DIGITAL MULTIMETERS

Analog multimeters were created in the early part of the twentieth century. The most common form measured dc and ac voltage, resistance, and dc current, and these became known as volt-ohm-milliammeters or VOMs.

In 1955, the first digital voltmeter was marketed by Non Linear Systems, Inc. This meter scaled inputs and then digitized them, displaying the results in a numeric digital display. Digital measurement and display technologies developed in parallel with digital integrated circuit technology until finally, in the late 1960s, portable digital versions of the VOM appeared. This form of meter shown in Fig. 1 has since become known as the digital multimeter (DMM).

Figure 1. Modern full feature DMM (Fluke 87 III).

THE ELEMENTS OF A DMM

A DMM is made up of several basic functional elements shown in Fig. 2.

1. Signal conditioning
2. Analog/digital conversion (A/D)
3. Numeric digital display

Signal Conditioning

The analog-to-digital converter (ADC) in most DMMs converts a dc voltage input to a digital form for display. Ac or dc voltage, current, and resistance are the most common parameters to be measured. Now many DMMs also measure frequency, and additional functions, such as temperature, have also appeared.

First these inputs must be switched and conditioned to present an equivalent dc voltage of the appropriate range to the ADC or a sealed input to the counting circuits.

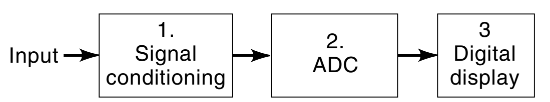

Figure 2. Basic DMM block diagram shows the basic flow of information from the analog input signal through the various analog signal conversion circuits which convert the measured quantity to a dc voltage equivalent. Then the ADC translates this dc signal to digital form, and the display system shows the resultant value with appropriate annunciation, such as measurement units of the original input signals. Not shown are the necessary, but not directly related, parts of the DMM. These include the power supply and mechanical packaging.

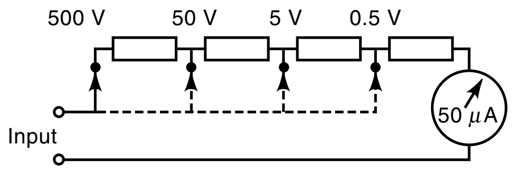

Figure 3. VOM input multiplier—dc volts. The basic input configuration for dc voltage input to an analog VOM. The major point of this diagram is that the input resistance varies as a function of range to maintain current through the meter movement within its limited dynamic range. This configuration leads to the common VOM sensitivity specification in ohms per volt. A 20,000 Ω/V meter draws 50 μA from the input at full scale indication on any dc voltage range.

Dc Voltage

It is necessary to scale a wide range of dc voltage inputs to the limited range of the ADC. A resistive divider and switching are generally used for this function. One of the major differences between the classical analog VOM and the DMM is in the way this scaling occurs.

In the analog VOM, the input circuit is designed to provide full-scale current to operate the d'Arsonval meter movement (refer to Fig. 3). A typical meter has 50 μA full-scale sensitivity. The input sensitivity of such a meter is specified by calculating the series resistance per volt at 50 μA, $R = 1/0.00005$ or 20,000 Ω/V. A 5 V range therefore has an input resistance of 100,000 Ω, and a 500 V range has an input resistance of 10 MΩ as more resistors are added to the input multiplier.

The DMM, on the other hand, operates with a fixed resistive divider across the input (typically 10 MΩ) regardless of the range chosen (see Fig. 4). In this case the input resistance is a divider with output taps switched to present a voltage, usually less than 1 V, to the ADC. For this reason, the DMM uses much less current (is more sensitive) on the lower voltage ranges than the typical VOM, thereby reducing circuit loading errors.

Another difference between the VOM and the DMM is in the rejection of ac noise which is present along with the dc voltage to be measured. In the VOM, the mechanical damping provided by the d'Arsonval meter movement averages this noise and presents a stable reading even when the noise is a significant portion of the signal being measured. The DMM input circuit, combined with the ADC method used must filter to provide equal or better performance. See a discussion of noise rejection in the section on A/D conversion.

