Calibrating Precision Multimeters Using a Characterized Multifunction Calibrator

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1. Abstract
Can a multifunction calibrator really verify a long scale digital multimeter that is more accurate than the calibrator? This paper describes methods to characterize a multifunction calibrator to better than manufacturer's 24 hour specification at all points that are used to verify 8.5 digit multimeters. Using automated processes, data collection and statistical methods, it was found that a calibrator can be characterized at all required values to uncertainties capable of verifying long scale DMMs. Sources of error that had to be overcome include thermal EMF, loading errors from the devices used to measure the calibrator output and loading errors from DMMs when measuring the characterized output. Data from repeated measurements of the calibrator shows 10 V will drift less than 0.3 µV/V for 30 days. For resistance, 10 kΩ can be shown to stay within 0.25 µΩ/Ω for the same period. As the uncertainty of the calibrator was reduced, standards and techniques used to verify the multifunction calibrator had to be re-evaluated to decrease their uncertainty also.

2. Introduction
The Primary Standards Laboratory had been characterizing a 5700A/EP and using it to calibrate the Agilent 3458A/HFL. Long scale DMMs can be calibrated without a characterized source but guardbanding must be used for some verification points [1]. When the Fluke 8508A arrived we had the history of the 3458A calibration points and knew the 5700A/EP that we had in the station was good enough for the 3458A, but was it good enough for the 8508A? This paper explains the steps we went through to find out the answer to that question.

3. Overview of the Characterization of the Calibrator
A Met/Cal procedure was written to automate the characterization of the calibrator. The procedure directly writes the new characterized values into the 5700.cor file that is in turn used during the verification of the Agilent 3458A. The procedure was updated to include the points required for the Fluke 8508A verification points for a total of 148 individual points that are characterized. The calibrator used for the calibration of DMMs is mounted in a rack along with most of the equipment used for the characterization of the calibrator, such as the System DMM, Data Proof 160A scanner, 742A Standard Resistors, 732A and 752A divider. This equipment in the rack and is always powered on and removed only for routine calibrations of the standards. The laboratory environment is kept at 23 °C ±0.6 °C.

4. DCV Characterization of the Calibrator
Characterizing the DCV parameter of the calibrator is accomplished using a Fluke 732A DC Reference Standard, Fluke 752A Reference Divider and a detector. To improve the automation,

the detector is a DMM. Usually a null detector is used as the detector and by using a DMM errors due to bias current have to be evaluated. The errors induced by the DMM were shown to be small in our particular system DMM. Characterized values for 100 mV, 1 V, 10 V, 100 V and 1 kV are measured for both positive and negative polarities. The 10 V output of the 5700A/EP is measured on both the 11 V and 22 V ranges. This is required because for the 8508A we need to characterize the 15 V and 19 V outputs of the 5700A/EP. The automated procedure takes the deviation in proportional parts of the 10 V output of the 22 V range and computes the 15 V and 19 V by applying the same deviation in proportional parts. For the uncertainty analysis of these values, the published 5720A linearity specification is included in the uncertainty. This same technique is used to compute the 5 V characterized values based on the 10 V output of the 11 V range.

The characterization must take into account how the UUT will be measured. For example, in the 3458A automated procedure, we use a copper short on the terminals to measure the zero volt offset voltage and then make an absolute measurement of the 100 mV. Our reference point for this measurement is the copper short (0 volts). The 100 mV output of the calibrator must be measured from zero volts. Since the gain is measured from a direct short, this is an absolute measurement. For the Fluke 8508A the procedure zeroes the 8508A range by applying zero volts from the calibrator. The floor specification for the 100 mV range of the calibrator is 0.5 μV. If the calibrator was at its specification limit, it would cause a 5 μV/V error at 100 mV. This offset must be compensated for. The way we compensate for this is by running an additional characterization of the 100 mV output of the calibrator. We connect the calibrator output to the 752A input and apply zero volts from the calibrator. With the reference shorted, we record the offset from the system meter. The offset recorded on the meter is the calibrator zero volt offset. This becomes our reference. When 100 mV is applied, we record the gain shift based on the zero output of the calibrator, not an absolute zero. This measurement of the 100 mV is relative to the calibrator zero offset. With these two characterized values of the 100 mV output we can source either a 100 mV output based on an absolute zero volts (copper short), or 100 mV relative to the zero voltage output of the calibrator.

A quick note about specifications and uncertainties shown in this paper. Specifications in manufacturers' manuals have all kinds of adders listed in fine print for all the different modes of operation. For this paper the specifications shown are absolute 1 year specifications at 99 % confidence level. I added the gain and floor together [2, 3, 4]. For the Agilent 3458A/HFL the additional error for Agilent factory traceability was added to make these specifications absolute. The uncertainty limits shown in the charts, labeled "Char Uncert", are uncertainties assigned to the characterized calibrator and are at the 95 % confidence level. Uncertainties reported for the calibration of the DMMs include the uncertainty of the characterized calibrator, Type A components of the DMMs and in some cases additional adders for system effects. The reported uncertainties for the DMMs are not provided in this paper.

Figure 1. +100 mV stability of calibrator.

Model	µV/V
Agilent 3458A	14
Agilent 3458A-002	10
Agilent 3458A/HFL	9
Fluke 8508A	7.2
Fluke 5720A	15
Fluke 5720A (24hr Rel)	6
Char Uncert	1.98

Table 1. 100 mV specifications.

