Calibration:
Philosophy in Practice

Chapter 17:
Digital Multimeter Calibration

FLUKEâ

Table of Contents

General Calibration Requirements

Regardless of the type of DMM, calibration adjustments are performed to reduce instability in the offset, gain, and linearity of the transfer functions of the signal processing circuits. Each of the functional blocks in a DMM's measurement section is subject to these sources of variation in performance.

Theory of Calibration Adjustment

Assume that all of the DMM's signal processing blocks have a transfer function of:

$$y = mx+b$$

Where:

y = the output
x = the input
m = the gain
b = the offset from zero

The DMM is designed in such a way that m has an exact nominal value such as 10 and b should be zero. For example, when m is 10 and b is zero, y will equal $10x$.

When m is not equal to its nominal value, all values of y will deviate from nominal by the same percentage. When b is not equal to zero, all values of y will be offset from their correct value by a constant amount. Even though m and b deviate from their nominal values, the slope of y as a function of $mx + b$ should be a straight line. (Departures from a straight line are referred to as nonlinearity.)

A DMM operates under this $y = mx + b$ relationship. It takes an unknown input x (whether in voltage, resistance, or current), and converts it to y (in volts, ohms, or amperes). This is what is displayed by the DMM. Figure 17-12 depicts the variations in gain, offset and linearity for a typical DMM. Traditionally, these deviations are referred to as gain, offset, and linearity errors.

Voltmeter specifications are based primarily on offset, gain, and linearity: the % of reading specification is the gain uncertainty.

Zero uncertainty is due to voltage offsets in the adc amplifiers and comparators; gain uncertainty is tied to inaccuracies of the dc voltage reference and any gain-determining networks of the adc. Linearity uncertainty is due to secondary error sources, such as mismatches in resistive ladders of the dac in R^2 converters, or dielectric absorption errors by storage capacitors, resulting in a drooping response at full scale.

Figure 17-12. Offset, Gain and Linearity Variations

In addition to these sources of uncertainty, some DMMs have spurious voltage spikes, dc bias currents, and pump-out currents present at their input terminals. These can introduce errors in the output of the MFC calibrating the DMM.
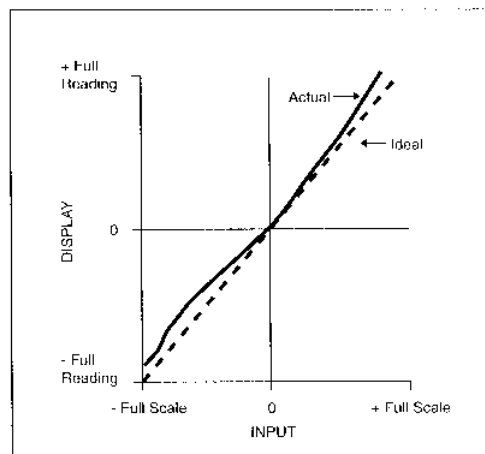
Internal References

Every DMM has a dc voltage reference. References range from 1 V to 15 V The dc voltage reference is used as the reference for the adc and is the limiting factor for the DMM's best accuracy for all voltage and current measurements. DMMs may or may not require separate calibration of the dc voltage reference. Often, the DMM design is such that an actual measurement (using another DMM) of the dc voltage reference is not required. Instead, a known input voltage is applied to the unit under test (UUT), and an adjustment is made until an accurate representation of the known input voltage appears on the UUT display. Figure 17-13 is an example of a typical high precision direct voltage reference.
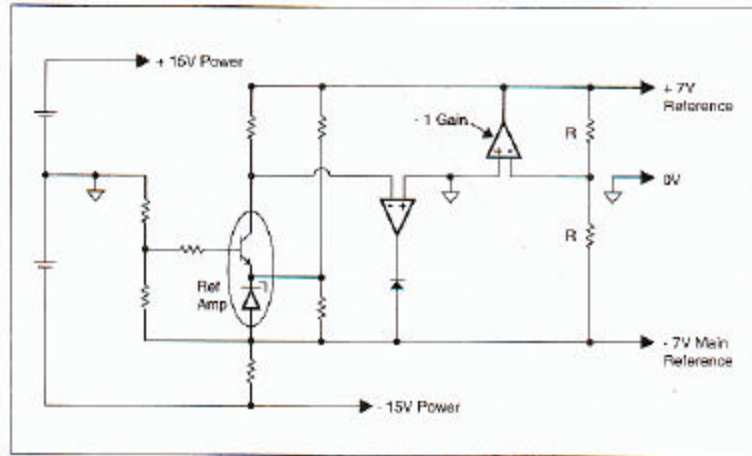

