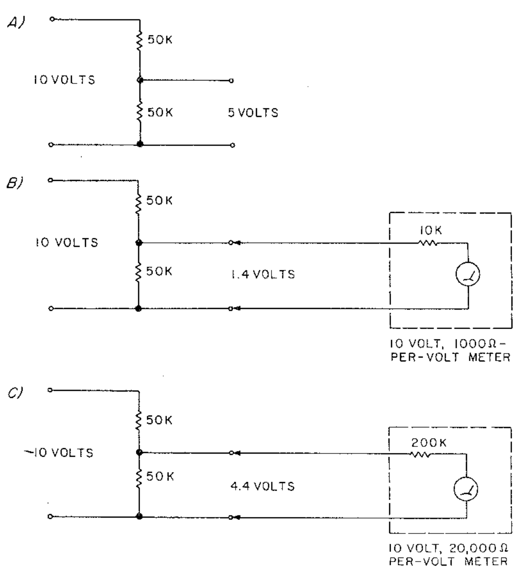


Fig. 3. Voltmeter circuit loading. (a) High-impedance voltage divider. (b) The result of a voltmeter loading down the circuit in 3(a). (c) Using a meter with higher internal resistance gives more accurate results.

Meter Resistance Problems

In the case of voltmeters, the resistance of the meter and its series resistors must be high with respect to the resistance of the circuit being measured. If it is not, the voltmeter will load down the circuit and the voltage measurement will be low. This is illustrated in Fig. 3. Note in Fig. 3(a) that the real divider voltage is five volts and that a 1,000-Ohms-per-volt meter, see Fig. 3(b), loads the circuit down to 1.4 volts (72% low). Even a 20,000-Ohms-per-volt meter as shown in Fig. 3(c) loads the circuit down to 4.4 volts (12% low). If an 11-megohm vacuum-tube voltmeter were used, the indicated voltage would be essentially correct, at about 4.99 volts (0.2% low). The moral here is very clear: Use the highest resistance voltmeter that you can if you want to avoid loading down the circuit being measured.

Voltmeters are rated for their resistance in Ohms-per-volt. Simply, this means that a 10-volt, 20,000-Ohms-per-volt meter will have a resistance of $10 \times 20{,}000 =$ 200,000 Ohms. In a multi-range voltmeter, the resistance of the meter accordingly increases with the voltage range in use. Electronic voltmeters are frequently an exception to the foregoing statement. They have a fixed input resistance (frequently 11 megohms) regardless of the range they are set to.

However, do not write off the lowly 1,000-Ohms-per-volt meter (made from a 0-1 mA meter). In this day of solid state, circuit resistances (with certain exceptions such as FET circuits) tend to be quite low and quite tolerant of low-resistance voltmeters. Additionally, one should examine one's needs carefully. The 1,000-Ohms-per-volt meter is rugged, inexpensive, and is just the thing for an occasional check of power supply and battery voltages. If general servicing of tube and solid-state circuits is to be done, nothing short of a voltmeter with megohms of input resistance should be considered.

For the most part, insertion of a meter for current measurements does not cause significant circuit change. Milliammeters have resistances of less than 100 Ohms, which is small with respect to resistances (impedances) they are connected in series with. Consideration should be exercised with meters in the microampere ranges. A sensitive microammeter may have over 1,000 Ohms resistance and could add significant resistance to the circuit being measured.

Making Voltmeters from Milliammeters/ Microammeters

Voltmeters with convenient scales can be made by adding series resistance to a milliammeter or microammeter, most often to a 0-1 milliammeter or more sensitive meter. It is most convenient to choose a meter range whose scale can be multiplied by a factor of 10, 100, and so on, to give the desired voltmeter scale. For example, say you want a 1,000-volt, full-scale meter. If a 0-1-milliamp meter is

Meter Range	Ohms to Produce One Volt Full Scale (Ohms-per-Volt)
0-1 mA	1,000
0-500 μa	2,000
0-200 μa	5,000
0-100 μa	10,000
0-50 μa	20,000

Table 2. Voltmeter series resistance ratings.

used, the scale is multiplied by 1,000 and a label can be added to the meter face saying: "1,000 volts." Half-scale (0.5 mA) will be 500 volts. Similarly, a 100-microamp meter could be used with a × 10 multiplier.