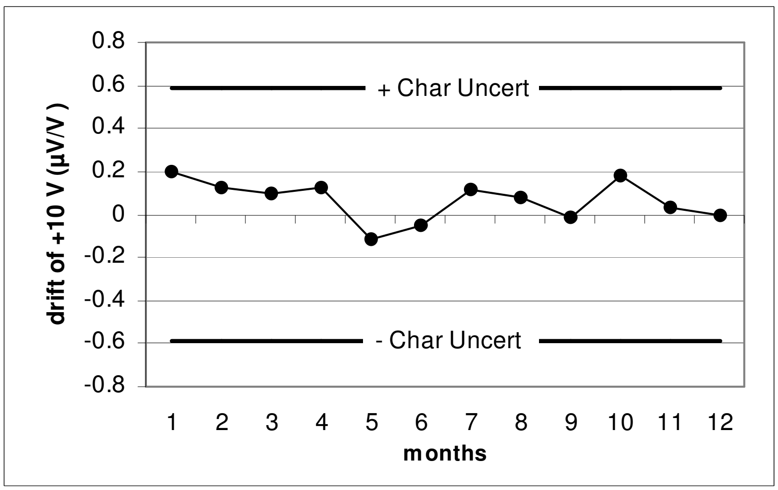

Figure 2. +10 V stability of calibrator.

Model	µV/V
Agilent 3458A	10.05
Agilent 3458A-002	6.05
Agilent 3458A/HFL	5.05
Fluke 8508A	4.5
Fluke 5720A	4.3
Fluke 5720A (24hr Rel)	1.3
Char Uncert	0.6

Table 2. 10 V specifications.

Figure 1 shows the stability of the +100 mV value of the calibrator over a 12 month period. The plotted data shows the shift in µV/V using the last reading (month 12) as the reference. This measurement is one of the more difficult measurements, mainly because of the thermal EMFs. Table 1 lists the models and specifications for 100 mV. As you can see from the chart, the performance of the calibrator is remaining well within the 24 hour relative specification of the calibrator over this 12 month period. The shifts between the monthly measurements show that the uncertainty of the 100 mV value can be kept to a level that is less than 15 % of its 1 year specification. The uncertainty of 2 µV/V is about 27 % of the 8508A specification. Looking at the drift and repeatability of the last 6 months the potential is there to reduce the uncertainty to well below 25 % of the 8508A specification.

Figure 2 is a plot of the +10 VDC output over the same 12 month period. The stability of the calibrator's 10 V output is outstanding. The major contributor for the uncertainty is the reported uncertainty of the 732A (0.5 µV/V). The specifications for the different models are listed in Table 2. The stability of the calibrator is about 0.2 µV/V per month which represents less than 5 % of the specification of the 5720A. Even the 5720A 24 hour relative specification of 1.3 µV/V seems huge when compared with the actual measurements of the 10 V output over the 12 month period.

The DCV verification of the DMMs are fairly straight forward. The calibrator is connected to the DMM. A nominal voltage is applied and the characterized calibrator value is compared with the DMM indication. Errors associated with the verification are mainly thermal EMFs. For a detailed discussion of thermal EMFs and how to reduce them, refer to Peter Dack's paper [5].

5. Resistance Characterization of the Calibrator

The calibrator is characterized for 1 Ω, 10 Ω, 100 Ω, 1k Ω, 10k Ω, 100k Ω, 1 MΩ, 10 MΩ and 100 MΩ. The calibrator is measured by comparing each nominal resistance against a Fluke 742A of the same nominal value. The Fluke 742A resistors are connected to a Data Proof scanner. The system multimeter measures the Fluke 742A and the automated procedure stores a correction for the meter for each value. Next, the calibrator is connected to the system multimeter and all values are measured. The characterized value is computed by applying the meter correction measured just prior to the meter indication when measuring the calibrator. 100 MΩ was characterized by placing the 742A-10M in parallel with the calibrator 100 MΩ output and computing the 100 MΩ value based on the known 10 MΩ in parallel. Reviewing the data showed the stability and repeatability of the 1 Ω, 10 Ω, 10 MΩ and 100 MΩ values did not meet the required uncertainties needed for the verification of the 8508A.

The resistance standards were adequate to meet the needed uncertainties, however the measurement technique was not adequate. The system DMM was applying 10 mA during the 1 Ω measurements which caused the readings to be noisy. It was decided at that time to use the same technique that is used in several places within the Fluke Primary Standards Lab. An additional DC current source is used to apply 100 mA to the 1 Ω resistors while the voltage developed across the resistors is measured with the system DMM. This same technique is used to measure the 10 Ω resistance with 10 mA applied. Figure 3 shows the improvement in the measurements by using an additional current source for the 1 Ω characterization. Table 3 shows the specifications of the different models at 1 Ω. The stability of this calibrator remained within the 24 hour relative specification during the 17 month period.

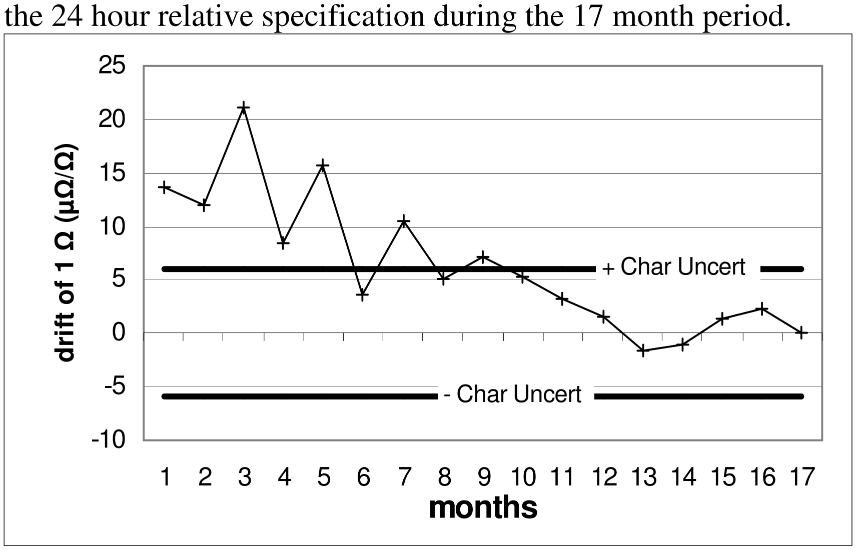

Figure 3. 1Ω stability of calibrator.

Model	μΩ/Ω
Fluke 8508A	32
Fluke 5720A	110
Fluke 5720A (24hr Rel)	32
Char Uncert	5.99

Table 3. Specifications.