Figure 17-13. *Precision Direct Voltage Reference*

Also, in any DMM, there are one or more resistor references that determine the accuracy of the resistance converter. Most DMMs do not require a separate measurement of the reference resistors during calibration. Instead, a standard resistor of known value is applied to the DMM, and the DMM is adjusted for the correct readout. Figure 17-14 illustrates a typical resistance reference.
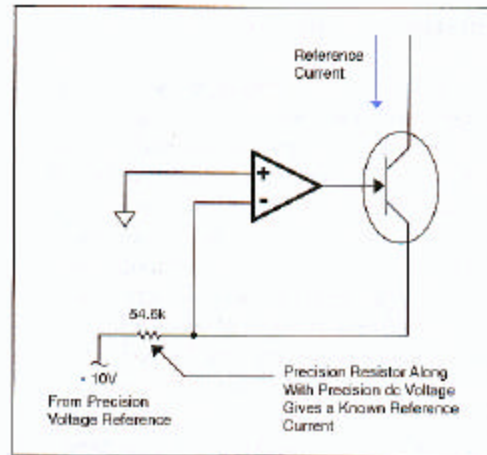

Figure 17-14. *Resistance Reference*

ADC Adjustment Considerations

Since all functions use the adc, it must be calibrated as one of the first steps. Some DMM calibration schemes call out separate adc and reference calibrations; other schemes merely call out dc voltage range calibrations and do not burden the calibration technician with the specific details of the adc calibration. DMMs whose procedures do not call out separate adc adjustments do have internal corrections. The calibration procedure simply calls for an adjustment in the straight-in dc voltage range first. This range, going directly into the adc, has unity gain and thus has no significant error in scale factor. The calibration procedure will often call for a zero offset adjustment of the dc range, and then the adc is adjusted.

Integrating ADC

The integrating adc has simpler calibration adjustments than successive approximation adc. The major error source of this type of converter is the dc voltage reference; its calibration adjustment can be as simple as applying a known dc voltage of about the same magnitude as the dc voltage reference, and then making an adjustment within the DMM so that the adc's displayed output is the same within an acceptable tolerance, as the applied input.

Some integrating converters have a more complicated calibration adjustment near zero volts. The slew rate of both the integrator and comparator can cause errors near zero volts; these errors are often polarity sensitive. As a result, there may be one or more adjustments near zero volts to correct for this anomaly.

Traditional dual-slope converters often exhibit dielectric absorption in the integrating capacitor. This phenomenon is caused by the capacitor's memory effect which results in a not-as-predicted integrator output voltage over large voltage swings, that is, near full-scale inputs. An uncorrected dual-slope converter will typically droop by 10 to 50 ppm near both positive and negative full scale. To correct for this, the adc is adjusted with a known near-full-scale input applied. For more information on dielectric absorption, see Chapter 33, "A Rogues' Gallery of Parasitics."

R^2 ADC

The R^2 converter calibration adjustment procedure generally requires more adjustment points to correct for mismatches in the resistive ladder networks that make up the dac. And certain steps of the calibration may need to be repeated a number of times (iterated) for optimum results. Very specific voltage inputs are required during the calibration, forcing the R^2 converter to use various combinations of the dac ladder. Iteration allows the matching between the resistors of the ladder to be more accurate. R^2 calibration is no more demanding than the calibration of a simple dual-slope converter. It is easily accomplished with MFCs such as the Fluke 5700A, which allow quick keyboard entry of any voltage.

DC Voltage Range Calibration

DMMs usually have full-scale ranges of 200 V dc, 300 V dc, or 1000 V dc, typically divided by factors of 10 to determine the lower ranges. Normal calibration practice limits the testing of ranges to just less than full scale. This is because most DMMs are auto ranging, and will go to the next higher range if the input is a certain percentage of full scale. So the calibration voltages for DMMs with full-scale ranges of 200 V dc usually follow a 190 mV, 1.9 V, 19 V, 190 V and 1000 V dc sequence.
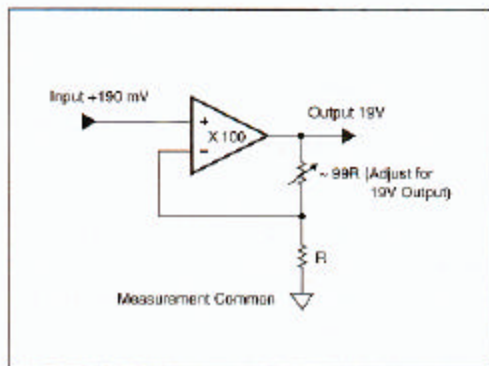

Figure 17-15. mV Gain Adjustment

Modern MFCs take advantage of this structure. For example, the lower four of the ranges in the preceding list are very quickly calibrated by the Fluke 5700A by setting up its output on the lowest range and then using its MULTIPLY OUTPUT BY 10 key to step through the next three ranges.