For most amateur purposes, the series resistors can be 5% tolerance and the meter resistance can be neglected. Table 2 can be used to select the series resistance required to obtain a one-volt full-scale meter from various basic meter movements. If the series resistance is increased by a factor, the full-scale reading will be increased by the same factor. Typically, if 1,000 Ohms is required for one-volt full scale, 2,000 Ohms will result in two-volts full scale and 10,000 Ohms will give 10 volts. The series resistance rating for a basic meter may be calculated by dividing one by the basic full-scale meter reading. Typically, a 0-3 milliammeter would require 1 ÷ 0.003 = 333 Ohms-per-volt.

The accuracy of a meter with added series resistance depends on the meter accuracy, the series resistor accuracy, and the meter's internal resistance. The latter effect is generally small for the accuracies needed by the amateur. For a 1-volt, 1,000-Ohms-per-volt meter that uses a basic 0-1 milliammeter with 50-Ohms internal resistance, the total series resistance is 1050 Ohms (assuming a 1000-Ohm external series resistor). Ohm's Law tells us that 1.05 volts will be required for a full-scale reading. This is a 5% error and could be corrected by using a 950-Ohm series resistor. For high voltage ranges, the error becomes proportionately less.

If you have a means of accurate calibration at hand, the series resistance can be trimmed to eliminate essentially all of the error at *one* scale reading. The remaining error will be the meter's inherent inaccuracy. For the best possible accuracy, the error at various scale values has to be plotted using a highly accurate calibration standard. This discussion of accuracy is included only to satisfy the reader who has special accuracy requirements.

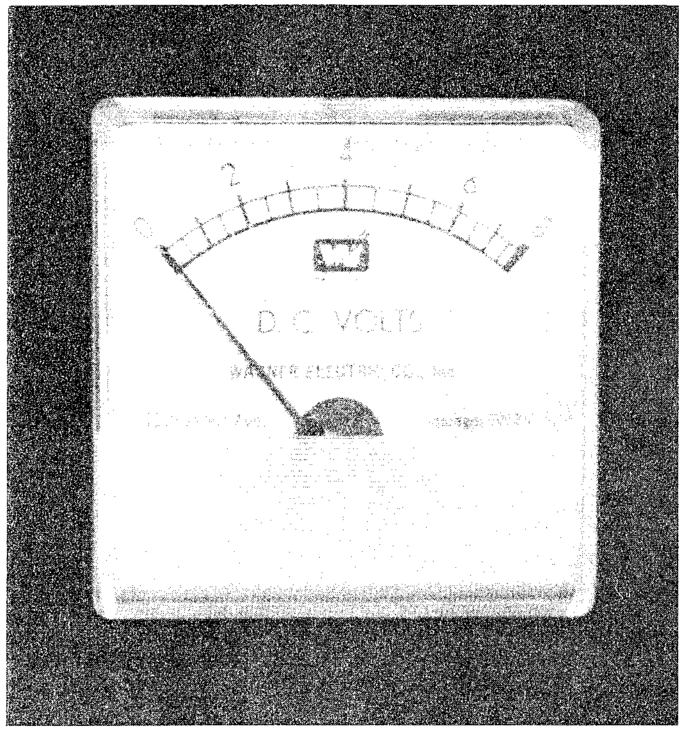
The average amateur can use series resistance values calculated from the basic values in Table 2. He can assume that his accuracy will be roughly that of the series resistance tolerance plus the meter's tolerance, i.e., on the order of ±10%, if ±5% series resistors are used.

Shunting to Obtain Higher Current Ranges

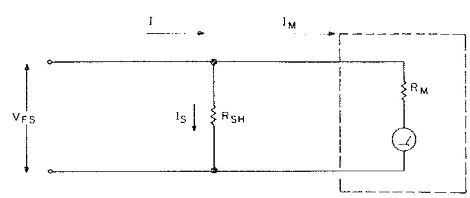
Shunting is just a bit more difficult than adding series resistances to obtain different voltage ranges. First, the resistance of the shunt must be calculated. Then, the shunt resistor must be obtained. Most often, the shunt resistor will have to be wound or otherwise fashioned. This is because the resistance values turn out to be quite low and most often of non-standard value.

