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THE EFFECTIVENESS OF ARTIFACT CALIBRATION IN COMPUTING INTERNAL RESISTANCE VALUES

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Abstract - Originally intended as part of a process to characterize a 5720A calibrator for subsequent use calibrating the Datron (Fluke) 4950 Multifunction Transfer Standard (4950MTS), external verification of the 5720A's available resistance values utilizing state-of-the-art measurement apparatus ultimately provided valuable insight into the accuracy with which the internal Artifact Calibration process characterizes the calibrator's resistance function. Based on the results of this investigation, however, it is believed the artifact calibration function and specifically its ability to measure the internal resistance of the 5720A (5700A) calibrator, in particular, deserves a further look.

INTRODUCTION

After several years of spirited competition in the marketplace between Fluke and Datron (later Wavetek, Wandel & Goltermann) calibration products, the Datron division of WWG® was acquired by Fluke in January, 2000. In order to continue to provide exemplary service and support to the customer, it was necessary to broaden the existing mechanisms to allow both of the former rivals to now support products manufactured by the other. One such product is the 4950 Multifunction Transfer Standard.

BACKGROUND

The 4950 has been in service for several years and was designed expressly for the purposes of verifying multifunction calibrators of moderate to high accuracy, e.g., Datron 4800 and Fluke 5700A. It is itself calibrated, or perhaps more precisely, characterized at a number of discrete points (corresponding to typical calibrator outputs) that are, in turn, utilized to measure the Unit Under Test (UUT) calibrator. The UUT verification is most often performed under the control of the specially designed 4950MTS software.

The characterization of the 4950, like the UUT verification, has historically been performed in the 4950MTS software environment as well. This process has been accomplished using a 'golden' multifunction calibrator that has itself been specially characterized at the necessary points. The 4950 characterization process typically is repeated every 30 or 90 days, depending on the specification level desired.

Proceeding up the traceability ladder to the next echelon, we come to the 'golden' calibrator. This role has in the past, typically been filled by a Datron 4808, characterized manually/semi-automatically against higher, if not primary standards. The task of characterizing the golden calibrator is a labor-intensive one, requiring approximately 18 hours of a highly skilled metrology technician's time. The frequency of this operation depends on the stability of the particular calibrator being used, as established through statistical analyses of some one hundred-plus test (characterization) points.

The Golden Calibrator

As mentioned previously, a Datron 4808 calibrator has been the ‘specified’ golden calibrator of choice, as far as supporting the 4950. This has largely been due to the immediate availability and access of the necessary support equipment by the manufacturer at the time the 4950 was originally designed and marketed. Now, however, that Datron and Fluke have combined corporately, it is desirable to re-examine the support paradigm to envelop a larger installed base of units, not only for our own internal support purposes, but also for 4950 customers who may choose to support the unit themselves.

From the (traditional) Fluke side of the equation, the natural choice to supplement the 4808 in the role of the golden calibrator is the Fluke 5720A. (For our purposes, the use of the word “golden” as it applies to the calibrators here refers to their hierarchical position in the calibration scheme, not necessarily any special, selected qualities.) The 5720A’s published specifications are similar to those for the 4808 in many areas, as well as sharing many of the same performance and functional characteristics. Add to that the relatively large installed base of 5720A units, and the choice becomes obvious.

5720A ARTIFACT CALIBRATION

In normal practice, the 5720A is routinely maintained/supported via artifact calibration. Over the years, the technical aspects of artifact calibration, as it applies to the 5700A-series of calibrators, have been well documented.[1,2] Previous studies[3,4,5,6] have also exhaustively discussed the various aspects of traceability and operational functions of Artifact Calibration, including the acceptability of accrediting the process.

Briefly, the resistance values of the 5720A (5700A) are measured during artifact calibration by internally comparing externally applied values of resistance (suitable 1Ω and 10kΩ standard resistors) to the internal ones, either directly or through ratio comparisons. Based on the outcome of these comparisons, “measured” values are assigned to each available internal value and are stored in the non-volatile memory of the calibrator. This is in contrast to the other ‘active’ parameters of the unit, whose values are electronically ‘adjusted’ during artifact calibration to output the nominal value requested. Instead, the measured values for each resistance level are displayed to the operator or are available over the IEEE bus whenever the nominal value is entered/requested. Table 1 illustrates this relationship, using the actual values from one of the calibrators used in this investigation.