The zero on each range may also need to be adjusted or recorded. This is usually done by applying an external short to the DMM input and taking the appropriate action. After the zero is adjusted or recorded, the full-scale input voltage is applied and the range gain is adjusted.

For example, assume that a DMM's adc operates within the range of ±20 V Its 200 mV dc range scales the input signal x 100 to keep the full-scale adc input to within the proper range, as shown in Figure 17-15. The amplifier used in the 200 mV dc range has a voltage offset error, and the gain provided by the feedback is not exactly 100. This causes a scale-factor error.

The calibration procedure is to apply a short circuit to the input to the amplifier and adjust the DMM reading to exactly 0 V dc. This would be followed by an input near full scale, in this case, 190 mV dc. The DMM is then adjusted to display the exact input voltage, In effect, the user is making the gain exactly 100. A DMM calibration may also require an input of opposite polarity, -190 mV. This is to correct either for secondary linearity errors of the range amplifier, or for linearity errors within the adc.

AC-DC Converter Calibration

AC-DC converter calibration is similar for all types of converters. Amplitude adjustments are often made at two or more frequencies on each range. Zero adjustments are not usually made.

Average Responding AC-DC Converters. Calibration adjustment of average responding converters corrects for deviations in the equation $y = mx + b$. However, the b term is solved not for inputs at zero volts, but typically for inputs at 1/10 th or 1/100 th of full scale. This is because precision rectifiers tend not to work well at zero volts input. Near zero volts, they rectify noise that would otherwise ride on the input waveform and average to zero. By moving the b term calibration off of zero, this problem is avoided. For more information, see Chapter 33, "A Rogues' Gallery of Parasitics."

TRMS AC-DC Converters. True rms converters need similar calibration of ranges at full-scale and at near-zero input levels. But true rms circuits have an even greater problem near zero volts than average responding converters. For example, analog log/antilog schemes employ a precision rectifier, resulting in noise rectification problems like those associated with an average responding converter. Also, since the displayed output voltage is:

$$\sqrt{V_{noise}^2 + V_{sig}^2}$$

Where:

V_{noise} = rms value of the noise voltage
V_{sig} = rms value of the signal being measured

Very small input signals cause the noise term to dominate. Consequently, true rms calibrations are accomplished with inputs well above zero volts.

There are additional adjustments to correct for errors in linearity of rms converters. If the DMM has a dc-coupled ac voltage function, there may be zero input adjustments to correct for offset errors of the scaling amplifiers.

The ac voltage converter can have a separate calibration for the true rms converter, but often its calibration is combined into the main ac voltage function calibration. For example, if the true rms module can handle a 2V full-scale waveform, the 2V ac range should be calibrated first; then adjust the true rms module. The other ranges are then adjusted to correct for their gain errors. In some cases, the true rms module needs more than two different inputs to correct for linearity errors. For example, an ac voltage calibration adjustment may call for inputs of 19 mV, 190 mV and 1.9V on the 2V range.

Scaling sections, averaging converters, and true rms converters have resistive and capacitive errors. A major consideration when calibrating ac voltage is frequency response. The general requirement is to use a constant-amplitude calibrator that covers the entire frequency range of the DMM. The conversion takes some time, and slewing through the pass band is time consuming. Because of this, spot frequency checks are usually made instead.

Low frequency calibration is generally performed at 400 Hz to 1 kHz. The high frequency adjustments are done afterwards. The frequencies used for high frequency adjustments are largely determined by the capacitive vs. resistive characteristics of the scaling circuits. When making a high frequency adjustment, one of two actions is performed:

- The actual frequency response of a scaling amplifier or attenuator is physically adjusted. See Figure 17-16.

- The DMM's frequency response at cardinal points is stored in its non-volatile memory. The DMM firmware then displays the correct reading at any frequency by interpolating between frequency points.

The second method requires a DMM with an internal frequency counter to determine input frequency.

