ısurement Services:

NIST Multifunction Calibration System

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Nile Oldham and Mark Parker

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[1] At Boulder, CO 80303.
[2] Some elements at Boulder, CO.

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NIST MEASUREMENT SERVICES:
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NIST MULTIFUNCTION CALIBRATION SYSTEM

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Abstract - The NIST automated Multifunction Calibration System (MCS) for voltage, current, and resistance is described. Developed primarily to calibrate digital multimeters and calibrators, the system can also be used to test thermal converters, and micropotentiometers. Methods for characterizing the MCS over a wide range of amplitudes at frequencies from dc to 30 MHz are described.

1. INTRODUCTION

Digital multimeters (DMMs) from a number of manufacturers claim uncertainties and stabilities that approach those of the laboratory standards used to support them. This is possible because these DMMs are essentially miniature standards labs with built-in zener references, stable resistors, and ac-dc transfer standards, all controlled by a central processor that applies corrections and performs data analysis. In addition to being easier to use than most standards, DMMs are also quite rugged, able to withstand the mechanical and thermal shocks of transportation from one laboratory to another with little degradation in performance. These properties make them ideal transport standards to provide traceability for the five quantities that most DMMs measure (dc voltage, current, and resistance, and ac voltage and current).

The National Institute of Standards and Technology (NIST) offers *calibration services*[1] for dc voltage, dc resistance, and the ac-dc difference of thermal converters [1-4]. With these three services, standards laboratories can provide direct NIST traceability for the functions measured by most DMMs. Based on customer demand, *special tests*[2] for DMMs (all functions) were offered beginning in 1990 [2-4]. This technical note describes the NIST Multifunction Calibration System (MCS) that is used to provide special test services for DMMs, multifunction calibrators (the programmable sources designed to calibrate DMMs), and special tests for low voltage thermal converters, and micropotentiometers. The MCS is periodically calibrated using reference electrical standards available at NIST. Results of these system calibrations and of frequently performed self-tests are analyzed statistically to maintain quality control of the MCS.

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[1]NIST *calibration services* are well documented and analyzed measurements offered at a fixed cost.

[2]NIST *special tests* are generally undocumented measurements that are charged "at cost."

2. DESCRIPTION OF THE MCS

2.1 MCS Hardware[3]

A block diagram of the MCS instrumentation is shown in Fig. 1. The basic system is quite simple, consisting of a controller, a characterized calibrator (to test DMMs), and two characterized DMMs (to calibrate calibrators and serve as check standards for the system calibrator).

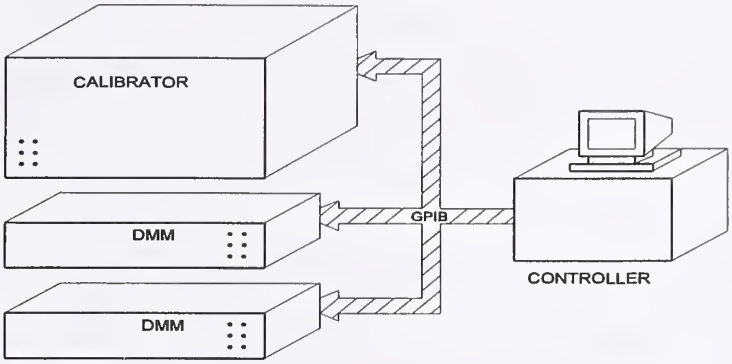

Fig. 1. Simplified diagram of the MCS.

The NIST test facility consists of two such systems which utilize the instruments shown in Table 1:

Table 1
MCS Instrumentation

System 1	System 2
Fluke 5720A Multifunction Calibrator	Wavetek 4808 Multifunction Calibrator
Hewlett Packard 3458A Digital Multimeter	Hewlett Packard 3458A Digital Multimeter
Wavetek 4950 Digital Multimeter	Wavetek 4950 Digital Multimeter
PC Controller with GPIB Card	PC Controller with GPIB Card
Keithley 7001 Switch System	Keithley 7001 Switch System

[3]Commercial instruments and software are identified in this report to describe the measurement system. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the instruments or software are necessarily the best available for the purpose.

The system calibrator and DMMs are periodically characterized using the support equipment and NIST reference standards shown in Table 2 and in Fig. 2.

Table 2
Support Equipment

Function	Support Equipment and NIST Reference Standards
DC voltage (DCV)	NIST 10 V Josephson array Wavetek 4911 10 V zener reference Fluke 752 resistive voltage divider (0.1:1 to 100:1)
DC current (DCI)	NIST standard resistors (0.1 Ω to 100 MΩ) System DMM (DCV)
DC resistance (DCR)	NIST standard resistors System DMM (RES)
AC voltage (ACV)	System calibrator (DCV) NIST thermal voltage converters (0.1 V to 1 kV, 10 Hz to 100 MHz) Ballantine 440 and Holt 12 micropotentiometers (1 mV to 200 mV, 10 Hz to 30 MHz) Wavetek 4920 ac digital voltmeter (1 mV to 200 mV, 1 Hz to 30 MHz) NIST DSS-5 Digitally Synthesized Source (1 mV to 7 V, dc to 1 kHz) Keithley 181 and 182 dc nanovoltmeters Hewlett Packard 34420A nanovoltmeters
AC current (ACI)	System calibrator (DCI) NIST thermal current converters (2 mA to 20 A, 10 Hz to 100 kHz) NIST DSS-5 NIST Transconductance Amplifier NIST ac resistors (0.1 Ω to 100 kΩ)

Instruments are controlled using a PC (486 or higher) and a National Instruments GPIB-PCIIA general purpose interface bus (GPIB) interface card.

2.2 MCS Software

The system software, developed in National Instruments LabVIEW™, allows the operator to perform all of the tests needed to characterize the system calibrator and DMMs, store and edit correction files, and set up and perform tests of the instrument under test (IUT). Since the instrumentation is

