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Getting the Best out of Long Scale DMMs in Metrology Applications

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Introduction

Long-scale multifunction DMMs now have the accuracy, resolution and stability to be used in a wide range of metrology applications. This paper describes how one such DMM can be used as an alternative to traditional equipment such as Null Detectors, Kelvin-Varley dividers, and Resistance Bridges. Practical examples are provided, together with a discussion of the precautions that need to be taken to ensure optimum performance, the uncertainties that can be achieved and the relative ease of use compared with traditional methods.

DMM Technology

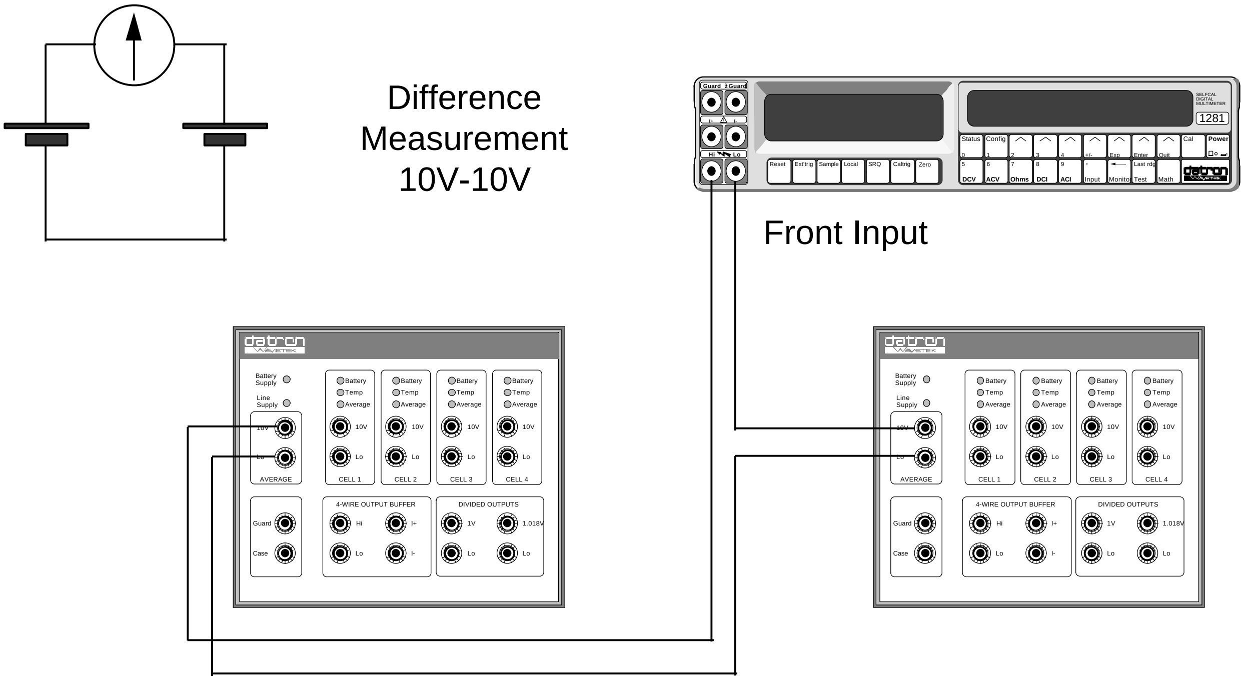
For the purposes of this paper, a long scale DMM is defined as having an available resolution of up to 8½ digits, this corresponds to a scale length or maximum count of ±1.999 999 99. Such resolutions are achieved by the use of multi-slope, multi-cycle analogue to digital converters (ADCs), which are the result of a long and continuous development of a basic and well known charge-balance integrating ADC. A modern DMM[1] can achieve stabilities of better than 2ppm per year, linearity of 1 part in 20 million, noise levels of less than 50nV, input bias current of <10pA and an input resistance of $>10^{10}\Omega$ (for an input up to ±20V). This kind of performance makes them eminently suitable for metrology applications.