Table 1. Resistance Values Determined Via Artifact Calibration

Nominal Value	Calculated Value
Short	0.0000000Ω
1Ω	0.9998616Ω
1.9Ω	1.8995473Ω
10Ω	9.999416Ω
19Ω	18.998387Ω
100Ω	99.99502Ω
190Ω	189.99169Ω
1kΩ	0.9999908kΩ
1.9kΩ	1.8999898kΩ
10kΩ	10.000010kΩ
19kΩ	18.999357kΩ
100kΩ	99.99947kΩ
190kΩ	189.99771kΩ
1MΩ	0.9999683MΩ
1.9MΩ	1.8999636MΩ
10MΩ	9.998768MΩ
19MΩ	18.998546MΩ
100MΩ	99.99353MΩ

CHARACTERIZING THE 5720A

The characterization of the 5720A as a golden calibrator is a relatively straightforward process; the various discrete outputs are measured directly using primary standards. For example, DC voltage is measured using a Fluke 732B DC Reference Standard in conjunction with a Fluke 752A Reference Divider and suitable Null Detector, AC voltage is measured using a Fluke 792A AC-DC Transfer Standard and an appropriate detector, and so on. Perhaps a notable departure from this procedure, in this case, is the characterization of the resistance outputs. In the past, a typical process employed consisted of measuring known standard resistors (whose nominal values correspond to that of the calibrator) using a long-scale digital multimeter (DMM), for example, a Datron 1281, computing a correction or scale factor for the DMM at each value, then measuring the 5720A output and computing its true value, based on the DMM's measured value and the calculated correction factor. Given the available access to a set of industry-recognized resistance bridges, i.e., Measurements International, Ltd. (MIL) 6000A and 6010A[a], it was decided to attempt to measure the resistance outputs of the 5720A directly, instead of utilizing the indirect standard resistor/DMM 'transfer' method.

The MIL 6010A is a Direct Current Comparator (DCC) bridge, used for characterizing the resistances in the range of 1Ω through 10kΩ. Generally speaking, this type of technology has been used for resistance measurement in standards and calibration laboratories for many years. The 6000A, on the other hand, used for characterizing the 5720A resistances of 10kΩ through 100MΩ, is a voltage ratio bridge, based on an extension of a binary voltage divider technique. Though a variant of this technique[7] using discrete voltage standards has been used in the Fluke Primary Standards Laboratory (FPSL) for many years, this specific approach had not been previously utilized in a bridge of this type for resistance measurements prior to the introduction of the 6000A.

First Things First

The first quandary in which we found ourselves was in determining exactly how to connect the bridges to the 5720A to obtain valid results. Typically, when we measure a standard resistor or SPRT, we are dealing with an isolated device, i.e., it has no electrical connections to the power line or to earth ground. That is not the case, however, with the 5720A. Though internally the unit does in fact use passive thin-film devices (with the exception of the 1 and 1.9Ω values, which are wirewound) for resistance, the unit as a whole does indeed connect to power line mains AND earth ground. Moreover, as most are aware, no matter how good a device of this type may be there is always some amount of leakage with which to contend. In addition, because the two resistance bridges employ different measurement techniques, the MIL 6010A being a DCC bridge (using an internally generated current source) and the 6000A being a voltage ratio bridge (using an external voltage source, in this case, the 10V output of a Fluke 732B), several connection options were available for each bridge. Therefore, experimental tests were conducted, trying various connection schemes of each bridge guard and/or ground connection to the 5720A V-GUARD and GROUND terminals until valid results were obtained.

After trying several different connection and calibrator configuration permutations with each of the two bridges connected, it was discovered what are believed to be the proper connection configurations. When using the 6010A (low ohms) DCC bridge, this was achieved with the 5720A EXT GUARD function selected, the shorting strap that normally connects the calibrator's V-GUARD and GROUND terminals disconnected, and the 6010A shield (ground) connected to the 5720A GROUND. For the 6000A (high ohms) bridge, the connections were similar, except that the 6000A shield (ground) must be connected to the 5720A V-GUARD, *instead* of the GROUND, as was the case when using the 6010A. It's not known exactly at this point why the two bridges require a slightly different connection scheme (though the internal guarding/grounding connections of the respective power sources seems likely), but the connection scheme used in each case appears to produce valid results.