The 10 M and 100 MΩ characterization had the same sort of problem with noisy readings from the system DMM. By using a Fluke 8508A in the High Voltage resistance mode, 100 V is applied to the standard resistor giving much more repeatable measurements. 10 MΩ uses a Fluke 742A-10M as the standard. To improve the 100 MΩ characterization a Fluke 742A-100M developmental resistance standard is used as the standard, allowing a 1:1 measurement of the calibrator 100 MΩ output. Figure 4 shows the improved repeatability of the 5700A 100 MΩ output using this technique over the previous technique of measuring 10 MΩ in parallel with the 100 MΩ output. This improvement allowed a reduction in the characterization uncertainty from 50 μΩ/Ω to 20 μΩ/Ω. Table 4 shows the specifications of the different models.

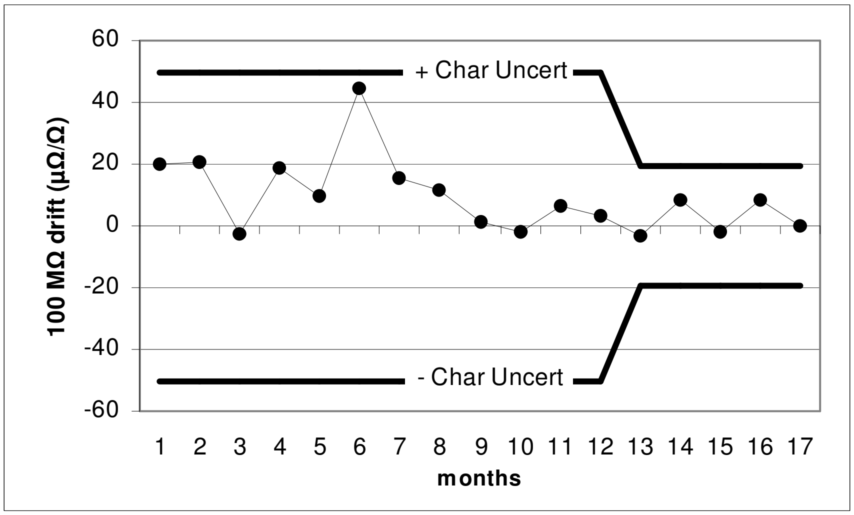

Figure 4. 100 MΩ stability of calibrator.

Model	μΩ/Ω
Agilent 3458A	512
Fluke 5720A	130
Fluke 8508A	87
Fluke 5720A (24hr Rel)	50
Char Uncert	50
Improved Char Uncert	20

Table 4. 100 MΩ Specifications.

Now with the calibrator's resistance values characterized we can plug in the meter under test and perform the verification being confident of the characterized values. However, we need to consider how the meter measures the resistance and what some of the differences are between a standard resistor and the resistors inside a calibrator. All long scale DMMs have some method to correct for errors while measuring lower resistance values, the Agilent 3458A uses OCOMP and the Fluke 8508A uses Tru Ohms [5, 6]. The Fluke 8508A has an additional resistance measurement mode called Normal, which does not use any special method for compensating for thermal EMFs. In Normal mode a Range Zero is performed to compensate for thermal EMFs. This works fine when you can connect the wires to the resistor and short them together to zero the range. When using a calibrator we can not connect directly to the resistor so the thermal EMFs are a concern. There are a couple of methods for checking the calibrator for thermal EMFs. One method is to measure the voltage of the sense terminals while the calibrator is set for 4 wire ohms function. Another method is to connect a Fluke 8508A to the calibrator and use the Normal four wire mode, make a measurement and record the measurement. Reverse the leads and make the same measurement. Half the shift between the forward and reversed readings indicates the errror caused by thermal EMFs. Using this technique for 1 Ω through 1 MΩ we found the effects of thermal EMFs to be insignificant for the Normal mode. For Lo Current measurements where some ranges reduce the current applied to a tenth of the current applied during Normal mode there was enough of an affect that the thermal EMFs had to be included in the uncertainty analysis. This may not be true for every calibrator, but thermal EMFs are a source of error that should be checked when using a characterized calibrator to the uncertainty required for long scale DMMs.

Measuring high resistance values of the calibrator with all the different modes of the 8508A requires understanding how both instruments interact with each other. The 8508A has a Normal and Lo Current resistance mode. These two modes generally allow measurements of the same resistance with two different current amplitudes, depending on the range. Unlike standard resistors that are not tied to ground, the calibrator is tied to ground. If you are measuring 1 MΩ in the Normal mode, the source current from the 8508A will be 10 µA. This current will charge the capacitance in the 5700A between the Hi and ground. If you were to change the resistance mode to Lo Current mode, the current is cut by a tenth to 1 µA but the capacitance of the 5700A still has the charge developed with 10 µA measurements. The capacitance will discharge but with the high resistance in the circuit it can take several minutes before you get a stable reading. What you should do if you are measuring the 5700A, or any other resistance source that has capacitance to ground, is set the 5700A to zero resistance and let the meter take a reading in the Lo Current mode, this will discharge the capacitance to ground. Now you can set the 5700A to the resistance value you want and you will be able to get a stable reading much quicker. Again, this is necessary measuring a resistance where a capacitance can build up a charge. If you were to measure a resistor such as a Fluke 742A-1M and switch from Normal Mode to Lo Current Mode you will not see the reading slowly decreasing since there in very little capacitance to ground in the 742A-1M.

6. DC Current Characterization of the Calibrator

To reduce connection changes while verifying a DMM, the calibrator's AUX terminals will be used. Because of this the AUX terminals will be used for the characterization also. The positive and negative DC current of the calibrator is measured by measuring the voltage drop across a Fluke 742A resistor for current values below 1 A. A Data Proof 160A scanner is used to automate this process. For 1 A a Guildline 9230/15 0.1Ω shunt resistor is used. For 10 A a Fluke Y5020 Current Shunt is used to measure the 10 A output of the Fluke 5725A. Table 5 shows the stability of the +10 mA calibrator output over a 12 month period. Table 5 shows the 10 mA specifications for the different models.