Resistance Converter Calibration

Calibration of resistance converters generally consists of zero and gain adjustments. For example, each range of the DMM's resistance function is first corrected for proper zero reading. Then a near-full-scale input is applied to each range, and adjustments are made if necessary.
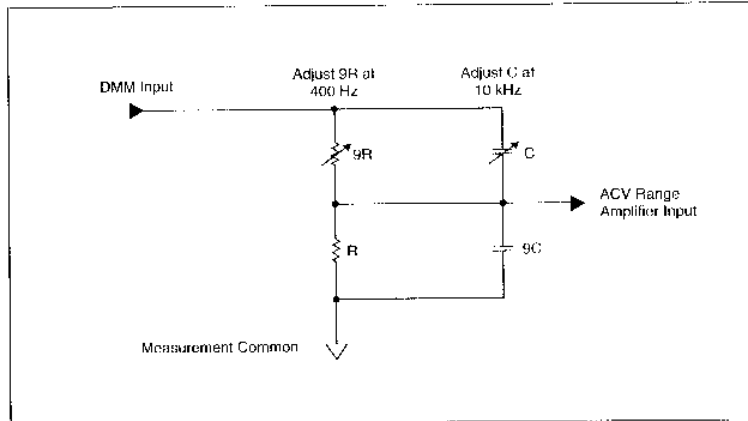

Figure 17-16. Frequency Response Adjustment

When calibrating DMMs with 4-wire resistance capability, resistance sources should have remote sensing capability, as with the Fluke 5450A Resistance Calibrator and the Fluke 5700A MFC.

In the 2-wire setup, the sense path and ohms current path are on the same set of terminals. Resistance errors due to the connecting leads can be significant. In general, proper connection of 2-wire resistance calibration for a meter with even 100 mΩ resolution can be a problem. Fluke has addressed this problem in the 5700A, which has its 2-wire ohms compensation feature. The 2-wire ohms compensation feature of the 5700A virtually eliminates the effects of lead resistance in a 2-wire hookup.

Separate 2- and 4-wire resistance calibrations could be specified in calibration procedures. Since the 4-wire sense path is the same as the dc voltage signal conditioning path, all that is required is to correct the gain of the current source for resistance converters with current sources. However, second-order effects cause discrepancies in apparent gain when the dc voltage amplifiers are configured to sense either a dc voltage input directly or the voltage across the unknown resistor. Because of this, many of the higher precision DMMs require calibration for both 2- and 4-wire resistance. For more information on contact resistance, insulation resistance, leakage currents, and bias currents, see Chapter 33, "A Rogues' Gallery of Parasitics."

Current Converters Calibration

Both ac and dc current converters are calibrated by applying a known current and adjusting for the correct reading. Direct current converters correct for zero and gain; alternating current converters correct for down-scale and full-scale response. Typically, there are no high frequency adjustments for alternating current, primarily because current shunts are not inductive enough to cause significant errors relative to the DMM's specifications.

Other DMM Calibrations

There are other characteristics of a DMM that require calibration. The DMM must not only measure dc voltage to a high degree of precision; it must also have a minimal loading effect on the source voltage. One aspect of circuit loading is the bias current error of the DMM's dc voltage amplifiers -- how much current does it draw from the circuit under test? Many high end DMMs, with bias currents in the 10 pA region, require a bias current adjustment of the dc voltage scaling section. These adjustments are made by comparing the DMM reading with a low impedance zero input against a high impedance zero input. The adjustment itself adds or subtracts an actual bias current into the main dc voltage amplifiers.

Simplified DMM Calibrations

Closed-Case Calibration

The calibration of microprocessor controlled, IEEE-488 bus or RS232 communicating DMMs has been simplified by automation. The DMM itself may provide a great deal of the automated capabilities. However, external software, running in a PC, provides even more advanced calibration automation.

DMM manufacturers all realize the benefit of simplifying the calibration task. The HP 3455A had a removable module containing the direct voltage and resistance references that could be sent to the calibration laboratory separately. However, this also required manual adjustments for complete alternating voltage calibration.

The Fluke 8500A was the first DMM with digitally-stored calibration constants. An optional calibration memory stored various offsets and gain corrections for each range and function in non-volatile memory. This allowed it to be calibrated quickly with the covers on for most functions. The 8500A was not yet a fully digitally-calibrated instrument, because periodically some open-cover high-frequency calibration adjustments were required.