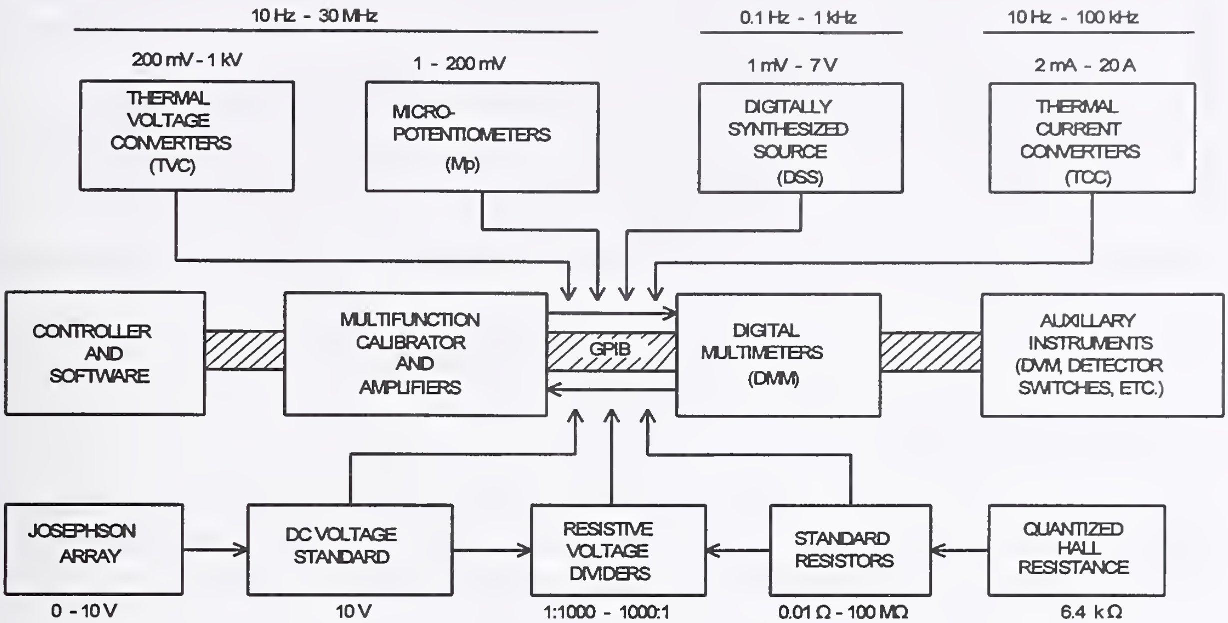

Fig. 2. Block diagram of MCS support equipment.

controlled through the GPIB, most tests can be completely automated, requiring an operator only to change connections between the calibrator and DMM for certain functions. Test data are numerically processed using commercial spreadsheet software. In addition to the software developed at NIST, the MCS also makes use of commercial software to control the 4950 DMM.

Table 3
A list of the software routines available in the MCS

Title	Description
DMM cal	Used to calibrate any of the functions on a test DMM using the MCS calibrator.
Calibrator cal	Used to calibrate any of the functions on a test calibrator using one of the MCS DMMs.
Thermal V/I cal	Used to calibrate the ac voltage and current functions of DMMs and calibrators using thermal converters.
DC V/I cal	Used to calibrate the dc voltage and current functions of the MCS calibrator and DMMs.

DCR	Used to calibrate the resistance function of the MCS calibrator and DMMs.
AC-DC diff	Used to determine the ac-dc difference of thermal voltage/current converters and micropotentiometers.
4950MTS	Software that uses a 4950 DMM to test a calibrator, and store a new set of firmware corrections in Wavetek calibrators.

3. CHARACTERIZING THE MCS

3.1 DC Voltage (DCV)

A Wavetek 4911 10 V zener reference is part of the MCS equipment used to support the DCV function of the system calibrator and DMMs. This instrument is periodically compared to the NIST 10 V Josephson array [5]. A control chart with the zener reference corrections is shown in Fig. 3.

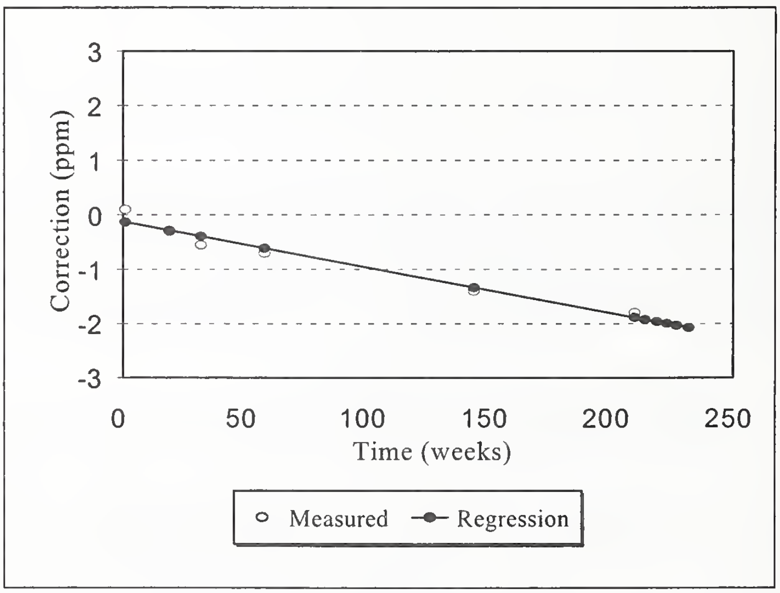

Fig. 3. Control chart with measured and predicted corrections for the zener reference.

Periodically, special resistive dividers, a Fluke 752, and another similar divider designed at NIST, are used to compare five calibrator voltages (100 mV, 1 V, 10 V, 100 V, and 1 kV) to the 10 V zener reference. The dc voltage corrections to the calibrator C_{cDCV} are related to the calibrator setting S and the actual calibrator output voltage V_{cDCV} by:

$$V_{cDCV} = S(1 + C_{cDCV}). \tag{1}$$

A control chart with selected calibrator corrections is shown in Fig. 4. Over long intervals, calibrator corrections tend to drift linearly with time, so a least-squares fit to the correction time series is performed and a linear equation is used to predict the calibrator correction between calibrations.

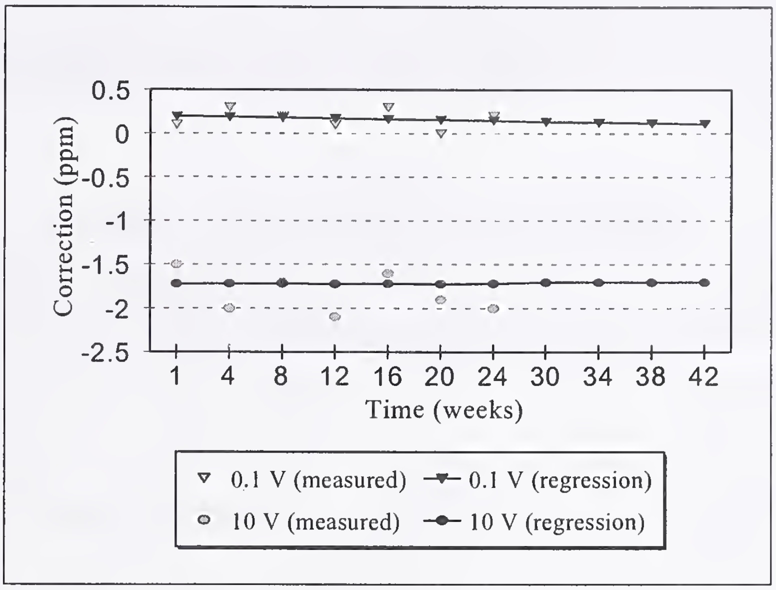

Fig. 4. Control chart with measured and predicted corrections for the MCS calibrator for DCV.

The system DMMs are calibrated at 10 V directly against the zener reference and at other voltages using the characterized calibrator. The DMM corrections C_{dDCV} are related to the DMM reading R and the true voltage V_{DC} by:

$$V_{DC} = R(1 + C_{dDCV}). \tag{2}$$

The system calibrator and DMMs rely on an internal zener voltage reference and timing to generate and measure voltage. The calibrator uses a scaling technique known as time-division-multiplexing, while the DMMs employ multislope integrating analog-to-digital converters. Both techniques are capable of excellent linearity. The linearity of one of the system DMMs has been shown to be better than 1 part in 10^7 of full scale between 1 V to 10 V using the Josephson array [5]. The linearity of other voltage ranges is measured using a calibrated DMM and resistive divider.