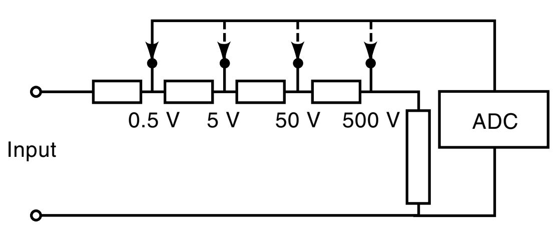

Figure 4. DMM input divider—dc volts. The constant input resistance input divider network in the typical DMM> The total resistance at the input terminals is relatively high, usually 10 MΩ. Output taps are selected to present a small voltage (less than 1 V) to the ADC even when the applied input is 500 V or more. The same divider is often used for AC voltage scaling. In this case, shunt capacitance should be specified.

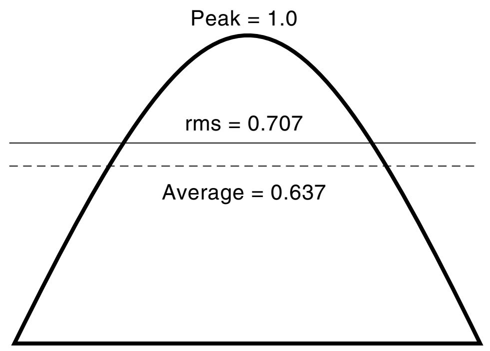

Figure 5. The positive half-cycle (180°) of a sine wave and the relationship between peak, rms, and average values. The simplest and least expensive DMMs have always used the rectified average value scaled to equivalent rms for display. This relationship is true only for the sine wave whereas most 'real-world' measurements are of waveforms that range from square to narrow pulse with varying rise and fall times. Therefore, this method is usually inaccurate to some degree, and it is difficult to predict the amount or direction of the error. A similar problem occurs when the peak value is scaled to the rms. The end message: If the rms value is important, measure the true rms.

Ac Voltage

For ac voltage, the signal must be scaled and then converted to a dc equivalent value before sending it to the ADC. Following are two popular methods of conversion (refer to Fig. 5).

Average Sensing-Rms Indicating ac Measurements. In the analog VOM, ac to dc conversion is accomplished by using a bridge rectifier in the meter circuit to provide a single polarity current that deflects the meter needle. This current has significant ripple at twice the frequency of the measured ac signal, but this is effectively filtered (or averaged) by the mechanical damping of the meter movement. In the DMM, an operational rectifier circuit is used, but the output must be filtered to reduce the ripple before it is applied to the ADC.

This rectified average value is equal to $2/\pi$, or 0.637 times the peak value for a sine wave. The desired ac voltage (or current) value is the rms, or heating value, which is equal to $1/\sqrt{2}$, or 0.707 times the peak of a sine wave. Therefore average analog or digital sensing meters, scale the rectified signal by $\pi/(2 \times \sqrt{2})$, or 1.111 times the rectified average value. This ratio of rms to average value is known as the form factor of the input waveform. Although this method works for a sine wave of a single frequency, significant errors occur when the waveform is distorted because these ratios are no longer true if harmonics are present.

True Rms ac Measurements. A more accurate conversion provides the true rms value–equivalent to a dc voltage which would heat a resistor to the same temperature. With true rms conversion, this is true regardless of waveform. Most DMMs, which offer true rms capability, use an analog computing circuit to perform the necessary calculation (Fig. 6).

Rms stands for root-mean-square, which is expressed mathematically as $\text{rms} = \sqrt{(\Sigma i^2/n)}$, where i is the instantaneous value and n is the number of points i (1 to n), which are squared and summed for use in the calculation (see Fig. 7).

Figure 6. An early 1980s true rms DMM (Fluke 8060A).

Some DMMs also allow measuring the peak value of the ac waveform.

Dc and ac Current. To measure current with a DMM, it is necessary to convert the current at the input to a voltage for use by the ADC. This is done through a series of switched resistors, called shunts. A small-valued resistor in the input is placed in series with the current to be measured and Ohm's law ($E = IR$) defines the small voltage proportional to the input current which is then measured.

Ac current uses the same method except that the voltage across the shunt is routed through an ac–dc voltage converter before going to the ADC.

Burden Voltage. The voltage drop across the current input resistance of a DMM connected in a series circuit is known as burden voltage and is subtracted from the voltage normally available to the load. Therefore the resistance added to the measured circuit should be kept as small as possible to minimize measurement error.