The shunt resistance in parallel with the meter resistance must result in a voltage across the meter that will produce full-scale deflection for the desired full-scale current. This voltage is calculated using Ohm's Law as follows: $V_{FS} = I_{M(FS)} \times R_M$. (Here, V_{FS} is the voltage across the meter at full scale, $I_{M(FS)}$ is the basic meter's full-scale current, and R_M is the meter resistance (see Fig. 4). The method of determining R_M was previously discussed. It should be noted that meter resistances can sometimes be found by referring to catalog descriptions. By using the parallel resistance expression and Ohm's Law, it can be shown that the shunt resistance is: $R_S = R_M(V_{FS}/I_{FS})/(R_M - V_{FS}/I_{FS})$, where I_{FS} is the desired full-scale current and R_S is the corresponding value of resistance needed to shunt the meter.

For example, the shunt required to make a 10-milliamp meter from a 50-Ohm, 1-milliamp meter is calculated as follows: $V_{FS} = .001 \times 50 = 0.05$ volts, and $R_S = (.05/.01) \times 50/50 - .05/.01) = 5.56$ Ohms.



This photo shows the face of an iron-vane-type meter. Note that it has an irregular (non-linear) scale. For the same amount of current change, less motion occurs near full scale than at the low end of the scale. In some applications this may have advantages. Most meters of this sort are made for low-cost applications or for use in ac applications. They are frequently found in automotive equipment, both in car instrument panels and in devices such as battery chargers.



a. $V_{FS} = I_{M(FS)} \times R_M$, FULL SCALE VOLTAGE

b. $R_{PAR} = \frac{R_{SH} \times R_M}{R_{SH} + R_M}$, SHUNTED METER RESISTANCE

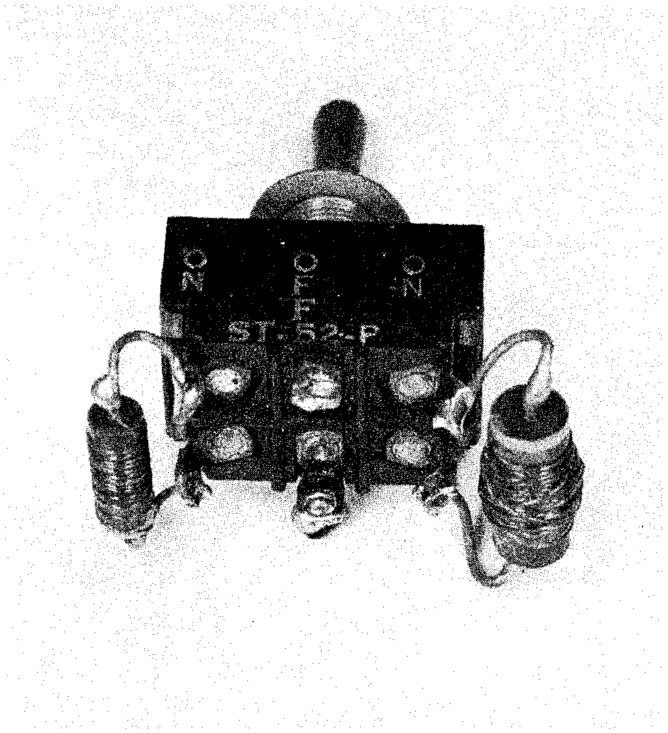
c. $R_{PAR} = \frac{V_{FS}}{I_{FS}}$, SHUNTED METER RESISTANCE

REQUIRED FOR A DESIRED VALUE OF CURRENT AT FULLSCALE (I_{FS}).

d. $R_{SH} = \frac{R_{PAR} \times R_M}{R_M - R_{PAR}}$, SHUNT RESISTANCE

OR $R_{SH} = \frac{\frac{V_{FS}}{I_{FS}} \times R_M}{R_M - \frac{V_{FS}}{I_{FS}}}$

Fig. 4. Shunt value calculation.