For the purposes of this characterization, the 6010A (low bridge) control software was set to take 30 measurements (each "measurement" consisting of both normal and reversed current), the first 10

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[a] Though the MIL 6000A and 6010A have been subsequently upgraded to 6000B and 6010B models, respectively, for the purposes of this investigation, there is believed to be no significant impact on the results.

readings were discarded (for settling), and the calculated mean and standard deviation data derived from the last 20 measurements. This included resistor values of 1Ω through 1.9kΩ. The 6000A, on the other hand, uses a different measurement technique than the 6010A (binary voltage divider versus a current comparator), and is somewhat slower than the 6010A as a result. Therefore, the 6000A control software was set to take 8 readings, each with a reversal (a total of 16 readings), at each value of resistance from 10kΩ through 100MΩ.

Reference Standards

The laboratory at the Fluke Worldwide Support Center in Everett, WA (where the tests were conducted) maintains primary resistance references at both the 1Ω and 10kΩ levels, utilizing a group of five (5) Leeds and Northrup (L&N) 4210 Thomas-type and four (4) Electro Scientific Industries (ESI®) SR104 standard resistors, respectively. The L&N 4210 resistors are maintained at 25°C in a high-quality oil-bath, whose temperature is continually monitored via a thermometer and SPRT. The ESI SR104 is constructed of Evanohm® wire and though its temperature coefficient is quite flat, for measurements at the best uncertainties its internal temperature is monitored via the built-in "10,000 OHM TEMPERATURE SENSOR" facility and the appropriate correction applied. At both resistance levels, designated 'traveling' standards are sent to the FPSL in Everett, WA for certification and are, upon return and periodically between recertification, intercompared with the remaining resistors in their respective groups. The remaining 'stationary' resistors in each group never leave the laboratory and thus, avoid being subjected to the rigors of any possible travel effects. Consequently, we can presently achieve working uncertainties (k=2) of approximately ± 0.3 parts per million (ppm) at the 1Ω level and ± 0.4 ppm at the 10kΩ level.

Up, Up, and Away

Having ascertained what is believed to be the proper connection scheme, the characterization began at the 1Ω level (using the 6010A DCC bridge), successively proceeding higher in resistance values. Because the DCC bridge's maximum ratio is 11:1, it was necessary to "build-up" using working standards in nominal 10:1 ratios as "tare" resistors throughout the measurement process. To begin with, the 1, 1.9, and 10Ω values of the calibrator were measured, directly using an L&N 4210 working (stationary) standard as the reference (R_S) unit. Following that, a Fluke 742A-10 10Ω standard resistor was then measured (vs. the L&N 4210) for immediate use as a tare resistor in the next step of the build-up. The 742A-series of resistors are designed for use in air at normal ambient laboratory conditions (23°C) and have excellent temperature coefficient characteristics.[8] In addition to their portability and ease of use, the demonstrated stability of these particular units has made them ideal candidates for this purpose, as well as for use as working standards in the laboratory. After measuring the 742A-10, it was substituted for the L&N 4210 as the "R_S" component of the 6010A, using its 'just measured' value and calculated uncertainty for the next set of measurements. Next, the calibrator was set to output first 19Ω, followed by 100Ω, both values being measured in terms of the 742A-10 tare resistor. The 742A-100 tare resistor was then connected and measured. It was subsequently substituted in place of the 742A-10 as R_S for use during the next step of the measurement/build-up process. The remaining resistance values of the calibrator (through 10kΩ) were measured in a similar fashion as the 19 and 100Ω values, using the 742A-100 and 742A-1k standard resistors as tare units, measured immediately prior to use. The internally computed (via artifact calibration), measured values, and the corresponding differences of the 5700A/EP calibrator (a 5700A upgraded for conformance to 5720A specifications) are shown in Table 2.