For both the calibrator and DMMs, calibration at full scale and 10% of full scale in each range is generally adequate to characterize the full range. The system software linearly interpolates between calibration points to compute calibrator corrections over the full range (>10^7 discrete voltages). These software corrections are applied during the test of a customer's DMM. DMM corrections are processed in a similar manner and applied during the test of a customer's calibrator.

The uncertainty of DCV measurements performed using the MCS depends on uncertainties computed during the test (Type A) and uncertainties associated with the calibration of the MCS (Type B). A description of these uncertainty types and methods of combining them is given in Section 5 and in reference [6].

The Type B standard uncertainties of the MCS calibrator for DCV are given in Table 4. These figures include uncertainties associated with the DCV support equipment described in Table 2. The uncertainties in Table 4 are for the set of points where the MCS is routinely calibrated and monitored (Calibrated Points) and for all other points within the range (Full Range) where corrections are interpolated estimates.

Table 4
MCS Type B Standard Uncertainties for DCV

Voltage Range	Calibrated Points	Full Range
1 mV to 100 mV	5 μV/V + 1 μV	10 μV/V + 1 μV
100 mV to 1 V	2 μV/V + 1 μV	4 μV/V + 1 μV
1 V to 10 V	1 μV/V + 1 μV	2 μV/V + 1 μV
10 to 100 V	2 μV/V	4 μV/V
100 V to 1 kV	3 μV/V	6 μV/V

3.2 DC Current (DCI)

The DCI function of the MCS calibrator and DMMs is periodically calibrated by applying various calibrator currents to a set of NIST reference, four-terminal resistors and measuring the voltage across the resistors using a system DMM. The set of reference resistors consists of values between 0.1 Ω and 1 MΩ that are maintained in oil and air baths with a temperature control of ±0.1 °C, and are periodically calibrated against the NIST resistance standards [7].

To measure the influence of compliance voltage, calibrator currents are measured with the following burdens:

a. reference resistor only,
b. reference resistor and each system DMM,
c. each system DMM only.

The compliance voltage is measured for each burden and the current differences vs compliance voltage are plotted. If there is a significant difference, additional burden measurements are made to cover the expected range of customer's DMM burdens. Linear interpolation between data points is generally adequate to correct the calibrator current.

The dc current corrections to the calibrator C_{cDCI} are related to the calibrator setting S and the actual calibrator output current I_{cDCI} by:

$$I_{cDCI} = S(1 + C_{cDCI}). \tag{3}$$

The system DMMs are also calibrated at various currents by this procedure. The DMM corrections C_{dDCI} are related to the DMM reading R and the true current I_{DC} by:

$$I_{DC} = R(1 + C_{dDCI}). \tag{4}$$

A control chart with selected DCI calibrator corrections is shown in Fig. 5. DCI corrections tend to drift linearly with time, so a least squares fit to the correction time series is performed and a linear equation is used to predict the calibrator correction between calibrations. The system software also linearly interpolates between calibration points to compute corrections over the full range. As with DCV, software corrections are applied during DMM and calibrator tests.

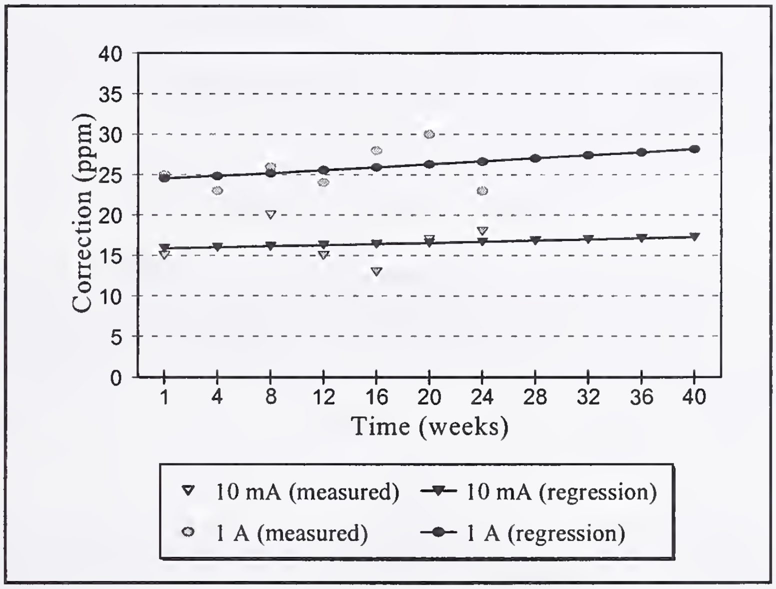

Fig. 5. Control chart with measured and predicted corrections for the MCS calibrator for DCI.

Measurements are performed at cardinal currents between 1 μA and 10 A. Measurements at other currents indicate that, for the calibrator and DMMs, the current linearity is generally as good or better than the current stability. However, for measurement at other than the calibrated points, the MCS corrections are interpolated estimates and uncertainties are somewhat larger. As with DCV, the uncertainty of DCI measurements performed using the MCS depend on Type A and Type B standard uncertainties. The Type B standard uncertainties of the MCS calibrator for DCI (which include the uncertainties of the DCI support equipment described in table 2) are given in Table 5.

Table 5
MCS Type B Standard Uncertainties for DCI

Current Range	Calibrated Points	Full Range
1 µA to 1 mA	20 µA/A + 10 nA	40 µA/A + 10 nA
1 mA to 10 mA	15 µA/A	30 µA/A
10 mA to 100 mA	10 µA/A	20 µA/A
100 mA to 1 A	20 µA/A	40 µA/A
1 A to 10 A	25 µA/A	50 µA/A

3.3 DC Resistance (DCR)

The DCR function of the MCS calibrator and DMMs is periodically calibrated against the set of NIST reference resistors described earlier. Each reference resistor is measured by the system DMMs using the 4-wire DCR function. The dc resistance corrections to the DMM C_{dDCR} are related to the DMM reading R and the true dc resistance R_{DC} by:

$$R_{DC} = R(1 + C_{dDCR}). \tag{5}$$

Once the DMMs are calibrated, they are used to measure the set of resistors in the system calibrator. The corrections to the calibrator resistors are based on the average of values assigned by the system DMMs. The dc resistance corrections to the calibrator C_{cDCR} are related to the calibrator setting S and the actual calibrator dc resistance R_{cDCR} by:

$$R_{cDCR} = S(1 + C_{cDCR}). \tag{6}$$

A control chart with selected DCR calibrator corrections is shown in Fig. 6. DCR corrections also tend to drift linearly with time, so a least squares fit to the correction time series is performed and a linear equation is used to predict the calibrator correction between calibrations. The system software also linearly interpolates between calibration points to compute corrections over the full range (DMMs only). As with other functions, software corrections are applied during DMM and calibrator tests.

Measurements are performed at nominal decade resistance values from 0.1 Ω to 100 MΩ using the DMMs. Decade resistance values between 1 Ω and 10 MΩ are available on the system calibrator.

Other than decade values may be measured using the system DMMs, which demonstrate resistance linearity as good or better than resistance stability. However, for measurement at other than the calibrated points, the MCS corrections are interpolated estimates and uncertainties are somewhat larger. The Type B standard uncertainties of the MCS DCR (which include the uncertainties of the

DCR support equipment described in table 2) are given in Table 6.