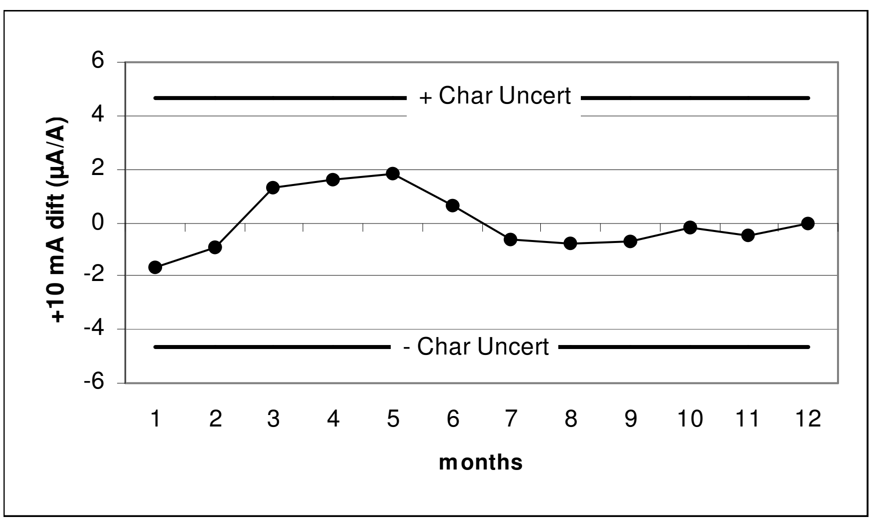

Figure 5. +10 mA stability of calibrator.

Model	µA/A
Agilent 3458A	10.05
Fluke 8508A	20
Fluke 5720A	45
Fluke 5720A (24hr Rel)	29
Char Uncert	4.66

Table 5. Specifications.

Now for the use of these characterized values when verifying a multimeter. A factor to consider is the difference in the compliance voltage (burden) when characterizing the meter vs. when the UUT is measured. In the case of the 8508A, the compliance voltage for 100 µA is 14 mV but, when the characterization was done, the compliance voltage was 100 mV. To measure the effect of different compliance voltages on the calibrator output, a UUT was connected to the calibrator, nominal current was applied to it, and the reading recorded. Next a suitable resistance was added in series to simulate the compliance voltage the calibrator had when the characterization was performed. The shift observed in the meter reading is the effect of the change in compliance voltage between the characterization and the verification of the multimeter. In the case of 100 µA our calibrator showed a shift of 0.3 µA/A because of the shift in compliance. This shift is insignificant compared to the characterization uncertainty.

7. ACV Characterization of the Calibrator

The calibrator is characterized by directly connecting a Fluke 792A to the output. The Fluke 8508A is verified at some frequencies that are not included in the calibration report for the Fluke 792A. For these frequencies an interpolation must be performed to determine the 792A AC/DC difference for that point [7]. Figure 6 shows the stability of 1 V 1 kHz output over a 12 month period. The 24 hour relative specification is 40 µV/V and the output has not moved a tenth of that specification over a year. Table 6 shows the specifications at 1 V 1 kHz of the different models.

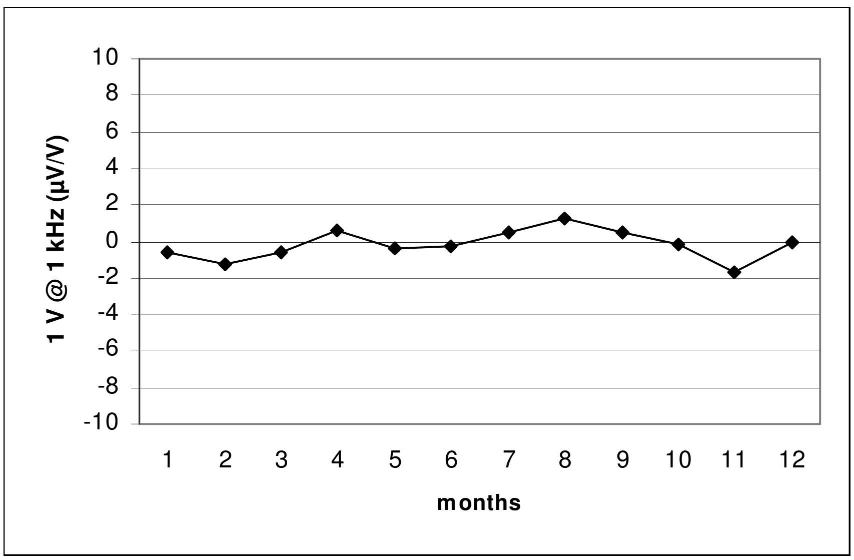

Figure 6. 1 V @ 1 kHz stability of calibrator.

Model	µV/V
Agilent 3458A	90
Fluke 8508A	99
Fluke 5720A	62
Fluke 5720A (24hr Rel)	40
Char Uncert	12.8

Table 6. Specifications.

Loading effects are the significant factors that must be taken into account during the verification. The loading of the calibrator can be different between the characterization, which has a Fluke 792A connected to the calibrator and the load of the 8508A or 3458A. For applied voltages below 220 mV the 5700A has a output impedance of 50 Ω. The input resistance for most meters on the ACV function have an input impedance of 1M Ω. The error caused by this impedance mismatch is approximately 50 µV/V. The actual loading errors of both the 792A and multimeter can be measured and corrected for [8]. Figure 6 shows the loading effect of the 792A used for the characterization of the calibrator and average loading effects of the Fluke 8508A and Agilent 3458A. The Agilent 3458A is specified to 1 MHz on the 100 mV range. Loading effects continue down off the chart to approximately -1600 µV/V at 1 MHz. The specification for 100 mV at 1 MHz is 1.01 %. It was not included on the figure so the loading effects of all the units at lower frequencies could be seen.

