

Precision in Practice

Achieving the best results with precision Digital Multimeter measurements

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Abstract

Digital multimeters are one of the most common measurement tools, ranging from simple handhelds to the more sophisticated precision metrology grade instruments. These precision dmms offer a range of specifications, features, and capabilities intended to allow users to make the best measurements for their particular application. However, choosing and applying the most appropriate dmm configuration can be a complex task and may often lead to unexpected results, even for experienced users. This paper explores and explains how precision dmms operate, and provides practical help and guidance on using advanced dmm features with the objective of helping users avoid sources of error in precision applications.

Introduction

Modern precision digital multimeters are sophisticated measuring instruments offering more than just the ability to measure voltage, current and resistance. The accuracy and stability of metrology grade instruments approach the levels available from the standards used to calibrate them. Such high performance allows these multimeters to be used in place of many traditional laboratory instruments such as voltage dividers and resistance bridges^[1]. Not only do metrology grade multimeters provide sufficient precision, they also bring a significant improvement in usability and throughput compared to traditional techniques – the latter being of great importance in today's economic climate where calibration laboratories of every type are challenged to meet technical and business objectives alike. Instrumentation designers pay careful attention to maximizing the functionality of the instruments, and at the same time ensure ease of use. But necessarily sophisticated instruments offering comprehensive capability can appear complex to users. Exhaustively exploring and explaining all of the subtleties of precision multimeter operation and applications is beyond the scope of a single paper, and the authors have chosen to focus on the area of resistance measurement where the potential for replacing traditional methods such as resistance bridges with more cost effective and simpler to implement techniques using a precision multimeter is likely to bring greatest benefits. A new type of precision multimeter, the Reference Multimeter^[2], has recently been developed, and aspects of its design and application will be used to illustrate the principles under consideration.

Precision Multimeter Architecture

In principle the architecture of a precision multimeter is no different to that of a low cost handheld. A block diagram is shown in figure 1. The key element is the analog to digital converter (ADC), defining the basic capability to take an electrical signal and provide a digital (numeric) representation. ADC accuracy, scale length, resolution, and speed vary tremendously from one instrument design to another. Precision metrology grade multimeters use an integrating ADC where the input signal is effectively compared to an internal reference through charge balance in an integrator circuit. Up to 8.5 digits resolution can be achieved with linearity better than 0.1ppm of full scale over a scale length of 2×10^8 counts. For DC voltage measurements the input signals are scaled by a combination of attenuators and amplifiers in the DC Preamp before being presented to the ADC for conversion. A low pass filter at the DC Preamp output, which the user can enable or disable, provides means to remove unwanted AC signals that might be present on the input. For AC voltage measurement another signal path, also with signal scaling, allows an RMS to DC converter to generate a signal representing the RMS value of the input, which is measured by the ADC. To allow current measurements the current converter circuit block incorporates current shunts which produce a voltage proportional to the current input for measurement by either the DC or AC voltage sub-systems. By employing appropriate design techniques the input burden voltage that the multimeter presents at its input terminal when measuring current can be essentially isolated from the voltage developed across the internal current shunts, reducing the disturbance that it presents to the source of current being measured. Resistance measurement capability is provided by a current source circuit block, generating a range of constant currents, which together with the various voltage ranges allows resistance to be measured (by application of Ohm's law). In the case of the new Reference Multimeter there are ranges from 2Ω full scale to $20G\Omega$ full scale. The design and operation of the resistance function will be discussed in detail later in the paper. The input switching block allows two sets of input terminals to be provided, one on the instrument front panel and one on the instrument rear panel. Two channels allows ratiometric measurements to be made in several functions.