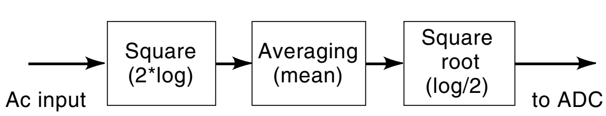

Figure 7. True rms ac-to-dc conversion. The functional blocks of the basic analog circuit that produce a dc voltage proportional to the rms value of a complex waveform. The logarithmic conversion for squaring is accomplished by using the current versus voltage relationship of a forward-biased base–emitter junction of a transistor. Factors which affect the performance of this conversion process include frequency response, crest factor, and slew rate. Commercial converters are available. Analog Devices (ADI) in Norwood, MA, has several products. Their rms converter website is http://products.analog.com/products_html/list_gen_117.html

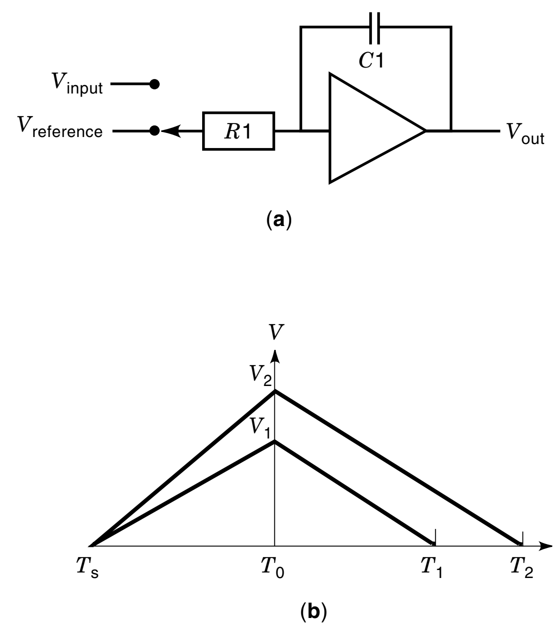

Figure 8. (a) The basic elements of the analog integrator circuit of the dual-slope integrator. The circuit uses an inverting operational amplifier to convert an input current (through input resistor $R1$) to a voltage across the integrator capacitor $C1$. From an initial condition when the voltage across $C1$ is zero, $R1$ is connected to V_{Input}, and integration occurs for a fixed period of time. This is the first slope of the dual-slope process. The polarity of the charge on $C1$ is determined, and a reference voltage, $V_{\text{Reference}}$ is selected. The purpose of the second slope integration is to determine the time needed to return the voltage on $C1$ to zero. This time is proportional to the voltage on $C1$ at the end of the first slope which, in turn, is proportional to the applied input voltage. (b) The voltage versus time diagram.

Resistance

Because the ADC measures only dc volts, it is necessary to create a voltage proportional to the resistance when that measurement is desired. The DMM input circuit must provide a dc current flowing through the resistor and then measure the resulting voltage. Ohm's Law provides the necessary relationship ($R = E/I$). Of course, it is necessary to know the applied current value for this method to be useful. Many DMMs provide a calibrated constant current source for this purpose. Many others use reference resistors in series with the resistor being measured, and then measure the unknown and reference voltage drops. When combined with the known reference resistor values, this voltage ratio technique also yields the desired resistance value.

ANALOG-TO-DIGITAL CONVERSION

There have been several schemes used for the ADC conversion in DMMs. Some of them read voltage by using successive approximation, a technique which measures the voltage directly with a digital-to-analog converter (DAC) and voltage comparator. Many others rely on time-counting techniques. The most common of these by far is dual-slope integration.

Dual-Slope Integration

This process uses an operational amplifier configured as an integrator [Fig. 8(a)]. First the integrator is set to zero. Then the input voltage (V_{input}) is applied for a precise period of time controlled by a counter. The input is then switched to a reference voltage of the opposite polarity ($V_{reference}$), and the time required to integrate back to zero is counted. When done correctly, this process relies only on the stability of the integrator capacitor, the precision and stability of the counter, and the accuracy of the voltage reference to achieve the desired result.

The process just described is represented by the voltage versus time diagram in Fig. 8(b). V_1 represents the integrator voltage output at the end of the fixed period when an input voltage is applied. T_1 represents the time required for the integrator to return to zero when the appropriate reference voltage is selected. A similar case is shown for a larger input voltage (V_2) where a longer time (T_2) is required to return to zero.