Practical DC Applications

Typical DC metrology applications include:- comparing voltage standards, voltage ratio measurements and resistance transfers. For voltage standards, the comparison will typically be of two or more voltages at nominally the same level e.g. comparing two or more Weston cells with a microvoltmeter. Provided that the meter is sensitive enough and the difference between the cells is less than 10µV, this simple detector can give very good results and be able to resolve differences as small as 200nV (0.2ppm of 1V). However, if the cells have a large voltage spread, or if cells at different temperatures are compared, the differences could be as large as a millivolt. A typical microvoltmeter under these conditions would only resolve 20µV on its 1mV range, due to the fundamental limitations of scale length and resolution. A long-scale DMM on its 100mV range can resolve 10nV. Subject to noise limitations, it could measure two cells that were well over 100mV apart and still resolve 10nV.

Electronic, Zener-based references are now widely used and often have outputs at the 10V 1V and 1.018V levels. Comparison between the different voltage outputs requires knowledge of the voltage ratio. Traditionally, high-precision voltage dividers would be used for this task, a known voltage at the 10V level would be divided by a known ratio through the (calibrated) divider and compared at the 1V or 1.018V level using a microvoltmeter. The divider would have to be known for all the required ratios and would be adjusted to null the microvoltmeter. A linear, long-scale DMM can replace these instruments and simplify the measurement. Figure 1 shows the basic arrangement for comparing two standards at the 10V level - the connections would be very similar for 1V or 1.018V.

Fig 1 Voltage Difference Measurement

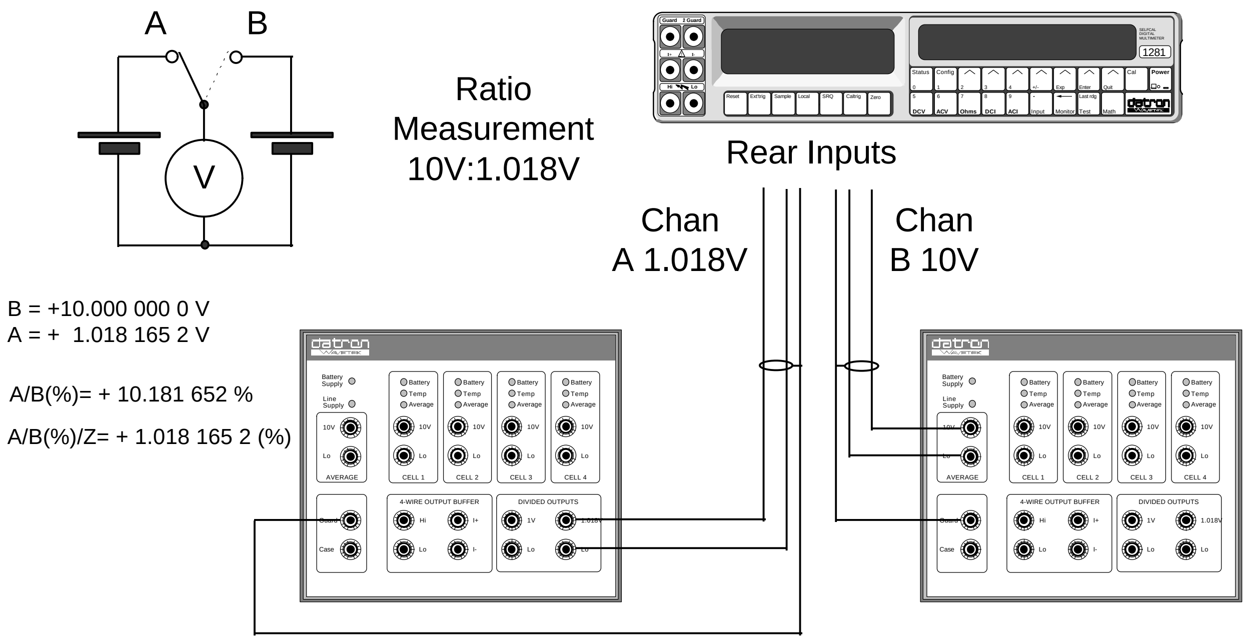


Note that the arrangement is very similar to that described for Weston cells except that now, the DMM (rather than a microvoltmeter) can handle large differences between the two devices without sacrificing resolution. There are no significant problems with this measurement provided that the DMM's isolation to ground does not load the output of either voltage reference and that a preliminary zero operation is performed to remove any residual offsets in the DMM and its connecting leads. The configuration shown is effectively a potentiometric or differential measurement. The DMM is configured to measure the *difference* between the two voltage references.