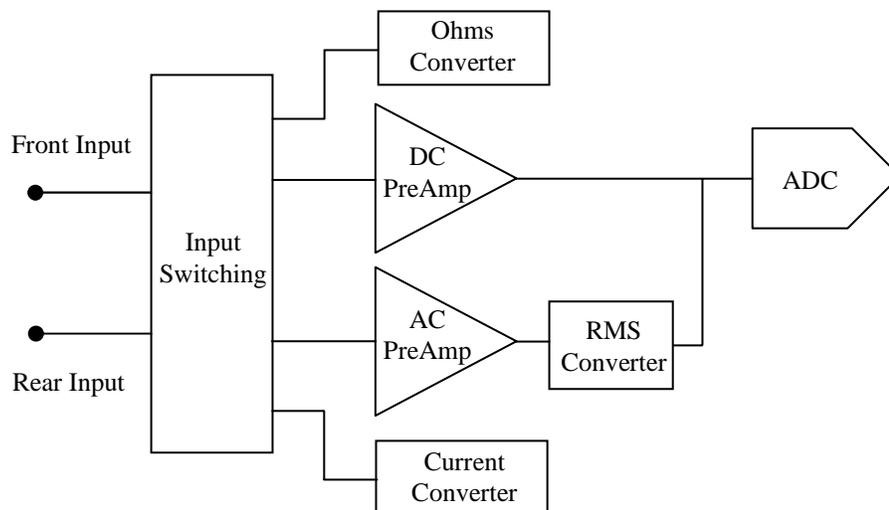


Figure 1. Simplified Dmm Block diagram

ADC Operation – Choosing the appropriate configuration for the measurement

The multi-slope integrating ADC is capable of extremely high resolution with linearity better than 0.1ppm of full scale. However, high resolution can only be achieved at relatively long integration times. In addition to trading off conversion speed and resolution, the integration time has a direct impact on noise rejection. The integration itself effectively averages any AC or noise content, but it can also be used to reject unwanted line frequency signals present on the signal being converted. If the integration time is equal to an exact multiple of the line period the unwanted line frequency signal integrates out to zero. The user is able to select the resolution, and in the design being considered is also able to choose between a ‘normal’ and ‘fast’ ADC mode, effectively determining the integration time. Because the ADC integration time is related to the power line frequency, the user must ensure the multimeter is configured correctly for the line frequency of the power supply to which it is connected. In the DC Voltage function the 5.5digit ‘fast’ mode has an integration time of 3.3ms at 50Hz and 60Hz line operation. For all the other combinations of resolution and ADC normal/fast selection, the integration time is a multiple of line frequency. Provided the user correctly configures the multimeter for line frequency the ADC will provide rejection of line related signal pickup in all modes except 5.5 digit ‘fast’. Up to 80dB of rejection at line frequency multiples is typically achieved. Failure to set the correct line frequency will result in excessively noisy readings if line pickup is present.

Choosing a higher resolution mode will effectively mean choosing a longer integration time, and the signal will be ‘averaged’ within the ADC integrator for longer. In addition to the higher resolution, the result is lower reading to reading runaround (noise) and a lower effective bandwidth. At the higher resolutions multiple ADC cycles are digitally averaged to provide a single displayed reading. The user can also employ the multimeter’s math modes to digitally average readings, allowing flexibility in the tradeoff between effective noise bandwidth and measurement time. Choice of most appropriate mode will depend on the application, required resolution and signal characteristics. For most calibration applications the 7.5 digit mode is appropriate, producing readings with a 1280ms conversion time at 50Hz line (1067ms at 60Hz). It should be noted that the effective read rate with the multimeter free running in internal trigger mode may not be as fast as expected from considering the conversion time alone, as ADC conversions are triggered by a clock at around 2Hz. Achieving faster read rate requires use of an external hardware trigger signal or triggering from the IEEE488 remote interface. All of the forgoing discussion is equally applicable to measurements made in the resistance function, which utilizes the DC Voltage measurement sub-system.

Resistance Measurement

Resistance measurement capability is provided by a multi-range constant current source which passes stimulus current through the resistance under test and the DC voltage measurement circuits used to measure the resulting voltage, proportional to the resistance value. Numerous topologies can be used to implement this basic principle, and the one chosen is illustrated in figure 2. A current source sinks current from the Input Lo terminal, and the Lo Follower acts to maintain the Lo sense terminal at analog common (0V) potential by sourcing the required current through the Input Hi terminal. The resulting voltage is sensed at the Sense Hi terminal by the DC voltage measurement sub-system. There are several advantages of this implementation, one being that the system is not sensitive to the input impedance of the DC measurement circuits. Also an ‘Ohms Guard’ is provided by connecting the Guard terminal to analog common, but the

theory and application of this feature for removing the effect of parallel leakage paths and in-circuit measurements is not discussed in this paper.