Shunts may be wound using resistors as forms. The shunts above are those used in the 0-3, 0-30, and 0-300 milliamp meter described in the text. The resistors should be at least 100 times the resistance value of the shunt. Use a two-Watt resistor if you have room. This gives better cooling and makes construction easier.

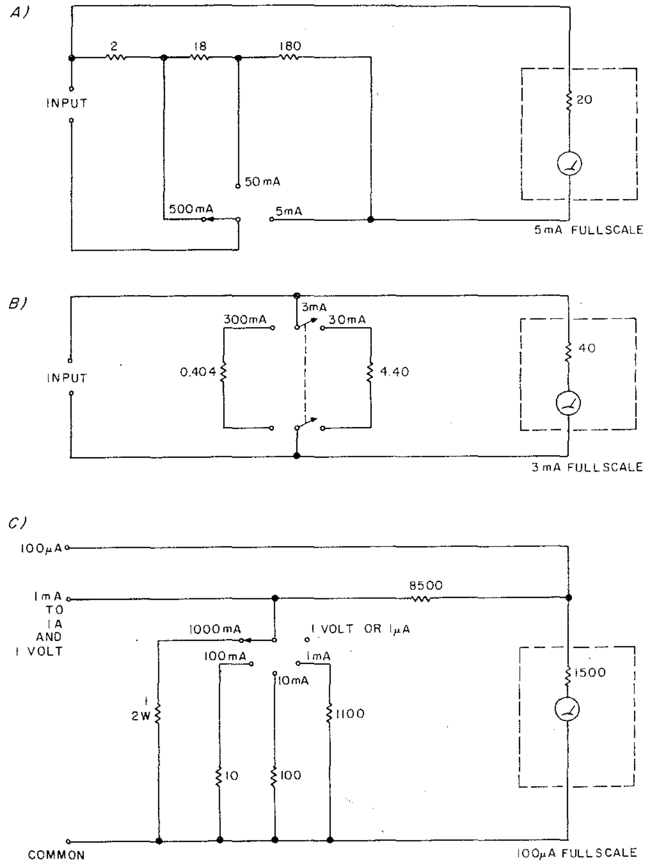


Fig. 5. (a) A multi-scaled milliammeter using an unusual series and parallel shunting scheme. (b) A multi-scaled milliammeter using standard shunting and a DPDT center-off switch. (c) A multi-scaled milliammeter/microammeter that produces less than one volt drop at full-scale current. Resistances are in Ohms.

If a 100-milliamp range were desired, the foregoing calculation would indicate that 0.505 Ohms was required. Note that in both cases the shunt resistor is in proportion to the amount of current that must bypass the meter. In the latter case, the shunt is about 1/100 of the basic meter resistance. As can be seen from these calculations, the resistances are low and (generally) non-standard.

However, shunt resistances can be constructed easily from copper wire. They also may be constructed from other less available wires such as nichrome if you have the materials available. By using the Standard Wire Tables found in the handbooks, the wire gauge and the length of this gauge wire necessary to construct a proper shunt can be determined easily. As in the case of series resistors for voltmeter applications, the shunts can be trimmed and adjusted if accurate calibration standards are available.

As in the case of voltmeters, the meter can be made truly accurate at one scale reading and must be error-noted at other readings because of the basic inaccuracies of the meter. For amateur use, this sort of accuracy is most often not necessary. Typically, in the 100-milliamp case cited above, a 0.5-Ohm, ±5% resistor will give overall accuracy on the order of ±10%. This would suffice in almost all amateur applications. A 5-Ohm, ±5% resistor would do for the 10-milliamp case.

To make low resistance shunts, choose a convenient wire size and determine what its resistance-per-unit length is. In most tables this is given in Ohms-per-thousand feet. Use the largest convenient wire size to ensure good current capacity, and try not to use very thin sizes (e.g., less then #30) to avoid variations in resistance because of stretching. Many choices may be made depending on the wire size(s) you have on hand. In the two cases calculated above, some of the choices are shown in Table 3.