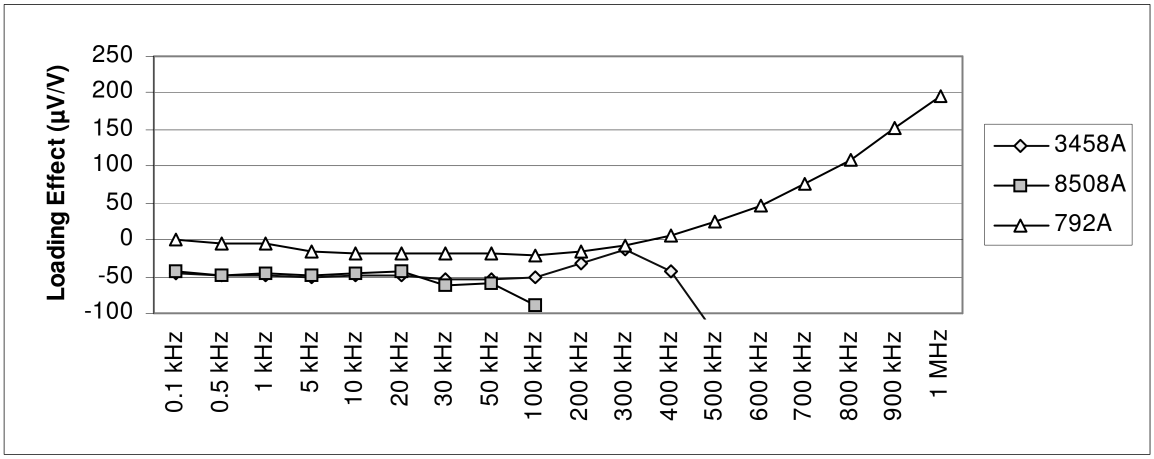

Figure 7. Loading effect of 792A and DMMs at 100 mV.

During the characterization of the calibrator, the 792A is connected directly to the output of the 5700A. During the verification of the multimeters, a cable is used to connect the calibrator to the multimeters. What effect will the cable have on the measurements? To measure the effect of the cable we first connected the multimeter input directly to the 5700A/EP output and ran the verification procedure. Next we connected the multimeter using the cable and ran the verification procedure again. The shift in multimeter indication is the effect of the cable. The results of this test indicated the need for corrections for frequencies above 500 kHz.

Loading effects vary from instrument to instrument so multiple units must be measured to determine the variations for a particular model. For the smallest uncertainties, the loading effect is measured for a particular unit and those loading effects can be applied. However, another method is to measure the loading effects of a sample population and add that as a component of the uncertainty of the measurement.

8. ACI Characterization of the Calibrator

Like DCI, the AUX terminals of the calibrator will be used for the characterization since those terminals will be used for the verification of the DMMs. A Fluke 792A and Fluke A40 shunt set is used to characterize the calibrator output for ACI. For the 100 µA outputs, a 1 kΩ resistor is used in place of an A40 shunt. For the 1 mA outputs, a 100 Ω resistor is used. To get the lowest uncertainties possible, both the resistors and the A40 shunts are calibrated as a set with the 792A. Frequencies range from 300 Hz to 10 kHz on all current ranges. Even short 4" cables between the source and the shunts can cause significant offsets at 10 kHz. Adapters are used so there are no cables between the calibrator output and the shunts. The calibrator ACI outputs above 1 kHz can vary due to changes in loading and inductance. The AUX output is even more sensitive than the normal output terminals. Figure 8 shows the drift of the 100 mA 1 kHz output of the calibrator over a year. Table 7 shows the specifications for the models.

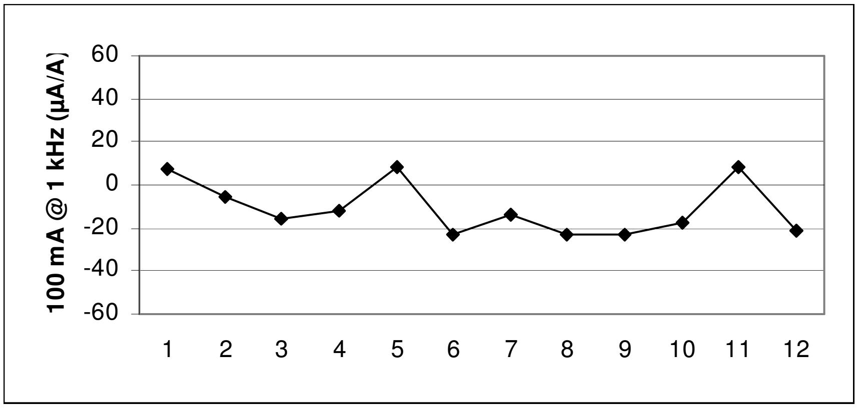

Figure 8. 100 mA at 1 kHz stability of the calibrator.

Model	µA/A
Agilent 3458A	500
Fluke 8508A	545
Fluke 5720A	170
Fluke 5720A (24hr Rel)	130
Char Uncert	78

Table 7. Specifications.

For the verification of the DMMs the AUX terminals from the calibrator are used to reduce connection changes. Because loading of the DMMs can be different than the loading of the A40 shunts during the characterization the shift caused by the loading change will have to corrected. Along with the difference in loading, there is the effect of the cable that will be used during the verification that needs to be considered also. Since no cables were used during the characterization this could cause an additional shift in the calibrator output. The effects of loading differences vary between calibrators and the corrections for one calibrator won't be valid for another calibrator. The steps and measurements required to determine the loading effects is beyond the scope of this paper.

9. What About the Rest of the Characterization Points?

So far only a few results have been presented to show how the calibrator performed. Figure 9 is a chart that shows all the characterized points compared to the 1 year absolute specifications of the 5720A, 8508A and 3458A. The standard deviation of the characterized points over a year is taken, multiplied by two to give an approximate 95 % confidence interval then divided by the specification for each model. A point at 25 % indicates the repeatability of the characterization over a year could give a TUR of about 4:1 As the points go closer to zero the TUR rises, for example a point that indicates 10 % represents a TUR of approximately 10:1. This does not include any uncertainty for the traceability of the measurements. This only represents the Type A of the calibrator.