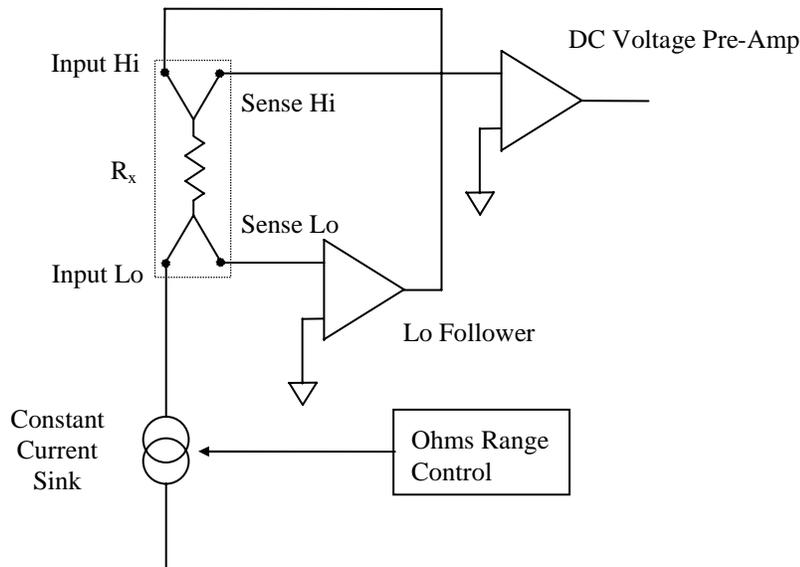
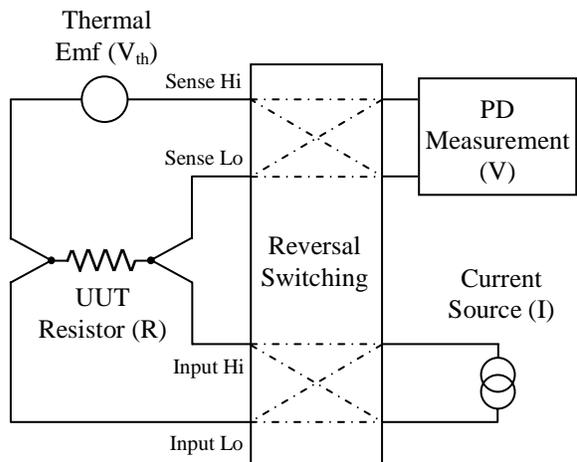


Figure 2. Resistance Measurement Topology

True Ohms – Avoiding thermal emf errors

The basic resistance measurement technique has been enhanced by a technique that automatically compensates for any static or changing thermal emfs in the potential difference sensing path. – True Ohms. By switching off the current source and taking an additional voltage reading at zero current and subtracting this result digitally from the 'current on' voltage, the effect of unwanted offsets in the measurement path can be eliminated. This technique has been used successfully in a number of commercial products^[3,4,5], sometimes under the name of Offset Compensated Ohms^[5]. However, it suffers the disadvantage that the measurement current changes at the read rate, modulating the power dissipation and temperature of the resistor under test. This effect can lead to significant errors when measuring certain types of resistors, particularly low values where the measurement current can be quite high, especially if they have large temperature and power dependencies – an example being platinum resistance thermometer elements.

To overcome this limitation, a current reversal True Ohms technique has been developed and implemented^[2], illustrated in figure 3. In this case, the current source is capable of being reversed. Each reading consists of two measurements, taken automatically under the control of the multimeter's processor. The first reading is taken with the current in the forward direction, the second with the current in the reverse direction and the two measurements are averaged to provide the displayed result. The power dissipation in the resistance under test remains constant, as the current is never switched to zero.



With forward current:
 $V_1 = IxR + V_{th}$

With reverse current:
 $V_2 = -(-IxR + V_{th})$

Averaging V_1 and V_2 :
 $= 0.5(2IxR + V_{th} - V_{th}) = IxR$

Sense path reversal ensures V_1 and V_2 have same polarity for ADC conversion. Note that any offset in the PD measurement path after the reversal switching is not cancelled, but is removed with zero calibration and input zero operations.

Figure 3. Current Reversal True Ohms

As with the DC Voltage function, when in the True Ohms function the user is able to select the resolution and ADC mode, effectively controlling reading resolution and sample (integration) time. At the higher resolutions relatively long effective integration times would limit the effectiveness of the True Ohms thermal emf cancellation if those thermal emfs changed significantly during the integration time. To avoid this situation at the higher resolutions where multiple ADC cycles are digitally averaged, the current is reversed several times during the reading sequence rather than just once, as illustrated in figure 3. Not only is static thermal emf cancellation achieved, but changing thermal emfs are also cancelled.