Ratio Mode and Rear Inputs

The Wavetek 1281 DMM[1] has 3 input channels, two of which (Channels A and B) may be automatically switched to perform a *Ratio* measurement. In ratio mode, the DMM displays the ratio of the inputs in the form A-B, or A/B(%), or (A-B)/B(%). The most commonly used of these ratios is A/B(%). In this mode with say, 10V connected to channel B (reference) and 1V connected to channel A, the display would show +10.000 000 %. This is the ratio of the unknown 1V to the known 10V reference. Note that the DMM is measuring the *whole* voltage for each channel and is configured to a single (10V) range. The only error contributions to this measurement are the uncertainty of the 10V reference standard, the noise and differential linearity of the DMM and the noise of the UUT 1V standard. Typical noise of the DMM is <50nV and differential linearity in 8½ digit mode is better than 0.1ppm over a 10:1 ratio. These figures are similar to that which might be obtained by a skilled metrologist with a freshly calibrated voltage divider and microvoltmeter. The DMM can make this measurement continuously and its linearity does not change significantly with time, so set up costs are lower and the measurement takes less time. Figure 2 shows how the DMM can be used to measure the whole voltage of each reference by using identical multiple input channels in the ratio mode.

Fig 2 Voltage Ratio Measurement



B = +10.000 000 0 V
A = + 1.018 165 2 V

A/B(%)= + 10.181 652 %

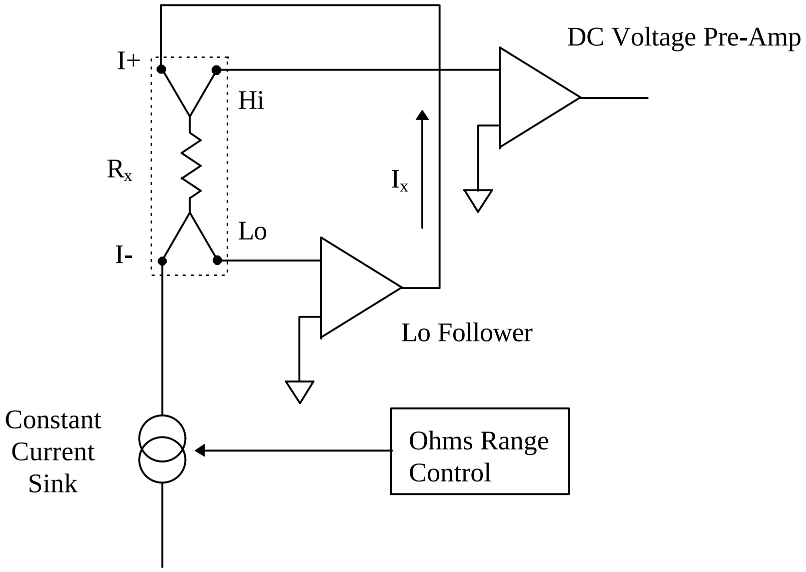
A/B(%)/Z= + 1.018 165 2 (%)

Confirmation of the DMM's linearity beyond the 0.1ppm level is difficult under normal circumstances, however, several instruments of varying age have now been evaluated by national laboratories against 10V Josephson arrays. In this measurement, the Josephson system can be made to generate a series of voltages between 1V and 10V with uncertainties at least an order of magnitude better than the DMM's linearity.

Resistance Applications

Another very useful application of the long-scale DMM is in resistance measurements. An 8½ digit DMM of the type described above has virtually the same linearity on its resistance function as for DC voltage, except in this case, there are no resistance standards accurate enough to be able to be able to *prove* resistance linearity in a conventional sense. One of the problems of trying to measure resistance linearity directly is the uncertainty of the individual resistor values[2]. For example, to measure linearity on the 10kΩ range of a 8½ digit DMM with a maximum indication of 19.000 000 0 kΩ would require several different resistance standards. Assuming that measurements were to be made at a minimum of five evenly spaced points throughout the range e.g. at zero, 5kΩ, 10kΩ, 15kΩ and 19.9kΩ, the difficulties in finding suitable standards soon become obvious. Typically, resistance standards will be available at the normal decade values of 10Ω (25Ω may be available), 100Ω, 1kΩ, 10kΩ, etc. and so do not provide even coverage throughout the range. When one considers that some DMMs have resistance linearity *specifications* of better than 0.3ppm, and that individual resistance standards may have uncertainties of 1ppm or more, test methods using separate resistors or decade boxes will be inadequate. For this reason, resistance linearity is not usually measured for routine calibrations of long-scale DMMs. However, linearity can be verified in the following way. Figure 3 shows the circuit configuration for resistance measurement used in a high accuracy DMM.