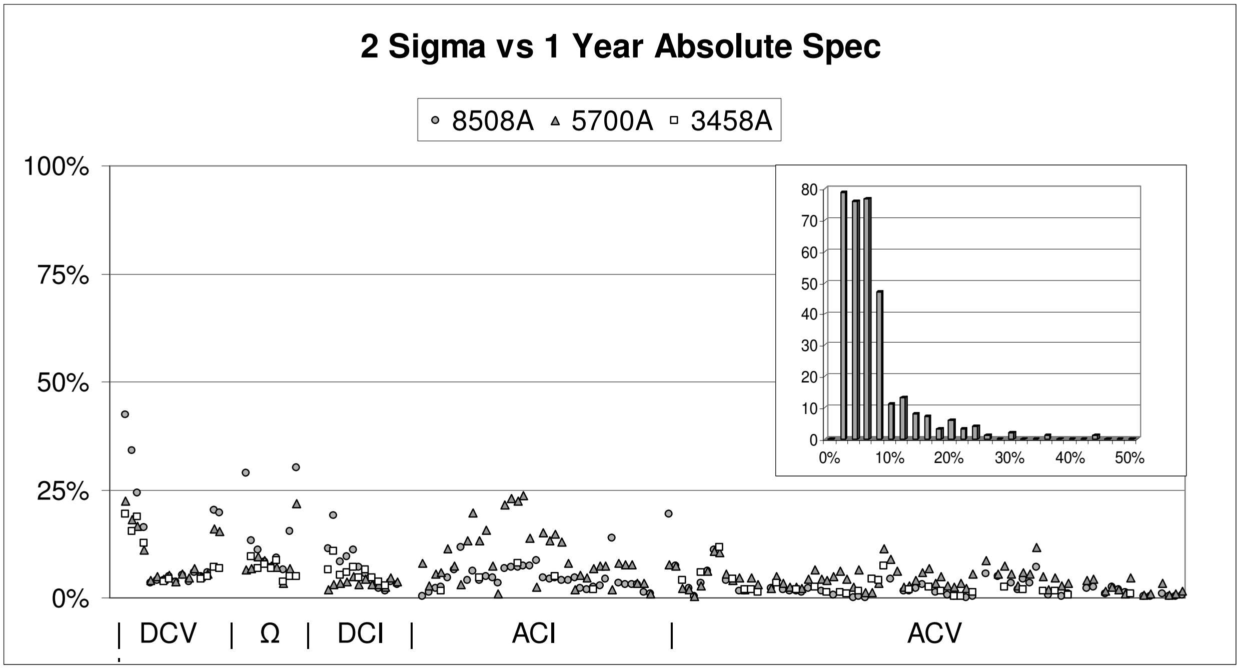

Figure 9. 2 sigma value versus the 1 year absolute specifications of the calibrator and DMMs.

As figure 9 shows, there are 4 points were the sigma compared to the specification exceeds 25 %. Those points are ±100 mV, 1 Ω and 100 MΩ. Those are the points that were covered in more detail previously in this paper. With the improvements already made to the measurement of these four points, the 2 sigma value over a year should be less than 25% of spec within the next 6 months.

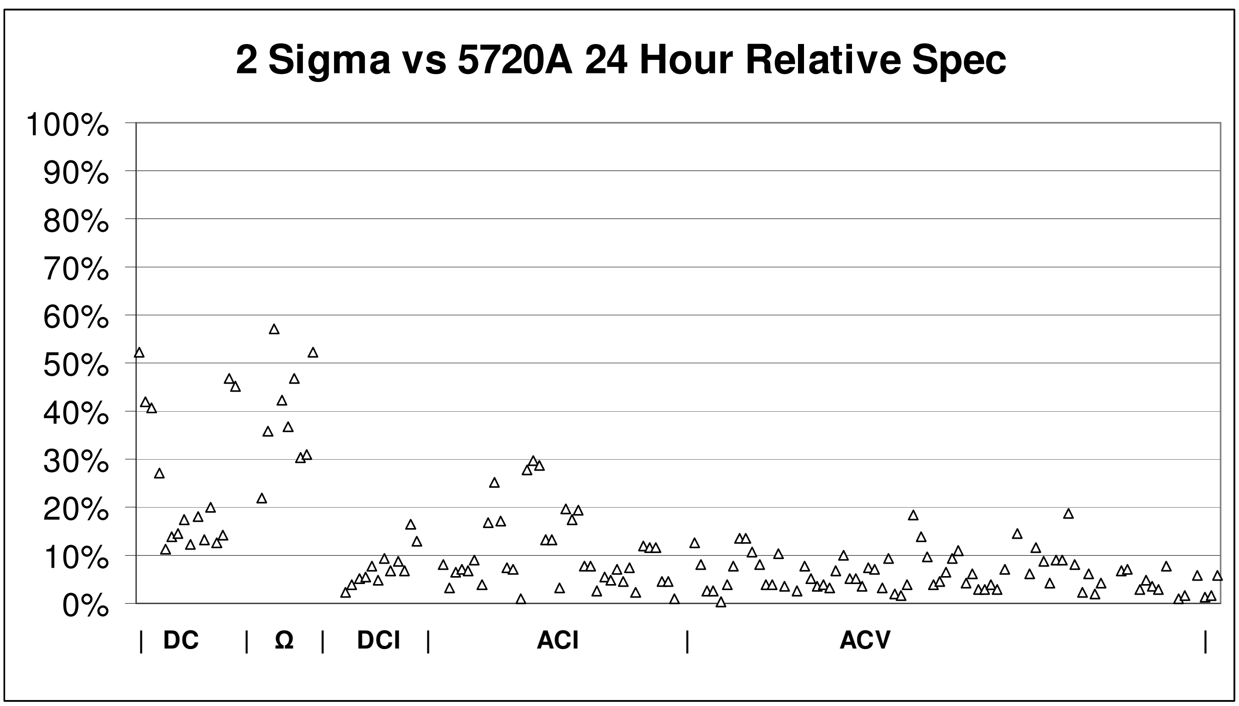

Figure 10. 2 sigma value versus the 5720A 24 hour relative specification.