In the Reference Multimeter design being considered^[2], a temperature readout function has been implemented for platinum resistance thermometers by making use of the True Ohms ranges and a stimulus current of 1mA.

Experimental confirmation of True Ohms

An experiment was performed to demonstrate and confirm the operation of the current reversal True Ohms technique under conditions of changing thermal emf. The experimental conditions were deliberately exaggerated to produce an emf several orders of magnitude larger and changing at a much greater rate than normally encountered in practice. Figure 4 illustrates the experiment where the reference multimeter was configured to measure a 10Ω standard resistor using its 20Ω True Ohms range. A thermally lagged K-type thermocouple was connected in series with the Sense Hi signal path, with another long scale dmm measuring the voltage produced across the thermocouple. Readings were taken and stored automatically via IEEE488 and a computer. To run the experiment, the set-up was first allowed to stabilize thermally so that the thermocouple voltage was close to zero (typically less than 100μV). The thermocouple was then plunged into a water bath (vacuum flask) at approximately 35°C with readings taken until the thermally lagged thermocouple element temperature stabilized and the thermocouple voltage reached a steady value (in the region of 400μV).

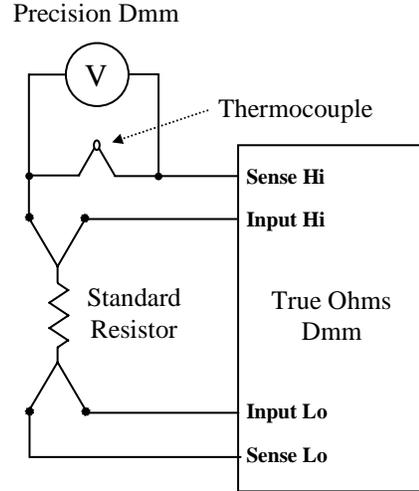


Figure 4. True Ohms experimental setup

The experiment was first run with the Reference Multimeter operating in the Normal Ohms function at 7.5 digit 'fast' resolution. The experiment was then repeated with the Reference Multimeter operating in the True Ohms function at 7.5 digit 'fast' resolution. Results are shown in figure 5. The stimulus current on the 20 Ω range for both Normal and True Ohms functions is 10mA, producing 100mV across the 10 Ω standard resistor. The effect of the changing series thermal emf can be clearly seen on the Normal Ohms readings, contributing 10m Ω for every 100 μ V of series thermal emf. However, the effect is reduced to virtually zero on the True Ohms readings. Close examination of the first few readings taken for True Ohms after the thermocouple was plunged into the water bath show a small changing reading which then settles back and remains constant. This is because the rate of change of thermal emf is extremely high immediately after the thermocouple is plunged into the bath – much higher than would be experienced in practice where thermal emfs are typically a few microvolts changing over several minutes rather than hundreds of microvolts changing in a few seconds. When the rate of change of the thermal emf is high compared to the ADC integration and current reversal times, the thermal emf cancellation is less effective.