An early DMM to offer full closed-case, digitally-stored calibrations was the Datron® 1061, which extended the concept introduced by the Fluke 8500A to include high frequency adjustments by dac programming of varactor diodes to replace trimmer capacitors. The limitations which older instrument designs had placed on calibration time and requirements for human intervention could now be circumvented.

Since then, the Fluke 8840A has simplified the closed-case calibration process even further: a calibration procedure built into the instrument firmware prompts the user through the exact calibration steps. Average calibration time is approximately 12 minutes in an automated system. Furthermore, the 8840A was one of the first precision DMMs with no potentiometer adjustments at all, eliminating even the socalled one-time-only factory adjustments. This DMM, from the date of manufacture or after any repair, could be calibrated with all covers on.

Closed-case calibration, along with the advent of IEEE-488 bus controllers and calibration instruments controlled by the IEEE-488 bus, revolutionized the traditional DMM calibration by fully automating it. This automated process is often referred to as closed-loop calibration.

Closed-Loop Calibration

Closed-loop calibration is one of the most Significant instrumentation developments in recent years. The loop is the connection between the measurement of an instrument's performance and the actual readjustment of its operating characteristics.

For example, in a manual calibration of an analog voltmeter, the operator first applies a short circuit to the UUT and adjusts the zeroing screw on the face of the meter; then removes the short and applies a known voltage, adjusting a potentiometer for the correct reading at full scale. The loop begins with the technician's interpretation of the reading, goes through the hand that turns the screwdriver, and to the screw being turned. The change in instrument response as the screw is turned is monitored by the technician to complete the loop.

With a programmable source and UUT connected by a suitable digital interface (such as the IEEE-488), the computer can set the source and UUT to the right range and value, then interpret the UUT performance. But if performance is modified by turning a screw on the UUT, either a complex robot arm or a human arm is needed to make the adjustment.

Closed-loop calibration eliminates the need for any kind of arm in the loop. New digital techniques use a microprocessor to store zero and gain corrections into non-volatile memory. These are then applied in real time to modify the displayed reading. Instead of solving the $y = mx + b$ equation by trimming resistor values or dc voltage references, the equation is solved and corrected in software. Electrical parameters of the dc voltage scaling circuits, for instance, are no longer changed; the DMM displays the correct reading y by using its internal microprocessor to apply calibration constants m and b to the digitized value of input x.

Closed-loop calibration is also possible for those circuits that do require a change in elec, trical performance. For example, high frequency ac voltage adjustments can consist of dac reprogramming of varactor diodes. Or a

dac can be reprogrammed to physically readjust the dc voltage sense amplifier bias current. The programming information is then stored in non-volatile memory.

For a DMM calibrator, the system can send the correct range and function over the IEEE-488 bus, apply the desired stimulus to the analog inputs, take the resultant reading back over the bus, and command a change in the digitally-stored correction. The loop is closed by the system CPU, and the hand on the screwdriver is eliminated. The operator is necessary only to connect leads and initiate the process.

Closed-loop calibration has resulted in faster, more repeatable, higher quality calibrations. Closed-loop calibration has other benefits as well. Customer demand for it has forced DMM manufacturers to actually design a higher quality product. Many DMMs today do not have mechanical potentiometers that wear out. Secondary error sources, such as integrator capacitor dielectric absorption, which are not easily correctable by software, have been eliminated by design.

For more information on closed-case and closed-loop calibration, see Chapter 19, "Automated Calibration."

Artifact Calibration

Another recent development in calibration is artifact calibration and automated internal cal, ibration. This method involves applying a few calibration standards (for example, a 10 V dc voltage standard and a 10 kΩ standard), and designing the means inside the DMM to calibrate all of its other ranges and functions using these selected input values. For this purpose, the DMM contains voltage- and resistanceratio and ac-dc voltage transfer circuitry to determine appropriate range constants for voltage, current, and resistance, and to derive ac voltage range constants from dc voltage ranges. The internal calibration techniques are functionally identical to those ordinarily used in a calibration facility.

In order to take advantage of stability performance that is much better than uncertainty or resolution, it is important that the resolution of the calibration constants be significantly greater than the resolution or uncertainty. Otherwise, recalibration of the instrument will result in noticeable discontinuities in the results, making the instrument unusable for monitoring accurate signal sources with high resolution.

Artifact calibration is treated in detail in Chapter 16, "Artifact Calibration."