Table 2. 5700A/EP (5720A) #1 Resistance (1Ω - 10kΩ) Artifact Calibrated vs. Measured Value

Nominal	Artifact Cal Value	Measured Value	Difference (ppm)
1Ω	0.9998616Ω	0.9998435Ω	-18.1
1.9Ω	1.8995473Ω	1.8995209Ω	-13.9
10Ω	9.999416Ω	9.999405Ω	-1.1
19Ω	18.998387Ω	18.998393Ω	+0.3
100Ω	99.99502Ω	99.99515Ω	+1.3
190Ω	189.99169Ω	189.99189Ω	+1.1
1kΩ	0.9999908kΩ	0.9999913kΩ	+0.5
1.9kΩ	1.8999898kΩ	1.8999909kΩ	+0.6
10kΩ	10.000010kΩ	10.000023kΩ	+1.3

The observed differences at the 1 and 1.9Ω levels were expected; deviations of approximately this magnitude have been noted consistently over the years during 5700A verifications. These particular values were not considered to require the highest level of accuracy/stability at the time the calibrator was designed (and probably still not today) due to the typical workload that the calibrator is intended to support. Thus, the physical resistors used in the calibrator are of a quality and performance level consistent with the majority of the expected workload. For example, very few DMMs have full-scale resistance ranges of 1 or 2Ω that demand better than the 5720A can deliver. The only other factor (if any) that could contribute to this offset, other than the resistors themselves, is some contribution attributable to the presence of thermal emfs inside the unit during artifact calibration. In any event, the differences relative to the specifications are not significant. Overall, for the range of values measured with the 6010A DCC, Table 3 illustrates the magnitude of the differences juxtaposed with the specifications and the DCC's uncertainty at time of measurement.

Table 3. Measured Differences Relative to 5720A Specifications

Nominal	Difference (ppm)	5720A [24 hour, 95%] Specifications (ppm)	6010A Measurement Uncertainty (ppm, *k*=2)
1Ω	-18.1	70	± 0.5
1.9Ω	-13.9	70	± 0.5
10Ω	-1.1	20	± 0.5
19Ω	+0.3	20	± 0.5
100Ω	+1.3	8	± 0.5
190Ω	+1.1	8	± 0.5
1kΩ	+0.5	6.5	± 0.5
1.9kΩ	+0.6	6.5	± 0.5
10kΩ	+1.3	6.5	± 0.5

As you can see, even when compared to the instrument's most stringent (*24 hour, 95% Confidence Level*) specifications, the difference between the values derived via the normal artifact calibration process and the actual measured values is remarkably small.

At this point, a few words about the reported uncertainty are in order. The bridge's control software not only computes the real-time uncertainty in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM), but also retains it for subsequent use during build-up. Thus, one can start with a standard resistor whose certified value and uncertainty are known from, for example, the 1Ω level, and build-up to 10kΩ with the cumulative uncertainty for the entire process computed automatically! Such was the case during this investigation. Moreover, uncertainties *do* increase as one proceeds to build-up from 1Ω to 10kΩ. However, due to the exceptional ratio accuracy of this bridge, the very low standard deviation of the detector, and the uncertainty targets of the process, the computed uncertainty at 10kΩ after build-up was indicated to be ± 0.5003 ppm and thus, after rounding, does not show up in Table 3. It should be emphasized that this is what was achieved using this particular bridge and may not necessarily be the same when using a similar model bridge in another system. To clarify this, the author contacted the bridge's manufacturer for further information. We were informed by the manufacturer that they periodically compare their bridge's performance with the National Research Council (NRC) of Canada's cryogenic current comparator (CCC) apparatus. In many cases, they have demonstrated agreement with the CCC of better than 0.02 ppm when transferring four orders of magnitude from 1Ω to 10kΩ. They have also submitted product to the National Physical Laboratory (NPL) in the UK for certification. Results obtained from this measurement have substantiated those achieved at NRC.[9] However, specifically speaking, the ratio accuracy specification for this model bridge (6010A) is "< ± (0.1 ppm + 1 x 10^{-7})" for the range of 0.1Ω through 1kΩ, and "< ±0.2 ppm" for the 1kΩ to 10kΩ step. Thus, with regard to the specifications and available standards, the "worst-case" uncertainty of a build-up from 1Ω to 10kΩ in this case, would be ± 0.64 ppm (absolute) at 10kΩ.