In the dual-slope ADC, the time required to deintegrate (return to zero) is directly proportional to the integrator voltage at T_0, which, in turn, is directly proportional to the input voltage.

NOISE REJECTION

Normal-Mode Noise

Common implementations of the dual-slope ADC use the unique noise rejection characteristics of the process to minimize the effects of the major noise source, the 50 Hz or 60 Hz power system. The inherent filtering characteristic of this converter, set to integrate for 100 ms, is shown in Fig. 9. This integration time results in near infinite rejection of noise at integral multiples of 10 Hz and because exactly 5 cycles of 50 Hz and 6 cycles of 60 Hz occur in 100 ms, this technique addresses power system noise directly.

The presence of noise directly affects the performance of a DMM by causing a reading error or instability. The noise may be an integral part of the signal being measured but is outside the passband of the measuring system. In the preceding case, the circuit measures dc voltage, and the noise is at the power frequency. This is referred to as normal-mode or series-mode noise (Fig. 10).

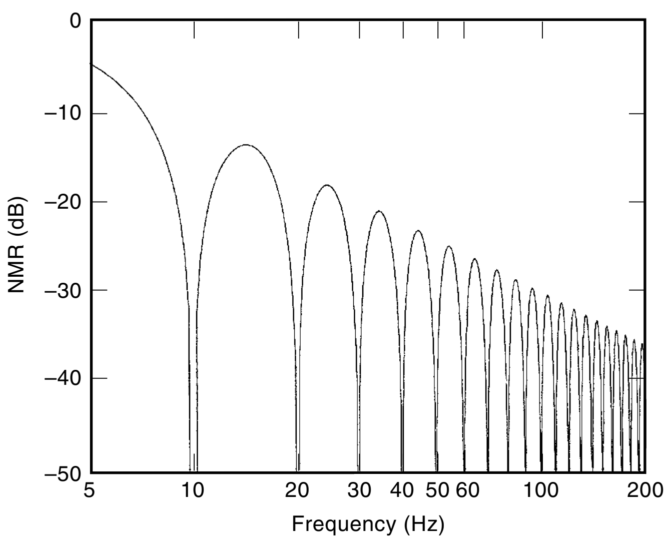

Figure 9. Dual-slope integrator normal-mode rejection (NMR)—100 ms integration time. The rejection characteristic of input frequencies whose periods are directly related to the inverse of the signal integration time. The 100 ms time used for this example equals a period of one cycle at 10 Hz. Therefore there is near infinite rejection of 10 Hz and its integral multiples.

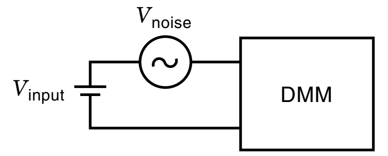

Figure 10. Normal (series)-mode noise. The interfering signal (noise) is a part of the measured signal seen by the meter. It may be ripple in the output of a power supply or may be induced in the signal leads connecting the input source and the DMM.

In Fig. 9, normal-mode noise rejection is expressed as a ratio of peak display disturbance divided by the in-band signal being measured. For example, if the DMM is reading 5.000 V with noise up to ±0.050 V, then 0.05/5.0 yields a normal-mode rejection ratio (NMRR) of 0.01—expressed in decibels as 40 dB NMRR.

Common-Mode Noise

If the noise is present between a third point and the two measurement connections in common, then it is known as common-mode noise (Fig. 11).

The common-mode rejection ratio (CMRR) is calculated similarly to the ratio for normal-mode noise, the peak error or instability displayed in the measurement reading divided by the nominal reading value.

These examples have shown dc voltages affected by ac noise. However, the same principle also applies to ac measurements. For example, when measuring the ac voltage in a three-phase power system, neither input terminal is at ground, and a large common-mode signal with respect to ground is present. Now this frequency is the same as the frequency of the voltage being measured. The result may be a measurement that is stable, but either higher or lower than the actual phase-to-phase voltage. Reversing the test leads shows this possible “turnover” error. The shielding and filter-

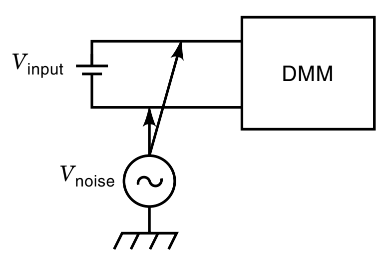

Figure 11. Common-mode noise. The interfering signal (noise) influences both the input and common leads of the DMM input. This type of noise results when the circuit being measured is floating with respect to local “ground.”