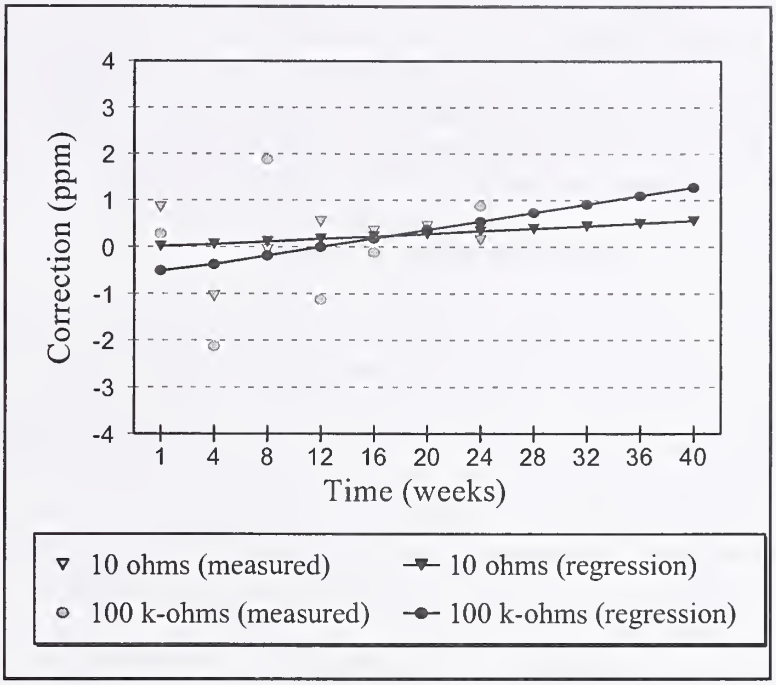

Fig. 6. Control chart with measured and predicted corrections for the MCS calibrator for DCR.

Table 6
MCS Type B Standard Uncertainties for DCR

Resistance Range	Calibrated Points	Full Range
1 Ω	20 μΩ/Ω	60 μΩ/Ω
10 Ω	10 μΩ/Ω	30 μΩ/Ω
100 Ω	6 μΩ/Ω	18 μΩ/Ω
1 kΩ	3 μΩ/Ω	9 μΩ/Ω
10[illegible] Ω	3 μΩ/Ω	9 μΩ/Ω
100 kΩ	4 μΩ/Ω	12 μΩ/Ω
1 MΩ	5 μΩ/Ω	15 μΩ/Ω
10 MΩ	20 μΩ/Ω	60 μΩ/Ω
100 MΩ	30 μΩ/Ω	90 μΩ/Ω

3.4 AC Voltage (ACV)

The low-frequency ACV function of the MCS calibrator and DMMs is periodically calibrated using a multirange thermal voltage converter (TVC) that has been calibrated against a set of NIST reference TVCs, micropotentiometers, and a calculable DSS [8] . The ac-dc differences of these support instruments are ultimately referenced to a set of characterized TVCs that are the NIST standards for ac-dc difference [9]. The test procedures for characterizing the system calibrator and DMMs for ACV are more complex than the other functions and will be described in detail.

3.4.1 Voltages from 1 mV to 1 kV from 10 Hz to 1 MHz

The multirange TVC is connected to the MCS calibrator and to the DMM (both set to the ACV mode) as shown in Fig. 7. The nominal ac voltage V at frequency f_1 is programmed and the output emf of the TVC, e_a is measured using the dc digital voltmeter (DVM). The calibrator function is switched to +DCV and the amplitude is programmed to $+V$. The calibrator voltage is adjusted to V_{+d1} to bring the TVC emf e_{+d1} to within $\pm t$ of e_a . [The operator selectable tolerance t is typically between 10 µV/V and 50 µV/V.] The calibrator is switched back to ACV and the TVC emf e_{a1} and the DMM ACV reading R_{a1} are recorded. The calibrator is then switched to -DCV and adjusted to V_{-d1} to bring the TVC emf e_{-d1} to within $\pm t$ of e_{a1} . The above procedure is repeated for frequencies f_2 through f_i

The TVC is disconnected, the calibrator is switched to ACV, frequencies f_1 through f_i are set at the same nominal voltage V, and the DMM readings R_{b1} through R_{bi} are recorded.

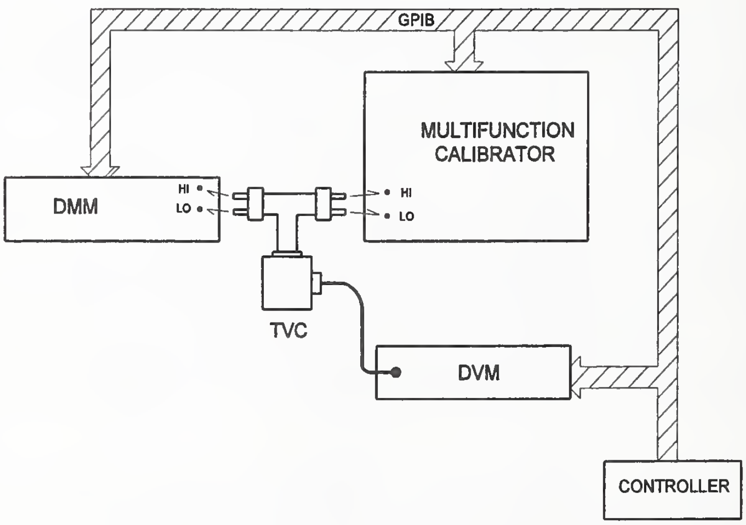

Fig. 7. Setup for characterizing the ACV function of the MCS using a multirange TVC.

The calibrator correction for each test voltage at frequency f_i is described by:

$$C_{cACVi} = (V_{di} - V) / V_{di} + (e_{ai} - e_{di})/(ne_{di}) + D_i + C_{cDCV}, \tag{7}$$

where $V_{di} = (V_{+di} - V_{-di})/2$ {ave. dc voltage}
$e_{di} = (e_{+di} + e_{-di})/2$ {ave. TVC emf with ±DCV applied}
n = the TVC power coefficient at the nominal voltage
D_i = the ac-dc difference of the TVC at the nominal voltage at f_i
C_{cDCV} = the average calibrator DCV correction.

The DMM correction for each test voltage at frequency f_i is given by:

$$C_{dACVi} = (V(1 + C_{cACVi}) - R_{ai})/R_{ai}. \tag{8}$$

where R_{ai} = the DMM reading of the test voltage at f_i.