Laboratory DMM Calibration

The calibration of laboratory DMMs raises interesting issues because, as their accuracy approaches that of the calibrator, the test uncertainty ratio (TUR) approaches 1:1. In these cases, the metrologist must analyze the uncertainties in his measurements to support using TURs of less than 4: 1.
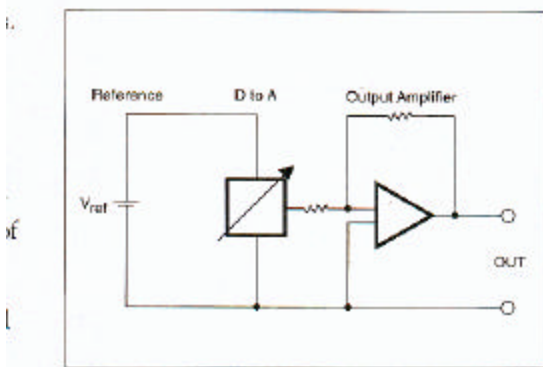

Figure 17-18. MFC Direct Voltage Function

Figure 17-17 is a simplified block diagram of the dc voltage function of a laboratory DMM. Figure 17-18 is a similar block diagram for a precision multifunction calibrator (MFC).

As inspection shows, the circuit elements of Figures 17-17 and 17-18 are identical but appear in reverse order. As a matter of fact, it is easier to manufacture the DMM because it uses simple resistive attenuators to reduce high voltage ac voltage inputs to the 10 V level at which it processes the attenuated signal.

Because the best calibrators and the best DMMs will have a 1:1 TUR for the dc voltage function, users may wish to use additional test equipment, such as precision voltage dividers and secondary standards of voltage, to enhance the accuracy of the calibrator's direct voltage output (see Figure 17-19).

It is also possible to evaluate the calibration results statistically. For example, if the test limits are set at 1.414 (square root of 2) times the performance specifications for the DMM or calibrator, the distribution of variance in performance for a population of DMMs and calibrators will follow the curve in Figure 17-20.
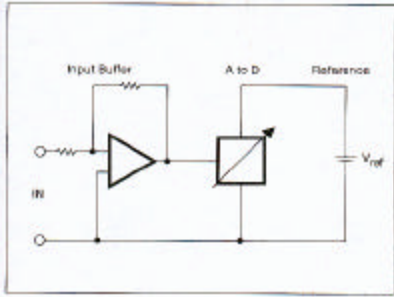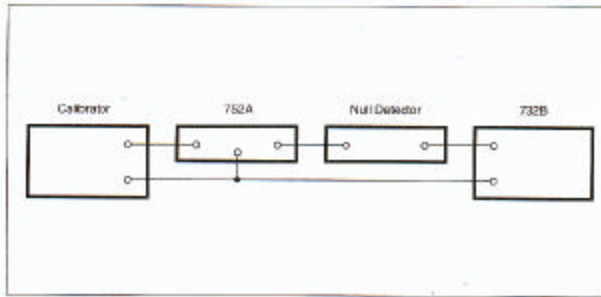

Figure 17-17. DMM Direct Voltage Function

Figure 17-19. Use of Dividers on DC Voltage Output

A modern calibrator that uses artifact calibration can collect a record of changes in its performance using internal circuits. A personal computer running data analysis software can analyze this record and assign accurate correction factors to the calibrator's output, thereby improving its TUR at each calibration point.

Key References

References for this chapter are in *the Resources* Appendix.
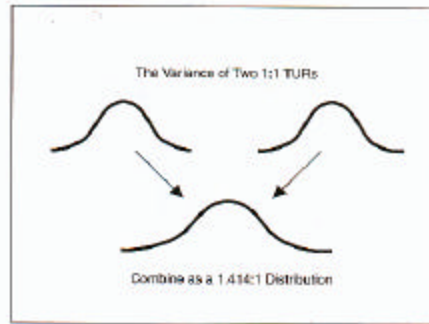

Figure 17-20. Distribution of Uncertainty for x-Member DMM Population

Table 17-1. DMM Summary

Type	Example	Functions	Comment
Laboratory	Fluke 8506A	voltage, current, and resistance	highly accurate, true rms ac voltage sensor
	Hewleft Packard 3458A	voltage, current, and resistance	artifact calibrated, IEEE-488 or manually operated
Bench/ Systems	Fluke 8842A	voltage, current, and resistance	IEEE-488 bus and front-panel controls. Evolved from early bench and systems DMMs of the 1960s and 1970s, such as the Fluke 8300A
Handheld	Fluke 87	voltage, current, resistance, frequency, time, capacitance, diode tests, and more	evolved from early bench DMMs of the 1970s,such as the Fluke 8120A and 8000A