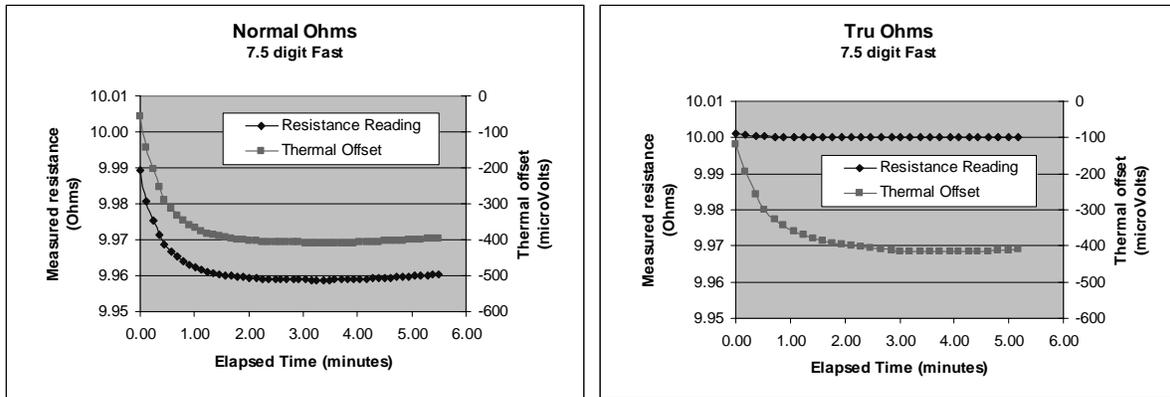


Figure 5. Effect of thermal emf for Normal and True Ohms in 7.5 digit Fast mode

The experiment was repeated, using a faster ADC integration and current reversal time by selecting the 6.5 digit ‘fast’ mode. Results are shown in figure 6, and the small deviation in the True Ohms reading immediately after plunging the thermocouple does not appear because the faster integration and switching times allow the thermal emf cancellation to more closely track the rapidly changing emf. It should be remembered that this experiment deliberately exaggerated the magnitude and rate of change of the thermal emfs compared to the sources of thermal emf that typically give rise to measurement errors in practice. The True Ohms implementation is able to completely cancel changing thermal emfs in practice, enhanced by the use of multiple measurement and reversal cycles for higher resolution reading modes.

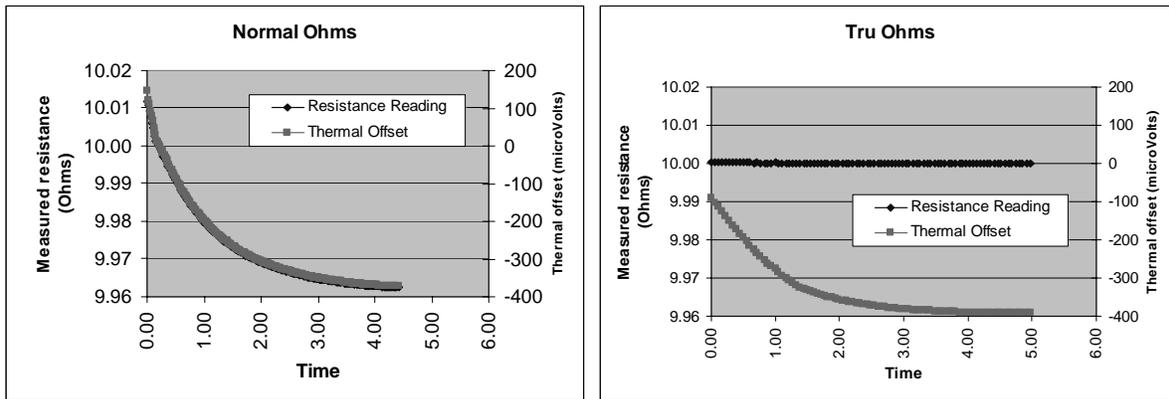


Figure 6. Effect of thermal emf for Normal and True Ohms in 6.5 digit Fast mode

True Ohms Ratio

Two independent input channels (the front and rear input terminals) allow the multimeter to automatically measure two inputs and display the ratio of the two values. This ratio mode is available in the voltage and resistance functions, allowing the multimeter to measure an unknown resistor connected to the front input with respect to a reference resistor connected to the rear inputs – much like a resistance bridge, but with greater simplicity and speed at comparable levels of accuracy. If the two resistances are measured on the same multimeter range the ratio can be measured extremely accurately, dominated by the multimeters linearity performance – better than 0.1ppm. A unique extension of this ratio capability has been implemented in the Reference Multimeter design^[2] to avoid power modulation effects in the resistances being measured as the stimulus and measurement is scanned between the two channels. Instead of switching stimulus current between channels, the two channels are effectively configured in series, as shown in figure 7, so that the stimulus current flows continuously through both resistances being measured. Only the potential difference measurement is scanned, measuring the ratio of the voltage across each resistor with the same constant current flowing continuously through both. The power dissipation in either resistor is constant throughout, regardless of which part of the measurement cycle is being executed. This technique is most beneficial on the lower resistance ranges where stimulus currents are higher, for example 100mA on the 2Ω range. Because lower value resistors are typically measured at relatively low voltages, thermal emf errors can also be more significant, so this special ratio

feature is combined with the True Ohms function, including current reversal. When the Ratio mode is selected in the True Ohms function, the multimeter automatically operates in this ‘voltage ratio’ manner.