Notes: i. *The above procedure is designed to allow the MCS to be calibrated using the reference TVCs as well as the multirange TVC. By driving the dc voltage to match the TVC output when ac voltage is applied, the importance of an accurate knowledge of the TVC power coefficient n is minimized by minimizing the numerator in the second term of (7). For the reference TVCs, this coefficient varies between 1.6 and 2 as a function of the test voltage and must be measured at each voltage. The multirange TVC has a nominal power coefficient of 1, which is relatively insensitive to the test voltage, so the tolerance t may be increased to reduce test time.*

ii. *The reference TVC time constants are typically 1 s to 2 s; therefore, a wait period of up to 30 s is required before recording the TVC emf. To minimize the effects of drift, it is important that all of the wait periods are the same for a particular set of measurements. The multirange TVC settles in about 10 s and has a low drift rate so timing is not as critical.*

iii. *It is important that the dead time in switching from the ACV to the DCV functions is minimized. For the highest accuracy using reference TVCs, a switch and auxiliary supply are used to keep the TVC energized while the calibrator is switching between functions. The multirange TVC is less sensitive to switching time.*

iv. *The dc DVM should be able to resolve the TVC emf to within ±1 μV/V. This resolution corresponds to several nV for the reference TVCs (which have output emfs from 2 mV to 10 mV) and several μV for the multirange TVC (which has a full scale output of about 2 V).*

v. *Depending on the random error of the measurements, an actual calibration consists of from 1-10 repeats of the described procedure.*

As the test frequency increases the calibrator becomes more sensitive to the load imposed by the TVC and the test DMM. Therefore, to obtain the lowest uncertainties, the calibrator must be characterized for each DMM type using the procedure described above. The second set of DMM readings R_{bi} is used to generate unique corrections $C_{cACVi(X)}$ for all DMMs of that type (type-X DMMs for this example). These corrections apply only when a type-X DMM is connected to the calibrator using the same connectors and cables that were used to obtain the set of R_{bi} readings. The unique set of calibrator corrections for each DMM type are given by:

$$C_{cACVi(X)} = C_{cACVi} + C_{di(X)}. \tag{9}$$

where $C_{di(X)} = (R_{bi(X)} - R_{ai(X)})/V_i$ represents the additional correction needed to compensate for the difference between the calibrator output voltage (programmed to V_i) with the TVC and type-X DMM connected and with only the type-X DMM connected.

3.4.2 Voltages from 1 mV to 250 mV from 10 Hz to 1 MHz

A reference micropotentiometer (μpot) is connected to the system calibrator output and a DMM is connected to its output as shown in Fig. 8. The calibrator is set to the ACV function at 1 kHz and its voltage is adjusted until the DMM reading R_{r0} is within ±t of the test voltage V. The DMM reading R_{r0} and the μpot output emf e_{r0} are recorded. The calibrator frequency is programmed to f_1 (the first test frequency), the calibrator voltage is adjusted until the μpot emf e_{a1} is within $\pm t$ of e_{r0}, and the DMM reading R_{a1} is recorded. The calibrator is programmed to 1 kHz, the calibrator voltage is adjusted until the nominal test voltage $V \pm t$ is read by the DMM, and its reading R_{r1} and the μpot emf e_{r1} are recorded. The procedure is repeated for frequencies f_2 through f_i interleaving a 1 kHz measurement between measurements at each test frequency.

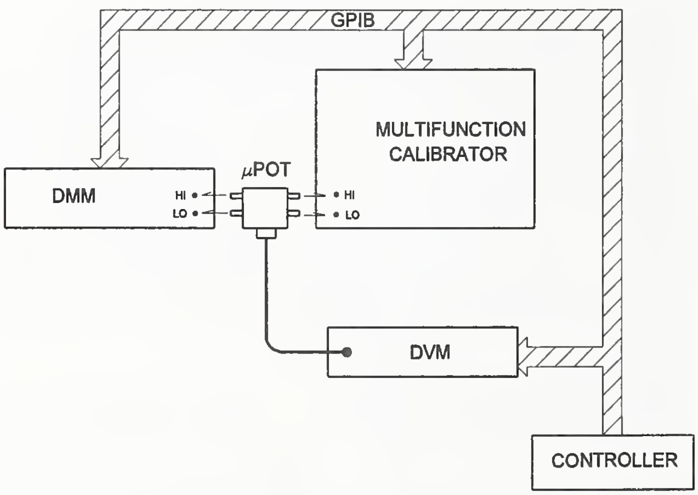

Fig. 8. Setup for characterizing the ACV function of the MCS using a μpot.

The μpot is removed, the DMM is connected directly to the calibrator output, frequencies f_1 through f_i are set at the test voltage V, and the DMM readings R_{b1} through R_{bi} are recorded.

The DMM corrections for each test voltage at frequency f_i is described by the following relationship:

$$C_{di} = (R_{Ri} - R_{ai})/R_{Ri} + (e_{ai} - e_{Ri})/(ne_{Ri}) + D_i + C_{dR}, \quad (10)$$

where $R_{Ri} = (R_{r(i-1)} + R_{ri})/2$ {ave. 1-kHz reading}
$e_{Ri} = (e_{r(i-1)} + e_{ri})/2$ {ave. μpot emf with 1 kHz applied}
n = the μpot power coefficient at output voltage V
D_i = the ac 1-kHz difference of the μpot at output V at f_i
C_{dR} = the DMM 1-kHz correction.

The calibrator correction is given by:

$$C_{ciA} = (R_{bi}(1 + C_{di}) - V)/V \quad (11)$$

where R_{bi} = the DMM reading of the test voltage at f_i.

3.4.3 Voltage from 250 mV to 7 V from 10 Hz to 30 MHz

Measurements are performed using the calibrator 50-Ω wideband output port. Special 50 Ω TVCs, calibrated out to 30 MHz, are used to measure the amplitude flatness of the calibrator using a technique similar to that described in 3.4.1, except the calibrator is left on the ACV function and each test frequency is referred back to 1 kHz.

A 50 Ω TVC is connected to the wideband output of the MCS calibrator and to a wideband DMM in a similar manner as shown in Fig. 7. The nominal voltage V at frequency f_1 is programmed and the TVC emf e_a is measured using the dc DVM. The calibrator frequency is set to 1 kHz and its amplitude is adjusted to V_{r0} to bring the TVC emf e_{r0} to within $\pm t$ *of* e_a. The calibrator frequency is set to f_1 and the TVC emf e_{a1} and the DMM reading R_{a1} are recorded. The calibrator is reprogrammed to 1 kHz and adjusted to V_{r1} to bring the TVC emf e_{r1} to within $\pm t$ *of* e_{a1}. The above procedure is repeated for frequencies f_2 through f_i.

The TVC is disconnected, frequencies f_1 through f_i are set at the same nominal voltage V, and the DMM readings R_{b1} through R_{bi} are recorded.

The calibrator correction for each test voltage at frequency f_i is described by:

$$C_{cACVi} = (V_{Ri} - V)/V + (e_{ai} - e_{di})/(ne_{di}) + D_i + C_{cR}, \quad (12)$$

where $V_{Ri} = (V_{r(I-1)} - V_{-ri})/2$ {ave. 1-kHz voltage}
$e_{di} = (e_{+di} + e_{-di})/2$ {ave. 1-kHz TVC emf}
n = the TVC power coefficient at V
D_i = the ac-dc difference of the TVC at V at f_i
C_{cR} = the calibrator 1 kHz correction at V.

The DMM correction for each test voltage at frequency f_i is then given by:

$$C_{dACVi} = (V\,(1 + C_{cACVi}) - R_{ai})/R_{ai}, \tag{13}$$

where R_{ai} = the DMM reading of the test voltage at f_i.