Fig 3 DMM Ohms Converter



The resistance option is primarily a range of selectable constant currents. A constant current generator forces a current I_x to flow through the test resistor. A true constant current source will generate a current independently of the voltage developed across its terminals, in this case designated I+ and I-. It therefore follows that if a known resistance is applied to the DMM and the display value noted, the insertion of an additional resistance in series with the I+ lead should not significantly affect the DMM's reading. This will confirm that the current source can deliver the same current through a range of resistance values. If it can also be confirmed that the DC voltage range used for the resistance measurement is also linear, there is then a technically sound way of confirming good resistance linearity without the need for a resistance linearity standard. Note that the series resistance does not need to be a precision resistor - it could be a low-noise potentiometer.

True Ohms

It is taken as read that four wire sensing techniques will be used for the measurement of lower value resistors of say <10kΩ, but what about the effects of voltage offsets? Offsets in resistance measurements have two basic forms or origins. The first of these is the static offset and is caused by junctions of dissimilar metals in the voltage measuring circuit. Typical sources might be within the resistor itself, or connecting leads and terminals. There will also be voltage offsets in the DMM. A simple zero operation (a mathematical subtraction) before the measurement commences will remove these offsets. The second type of offset is dynamic and has a thermal time constant. It is primarily caused by the direct heating of the resistor by the energizing current, but where large currents are involved, can also give rise to thermo-electric effects (Peltier and Seebeck) in external connections too. These dynamic thermal offsets only occur when the current is flowing but because of their long thermal time-constant, can be measured.

Traditional resistance bridge measurements use a specific process to isolate resistance from other unwanted parasitics i.e. voltage offsets. A typical arrangement would be to place the known and unknown resistors in series and pass a current through them. A voltage ratio measurement would then be made of the voltages developed across the potential terminals of each resistor. The current supply would then be reversed and the measurement repeated. The current reversal will remove the effects of the voltage offsets because in one polarity they would add to the measured voltage and in the reverse polarity would subtract from it. The average voltage ratio from the forward and reverse currents will remove the offsets. True Ohms is also very effective (although the current is not reversed), a sequence of measurements is made alternately switching the current through the unknown resistor or via a current bypass (to improve settling), The voltage measured across the resistor with no current flowing is subtracted from that developed across the resistor with the current flowing through it. Although a very simple process, it is *very* effective and can cope easily with *changing* thermal offsets. Figure 4 shows the true ohms principal. The on-off cycle timing of the current through the resistor is carefully chosen to ensure maximum rejection of dynamic offsets. True ohms would normally only be used for the measurement of resistors up to 1kΩ (although it is available up to 100kΩ), there is little effect from thermal emfs above this value and the *reactive* time constant of the resistor may introduce settling errors. A resistor can be modeled as shown in figure 4a with a series voltage source (thermal offset), series inductance and parallel capacitance. For (DC) values up to 100Ω, neither the inductance or capacitance will have any effect, but at 10kΩ and above (where offsets are not usually a problem), depending on the resistor construction, the voltage may never settle in a true ohms measurement.