Metrologists are sometimes likened to residents from the State of Missouri, i.e., "Show Me." In this instance, there was no difference. When the build-up process was completed at 10kΩ and it was noted that the calculated cumulative uncertainty was barely more than what was started with, it was unbelievable. In fact, the disbelief at this time was so great that the measurements and build-up from 1Ω through 10kΩ were repeated, resulting in virtually identical uncertainties being calculated, as well as measured values that agreed with the previous run in parts in 10^{-8}! Still not being satisfied, it was endeavored to alternatively verify the validity of the results another way. To accomplish this, one of the ESI SR104 10kΩ standard resistors from the working (stationary) group was substituted in place of the calibrator. Using the same bridge measurement parameters as for the calibrator, the measured value of the SR104 agreed *exactly* with the SR104's certified value. (The certified value of the SR104 was limited in resolution to 0.1 ppm.) For the reader's information, a few interesting facts that surround this revelation should be mentioned. First, the L&N 4210 1Ω working (stationary) standard used was not directly certified by the FPSL; its value was determined by a comparison (using the 6010A) with one of the 'traveling' 4210 units that *was* certified by the Primary Standards Lab. The circumstances for the ESI SR104 used were similar, i.e., it was not directly certified by the FPSL, but compared to another FPSL-certified SR104 in our lab using the 6000A. Overall, when considered along with a history of over 30 years for this particular SR104 resistor indicating a drift rate on the order of +0.05 ppm/year, I think that it is safe to say that it is the 6010A's reported uncertainty is probably in the ballpark, and certainly quite satisfactory for the task at hand.

Just one other pertinent fact before we move on to the 'upper register' of resistance values available from the calibrator. The specifications shown for the 5720A in Table 3 are, as previously mentioned, for 24 hours. The values externally measured with the DCC for this unit were accomplished *64 days after* the artifact calibration. So not only is the artifact calibration process extremely accurate, but the stability of the resistor elements themselves (compared to the specifications) appear to be quite extraordinary.

The Climb to the Top

Having completed the measurements on resistance values of 1Ω through 10kΩ, it was time to move on to the next echelon of resistance values. For this segment of the task, we moved over to the MIL 6000A Automated High Resistance Ratio Bridge. As previously stated, the 6000A is based on the technique of a binary voltage ratio divider. In our case, the voltage source used was a Fluke 732B DC Reference Standard (10V output). In addition, also in contrast to the 6010A, which utilizes an internal nanovolt detector, the 6000A uses an outboard voltmeter as a detector. In our installation, a Fluke 8842A is used for this purpose. Due to the design of the 6000A and the excellent isolation characteristics of the 8842A, uncertainties at 100MΩ of less than ± 10 ppm are quite typically achievable. We are, however, planning on "stepping up" to a Datron 1281 as a detector in the near future, where its external guarding capability and extended resolution should significantly lower the achievable uncertainties.

As a sanity check, we began by measuring the calibrator's 10kΩ output, deliberately overlapping the measurements from the two bridges. Not surprisingly, a difference of approximately –0.6 ppm was noted, i.e., the 6000A measured less than the 6010A (and closer to the calibrator's indicated value). However, both values were within the stated uncertainties, and even the 'worst-case' results (from the 6010A) were only offset from the calibrator's indicated value by +1.3 ppm! (The 6000A's measurement of the calibrator's 10kΩ resistance was offset by +0.7 ppm.) It is likely that the difference noted is the result of the 6010A's limited ability to source sufficient measuring current (substantially less than the average DMM, the calibrator's workload) at the 10kΩ level. (The 5720A specifications are derated when the source current falls below a defined range.[10]) However, the differences noted are only in the 1 ppm range so the power coefficient of the 5720A resistance function will likely only start to become significant when the lowest possible uncertainties, in some cases, a reduction of an order of magnitude or more, are sought. This assumption would appear to be substantiated by the fact that the 'closure' test (mentioned previously) that was performed using the SR104 generated satisfactory agreement between the two bridges. Thus for subsequent units, 10kΩ measurements would be accomplished using the 6000A (which incidentally, comes closer to matching the measurement voltage used internally during artifact calibration).