3.4.4 Voltages from 1 mV to 1 kV from 0.01 Hz to 1 kHz

A programmable digitally synthesized source (DSS) developed at NIST is employed in place of the system calibrator to perform high accuracy, low-frequency tests of DMMs. The DSS synthesizes a staircase approximation of a sine wave using a sine look-up table and a precision digital-to-analog converter (DAC). Output voltages are programmable between 1 mV and 7 V (for higher voltages an external dc-coupled amplifier is used). A DMM (on its DCV function) is used to measure the dc voltage of each of the steps in the approximation. The rms value of the output voltage V_s is computed by this step calibration:

$$V_s = (\Sigma v_i^2 / N)^{1/2}, \tag{14}$$

where v_i = the dc voltages of the steps
N = the number of step per period.

The frequency response rms error of the synthesized signal is measured between 20 Hz and 1 kHz using a calibrated multirange TVC. Below 20 Hz, it is assumed that the rms value remains constant to within ±2 μV/V. At 7 V, the frequency response out to 1 kHz is flat to within ± 5 μV/V. This performance degrades at lower voltages; however, even at 1 mV, the DSS may be treated as an ac calibrator with zero correction below 20 Hz. DMMs calibrated using the DSS are assigned corrections C_{dACVi} by:

$$C_{dACVi} = (V_s\,(1 + C_{DSSi}) - R_{bi})/R_{bi}, \tag{15}$$

where R_{bi} = the DMM reading at frequency f_i
C_{DSSi} = the DSS correction to V_s at frequency f_i .

Control charts for the ACV function corrections of the system calibrator and DMMs are quite complex covering voltage, frequency, and DMM type. A sample chart for the ACV calibrator corrections at 10 V at 10 kHz is shown in Fig. 9. ACV corrections are less predictable than the DCV corrections; however, until the drift patterns are better understood, a least squares linear fit to the correction time series is performed and a linear equation is used to predict the calibrator correction between calibrations. The system software also linearly interpolates between calibration points to compute corrections over the full range. Specific software corrections for the DMM type being tested are applied where possible and all interconnection parameters are specified. In a similar manner, when a calibrator is tested using a system DMM, the DMM type and all interconnection parameters are specified. Measurements are performed at a specific set of voltages and frequencies from 1 mV to 1 kV and 0.1 Hz to 30 MHz. Measurements can be made at other than the calibrated points;

however, because the corrections at these points are interpolated estimates, the MCS uncertainties are somewhat larger. The Type B standard uncertainties of the MCS ACV function are given in Table 7.

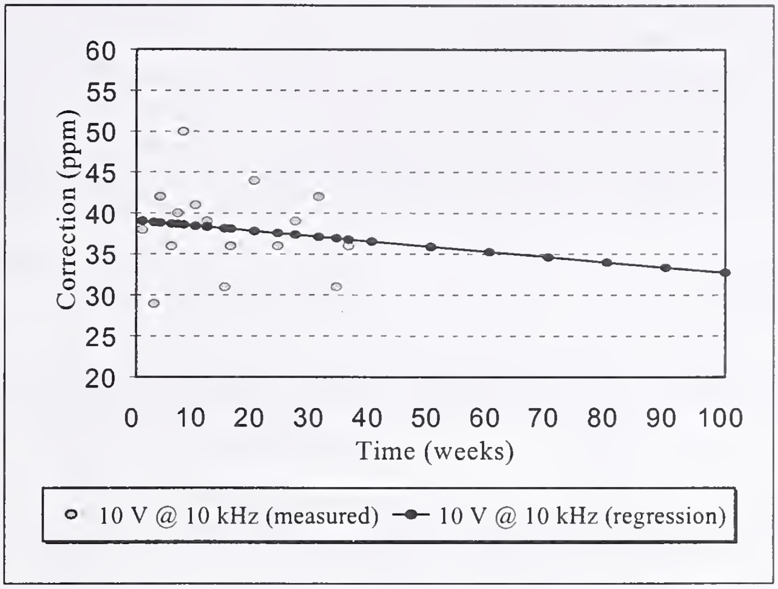

Fig. 9. Control chart with measured and predicted corrections for the MCS calibrator at 10 V and 10 kHz.

Table 7
MCS Type B Standard Uncertainties for ACV

Voltage Range	Calibrated Points	Full Range
1 mV to 10 mV	(10/v)(70 + f)μV/V	(10/v)(200 + f)μV/V
10 mV to 100 mV	(70 + f/2)μV/V	(200 +f/2)μV/V
100 mV to 500 mV	(20 + f /5)μV/V	(60 + f/5)μV/V
500 mV to 100 V	(10 + f/10)μV/V	(30 + f/10)μV/V
100 V to 1 kV	(20 + f/5)μV/V	(60 + f/5)μV/V

Where v = test voltage in mV and f = test frequency in kilohertz.

3.5 AC Current (ACI)

The ACI function of the MCS calibrator and DMMs is periodically calibrated against a set of reference thermal current converters (TCCs), ac shunts, and a calculable DSS. The ac-dc differences of these support instruments are ultimately referenced to a set of characterized TCCs that are the NIST standards for ac-dc difference [10]. The test procedures for characterizing the system calibrator and DMMs for ACI are also described in detail.

3.5.1 Currents from 2 mA to 10 A from 10 Hz to 100 kHz

The reference TCC is connected to the system calibrator and DMM (both set to the ACI function) as shown in Fig. 10. The calibrator is programmed for the nominal current I at frequency f_1 and the TCC output emf e_a is measured by the dc DVM. The calibrator function is switched to +DCI and programmed to $+I$. The calibrator current is adjusted to I_{+d1} to bring the TCC emf e_{+d1} to within $\pm t$ μV/V of e_a. The calibrator is switched back to ACI, the TCC emf e_{a1} and the DMM ACI reading R_{a1} are recorded. The calibrator is then switched to -DCI and the negative polarity dc current is adjusted
to I_{-d1} to bring the TCC emf to within $\pm t$ μV/V of e_{a1}. The above procedure is repeated for frequencies f_2 through f_i.

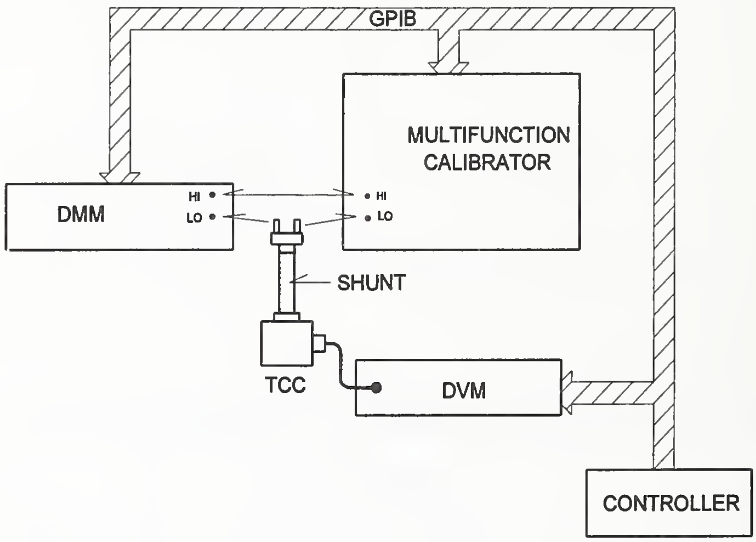

Fig. 10. Setup for characterizing ACI function of MCS calibrator using a TCC.