The determination of the required wire length is made quite easily by dividing the required resistance value by the resistance of the wire in Ohms-per-foot. The latter is determined by dividing the Ohms-per-thousand-feet rating by 1000 (see Table 3 for illustrations). Some trial-and-error calculation is generally required to choose a size that results in a relatively small coil (or spool) of wire of a size you have on hand. Shunts should be wound on forms such as a relatively high-value resistor (100 times the shunt value) and should be coated with varnish or other strong coating that will prevent the turns from moving as a result of on/off current change.

Shunts should be located as close to the meter ter-

	Wire Size	**Ohms-per-1000 Feet**	**Ohms-per-Foot**	**Required Length**
5.56 Ohms	30	105.2	0.105	52.4 ft.
5.56 Ohms	33	211.0	0.211	26.4 ft.
0.505 Ohms	28	66.17	.0662	7.63 ft.
0.505 Ohms	24	26.17	.0262	19.3 ft.

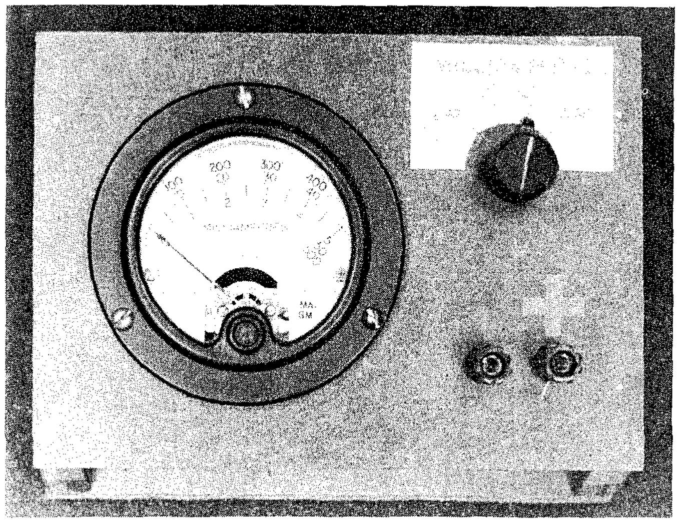
Table 3. Typical wire length for two values of resistance.

minals as convenient. However, low-current shunts can be located "in-circuit" with their meters in remote positions. In these cases, the circuit resistance to and from the meter must be low with respect to the meter.

If you are clever with Ohm's Law, many special cases can be developed for shunts. Fig. 5 shows a neat way of building a multi-scaled milliammeter using a 5-milliamp, 20-Ohm meter. A more conventional multi-scale approach is shown in Fig. 5(b).

Fig. 5(c) makes a lot of use of a 100-microampere, 1,500-Ohm meter. (Incidentally, these appear to be readily available from surplus houses these days.) Ranges are provided from 100 microamperes to one Ampere, and a bonus scale of one volt is provided. A drawback to this circuit in at least the one-Ampere range is the fact that the drop across the meter circuit will be one volt for full scale on all current scales except the basic 100-microamp range.

Examination of the circuit will quickly show that it is a one-volt, 10,000-Ohms-per-volt voltmeter that measures the voltage across shunts that develop one volt for full scale. Note that the one-milliampere shunt is 1100 Ohms. This, in parallel with the meter resistance, gives an input resistance of roughly 1000 Ohms. Consequently, the accuracy on this range is improved. On the other ranges, the shunt resistances are low enough to make the parallel effect of the meter circuit insignificant.



Home-built multi-scaled meters can be housed in metal or wooden cabinets. The example above is a multi-scaled milliammeter built into a Masonite™ and wood enclosure. Care should be taken to protect terminals and circuitry that may carry dangerous voltages. Further, circuitry of this sort should always be protected to avoid accidental shorts that may burn out the circuit under test or the meter itself.

Conclusion

This article has only scratched the surface of the subject of meters and their applications. However, it can serve as a basic reference for the many newcomers to our hobby.

The kind assistance of Robert Foley and Julius Hoffer W1DL is acknowledged. They reviewed the draft of this article and made valuable suggestions. ■

✓See List of Advertisers on page 114