Somewhat similar to the process employed with the 6010A, the initial resistance values of the calibrator after changing bridges (10k, 19k, and 100kΩ) were measured directly using an ESI SR104 10kΩ standard resistor (from the stationary group) as the reference. Fluke 742A-series resistors were again used as tare resistors, starting with the 742A-100k, which was also measured using the SR104. After measuring the 742A-100k, 190kΩ and the remaining resistance values of the calibrator through 100MΩ were measured similarly to the 10k, 19k, and 100kΩ values, using instead the 742A-100k, 742A-1M, and 742A-10M standard resistors as tare units, measured immediately prior to use. Similar also to the 6010A is the 6000A's proprietary control software's ability to compute cumulative uncertainty following a number of steps in a build-up routine. The computed and measured values (and the corresponding differences) are shown in Table 4.

Table 4. 5700A/EP (5720A) #1 Resistance (10kΩ - 100MΩ) Artifact Calibrated vs. Measured Value

Nominal	Artifact Cal Value	Measured Value	Difference (ppm)
10kΩ	10.000010kΩ	10.000017kΩ	+0.7
19kΩ	18.999357kΩ	18.999359kΩ	+0.1
100kΩ	99.99947kΩ	99.99965kΩ	+1.8
190kΩ	189.99771kΩ	189.99785kΩ	+0.7
1MΩ	0.9999683MΩ	0.9999666MΩ	-1.7
1.9MΩ	1.8999636MΩ	1.8999628MΩ	-0.4
10MΩ	9.998768MΩ	9.998711MΩ	-5.7
19MΩ	18.998546MΩ	18.998370MΩ	-9.3
100MΩ	99.99353MΩ	99.99224MΩ	-12.9

At first glance, the relative differences between these values and those in Table 2 appear to be quite large. It is important, however, to keep not only the specifications of the 5720A in perspective, but also the specifications of the typical workload that is addressed. With that in mind, the magnitudes of the differences are still quite small. Table 5 illustrates the magnitude of the measured differences compared with the 5720A specifications and the bridge's computed uncertainty at time of measurement.

Table 5. Measured Differences Relative to 5720A Specifications

Nominal	Difference (ppm)	5720A [24 hour, 95%] Specifications (ppm)	6000A Measurement Uncertainty (ppm, *k*=2)
10kΩ	+0.7	6.5	± 0.6
19kΩ	+0.1	7.5	± 0.6
100kΩ	+1.8	7.5	± 1.7
190kΩ	+0.7	7.5	± 1.5
1MΩ	-1.7	13	± 1.4
1.9MΩ	-0.4	15	± 1.7
10MΩ	-5.7	28	± 2.2
19MΩ	-9.3	38	± 2.4
100MΩ	-12.9	85	± 7.5

While some of the details are beyond the scope of this discussion, it is important to have at least a basic understanding of the factors that can affect the final uncertainties that are realized here. You will no doubt notice in Table 5 how the uncertainties begin to broaden as we proceed higher in resistance, especially at 100MΩ. There are several factors that can impact the final computed uncertainty, four of which I mention here. First, and fundamental to the entire process, is the value (and quality of the resistor) to be measured. When the resistance level of interest is say, 100MΩ, the resultant noise (and the uncertainty contribution) of the detector become significant. So obviously, the choice of detector is the second important factor. Earlier on, it was stated that a Fluke 8842A was used as a detector and that an externally guarded detector may provide a significant advantage. This is an example of where the use of a 1281, for instance, may have a sizable impact. On the other hand, when one considers that NIST is offering a "Nominal Relative Expanded Uncertainty" of approximately 40 to 400 ppm at the 100MΩ level (according to their website), the uncertainty that was achieved here (± 7.5 ppm) doesn't look so bad after all. The next major factor in the final uncertainty is the voltage source characteristics. Although it is important that the source be relatively free from the effects of short-term low frequency noise excursions, a much larger contributor is the voltage level used and the resulting resolution improvement. As previously stated, a Fluke 732B's 10V output was utilized in this effort. (The current offering of this bridge from MIL, the 6000B, allows the use of up to a 100V source, further enhancing the attainable uncertainties.) Probably the last, but not least major contributor to the uncertainty picture is the environment in which the measurements are performed. The facility in which these tests were run is the Fluke corporate service center in Everett, WA, where a high volume of work and activity takes place. Every effort was made on the author's part to have tests performed overnight (when the facility was quiet), but workload and scheduling sometimes prevented it. It should be added that though this may seem to be somewhat of a handicap, it also serves to more realistically demonstrate the type of results that may be achieved in a typical calibration lab, rather than the "sterile" environment of the standards lab. Having said that, the scientific or informational value of reporting uncertainties to parts in 10^{-8} of 10^{-9} is nil (at least for the purposes of this investigation), so the reported resolution of the uncertainties here is deliberately limited to 0.1 ppm.