Figure 10 takes the same 2 sigma value over the year from figure 9 and compares it against the 24 hour relative specification for the 5720A. Only three points are above 50 % of the specification. This is showing the outstanding stability for this calibrator. The points that are above 50 % are the 100 mV measurements and a couple of resistance points.

10. Can This Excellent Performance be Repeated in Other Calibrators?

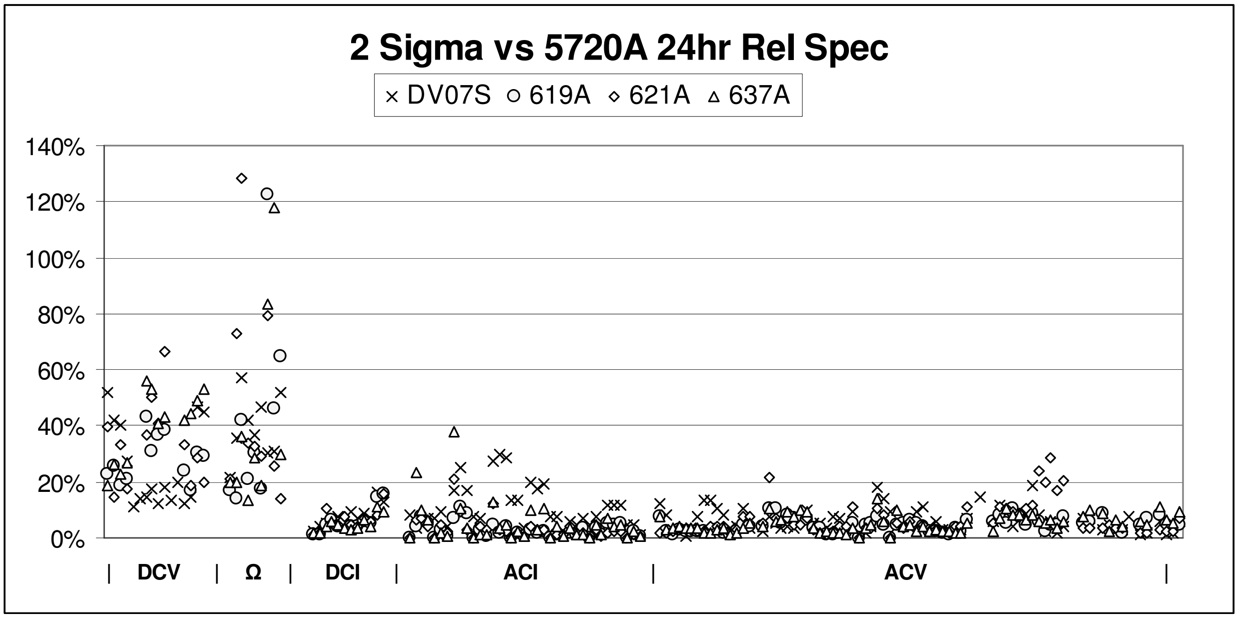

Figure 11. 2 sigma versus 5720A 24 hour specification of three more calibrators.

The Fluke Precision Ltd. Laboratory in Norwich England has three calibrators that are characterized every 45 days. Figure 11 shows the 2 sigma comparison with all four calibrators. DV07S is the calibrator from Fluke Primary Standards Laboratory. Calibrators 619A, 621A, and 637A are the calibrators from Norwich. In this data you can see that 2 sigma of 621A is approximately 130% of the specification. 130% seems terrible until you realize that represents two times the scatter of readings over 1 year compared to the 24 hour relative specification. With that in mind it, all four calibrators are showing quite remarkable performance compared to their 24 hour relative specifications. You're still curious about that point hanging out there at 130% though, aren't you?

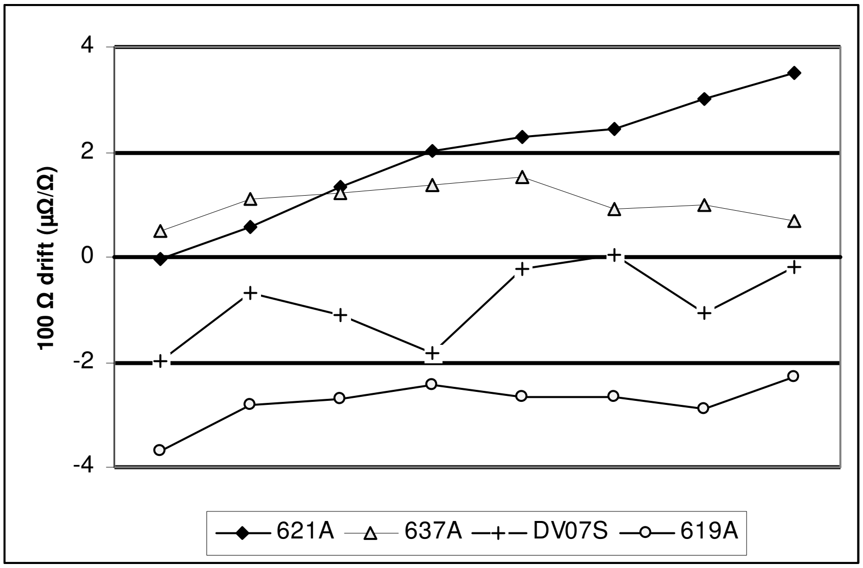

Figure 12. 100 Ω drift over 12 months.

5720A	µΩ/Ω
1 Year Abs	12
90 day Rel	4
24 hr Rel	2

Table 8. Specifications.