Fig 4a Resistor Parasitics

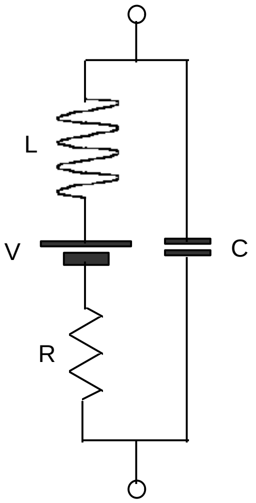
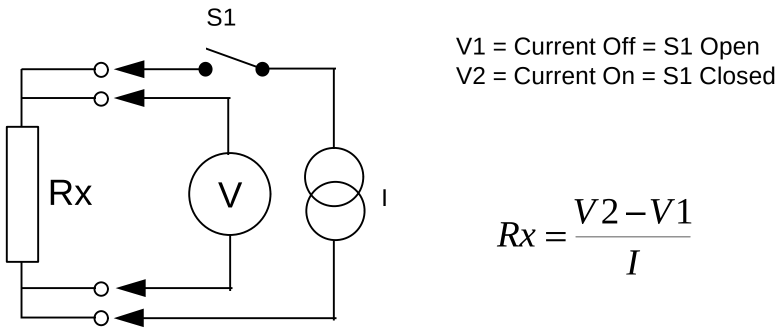


Fig 4b True Ohms Principle

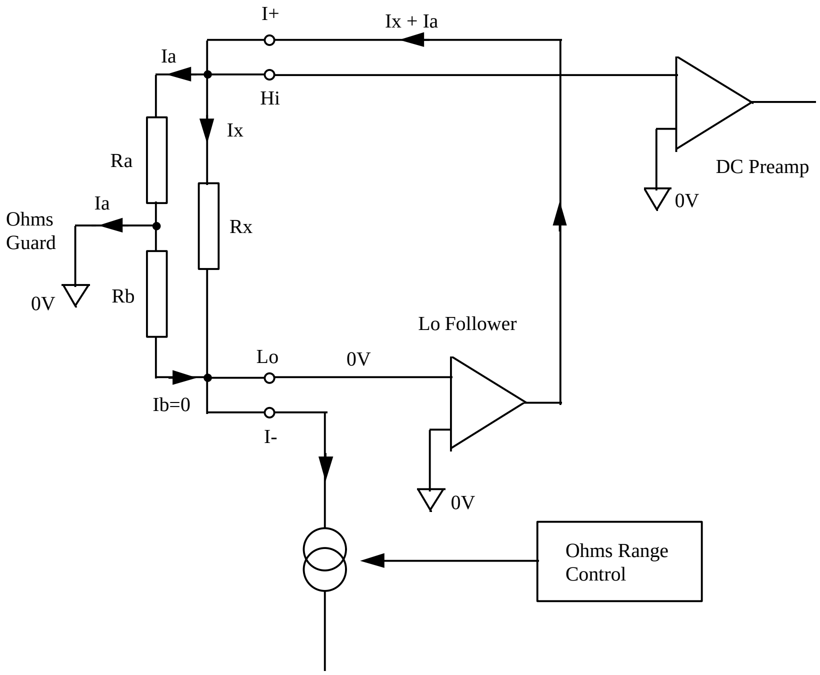


$$Rx = \frac{V2 - V1}{I}$$

Ohms Guard

Another consideration is the effect of parallel leakages in the measurement circuit. Such leakages will divert some current away from the resistor being measured and cause an error in the measurement. A DMM’s Ohms Guard can effectively remove the effects of leakage provided that a suitable connection for the guard is available. Figure 5 shows the Wavetek 1281 DMM’s Ohms guard in use.