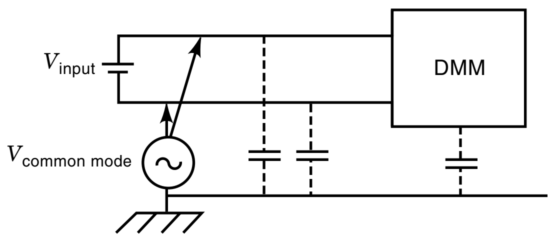

Figure 12. Common-mode capacitive leakage effects. The common lead of the meter is usually more closely associated with shields and power supply reference in the meter and therefore has the lowest impedance for possible ground loops. The voltage input is the high (typically 10 MΩ) input. The net effect is for the common-mode signal to appear as an equivalent normal-mode noise input in this unbalanced circuit.

ing characteristics of the DMM become important in minimizing the effect of leakage capacitance (Fig. 12).

Dc voltage measurements also show this effect with a dc common-mode voltage. In this case, leakage resistance is the issue.

DIGITAL DISPLAY

The final element of the DMM is the digital display. Several display devices are in use now including vacuum fluorescent, light-emitting diode (LED), and liquid crystal display (LCD) technologies. The LCD is the most common display in use today, primarily because it requires the least power to operate. Typical digital displays show the measured value using seven segments per digit plus decimal points and polarity indicators. More capable DMMs also provide bar graph and measurement unit annunciation elements. Typical displays are shown in Fig. 13.

DISPLAY RANGE, RESOLUTION, AND ACCURACY

Range

The effective range of a DMM display is described in several different ways:

1. In counts (2000 counts, 3000 counts, etc.). The count reference comes from the fact that most DMMs use a COUNTER circuit to drive the display circuitry.
2. As a number of digits (3 1/2, 4 3/4, etc.). Referring to a display as "3 1/2 digits" or "4 3/4 digits" indicates that the leading, or most significant, digit in the display never exceeds the numeral 2, 3, or 4. A 3 1/2 digit meter might operate to 2.999, a 4 3/4 digit might operate to 3.999, etc. Attempts have been made to make the reference scientific by calculating the base 10 logarithm of the maximum number. For example, 1999 has 3.3 digits, 2999 has 3.5 digits, and 39999 has 4.6 digits.
3. By showing the actual measurement limits in volts, etc. (−2.999 to +2.999). This is the simplest and least ambiguous way to describe the effective measurement range of a DMM.

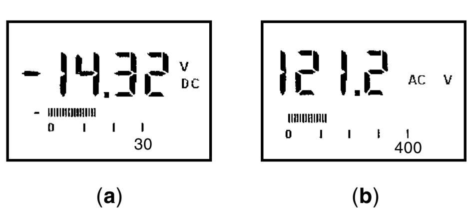

Figure 13. (a) Dc volts on 30 V range. (b) Ac volts on 400 V range.

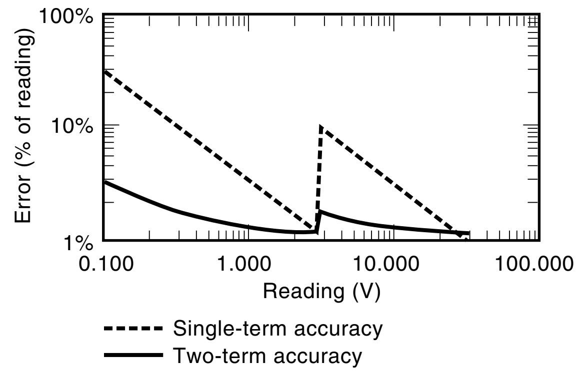

Figure 14. Single-term (dashed line) versus two-term (solid line) accuracy. The graph assumes that range change occurs exactly at the 3 V point. In fact, when an instrument is autoranged, the decision to down range comes at about 90% of the next lowest range. This is at 2.7 V in this example. The reason for the overlap is to minimize "hunting" of the ranging circuit because of slight instability or noise near the ranging point.

Resolution

The resolution of measurement may be specified in least significant digits (LSD), counts, percentage of range, or absolute units (0.01 V), or it may be implied in the range specification. When in the 2.999 V range, for example, the implied resolution is 0.001 volts.