OTHER VOICES (OTHER CALIBRATORS)

The 5700A/EP calibrator, serial number 4645011, from which the above data was taken, was chosen completely at random from available units. It is owned and maintained by the Fluke Service Center in Everett, WA. However, though previous studies have satisfactorily demonstrated the repeatability of artifact calibration, metrology is a field that is driven by data and in this regard, it is not intended to disappoint the reader.

The 5700A/EP was artifact calibrated using the working standards of the Fluke Service Center some 64 days prior to the measurements taking place. A second calibrator, 5720A, serial number 7705203, last artifact calibrated on the factory floor in Everett on 24 October 2000, was measured over the time span of 13 – 20 June 2001, approximately 8 months (232 days) having elapsed since the artifact calibration. Uncertainties at the time of measurement were on the order of those documented above, so they are omitted from the following data for the sake of brevity.

Table 6. 5720A #2 Resistance (1Ω - 1.9kΩ) Artifact Calibrated vs. Measured Value

Nominal	Artifact Cal Value	Measured Value	Difference (ppm)	5720A [24 hour, 95%] Specifications (ppm)
1Ω	0.9997926Ω	0.9997488Ω	-43.8	70
1.9Ω	1.8999803Ω	1.8998829Ω	-51.3	70
10Ω	10.000255Ω	10.000304Ω	+4.9	20
19Ω	19.000050Ω	19.000137Ω	+4.6	20
100Ω	100.00159Ω	100.00216Ω	+5.7	8
190Ω	189.99097Ω	189.99169Ω	+3.8	8
1kΩ	0.9999927kΩ	0.9999938kΩ	+1.1	6.5
1.9kΩ	1.8999923kΩ	1.8999964kΩ	+2.1	6.5

The proximity of the above data to the nominal (artifact calibrated) values does not appear to be quite as close as that demonstrated by the initial calibrator. However, when compared with the 24 hour specifications of the 5720A, and given the fact that the interval since the unit was artifact calibrated was substantially longer, the performance is still quite remarkable.

Similar performance was exhibited for the higher (10kΩ and above) resistance values as well. As with the initial unit, compliance to internally measured values was quite good, especially considering the extended interval since artifact calibration.

Table 7. 5720A #2 Resistance (10kΩ - 100MΩ) Artifact Calibrated vs. Measured Value

Nominal	Artifact Cal Value	Measured Value	Difference (ppm)	5720A [24 hour, 95%] Specifications (ppm)
10kΩ	9.999873kΩ	9.999876kΩ	+0.3	6.5
19kΩ	18.999382kΩ	18.999395kΩ	+0.7	7.5
100kΩ	99.99901kΩ	99.99890kΩ	-1.1	7.5
190kΩ	190.00585kΩ	190.00537kΩ	-2.6	7.5
1MΩ	0.9999598MΩ	0.9999545MΩ	-5.3	13
1.9MΩ	1.8999585MΩ	1.8999504MΩ	-4.3	15
10MΩ	9.998903MΩ	9.998828MΩ	-7.5	28
19MΩ	18.998816MΩ	18.998560MΩ	-13.5	38
100MΩ	100.01630MΩ	100.01301MΩ	-32.9	85

Looking at the data from the third and final calibrator in this study, 5720A, serial number 7630206, the trend in performance shown with the previous calibrators continues. This unit was last artifact calibrated on the Fluke production line, 8 Aug 2000, some 463 days (more than 15 months!) prior to the following measurements taking place. Furthermore, the performance shown by the second and third units in this study would suggest that the stability of the internal resistors improve as they age. Both units were basically new (#3 is actually over 2 months newer than #2) at the outset of this study. Both were last artifact calibrated on the Fluke factory floor. Yet the difference in the data between #2 (taken approximately 8 months following artifact calibration) and #3 (taken 15 months after artifact calibration) indicates that the stability is actually improving. This example of stability improvement over a relatively short time (less than 6 months) confirms what has been shown previously with resistors of the type used in the 5720A. It is quite common when referring to laboratory-grade standard resistors to think of increasing stability improvement over time (1 to 2 years, or more) but it is quite surprising to see it demonstrated in a multifunction calibrator in a matter of a few months!