The resistance value that is at 130% in figure 11 is the 100 Ω output of calibrator 621A. Figure 12 shows the drift of the 100 Ω output for all four calibrators. The data show that 621A's 100 Ω output is drifting, very linearly, but still drifting. The drift is just under 4 µV/V over the 12 month period. Table 8 shows the 1 year, 90 day relative and 24 hour relative specifications. The drift never exceeded the 90 day relative specification and never came close to the 1 year absolute specification. Although from table 11 it would appear there was something wrong with 621A, reviewing the data in detail shows that the drift must be taken into account when we look at just the standard deviation over an extended period of time, in this case 1 year.

Figure 12 shows something more besides 621A is actually performing very well. The characterizations for the units in Norwich are much more repeatable than the results from Everett. The reason is the method of resistance characterization, DV07S's 100 Ω is measured with a 1 mA source while the units from Norwich are measured with a 10 mA source, giving their readings much more repeatable results.

11. Environmental Effects on the Calibrator

In the beginning of this paper, it was stated that the calibrator was kept in a rack and that the laboratory environment was kept at 23 ± 0.6 °C. Is this calibrator performing so well because of it's environment? What effect does the environment have on the calibrator. Figure 13 shows the effect of temperature changes on the 10 kΩ output of DV07S. The first thing that jumps out is the huge shift in the 10 kΩ output between characterization number 5 and number 6. Just before the sixth characterization the calibrator and the rack was moved, only a few feet, to make the area more productive. Before the move, the rack was within 6 inches of the wall behind it. The rack was moved so the wall is now 2 feet behind the rack. An unused DCV source that had always been in the rack was powered off and removed. The shift caused all kinds of extra work to figure out what happened. It was manually measured and verified that the new value was correct, it wasn't just a bad reading. The DCV source was put back in the rack and powered on and repeated measurements were made. The results of those measurements showed a +0.5 µΩ/Ω shift after about an hour. That accounted for a portion of the shift but where did the rest come from? At that time, the additional shift was attributed to the placement of the rack further from the wall that allowed the calibrator to be slightly cooler. Looking again at figure 13 the bottom portion is the laboratory temperature during the characterizations. The 10 kΩ value shifted +0.4 μΩ/Ω between characterizations #2 and #3. Checking the shift in the environment shows that the lab temperature had gone from the low limit on the day of the second characterization to almost the high limit on the day of the third characterization. The difference between the lab temperatures at characterization #5 and #6 shows a large decrease. The combined shift in laboratory temperature and the -0.5 μΩ/Ω shift caused by the removal of the DC source from the rack, corresponds closely to the previous change in the 10 kΩ related to the laboratory environment. Further investigation is needed to better quantify the true effect of environmental changes to the calibrator. A 0.4 μΩ/Ω shift represents half the $k = 2$ uncertainty of the 742A-10k standard used to measure the 10 kΩ output. The normal shift observed between characterizations is usually within 0.25 μΩ/Ω, when the laboratory environment is stable between characterizations. To maintain the uncertainties we desire the environmental changes must be carefully monitored, including equipment near the calibrator.

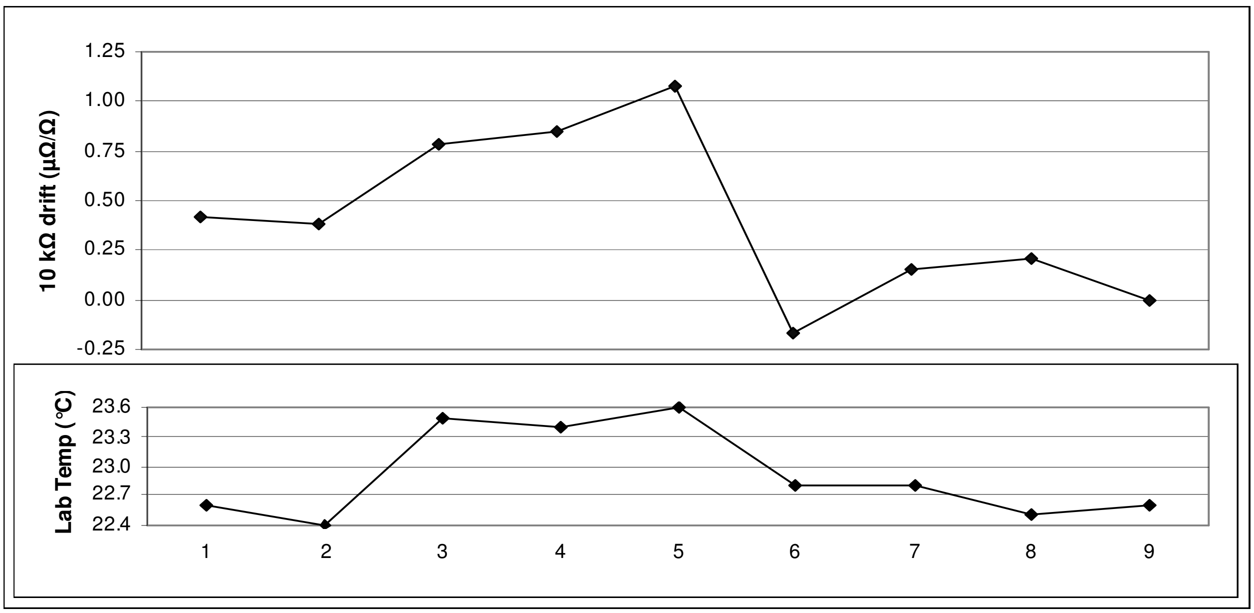

Figure 13. 10 kΩ value and the laboratory environment.

12. Summary

The data from the characterizations of these four calibrators show excellent long term stability over a 12 month period. All the calibrators stayed within the manufacturer's 24 hour relative specification for virtually all the points that are used to verify long scale DMMs. Comparing the results of the characterizations between Norwich and Everett revealed there are a few methods used to characterize the calibrator that could be improved. Environmental control is a very important component to maintain the excellent stability of the calibrators, even when in a laboratory where the temperature is within ±0.6 °C of 23 °C.

References:

1. Fluke Application Note, Calibrating the Hewlett-Packard 3458A DMM with the 5720A Multifunction Calibrator, 1997.

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