Fig 5 Ohms Guard Operation

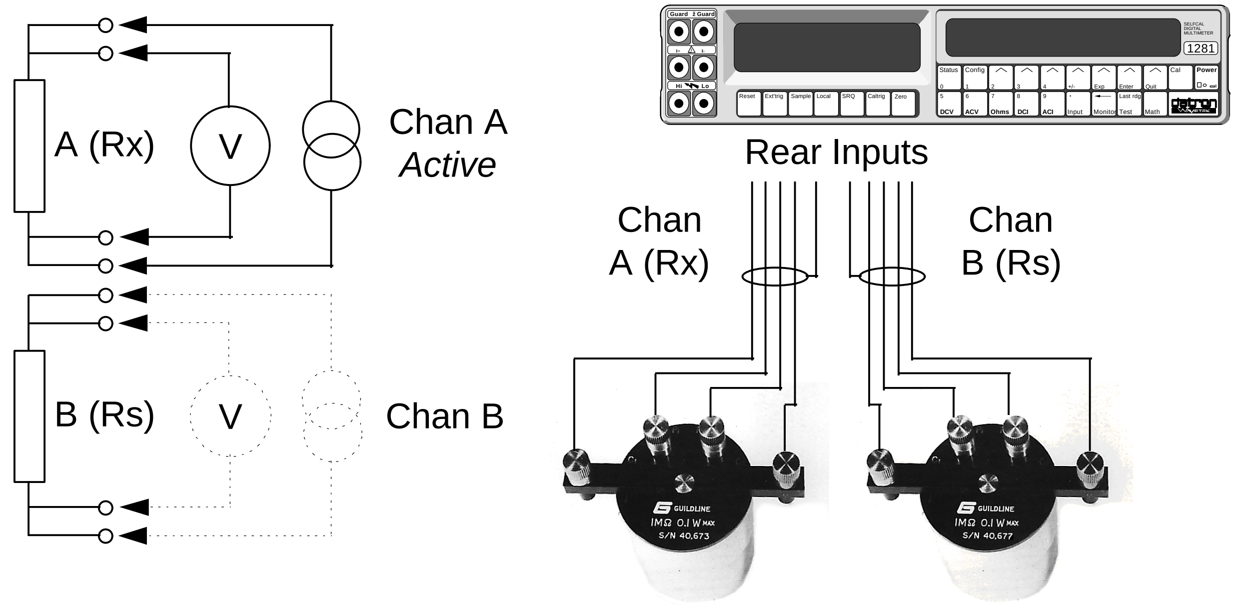


The Lo Follower will maintain Lo and Analogue Common (0V) at the same potential by forcing more current through Rx and Ra until Lo is at 0V (Ib=0). The calibrated current Ix will then be flowing through Rx. Note that where the connection lead insulation is suspect, running I+ and Hi in one screen and I- and Lo in another, whilst connecting both screens to Ohms guard, will remove any leakage between Hi/I+ and Lo/I- because the leakage is “seen” as a parallel resistance path with a convenient tapping (the cable screens) for Ohms guard. Provided the leakage path is less than 250Ω, not only will the leakage current be sourced from the Lo follower (as Ia), but any lead capacitance charge current will also be driven resulting in reduced settling times for high value resistors.

Resistance Transfers and Ratio

True Ohms and Ohms guard are both available from the DMM front and rear inputs, this means that lead leakage can be eliminated from high resistance measurements and voltage offsets eliminated from low resistance measurements. When combined with ratio switching, very high accuracy automated resistance transfers can be performed for both 1:1 and 10:1 ratios. In either case, the DMM will be configured for the appropriate resolution (4½ to 8½ digits), ADC speed, Ohms source current, analogue/digital filter and ratio mode for the particular resistor values concerned. The range selection will be chosen to accommodate the higher of the two resistor values. For example, a 10kΩ to 1kΩ ratio will use the DMM's 10kΩ range - the DMM's excellent DC linearity will ensure the maximum transfer accuracy between the two values. Fig 6 shows the DMM configured via the rear inputs to compare two resistance standards using resistance ratio.