Table 8. 5720A #3 Resistance (1Ω - 1.9kΩ) Artifact Calibrated vs. Measured Value

Nominal	Artifact Cal Value	Measured Value	Difference (ppm)	5720A [24 hour, 95%] Specifications (ppm)
1Ω	0.9998851Ω	0.9998428Ω	-42.3	70
1.9Ω	1.9000198Ω	1.8999311Ω	-46.7	70
10Ω	10.000247Ω	10.000187Ω	-6.0	20
19Ω	18.999421Ω	18.999312Ω	-5.7	20
100Ω	100.00203Ω	100.00181Ω	-2.2	8
190Ω	189.98857Ω	189.98783Ω	-3.9	8
1kΩ	0.9999637kΩ	0.9999618kΩ	-1.9	6.5
1.9kΩ	1.8999554kΩ	1.8999552kΩ	-0.1	6.5

As with both units previously, performance exhibited for the higher (10kΩ and above) resistance values continued to be quite good. This reflects not only good compliance to internally measured (artifact calibrated) values, but also demonstrates exceptional stability, particularly when comparing the difference of the measured values from the indicated values with respect to the 24 hour, 95% specifications and especially in light of the extreme values measured (e.g., 100MΩ).

Table 9. 5720A #3 Resistance (10kΩ - 100MΩ) Artifact Calibrated vs. Measured Value

Nominal	Artifact Cal Value	Measured Value	Difference (ppm)	5720A [24 hour, 95%] Specifications (ppm)
10kΩ	9.999833kΩ	9.999838kΩ	+0.5	6.5
19kΩ	18.999307kΩ	18.999304kΩ	-0.2	7.5
100kΩ	99.99820kΩ	99.99825kΩ	+0.5	7.5
190kΩ	189.99566kΩ	189.99528kΩ	-2.0	7.5
1MΩ	0.9999598MΩ	0.9999553MΩ	-4.5	13
1.9MΩ	1.8999280MΩ	1.8999211MΩ	-3.6	15
10MΩ	9.999607MΩ	9.999496MΩ	-11.1	28
19MΩ	18.998505MΩ	18.998124MΩ	-20.1	38
100MΩ	100.01033MΩ	100.00763MΩ	-27.0	85

SUMMARY

As stated at the outset, the initial goal was to determine if the 5720A was satisfactory for use as a golden calibrator to support the calibration of the 4950MTS. This study, in particular, focused on the capability of the 5720A as an automated resistance standard to achieve that end. The goals were satisfied. However, during the course of this investigation, several beneficial side effects were also pleasantly discovered that bear mentioning: 1) the exceptional stability, relative to published specifications, that these calibrators exhibit (based on this small sample) for the resistance values available; 2) the resultant capability of the calibrator to measure quite accurately its own direct current function (which is derived from the internally measured resistance values). This latter aspect has also been previously substantiated in references (3) and (4).

The calibrators used in this investigation were chosen completely at random. Nevertheless, in many previous studies, the evidence shown is a testament to the integrity and repeatability of artifact calibration. Furthermore, with literally thousands of these calibrators in use around the world, the viability of artifact calibration has stood the test of time in practical applications as well. Some recent papers[11,12] have continued to reinforce this fact, as well as to demonstrate the overall value of characterizing these units. Therefore, it is reasonable to assume that the majority of the population of these calibrators are capable of achieving similar levels of performance.

The author has been associated with the 5700A-series of calibrators (in one way or another) since its release into the market in August, 1988. Since that time, practical experience gained through the characterization of various parameters of these calibrators, both internally at Fluke and by many external users, has confirmed their stability, as well as the efficiency of the artifact calibration process. However, it wasn’t until this investigation was undertaken, using high accuracy resistance measuring apparatus, that the extreme proficiency of the artifact calibration process for resistance in particular was appreciated and the excellent typical stabilities that can be achieved was fully realized. The level of performance attainable through characterization of the calibrator’s internal resistance function produces a programmable resistance standard of sufficient quality to rival many of today’s working standards, making it a boon to the efficiency and uncertainty requirements of the calibration laboratory.

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