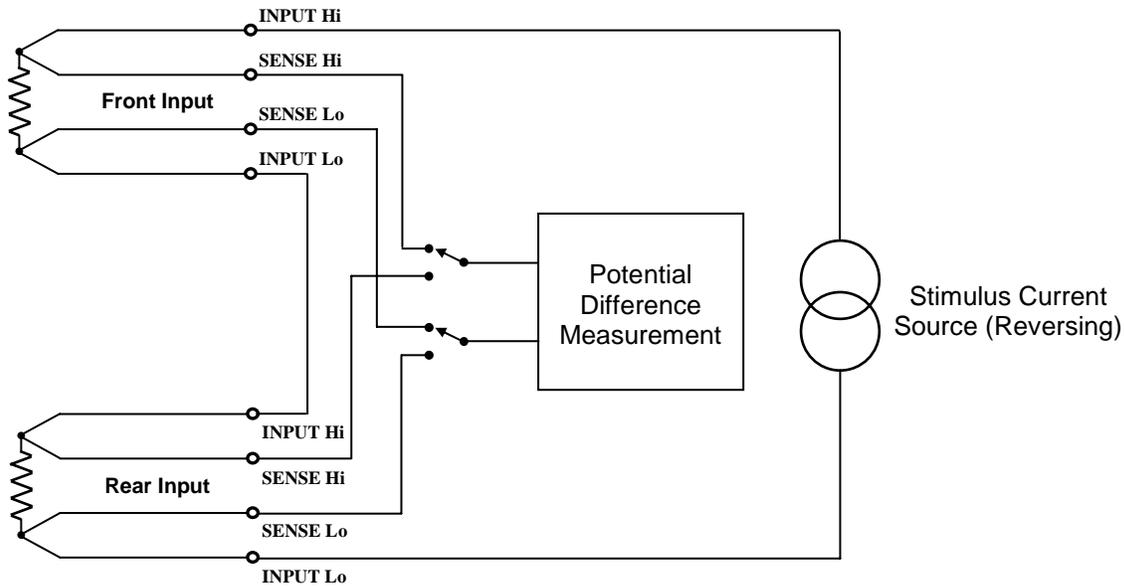


Figure 5. True Ohms Resistance Voltage Ratio Measurement

High Voltage resistance measurements

By increasing the output voltage drive capability of the Lo Follower in figure 2, the ability of the system to measure high resistances can be significantly improved, with ranges up to 20GΩ. In previous implementations of this topology the maximum voltage was 20V, but in this design it has been increased to over 200V. This requires use of the higher voltage ranges within the DC Voltage measurement sub-system (the 200V range) with an input impedance of approximately 10MΩ. However, this relatively low impedance in comparison with the resistances to be measured (up to 20GΩ) is not a problem as any input current taken by the DC Voltage measurement sub-system is simply supplied by the Lo Follower output via the Input Hi terminal, which does not affect the stimulus current provided by the current sink via the Input Lo terminal. Measurement of high resistances at higher voltages improves noise performance, reduces the impact of leakages (because the stimulus current is higher) and allows evaluation of resistor voltage coefficients by making measurements of the same resistor in both normal and high voltage resistance modes.

Conclusion

When using precision multimeters, users should be aware of the impact of ADC integration time selections, how the ADC integration time is related to line frequency to provide rejection of unwanted line pickup, and how an appropriate tradeoff can be made between read rate, effective bandwidth, noise, and resolution.

A new multimeter design^[2] allows users additional capability to avoid common error sources in resistance measurements. By having an appreciation of the internal operation of the multimeter in its various resistance functions and modes, users can select and configure the most appropriate measurement conditions for their application. In doing so many error sources such as thermal emfs and thermal modulation can be avoided, improving the ease and accuracy of precision resistance and related measurements, such as those involving platinum resistance thermometers.

References

- [1] P. Crisp, 'Getting the best from Long Scale Dmms in Metrology Applications', NCSL Conference Proceedings 1997.
- [2] Fluke model 8508A Reference Multimeter
- [3] Solartron model 7081 Digital Multimeter
- [4] Wavetek-Datron model 1281 Digital Multimeter
- [5] Agilent models 3458A and 3458A/HFL Digital Multimeters