Fig 6 Resistance Ratio

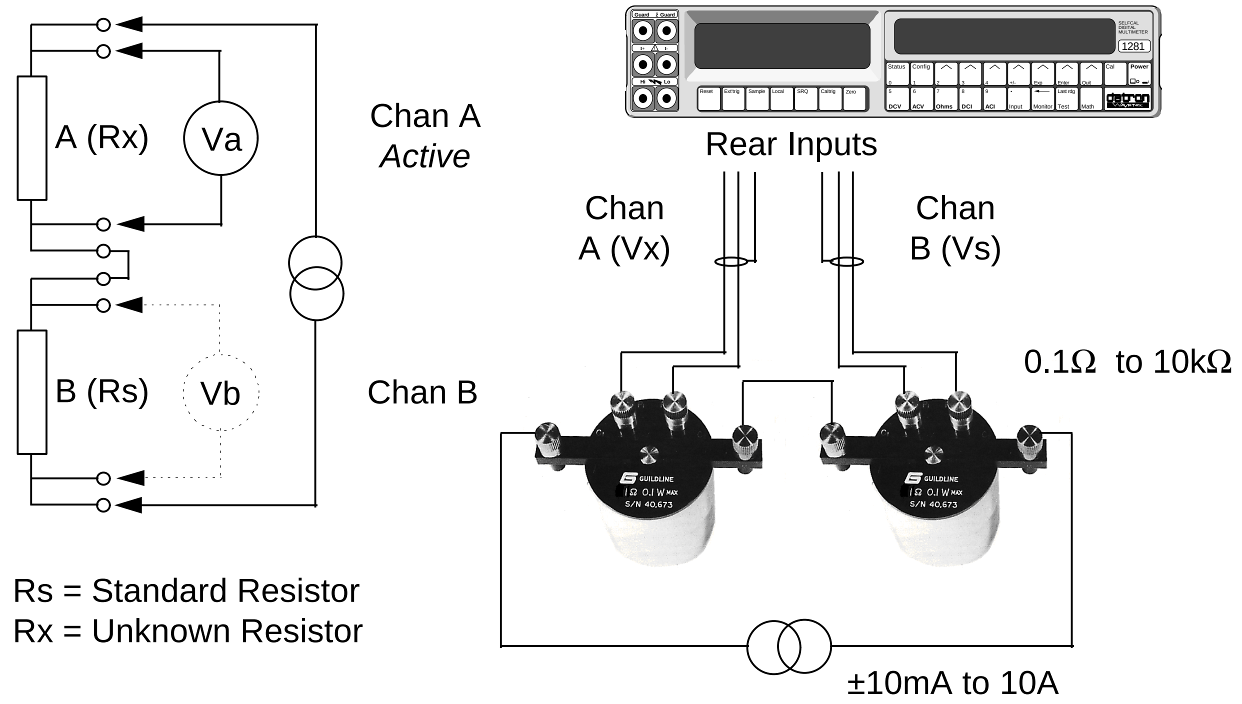


Rs = Standard Resistor
Rx = Unknown Resistor

0.1Ω up to 1GΩ in 1:1 or 10:1 Ratios

Where the value of the resistors to be measured is low e.g. 100Ω or less, a voltage ratio method can also be used. In this mode an external current source provides the test current which is passed through the series connected resistors. The DMM is used in its DC voltage ratio mode. The DMM's internal current source provides a maximum current of 10mA. Using the voltage ratio mode as shown in figure 7, a 100mA, 1A or 10A source could be used. This method allows the resistance ratio range to be extended to include values below 1Ω, e.g. 100mΩ, 10mΩ or even 1mΩ. As mentioned earlier, thermal offsets will be significant for low value resistors - particularly where high currents are involved, therefore it will normally be necessary to reverse the current and take the average of the two voltage ratio measurements.

Fig 7 Voltage Ratio (Resistance)