The TCC is removed, the calibrator is switched to ACI, frequencies f_1 through f_i are set at the same nominal current I, and the DMM readings R_{b1} through R_{bi} are recorded. The calibrator correction at each test current at frequency I is described by:

$$C_{cACIi} = (I_{di} - I)/I + (e_{ai} - e_{di})/(ne_{di}) + D_i + C_{cDCI}, \tag{16}$$

where $I_{di} = (I_{+di} - I_{-di})/2$ {ave. dc current}

$e_{di} = (e_{+di} + e_{-di})/2$ {ave. TCC emf with ±DCI applied}

n = the TCC power coefficient at the nominal voltage

D_i = the ac-dc difference of the TCC at the nominal voltage at f_i

C_{cDCI} = the average calibrator DCI correction.

The DMM correction at each frequency C_{dACIi} is given by:

$$C_{dACIi} = (I\,(1 + C_{cACIi}) - R_{ai})/I. \tag{17}$$

As the frequency increases the calibrator becomes more sensitive to the load imposed by the TCC and the test DMM. Therefore, for the highest accuracy test of a particular DMM type, the above procedure must be performed using that DMM type. The second set of DMM readings R_{bi} is used to generate unique corrections $C_{cACIi(X)}$ for all DMMs of that type (type-X DMMs for this example). These corrections apply only when a type-X DMM is connected to the calibrator using the same connectors and cables that were used to obtain the set of R_{bi} readings. These corrections are given by:

$$C_{cACIi(X)} = C_{cACIi} + C_{di(X)}, \tag{18}$$

where $C_{di(X)} = (R_{bi(X)} - R_{ai(X)})/I$ represents the additional correction needed to compensate for the difference between the calibrator output current (programmed to I_i) with the TCC and type-X DMM connected, and with only the type-X DMM connected.

As with DCI, ACI measurements are made at various compliance voltages and a correction factor for the calibrator compliance voltage is applied when testing a DMM type that has not been characterized with the system calibrator.

Control charts for the ACI function corrections of the system calibrator and DMMs are also quite complex covering current, frequency, and DMM type (or compliance voltage). A sample chart for the ACI calibrator corrections at 1 A, at 1 kHz for one of the DMM types is shown in Fig. 11. ACI corrections are less predictable than the DCI corrections; however, until the drift patterns are better

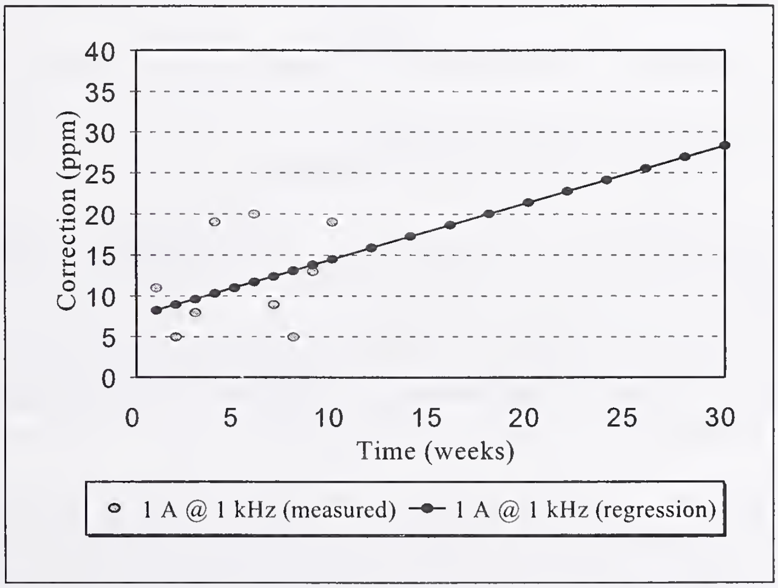

Fig. 11. Control chart with measured and predicted corrections for the MCS calibrator for ACI.

understood, a least squares linear fit to the correction time series is performed and a linear equation is used to predict the calibrator correction between calibrations. The system software also linearly interpolates between calibration points to compute corrections over the full range. Specific software corrections for the DMM type being tested are applied where possible and all interconnection parameters are specified. In a similar manner, when a calibrator is tested using a system DMM, the DMM type and all interconnection parameters are specified.

3.5.2 Currents from 2 mA to 10 A from 0.01 Hz to 1 kHz

The NIST DSS and Transconductance Amplifier are employed to perform high accuracy, low frequency current tests of DMMs. A DMM (on its DCI function) is used to measure the dc current of each of the steps in the waveform approximation. The rms value of the output current I_s is computed by this step calibration:

$$I_s = (\Sigma i_i^2 / N)^{1/2}, \tag{19}$$

where i_i = the dc currents of the steps
N = the number of steps per period.

The frequency response error of the synthesized signal is measured between 20 Hz and 1 kHz using a calibrated TCC. Below 20 Hz, it is assumed that the rms value remains constant to within ±2 μA/A. At currents between 100 mA and 10 A, the frequency response out to 1 kHz is flat to within ±100 μA/A. This performance degrades at lower currents; however, even at 1 mA, the DSS may be treated as an ac calibrator with zero correction below 20 Hz. DMMs calibrated using the DSS are assigned corrections C_{dDCIi} by:

$$C_{dDCIi} = (I_s\,(1 + C_{DSSi}) - R_{bi})/R_{bi}, \tag{20}$$

where R_{bi} = the DMM reading at frequency f_i
C_{DSSi} = the DSS correction to I_s at frequency f_i .

Again, a least squares linear fit to the correction time series is performed and a linear equation is used to predict the calibrator correction between calibrations. The system software also linearly interpolates between calibration points to compute corrections over the full range. Specific software corrections for the DMM type being tested are applied where possible and all interconnection parameters are specified. In a similar manner, when a calibrator is tested using a system DMM, the DMM type and all interconnection parameters are specified.

Measurements are performed at a specific set of currents and frequencies from 1 mA to 1 A and 0.1 Hz to 1 kHz. Measurements can be made at other than the calibrated points; however, because the corrections at these points are interpolated estimates, the MCS uncertainties are somewhat larger. The Type B standard uncertainties of the MCS ACV function are given in Table 8.

Table 8
MCS Type B Standard Uncertainties for ACI

Current Range	Calibrated Points	Full Range
1 mA to 10 A	$(50 + 2f)\mu A/A$	$(150 + 3f)\mu A/A$

Where f = test frequency in kilohertz.

4. CALIBRATIONS AND TESTS USING THE MCS

Once the system calibrator and DMMs have been characterized, the MCS is used to test customer's DMMs, calibrators, and related instruments.

Prior to testing, the test instrument is energized in the MCS lab overnight, to allow it to stabilize and to satisfy any warmup requirements. Then, self-calibration or auto-zeroing routines are performed to bring the instrument to its rated uncertainty.

4.1 Calibration of DMMs Using the MCS Calibrator

Unless otherwise requested, the DMM is calibrated at its input terminals. Using an adjustable platform, the DMM terminals are brought "nose-to-nose" with the MCS calibrator terminals so that only a few centimeters of connectors are required to interconnect them as shown in Fig. 12. The calibrators have six output terminals including outputs (hi and lo), sense (hi and lo), guard and ground. Test DMMs have a similar set of input terminals. Tables 9 - 11 list the interconnections made for typical DMM calibrations.