From a practical standpoint, usable resolution is sometimes less than display resolution. Reading instabilities may dictate that the usable resolution of a meter is only ±0.002 V or 0.003 V even though it has a display resolution of 0.001 V.

Accuracy

An accuracy statement for a DMM includes many factors. Among these are resolution, linearity, long-term stability, ambient temperature, and humidity.

Single-Term Accuracy. The simplest DMM accuracy specification uses one term, such as 3% of range, for each function. This applies over all temperature and humidity conditions for some period of time. One year is a common period. This is the usual way to specify the accuracy of analog VOMs whose ranges may be organized in 1, 2, 5 or 1, 3, 10 sequence. For example, ±3% of full scale on the 10 V range (±0.3 V) means that the accuracy of a 10 V reading is 3% of the reading whereas that of a 3 V reading on the same range is 10% of the reading. The user can switch to a 3 V range in this case and return to 3% of reading accuracy at full-scale.

In the DMM, however, the digital display ranges are in decades, such as a 3, 30, 300 sequence. Ranging occurs near one-tenth of range. For the following descriptions it will be helpful to refer to Fig. 14.

Single-Term DMM Accuracy. A reading on the 30.00 range displays 3.00 (10 mV resolution) before ranging allows a change to 3.000 where 1 mV resolution is possible. A specification of 1% of full scale (±0. 3 V) becomes 10% of the reading at 3 V before the range is changed. This leads to an accuracy statement which combines a percentage of the reading term and a resolution-based (percentage of range) term.

Two-Term Accuracy. The input divider, amplifier gain, and reference voltage accuracies are combined in a percentage of reading term because they all contribute to the actual value displayed. The amplifier offset, noise, and least significant digit considerations for the ADC and display are combined in a percentage of range term stated as counts, digits, or percentage of range. In the 30 V range example before, such a specification might read as follows: ±(1% of reading + 2 counts).

At 30 V, the resulting maximum error is 1% of 30.00 (0.3) plus 2 counts (2 × 0.01 or 0.02) for a total of 30.00 ± 0.32 V. Taken as a percentage of the reading, this equals about 1.07% of the reading. At 3 V in the same range, the error is 1% of 3.00 (0.03) plus the same two counts (0.02) for a total of 0.05 V. As a percentage of reading this is now only 1.6% of the 3 V input, far better than the single-term (% of full-scale) accuracy described previously.

Other Factors To Be Considered

Resolution and linearity are included in the basic accuracy specification for most DMMs. Most specifications indicate the time (6 months, 1 year, etc.) for which the specification applies. This takes care of the long-term stability consideration. An accuracy specification may also indicate a temperature range and humidity level which are included in the basic statement. Additional specifications may be furnished to indicate added error terms for operating temperatures and humidities outside the basic range stated.

APPLICABLE STANDARDS AND RATINGS

International Safety Standards for DMMs

IEC 61010 establishes international safety requirements for electrical equipment for measurement, control and laboratory use. There are four categories, CAT I, CAT II, CAT III, and CAT IV ranging from electronic to outdoor electrical power distribution, respectively. There are also maximum voltage ratings that indicate the maximum service voltage to be applied to a meter which is so rated. A meter intended for use at interior single-phase receptacles might carry a notation of CAT II, 300 V, for example. Independent testing organization, such as UL, CSA, TUV, certify that a DMM meets the appropriate IEC standards. Overload ratings are also useful. These ratings indicate maximum values of voltage or current that may be applied to a DMM input without causing damage.

Standards for DMM Measurements and Accuracy Statements

Work began in 1961 to develop a standard that covers digital measuring instruments. At the end of that decade, American National Standard Reqirements for Automatic Digital Voltmeters and Ratio Meters, ANSI C39.6-1969, was approved. It was published by ANSI in 1970. The last revision of this standard was approved in 1982 and published in 1983 as the American National Standard for Electrical Instrumentation-Digital Measuring Instruments, ANSI C39.6-1983. Although this standard has been withdrawn and is no longer in effect, many of the definitions of terms, testing methods, and specification presentations for DMMs today are based on the examples set in this standard.

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CHARLES B. NEWCOMBE
Fluke Corporation

DIGITAL PHASE MODULATION. See PHASE SHIFT KEYING.