Decade Box Calibration

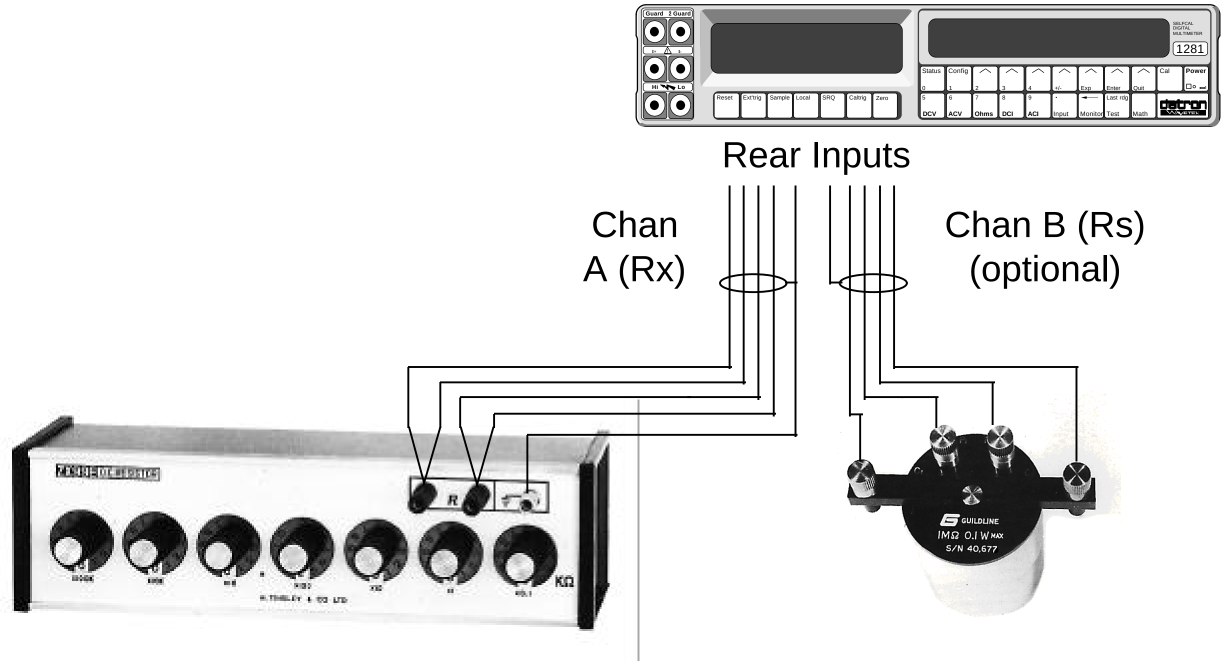
For the calibration of decade resistor boxes, the most convenient method is to use the DMM's accuracy for a direct measurement i.e. not in ratio mode. This is because of the number of measurements required and the reduced accuracy needed for most decade boxes. Most decade boxes are two terminal with a significant zero resistance. True Ohms is very effective for this kind of measurement because it will remove *voltage* offsets but not be affected by *resistance* offsets - although the DMM's input zero function can be used to suppress these also. Figure 8 shows a decade box connected to the DMM on channel A. Channel B would not normally be used, but for the utmost accuracy (a waste of time on most decade boxes!), a transfer could easily be made to a resistance standard connected to channel B. Note that the front input could also be used for either resistor.

A two-wire, six-dial decade box of nominally 10kΩ would require four ranges of the DMM to be used. The DMM would be used in the True Ohms mode with the ranges and resolution set as shown in table1 below. First, a four-wire zero would be made by connecting I+ and Hi to Lo and I- at the decade box Lo terminal. The input zero would then be used to remove any residual resistance offset. The DMM Hi and I+ wires would then be moved to the resistor Hi with all decades set to zero. The DMM will indicate the true zero error of the decade box. After recording the zero value, the resistance offset will be removed by the input zero function and each decade measured in turn at each dial setting up to a maximum of X.XXXXX (11.1111 kΩ). Note that from the resolution table, the relative accuracy of this measurement is very high, and because the DMM resolution is adjusted for each decade, it will also be very fast.

Table 1 Decade Box and DMM Resolution

Dial	Step	Decade	DMM	DMM	Measurement Resolution	
#	Value	Maximum	Range	Digits	% of Step	ppm of 10kΩ
1	1 kΩ	10 kΩ	10 kΩ	7½ d	0.0001%	0.1 ppm
2	100 Ω	1 kΩ	1 kΩ	6½ d	0.001%	0.1 ppm
3	10 Ω	100 Ω	100 Ω	5½ d	0.01%	0.1 ppm
4	1 Ω	10 Ω	10 Ω	5½ d	0.01%	0.01 ppm
5	0.1 Ω	1 Ω	10 Ω	4½ d	1%	0.1 ppm
6	0.01 Ω	0.1 Ω	10 Ω	4½ d	10%	0.1 ppm

Fig 8 Decade Box Calibration



Conclusions

The long-scale DMM has become a very valuable and versatile instrument for high-accuracy metrology applications and is widely used in commercial, military and national standards laboratories. It is a viable and cost-effective alternative to traditional methods and can greatly facilitate automation. This paper has only discussed DC applications of the DMM, there are other areas of DC measurement where such a DMM is invaluable, such as current measurements where the DMM is used to measure the voltage developed across a known resistive current shunt. There are also several AC applications that may be the subject of a future paper.

References

1. Wavetek Model 1281 Selfcal Digital Multimeter User's Handbook, Wavetek Ltd., UK.
2. "A Generic DMM Test and Calibration Strategy". Author: Peter Crisp, Wavetek Ltd., UK.