Table 9
Connections and configuration for a DCV or ACV calibration

From	**To**
Calibrator voltage output hi	DMM input hi
Calibrator voltage output lo	DMM input lo Calibrator guard and ground

The calibrator is programmed to *local sense* and *local guard*, and the DMM is programmed or switched to *local guard*.

Table 10
Connections and configuration for a DCI or ACI calibration

From	To
Calibrator current output hi	DMM current input hi
Calibrator current output lo	DMM current input lo Calibrator guard and ground

The calibrator is programmed to *local guard*, and the DMM is programmed or switched to *local guard.*

Table 11
Connections for a DCR (4-wire) calibration

From	To
Calibrator resistance output hi	DMM resistance input hi
Calibrator resistance output lo	DMM resistance input lo
Calibrator resistance sense hi	DMM resistance sense hi
Calibrator resistance sense hi	DMM resistance sense hi
Calibrator guard	DMM guard Calibrator ground

The calibrator is programmed to *remote sense* and *local guard*, and the DMM is programmed or switched to *local guard.*

Calibrations are performed by programming the MCS calibrator to the desired function and setting, triggering the DMM (the first reading is ignored), and recording the next N readings.

The average reading of the DMM under test R, its associated correction C_{TDMM}, the system calibrator setting S, and its correction C_{SCAL} are related by the following equation:

$$R(1+C_{TDMM}) = S(1 + C_{SCAL}). \tag{21}$$

Certain DMMs have software correction tables that are used to keep the instrument within a particular specification. Correction tables are updated by applying a reference signal from the MCS calibrator and then initiating a GPIB "correction" command that changes the appropriate correction value until the DMM displays the proper value to within a selectable tolerance. Both the MCS software and the Wavetek 4950 software have this capability. Repeat tests are performed to verify that the DMM correction table has been accurately modified. This service represents a change in the long-standing NIST policy of not adjusting instruments submitted for test. However, instead of making an analog adjustment which can not generally be undone, in this case the adjustment is digital. The initial corrections are stored in the instrument and the residual corrections are given in the test report. The uncertainties of the residual corrections are based on the standard uncertainty of the calibrator and the standard deviation of the repeat tests.

4.2 Calibration of Calibrators using the MCS DMM

Unless otherwise requested, calibrators are tested at their output terminals using the setup shown in Fig.12. The interconnections are the same as those given in Tables 9 - 11. The test calibrator setting S is related to the system DMM reading R:

$$S(1+C_{TCAL}) = R(1 + C_{SDMM}), \tag{22}$$

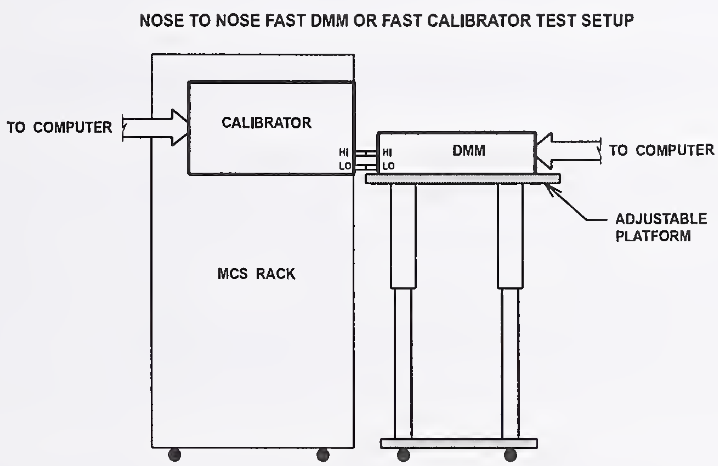

Fig. 12. Setup to calibrate a test DMM using the characterized MCS calibrator.

where C_{TCAL} is the test calibrator correction and C_{SDMM} is the system DMM correction.

As with DMMs, certain calibrators have software correction tables that are used to keep the instrument within a particular specification. Correction tables are updated by applying a nominal signal from the test calibrator to the MCS DMM, and then initiating a GPIB "correction" command, which changes the appropriate correction value until the DMM displays the proper value to within a selectable tolerance.

4.3 High Accuracy Special Test of DMMs and Calibrators

The highest accuracy test of a DMM or calibrator involves direct comparisons against the standards that are used to characterize the MCS DMMs and calibrator using the techniques described in 3.4. These are inherently more time consuming and expensive than the automated tests described in 4.2.

4.4 Special Test of Low Voltage Thermal Voltage Converters

Low voltage thermal voltage converters are tested using the MCS multirange thermal voltage converter. Tests are performed by placing the two instruments nose-to-nose, and then applying ac and dc voltages, while monitoring the output of each device. The ac-dc difference corrections for the TVC under test are calculated by using the techniques described in 3.4.

4.5 Special Test of Micropotentiometers

Micropotentiometers are tested using the MCS multirange thermal voltage converter. Tests are performed by connecting the µpot input to the calibrator output and the µpot output to the thermal converter input and then applying ac and dc voltages, while monitoring the output of each device. The ac-dc difference corrections for the µpot under test are calculated using the techniques described in 3.4.

5. QUALITY CONTROL AND UNCERTAINTIES

The MCS relies on standards that are calibrated in other laboratories in the NIST Electricity Division and it is important to maintain traceability back to these standards. Each of the support artifacts or instrument standards is calibrated on a regular interval (normally once a year) and a control chart describing its value and uncertainty at any time is maintained. The MCS calibrator and DMMs are normally characterized four times a year using the support standards. The calibrator and DMMs are also intercompared several times per month to track long-term stability. The standard deviation of this intercomparison represents a composite stability figure for the calibrator and two DMM types.

The standard uncertainty of each function in the MCS calibrators and DMMs is based on the standard uncertainties of the associated support instrument, the repeatability of the transfer process, and the long-term stability of the calibrator. The figures given in the tables in section 3 represent one-standard deviation (1-sigma) estimates of the system standard uncertainty. *Note: These are composite figures that serve for both the calibrator and the DMMs. Over a large parameter space the figures apply equally to both; however, at high frequencies, the stability of the calibrator may be significantly better than the DMMs. Under these conditions, a different set of uncertainty figures is used.* The total uncertainty of a test performed using the MCS includes the short-term stability of the instrument under test. For example, the uncertainty of a test DMM calibrated by the MCS calibrator on the ACV function depends on the uncertainties of the following parameters:

1. The ac-dc difference of the multirange TVC, U_{TVC} (see 3.4)
2. The correction of the dc voltage function of the calibrator, U_{DC} (see 3.1).
3. The standard deviation of the process in which the calibrator ac voltage is compared to its dc voltage, U_{SD} (see 3.4).
4. The long-term stability of the calibrator/DMM at the test point, U_{LTS} (the standard deviation of periodic comparisons with a system DMM).
5. The short-term stability of the test, U_{STS} (the standard deviation of the measurement including the MCS calibrator and the instrument under test).

These values (all 1-sigma estimates) are combined according to the procedures recommended in [6] to give the expanded total uncertainty, U_T

$$U_T = 2(U_{SD}^2 + U_{LTS}^2 + U_{STS}^2 + U_{DC}^2 + U_{TVC}^2)^{1/2} \tag{23}$$

where the first three terms are considered to be type A standard uncertainties and the last two are type B standard uncertainties.

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